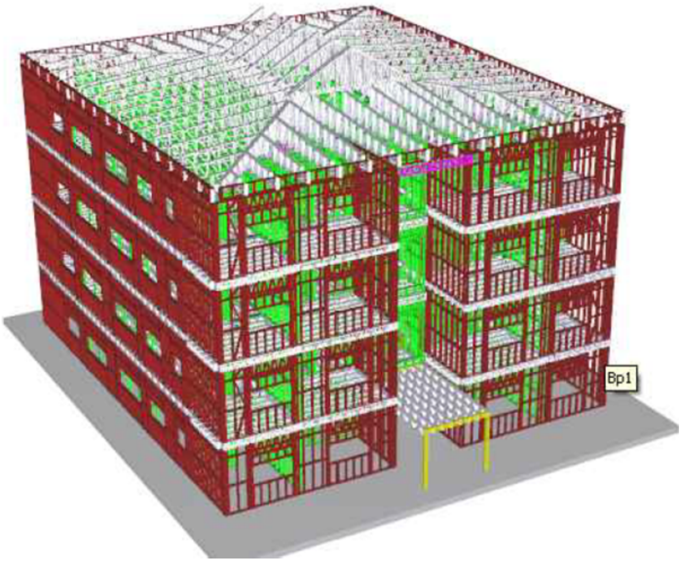
COMPARATIVE STUDY OF LIGHT STEEL FRAMING, HOT-ROLLED STEEL, CONCRETE AND TIMBER RESIDENTIAL SOLUTIONS – STRUCTURAL PERFORMANCE



Final Report – Case study – FORCATECH Building A

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EXECUTIVE SUMMARY

This report aims to provide unbiased information and resources to all stakeholders involved in the construction sector, identifying the strong and weak points of various structural solutions using different structural materials within the scope of low-rise (up to 4 storeys) multi-storey residential buildings, allowing them to make informed choices when selecting the structural material for their buildings.

The main goal of this study is to compare different structural materials, assessing their performance, based on a reference case study, the FORCATECH Building – A, provided by the Worldsteel Association. The reference solution is a residential, four storey building adopting a light steel framing solution, built in Luanda, Angola, modified as appropriate to match European requirements and design practice. The project consists of a four-storey residential building with a footprint of approximately 364 m^2. The benchmark study will compare the light steel framing solution with hot-rolled steel, reinforced concrete and timber solutions for residential buildings, all designed according to the relevant Eurocodes. Some scenarios were also defined in terms of seismicity levels, in order to assess its overall impact on all tested structural solutions. Simultaneously, constructive solutions for facades and for internal partitioning systems were detailed and prescribed, considering three climatic regions and two levels of performance, namely standard and high performance. The selected solutions are suitable for all different structural systems investigated and aim to tackle requirements related to thermal and acoustic comfort as well as requirements in terms of fire protection.

The light steel framing building comprises load bearing walls, fabricated using lipped channel profiles, and truss floor joist evenly spaced. The wall studs are spaced at 600 mm. In specific locations the cold-formed steel building is strengthened with some hot-rolled steel frames to resist lateral loading. A composite floor with profiled steel deck was selected for this building. A raft foundation was adopted for this building.

The hot-rolled solution is a moment-resisting system comprising standard steel sections. The solution consists of a composite floor system supported on hot-rolled steel frames. The considered spans are larger, and consequently the number of steel columns and footings is the smaller. For the foundation, isolated pad footings with lintels were adopted.

The reinforced concrete solution consists of reinforced concrete flat slabs with perimeter beams, supported by square columns and shear walls. The average span is smaller than the one adopted for the hot-rolled steel building, hence the larger number of columns and footings. For the foundation, isolated pad footings with lintels was selected, just like for the hot-rolled steel solution.

The timber building adopts a similar system to the cold-formed steel one. Hence, the timber framing solution comprises timber beams/joists and posts spaced evenly. For the floor a composite concrete-timber slab was selected. The lateral load resisting system comprises reinforced concrete shear walls and frames. A raft foundation was selected.

For the specific case study and for the established scenarios it was observed that the reinforced concrete structural solution was, by far, the heaviest one. The overall structural weight of the reinforced concrete building was about 120% higher than the cold-formed steel, 72% higher than the hot-rolled steel building and 76% higher than the timber building, for the reference situation with no-seismic action. Generally, the weight of the foundations and floors has a significant influence on the total weight of the structure. Hence, in some comparisons, these weights were neglected.

Generally, concerning the total weight of the superstructure, the seismicity level had some significant influence on the different buildings investigated. Depending on the structural system selected the overall impact varied. For instance, for the cold-formed steel and timber buildings, specific lateral force resisting systems were adopted ensuring that both cold-formed steel and timber structural elements were mainly resisting gravity loading. For the cold-formed steel building, the lateral force resisting system doubled its weight from a non-seismic location to a medium seismic location. The seismic location had a larger impact on the superstructure weight of the cold-formed steel building since the weight increase when considering the high seismicity level, was 25%. It was also observed that the seismic action had a higher impact on the lateral force resisting systems of the cold-formed steel and hot-rolled steel buildings. In some cases, the weight increased by 155% when compared with the reference case (no seismic action). For the reinforced concrete building the weight of the lateral force resisting system increased by 33% (from the reference case to the high seismicity level), and 29% for the timber building. It is noted that for the reinforced concrete and timber buildings, reinforced concrete shear walls were used.

Another very important aspect assessed in this study was the impact of the structural solution in the total weight of the foundation system. For the different building typologies, different foundation typologies were selected. As expected, the heaviest foundation system was the one prescribed for the reinforced concrete building and the lightest one for the cold-formed steel building. Assuming the cold-formed steel building as a reference, the reinforced concrete foundations were up to 74% heavier, whereas the hot-rolled steel foundations were up to 43% heavier and the timber ones up to 17% heavier. On the specific matter of foundations, it is also worth noting that the raft foundation adopted for the cold-formed steel and timber buildings is easier to build than the isolated pad footing system with equilibrium beams and suspended slab prescribed for the reinforced concrete and hot-rolled steel buildings. Comparing the foundation of the reinforced concrete and hot-rolled buildings, the latter benefits from the lighter structure and the larger spacing of the columns, explaining the 13% difference in weight between them. The selected seismicity levels had as well some impact on the total weight of the foundations. Specifically, for the hot-rolled steel and reinforced concrete buildings, considering the seismic action, led to an increase in the weight of the foundations of up to 16% and 25%, respectively, when comparing with the corresponding reference scenarios (HRS and RC buildings in a non-seismic location).

For the studied cases, a detailed construction schedule was conducted, assessing the competitiveness of each framing solution in terms of the duration of the construction. A detailed analysis was undertaken, ensuring that practical erection sequence and simplicity of assembly are taken into consideration. The construction schedule is a very important factor in the decision process. Faster construction schedules will lead to lower costs and earlier income for the owner. From the conducted analysis, clearly, the prefabricated cold-formed steel solution is more competitive in terms of the overall duration. Comparing the reinforced concrete with the cold-formed steel framing solution, the construction times can be reduced by about 23% for the reference case and 22% for the high seismic case for this specific building. Comparing the reinforced concrete with the hot-rolled steel framing solution, the construction times can be reduced by about 8.8% for the reference case and 8.7% for the high seismic case. Comparing the reinforced concrete with the timber framing solution, the construction times can be reduced by about 7% for the reference case and 10% for the high seismic case.

It is worth emphasizing the advantages of prefabrication in the building construction industry. Prefabricated solutions will have a lower impact on the construction site and its surroundings, reducing waste. Moreover, these solutions present higher potential and inherent added value in terms of adaptability and expansion of the building. Lightweight solutions with faster construction schedules may bring additional cost savings in different construction operations. For instance, the reduced number of on-site works will lead to lower waste and lower disposal costs, as well as to increased safety levels for the workers, whereas the reduced construction schedules will lead to reduced costs and usage of elevation equipment.

1. SCOPE

1.1 INTRODUCTION

The selection of the most adequate structural material has always been the subject of debate in the construction industry. Hence, comparing the merits of each of the most common structural solutions is crucial to provide to all stakeholders with relevant and reliable information concerning each structural material, therefore contributing to an informed decision. To achieve this objective, it was decided to carry out a comparative study of different structural solutions for a four-storey residential building. In this report, a light steel framing solution for multi-storey residential buildings is compared with other structural systems using different structural materials, namely hot-rolled steel, reinforced concrete and timber.

The purpose of this study is to design a reference building and compare the resulting structural solutions for subsequent life-cycle assessment in the framework of the ISO standards ISO 14040 and 14044 and the CEN standards from TC 350. The chosen reference case study is a light steel framed building, the FORCATECH BUILDING-A (Figure 1.1), originally located in Luanda, Angola, modified as appropriate to match European requirements and design practice. The structural design is carried out according to the relevant structural Eurocodes thus ensuring adequate performance levels for each solution. In this report, all comparisons are carried out on the basis of the structural weight of the different materials with some additional comparisons based on an estimation for the construction times associated with each one of the structural systems. It is emphasized that this study is followed by a full life-cycle assessment of all solutions, including life-cycle costing (LCC), whereby a proper cost assessment will be carried out since material costs are not representative of the total cost of a structure.

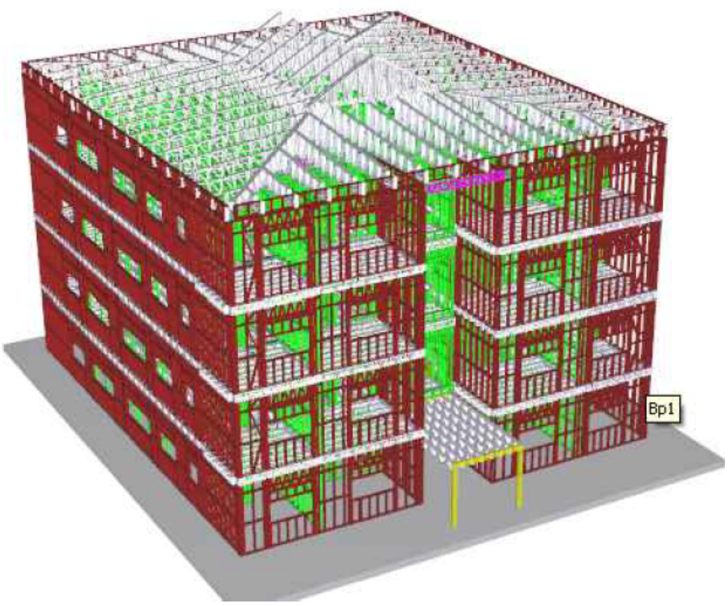


Figure 1.1. Adopted case study - FORCATECH BUILDING – A.

In order to achieve a representative coverage of Europe, geographically-dependent conditions had to be considered. Hence, besides the reference building located in a non-seismic region, different seismicity levels are also considered, corresponding to medium and high seismicity levels. Also, some variations within some of the structural materials are contemplated, namely the use of high strength steel, for the case of the cold-formed and hot-rolled steel buildings. Moreover, some hybrid solutions are also considered where, for instance, cold-formed steel structures are combined with hot-rolled steel ones in order to reduce the overall impact of the seismic action on the lightweight cold-formed steel structure.

To provide additional data to support the decision regarding the structural material to be adopted the execution programme for each solution is also presented and detailed. Just like the overall cost, the execution programme is also a key parameter when choosing the frame material. Issues related to prefabrication, buildability, adaptability, extendability and potential for reuse and recyclability will also be discussed.

1.2 MAIN ASSUMPTIONS

The general design criteria, strategies and assumptions in this study were prepared by ISISE/ACIV/UC, aimed at providing an unbiased comparison between light steel framing, hot-rolled steel, reinforced concrete and timber framing solutions, considering different seismicity levels. Moreover, for the light steel framing solution, two steel grades were considered and compared: S320GD+Z and high strength steel S550. Also, in the hot-rolled steel solution, two steel grades were considered and compared, namely S355 and S460. The following material grade/class were selected for the different tested buildings:

- cold-formed steel – high strength G550 and S320GD+Z;
- Hot-rolled steel – S355 and S460;
- Concrete – C30/37;
- Reinforcement bars – A500.
- Timber – C24 class.

Regarding concrete, a specific mix was assumed to provide additional details regarding material consumption. In Table 1.1 some details of the involved materials are presented.

Table 1.1. The density of different materials used in the concrete mix.

Materials used in the mix	**Density - ρ $[kg/m^3]$**
Cement Type I 32.5R [CEM]	3100
Aggregate 1 (12 to 18 mm) [A1]	2700
Aggregate 2 (5 to 12 mm) [A2]	2700
Sand (S)	2700
Filler [F]	2700
Fine sand (FS)	2600
Plasticizer (SP)	1030
Water (W)	1000

The considered concrete mix is presented in Table 1.2. In the estimation of all quantities, for the different studied buildings, a waste of 5% was considered.

Table 1.2. The composition of the concrete mix considered.

	CEM [kg]	SP [kg]	A1 [kg]	A2 [kg]	S [kg]	FS [kg]	F [kg]	W/C
C30/37	400	11.6	600	321	470	230	200	0.4

The designs were based on the relevant Eurocodes taking into account the site-specific location for the building, to determine appropriate design loads and ultimately the bill of materials. The following locations were considered:

- Bucharest, Romania – High seismicity zone;
- Faro, Portugal – Medium seismicity zone;

The scope of this study includes the structural framing, passive fire protection materials where applicable and foundations. The design did not include details for all connections or similar items. To estimate the material weights, allowances based on typical conditions and on some details assessed in this study were considered. Within this framework, four different structural solutions were modelled, representing the most common building materials, namely, cold-formed steel, hot-rolled steel, reinforced concrete and timber. For each structural system, different seismicity scenarios will be considered. Based on the same architectural layout 3D structural modelling and analysis have been performed by SAP2000. In this study, the bill of materials for each structural solution was determined, providing data related to the competitiveness of each material for the structural framing for residential buildings.

As a global overview, a summary of the construction options tested is presented in Table 1.3. Each structural solution will be further detailed in Chapter 3.

Table 1.3. Summary of the construction options tested.

Option	Floor System	Framing	Lateral load-resisting system
Light Steel Framing	Composite slab with steel deck (80 mm)	Cold-formed steel wall panels + Hot-rolled steel profiles	CFS wall panels and hot-rolled steel braced frame
Hot-Rolled Steel Framing	Composite slab with steel deck (140 mm)	Hot-rolled steel sections	Moment resisting frames
Reinforced Concrete	Flat slab (180 or 200 mm)	Reinforced concrete beams and columns	Moment resisting frames and shear walls
Timber	Composite slab with timber panel and reinforced concrete (80 mm)	LVL sections	Plywood or CLT shear walls in both directions + reinforced concrete shear walls

For the foundations, different solutions were also considered for the different types of buildings as follows:

- raft foundation with strengthening protruding beams – Cold-Formed Steel and Timber buildings;
- Isolated pad foundations with equilibrium beams and suspended ground floor – Hot-Rolled Steel and Reinforced Concrete buildings;

Cladding solutions are also proposed for both wall facades and internal partitioning, considering the different type of use of each compartment in the building and also different climatic areas and different levels of performance. The proposed solutions are versatile and consequently may be used in all tested buildings. In Chapter 3 the assumptions considered are presented and in Annex A the specific range of products is detailed.

2. CASE STUDY – FORCATECH BUILDING - A

The reference case consists of a four-storey residential building, the FORCATECH BUILDING – A, located in Luanda, Angola, with a footprint of approximately 364 m2, fabricated with cold-formed steel and a hot-rolled steel core for the stairs area. Hence, this is a hybrid building, combining both cold-formed steel and hot-rolled steel structural materials. The building comprises four two-bedrooms apartments per each floor level, an interior hall and stairs. In the original building, no elevators were considered. The reference case was located in Luanda, Angola, and regarding the seismic data, the corresponding importance factor (I) is equal to 1 according to IBC 2009 [1]. The structure was designed to withstand gravity loading (self-weight plus imposed) and the predominant wind loads. The total height of the building is 15.19 m with a 3.2 m storey height. The clear finished floor to ceiling height is 2.6 m. The building used a panellised system, comprising load bearing walls distributed in both directions and a floor system comprising truss beams and composite floor with profiled steel sheets and concrete (minimum concrete strength of F_0=20 MPa according to ACI 318-05 code), corresponding to C20/25.

A small change was introduced to the reference case, allowing for the incorporation of two elevators, fulfilling European requirements for this type of buildings. Moreover, for all tested solutions, it was assumed a flat roof. However, no changes were introduced to the overall dimensions of the building. In Figure 2.1, the original groundfloor footprints for the original case and for the modified building are depicted.

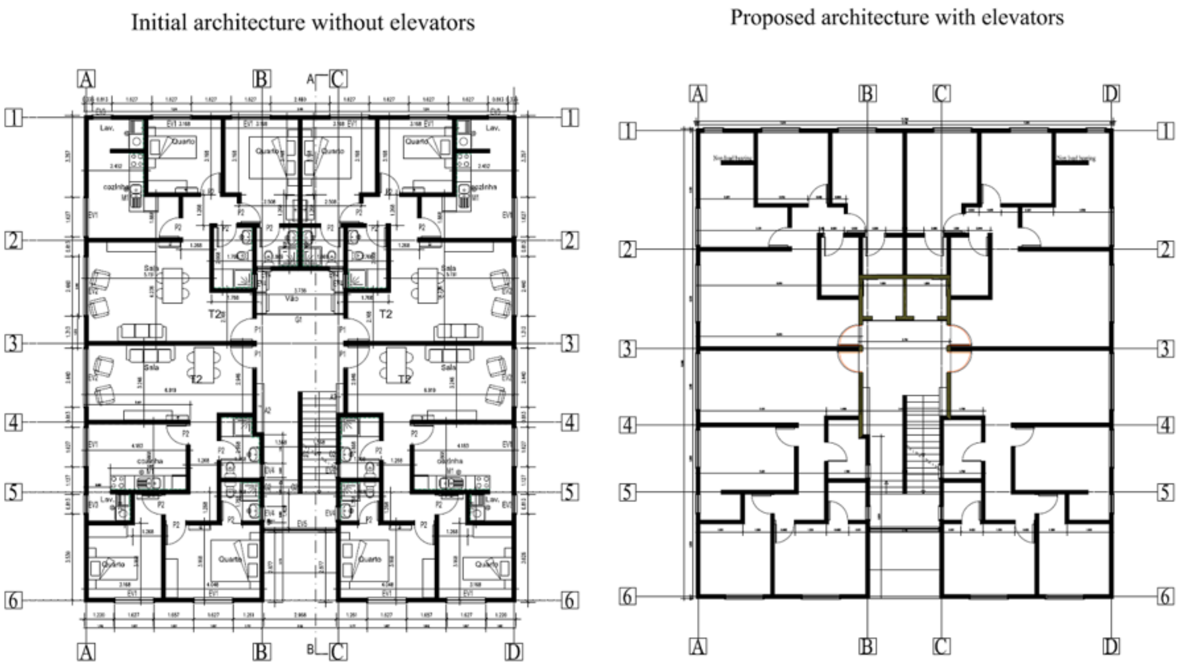


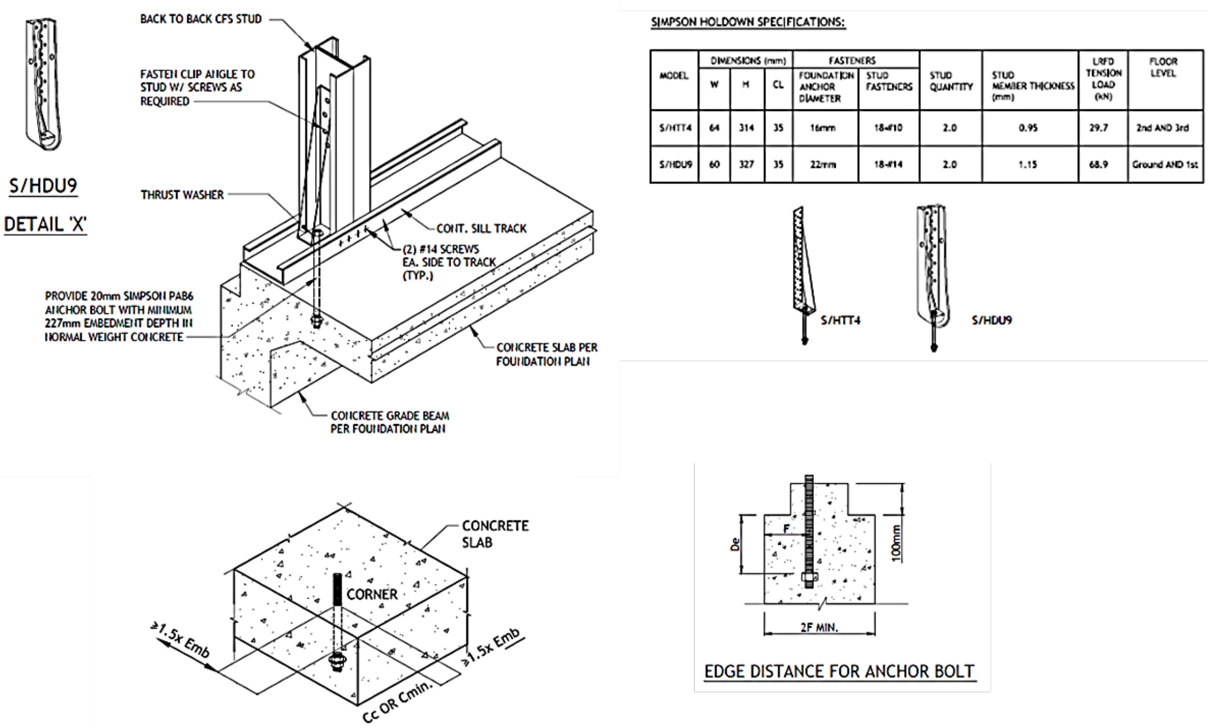
Figure 2.1. Comparison between the original and modified ground floor configuration.

The most relevant physical characteristics are detailed in Table 2.1.

Table 2.1. Relevant physical characteristics.

Building width	19.996 m
Building length	17.750 m
Wall height	3.2 m
Wall stud spacing (LBW)	0.406 m
Wall stud spacing (NLBW)	0.610 m
Floor joist spacing	0.406 m

The building consisted of wall framing solution made of high strength cold-formed steel (G550). The external and internal load bearing walls consisted of 150×41×11 studs with 1.15 mm thick and 12 mm or 9 mm fiber cement boards on each side for external and internal walls, respectively. Cold-formed steel straps were used as cross-bracing for the wall panels. To fix the load bearing and non-load bearing walls, anchor bolts and Simpson holdown devices were used as depicted in Figure 2.2. It is worth mentioning that double studs were used at each of the holdown device location (Figure 2.2).



MODEL	DIMENSIONS (mm)			FASTENERS		STUD QUANTITY	STUD MEMBER THICKNESS (mm)	LRFD TENSION LOAD (kN)	FLOOR LEVEL
	W	H	CL	FOUNDATION ANCHOR DIAMETER	STUD FASTENERS				
S/HTT4	64	314	35	16mm	18-#10	2.0	0.95	29.7	2nd AND 3rd
S/HDU9	60	327	35	22mm	18-#14	2.0	1.15	68.9	Ground AND 1st

Figure 2.2. Anchor bolts and Simpson holdown devices.

The floor framing comprises truss joists spaced at 0.406 m and aligned with the load bearing wall panels. The floor joists were 300 mm deep and fabricated with lipped channels 89×41×11 profiles with a thickness of 1.15 mm. The composite slab was 80 mm thick (Figure 2.3) made of normal strength concrete.

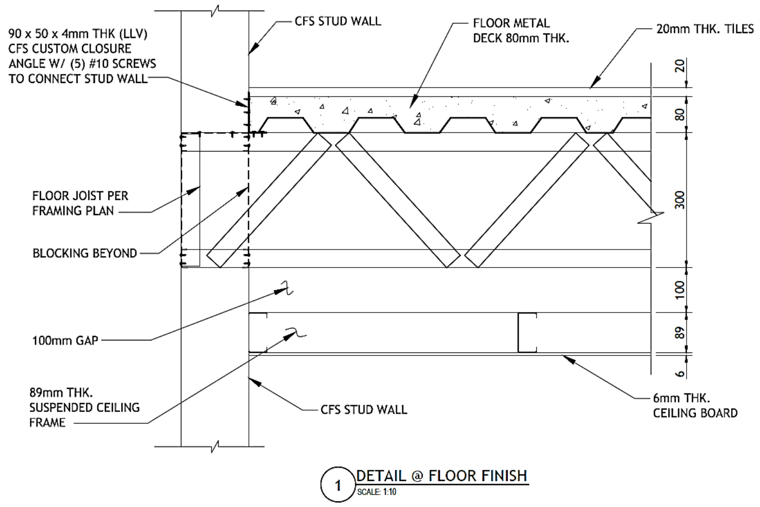


Figure 2.3. Floor joists and composite floor.

At the entrance of the building and in the stairs zone hot-rolled steel profiles were used. In order to accommodate the elevators in the modified version of the building, hot-rolled steel frames were also considered in that area (Figure 2.1).

For the foundations, a mat foundation was adopted, considering different thicknesses for the external load bearing walls (perimeter of the concrete slab) and for internal load bearing walls (entrance and stairs area of the building). The minimum height of the concrete slab is 250 mm and the maximum height is 600 mm in the external load bearing walls and 650 mm at the internal load bearing walls. For the external perimeter of the slab, a thickness of 350 mm was considered, whereas for the internal load bearing wall a thickness of 400 mm was adopted. In Figure 2.4 some details are depicted.

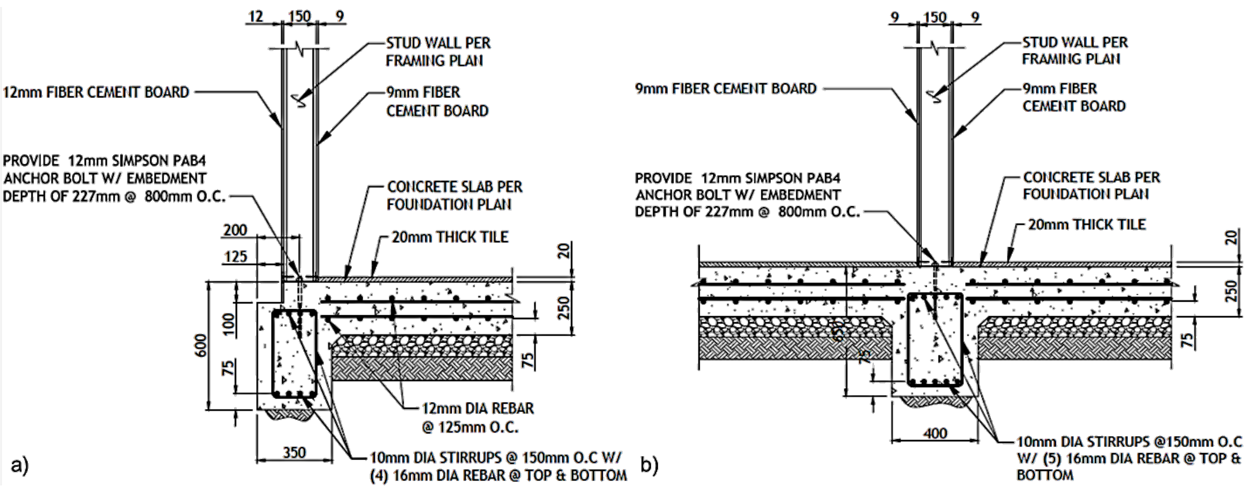


Figure 2.4. Details on the foundations for the reference building. a) Raft foundation at an external load bearing wall. b) Raft foundation at an internal load bearing wall.

3. FACADES AND INTERNAL PARTITIONS

Specifying the facades and internal partitions constitute an essential part of the design process of the building. They have multiple implications in the design process:

- Definition of mechanical loading actions on the structure;
- Thermal comfort and energy efficiency;
- Acoustic comfort;
- Hygrothermal performance
- Fire resistance;

Thermal comfort and energy efficiency and hygrothermal performance are highly dependent on the climatic region where the building will be located. In order to address this issue, the climatic zones in Europe were selected according to the Koppen-Geiger climate classification [2], as shown in Figure 3.1.

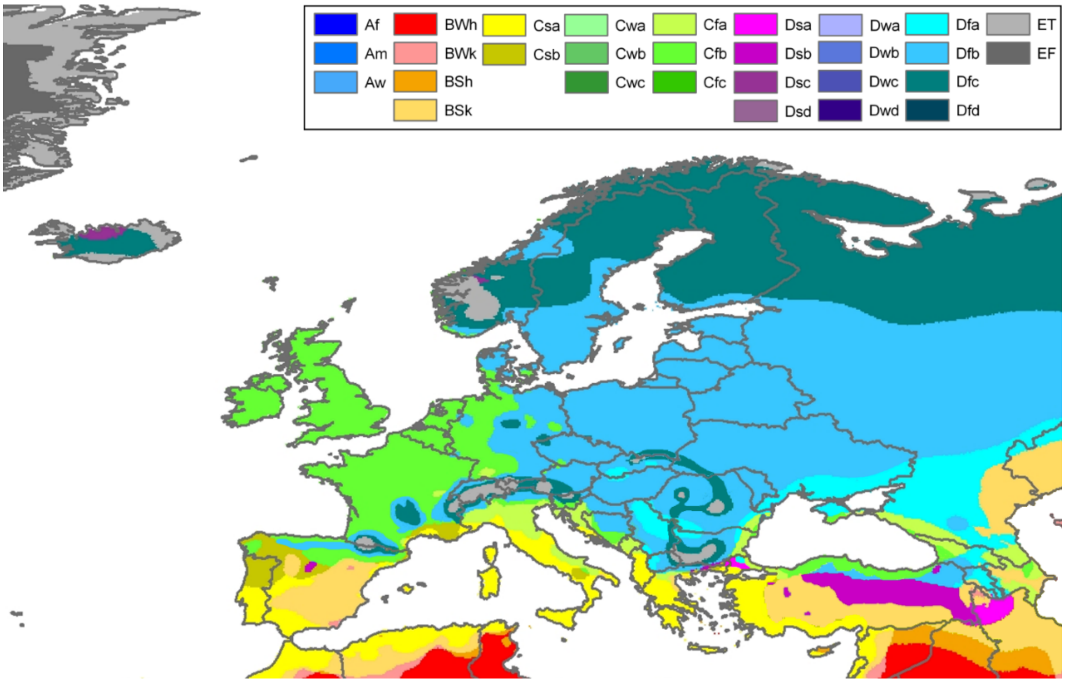


Figure 3.1. Koppen-Geiger climate classification for Europe. (Peel et al. (2007))

Specifically, the adopted climatic areas considered were as follows:

- Csa / Csb – Warm Mediterranean climate / temperate Mediterranean climate;
- Cfb – Temperate oceanic climate;

- Dfa / Dfb – Warm continental climate/humid continental climate / temperate continental climate/humid continental climate.

State-of-the-art dry solutions were chosen for the facades and internal partitions, common to all structural solutions. Commercially available cladding solutions for wall facades and internal compartmentation were prescribed to the tested structural solutions for each of the three climatic regions from 2 product lines (standard and high performance). Hence, for each climatic area, two product lines were prescribed, namely a standard/commonly used solution and a high-performance one. The products selected and prescribed fulfil the established requirements in terms of fire resistance, acoustic insulation and thermal insulation.

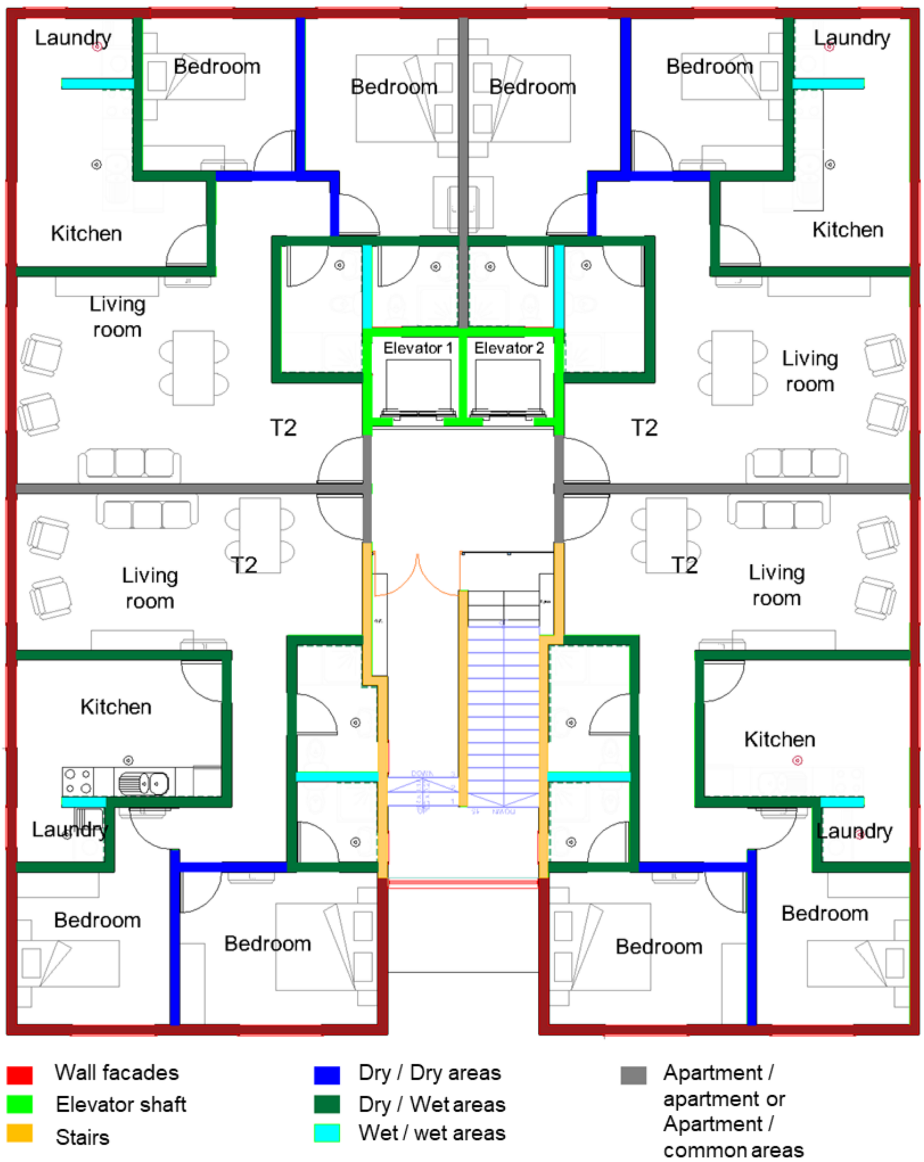


Figure 3.2. Partitioning solutions to be adopted.

Based on the architectural layout of the building, each compartment was analysed and the most adequate cladding solution was selected, considering two performance levels. In Figure 3.2, the adopted partitioning solutions are detailed for each compartment and external facades. In Annex A all solutions prescribed for wall facades and internal partitioning are prescribed and detailed based on the partitioning requirements defined in Figure 3.2.

It is worth mentioning that for the cold-formed steel and timber buildings the cladding solutions are fastened directly to the structural member (steel studs and joists, and timber posts and beams), excluding the need to use the metal profiles to hold the different panels. The spacing of the steel studs and timber posts is identical to the spacing used for the metal profiles in a cold-formed steel wall assembly. This represents an advantage for these types of buildings since the overall weight associated with the cladding solutions will be lower. The sheathing solutions, specifically for the cold-formed steel and timber buildings also contribute to the lateral resistance of the buildings provided that fixation is adequately prescribed, ensuring a spacing for the fasteners of 100 mm.

4. CONCEPTUAL DESIGN

4.1 GENERAL CONSIDERATIONS

In this chapter, the conceptual design of the alternatives considered is briefly summarised. Their structural design incorporates the interaction between the architectural requirements and the structural engineering capabilities. Hence, based on the initial reference case, the studied structural solutions were designed to ensure the structural functionality conforming to the architectural and structural constraints imposed by the reference case.

The structural model was implemented in software SAP2000 v.20.0.0 [3]. All the beams and columns were modelled with beam elements, the shear walls were modelled with shell elements. The slabs were modelled using a layered thin shell that considers also the steel sheet. At each floor, a rigid diaphragm was considered. The seismic action is included in the analysis by a response spectrum analysis. A static linear analysis was employed considering the fundamental group of combinations.

Concerning seismic design, a crucial issue is to define the design concept and the value of the behaviour factor q. The design concepts, Low-dissipative structural behaviour or Dissipative structural behavior, are illustrated in Figure 4.1.

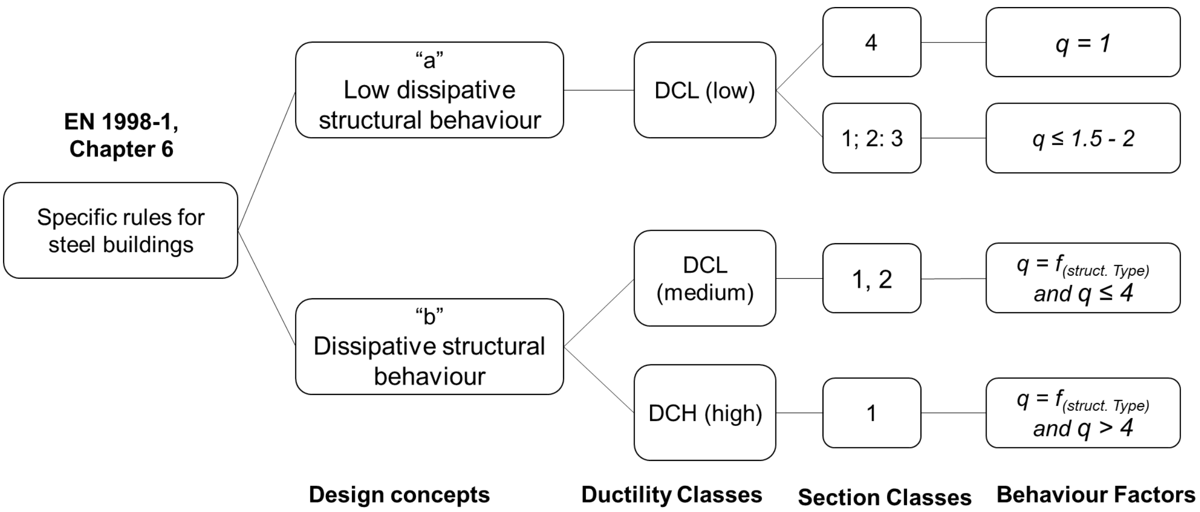


Figure 4.1. Design concepts according to EN 1998-1 [4]

In concept a), the action effects may be calculated on the basis of an elastic global analysis neglecting the non-linear behaviour, because a low dissipative structure does not fulfil the conditions to apply a plastic design for predominantly static loading. In this case, the behaviour factor assumed in the calculation must be less than 2. This is the case of the LSF solution and the timber solution, while for the HRS solution and the RC solution dissipative structural behaviour may be considered. In this case, the behaviour factor q depends on the structural system according to the relevant ductility classes considered by EC8-1 [4]. For the reinforced concrete solution Ductility Class Medium was selected whereas for the hot-rolled steel solution adopted ductility class was the Ductility Class High. Table 4.1 summarizes the adopted behavior factors for the 4 structural solutions. Complementary, some additional cases were studied for some structural solutions, namely hot-rolled steel and reinforced concrete. A low seismic location was selected, Coimbra, in Portugal, and different behavior factors were investigated. For the reinforced concrete the behaviour factor *q=3* was also considered and for the hot-rolled steel, the Ductility Class Medium with a behavior factor of *q=4* was also investigated. Specifically, for these cases, only the impact on the superstructure was assessed.

Table 4.1. Behaviour factors q.

LSF	HRS	RC	TS
2 (DCL)	6.5 (DCH)	3.9 (DCM)	2

Another very important aspect of this study is the assessment of the overall impact of the adopted structural solution on the foundations of the buildings. Foundations are the major part of the building's substructure. For each structural solution, specific foundation solutions were prescribed and designed. The following types of foundations were adopted for the different structural solutions:

- Cold-formed steel building – Raft foundation incorporating stiffening beams in the perimeter of the building and internal core;
- Hot-rolled steel building – Pad footings with suspended ground floor slab;
- Reinforced concrete building – Pad footings with suspended ground floor slab;
- Timber building – Raft foundation incorporating stiffening beams in the perimeter of the building and internal core.

Regarding the fire safety of the studied buildings different and tailored solutions have to be prescribed to each one of the buildings. Firstly, it is necessary to define clearly what are the requirements that the residential building with four storeys must fulfil in terms of load bearing capacity (R), integrity (E) and insulation (I). For the definition of the fire resistance requirements, the Portuguese legislation was adopted. Hence, according to the law, DL n.º 220/2008 [5] and Law n.º 1532/2008 [6] the risk category of the studied building is assessed considering the height of the building and the number of floors below the ground level. The height of the building corresponds to the height of the last floor susceptible to have a permanent use. Consequently, the height of the building for the definition of the category risk is 9.6 m, and according to the Portuguese legislation, the requirement in terms of fire resistance is R 60 for load bearing elements, REI 60 for loadbearing and compartmentation elements and EI 60 com compartmentation elements. The structural fire design is conducted according to the relevant Eurocodes, namely EN 1991-1-2 [7], EN 1992-1-2 [8], EN 1993-1-2 [9], EN 1994-1-2 [10] and EN 1995-1-2 [11]. It is worth mentioning that for all structural solutions the adopted cladding solutions present inherent fire resistance characteristics both in terms of load bearing capacity (for the cold-formed steel and timber buildings) and compartmentation. The presented solutions in Annex A were tested and certified according to the European standards for fire resistance.

In the following sections, the key aspects of the structural design for each solution are summarized.

4.2 COLD-FORMED STEEL

4.2.1 Description of the structural system

The structural solution in LSF closely follows the details provided in the reference case. However, since the Forcatech Building was not fitted with lifts neither it was designed for a seismically active area, some necessary structural modifications were implemented. Moreover, and as previously mentioned a flat roof solution was assumed for all buildings. Just like for the reference case, a hybrid solution was adopted for this building, combining both cold-formed steel and hot-rolled steel structural materials.

In the LSF solution, composite slabs were used for the floor system as in the real building. It was assumed that the floors were able to act as a rigid diaphragm, transferring the loads to the vertical load-bearing system.

The traditional light steel framing structural system comprises two basic types of walls [12]: *loadbearing walls*, for interior and exterior, and *non-loadbearing walls* (interior for partition). Structural lipped channel section, "C" steel profiles, are the most used shape. In case of loadbearing walls, the main structure is made by vertical studs spaced usually at 600mm, in line with floor joists, and fastened at each end to wall tracks, that have the function of distributing loads among the studs (see Figure 4.2). Sometimes, supplementary lipped channel profiles are installed to strengthen the stud along the height.

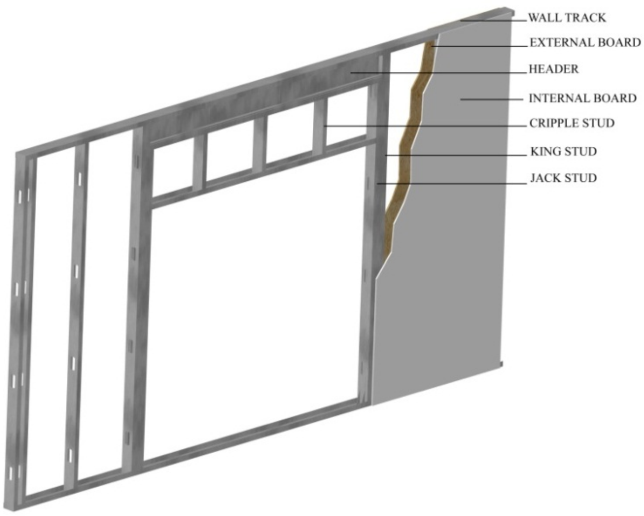


Figure 4.2. Structural layout for the light-steel framing building [ref].

The loadbearing walls should be designed to carry vertical loads transferred from upper floors and roof and they have to resist to horizontal loads (normal and in the plane of the wall) as wind and seismic actions. A typical light-framed shear wall transfers lateral loads, in the plane of the wall, through the mechanically attached sheathing, and into the framing members. The in-plane shear loads are transferred from the wall to the floor framing or foundation along the length of the bottom horizontal member (bottom track). The induced overturning forces are transferred through the vertical boundary members (end studs) and over-turning restraint system (hold-downs) at the ends of the wall. In particular, the ability to resist to horizontal in-plane actions can be achieved by different systems: a) X bracing; b) installing horizontal steel structural sheathing on one or both wall sides; c) fastening structural sheathing boards (OSB) on one or both studs sides, d) mixed solution a-b-c (see Figure 4.3). In particular, structural sheathings have to be installed with the long direction parallel to the studs and have to cover the full height.

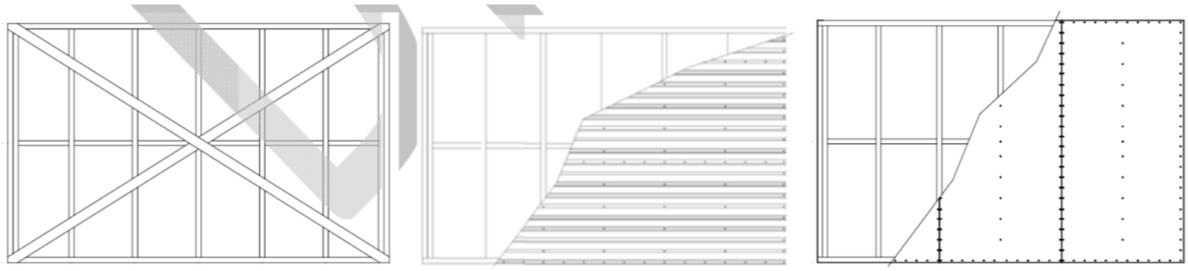


Figure 4.3. Structural layout for the light-steel framing building [ref].

Wall thickness can be varied to meet the structural and insulation requirements of the building. Exterior rigid insulation is applied to the walls to minimize thermal bridging and comply with building code requirements. The result is a sandwich construction where each panel can undertake perpendicular pressure on its surface as well as horizontal in-plane loads. The internal wall cavity is ideal for inserting cables, pipes and make easy to add equipment.

Hence, the load bearing system wall system is executed with cold-formed steel studs in order to assure the building resistance against vertical loads, as well as wind and seismic actions. In addition, steel bracings with steel straps for the diagonals were used to achieve appropriate in-plane resistance. The cold-formed steel load bearing wall panels are fixed using anchor bolts and Simpson connectors preventing up-lift of the walls.

The structural layout is shown in Figure 4.4. Moreover, hot-rolled steel moment resisting frames (painted in red in Figure 4.4) located on axes 4-6, B and F were considered in order to provide an inner rigid core for the lifts and the stairs and also to provide additional stiffness for the seismic action. Hence, a major part of the horizontal loads is resisted by these frames allowing for a lighter cold-form steel solution.

For the seismic design of the structure, the moment resisting frames are assumed as Ductility Class Low with a behaviour factor q=2.

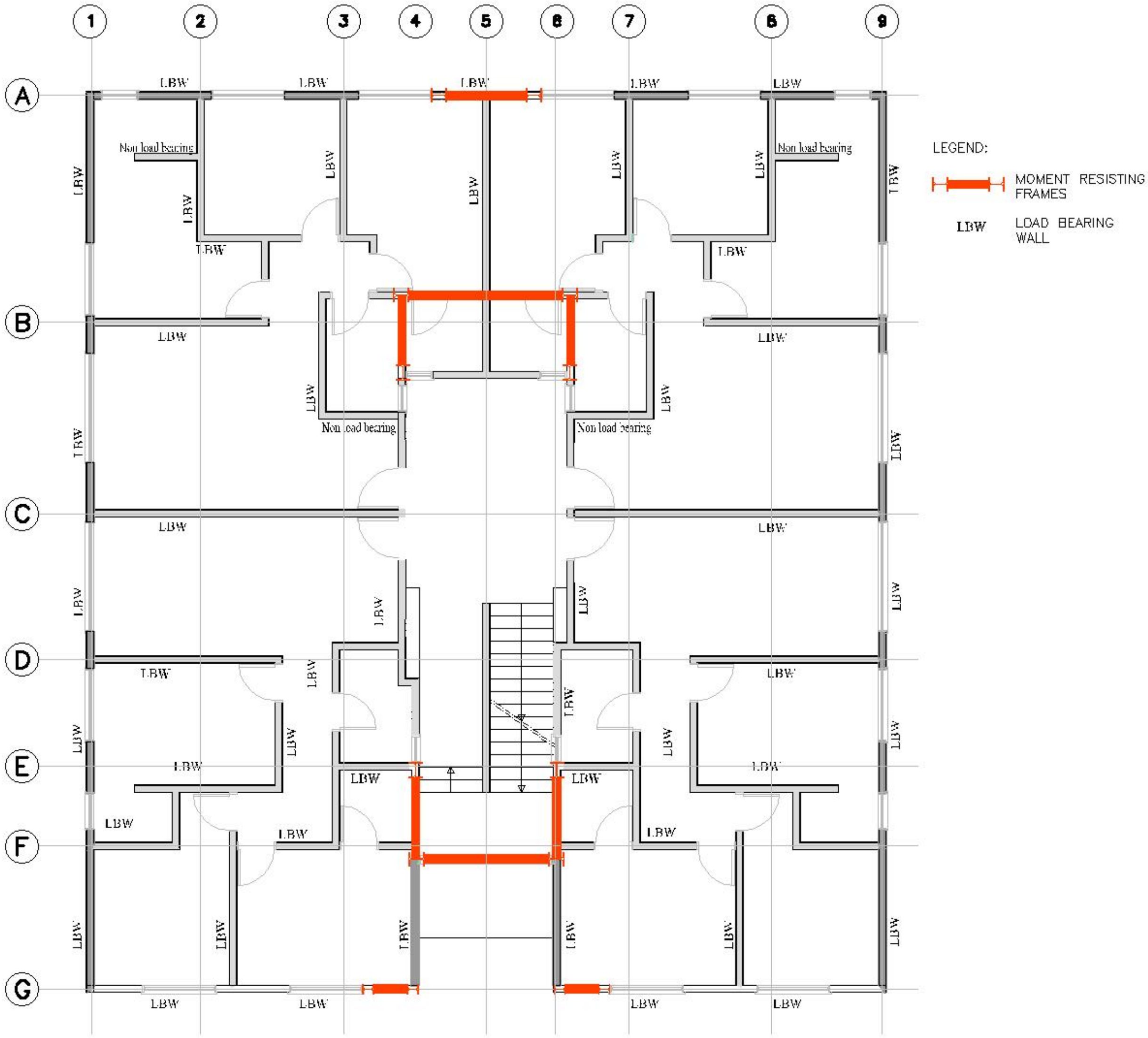


Figure 4.4. Structural layout for the light-steel framing building.

4.2.2 Structural fire design

Light steel framing solutions, using cold-formed steel profiles usually present a good fire resistance since fire protection is always used considering one or two layers of gypsum boards or calcium silicate boards, which are able to provide fire resistance periods of more than 60 minutes. Many different cladding solutions with fire resistant properties can be prescribed for this type of construction. In Annex A some solutions are presented for both facades and internal partitions. For separating walls and considering the target of 60 minutes of fire resistance, two 12.5 mm boards are commonly used. Even for suspended floor ceiling, two 12.5 mm boards shall be used.

4.2.3 Foundations

The overall reduced weight of the cold-formed steel structure allows the use of a shallow reinforced concrete raft foundation. Hence, the forces are transmitted to the soil by means of a reinforced concrete slab. In the perimeter and in the core area of the building a thickening of the slab is prescribed, forming strengthening beams in the more heavily loaded zones. A minimum thickness of 250 mm is necessary for the anchor bolts that are used to fix the load bearing walls to the ground floor slab.

In terms of design the adopted raft foundation, strengthened with protruding beams in the more heavily loaded areas, is designed assuming that the slab spans in two directions and that the beam and slab act as inverted beams and slab floor.

The geotechnical design for raft foundations is conducted according to the section 6 of the EN 1997-1 [13]. For this particular study it was assumed a non-cohesive soil, namely a medium gravel or medium gravel and sand with an allowable bearing pressure of 200 kPa.

4.3 HOT-ROLLED STEEL

4.3.1 Description of the structural system

The second structural solution is a moment-resisting structural system composed of hot-rolled steel sections, which are commonly used in residential and office buildings. A typical plan of the structural layout is shown in Figure 4.5. The structural solution consists of a composite floor system, supported on steel frames. The floors are designed with profiled steel sheeting filled with reinforced concrete. In order to guarantee the composite action, a sufficient number of shear studs connecting the steel sheeting to the beams was considered.

Due to the architectural restrictions, it is not possible to use vertical bracing against lateral loads, for that moment resisting frames in both major directions are considered, namely the frames on axes A, B, F, G, 4 and 6, which are pained in red in Figure 4.5.

For the seismic design of the structure, the moment resisting frames are assumed as Ductility Class High with a behaviour factor of q=6.5 for a moment resisting steel framed structure [14]. A solution considering Ductility Class Medium with a behaviour factor of q=4 was also tested for comparison purposes.

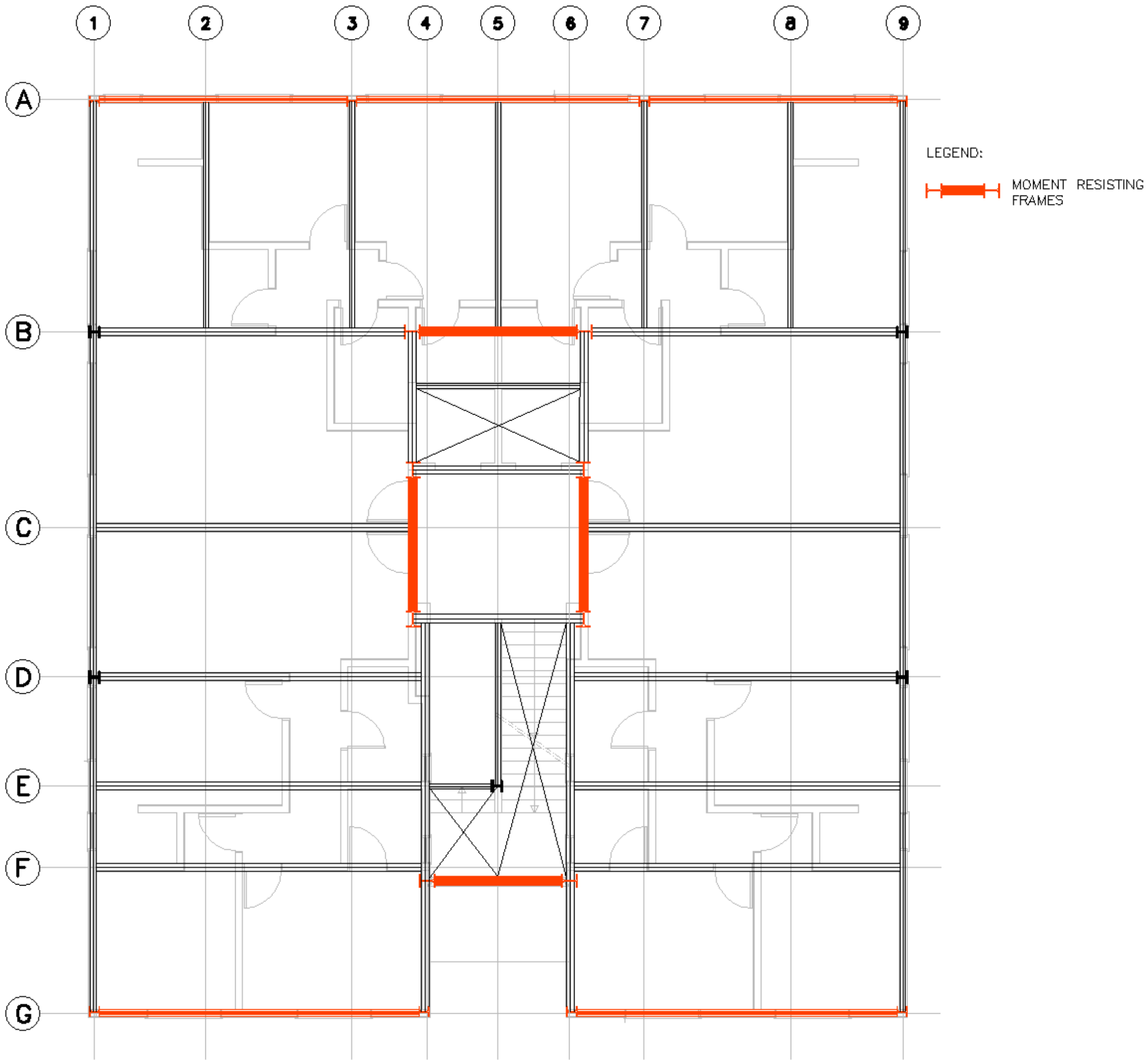


Figure 4.5. Hot-rolled steel structural layout.

4.3.2 Structural fire design

Steel has high thermal conductivity and specific heat, meaning that the temperature will rise very fast in a cross-section. Moreover, the mechanical properties of steel degrade with temperature increase. For instance, at 600ºC the reduction of the yield strength of the steel is more than 50%, whereas the modulus of elasticity reduced by 70%. Nowadays, the most common solution to protect steel structures is the use of intumescent paints applied on-site or in the workshop. However, specifically in this study, it was decided to take advantage of the selected wall facades and internal partitioning systems that use gypsum boards.

4.3.3 Foundations

For the hot-rolled steel building, the columns carry larger axial loads than in CFS buildings, at fewer supports. Due to this structural solution, it was assumed a foundation composed of rectangular concrete footings connected with concrete lintels, that are also responsible for supporting ground floor slabs.

Axial loads from the columns are transmitted to the soil by the rectangular footings. The lintels are designed to resist bending moments from columns, support ground floor slabs and to work as a tie-beam, providing enough stiffness to uniformly transmit the localized actions received from the superstructure to the ground.

The geotechnical design for these foundations is also conducted according to the section 6 of the EN 1997-1 [13]. It was also assumed a non-cohesive soil, namely a medium gravel or medium gravel and sand with an allowable bearing pressure of 200 kPa.

4.4 REINFORCED CONCRETE

4.4.1 Description of the structural system

As a very common solution in practice, a reinforced concrete structure was also considered in this comparative study. The typical plan view is presented in Figure 4.6. The structure consists of reinforced concrete flat slabs supported by square RC columns and shear walls. On the outer perimeter of each floor, RC beams were introduced to release the critical verification of punching shear at the slab edges.

As commonly assumed, the RC flat slab is expected to have sufficient in-plane stiffness in order to provide a rigid floor diaphragm at each floor. This action allows for the smooth transfer of lateral loads to the vertical load bearing system. In the RCS case, the lateral loads are resisted by the core located in between axes 4-6 and B-C; the shear walls on axes 4-6 and F; moment resisting frames along axes A and G; and additionally, the participation of all RC columns was also accounted for in the structural analysis. All members were designed assuming Ductility Class Medium with a behaviour factor q=3.9 for an RC structure with shear walls and RC frames.

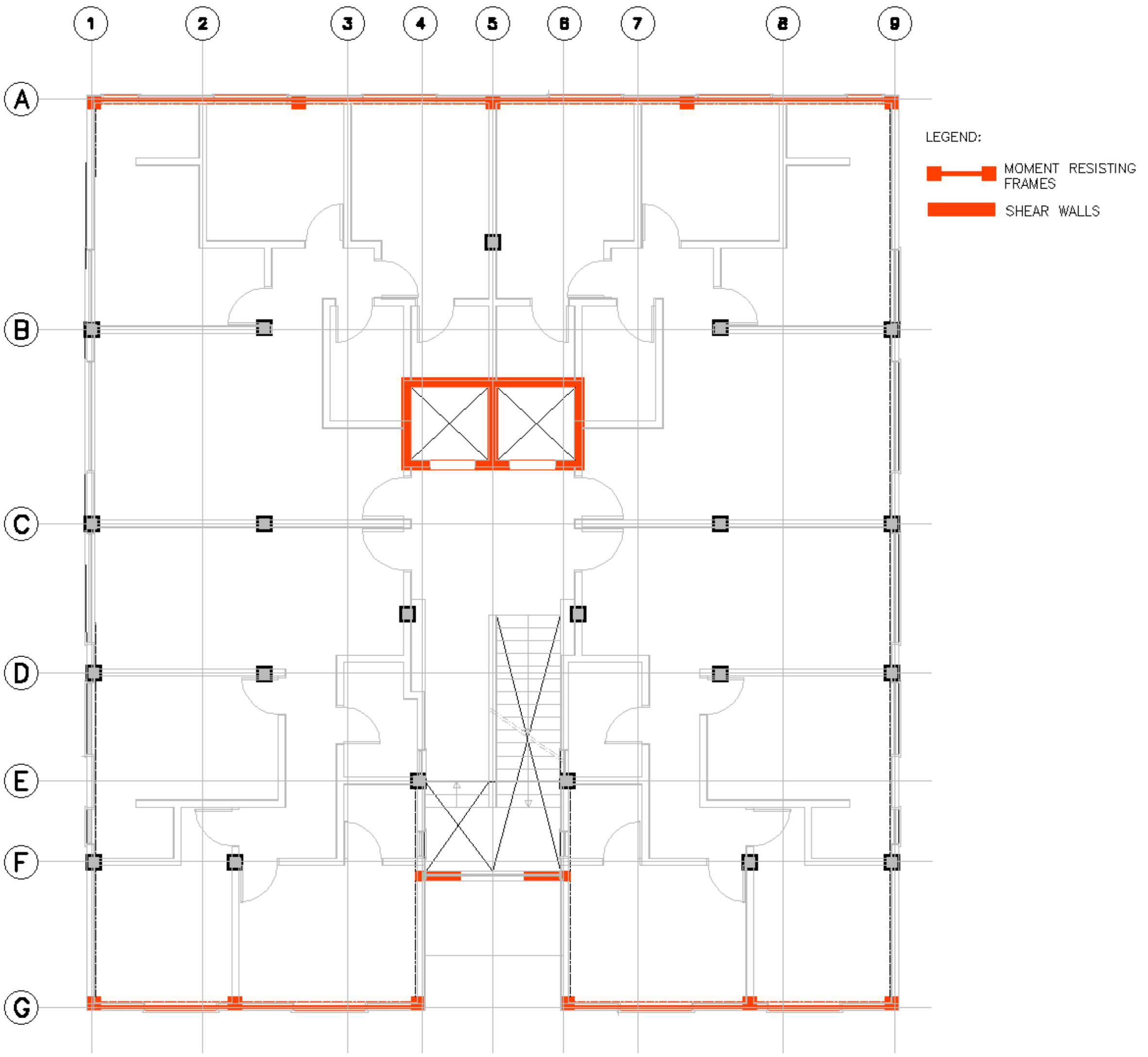


Figure 4.6. Reinforced concrete with flat slabs structural layout.

4.4.2 Structural fire design

Reinforced concrete has very good behavior when exposed to fire. Just like steel does not burn and is non-combustible, however, unlike steel, has high thermal massivity, and low thermal conductivity. This will slow down the rate of temperature increase in a reinforced concrete cross-section. To meet the required fire resistance of R60 for the studied building simplified calculation methods and tabulated data can be used to check the safety of the different structural elements. The tabulated data is based on empirical data, combined with evaluation of test results. The tabulated data provide minimal dimensions of the cross-section and minimum distance of the reinforcement until the concrete surface. Reinforced concrete solutions may not require additional fire protection to meet the R60 requirements. For compartmentation purposes, the wall systems prescribed for this solution and detailed in 8.ANNEX A were used, just like for the other framing solutions.

4.4.3 Foundations

Foundations for RC building are similar than assumed for HRS Buildings. Rectangular footings and lintels have different cross sections, as the loads applied, and spans are different.

For the geotechnical design, the same characteristics were assumed for the soil.

4.5 TIMBER

4.5.1 Description of the structural system

A timber building system can also be considered as a viable alternative for residential buildings and was also in this study. Timber residential buildings are very common in central and northern Europe as well as in the United States. The proposed solution for the timber building comprises a composite timber-concrete floor and a light frame system similar to the one adopted for the cold-formed steel building. Hence, the framing system will comprise timber beam/joists and posts spaced evenly.

Just as for cold-formed steel structures on the most relevant structural issues is the stabilization against horizontal loading (wind and earthquakes). Due to architectural restraints, the use of diagonal bracing is not considered. Hence, for the timber building a reinforced concrete shear wall or concrete frame system and if needed additional shear walls (using, for example, wood-based panels or gypsum boards) was considered to resist horizontal loads.

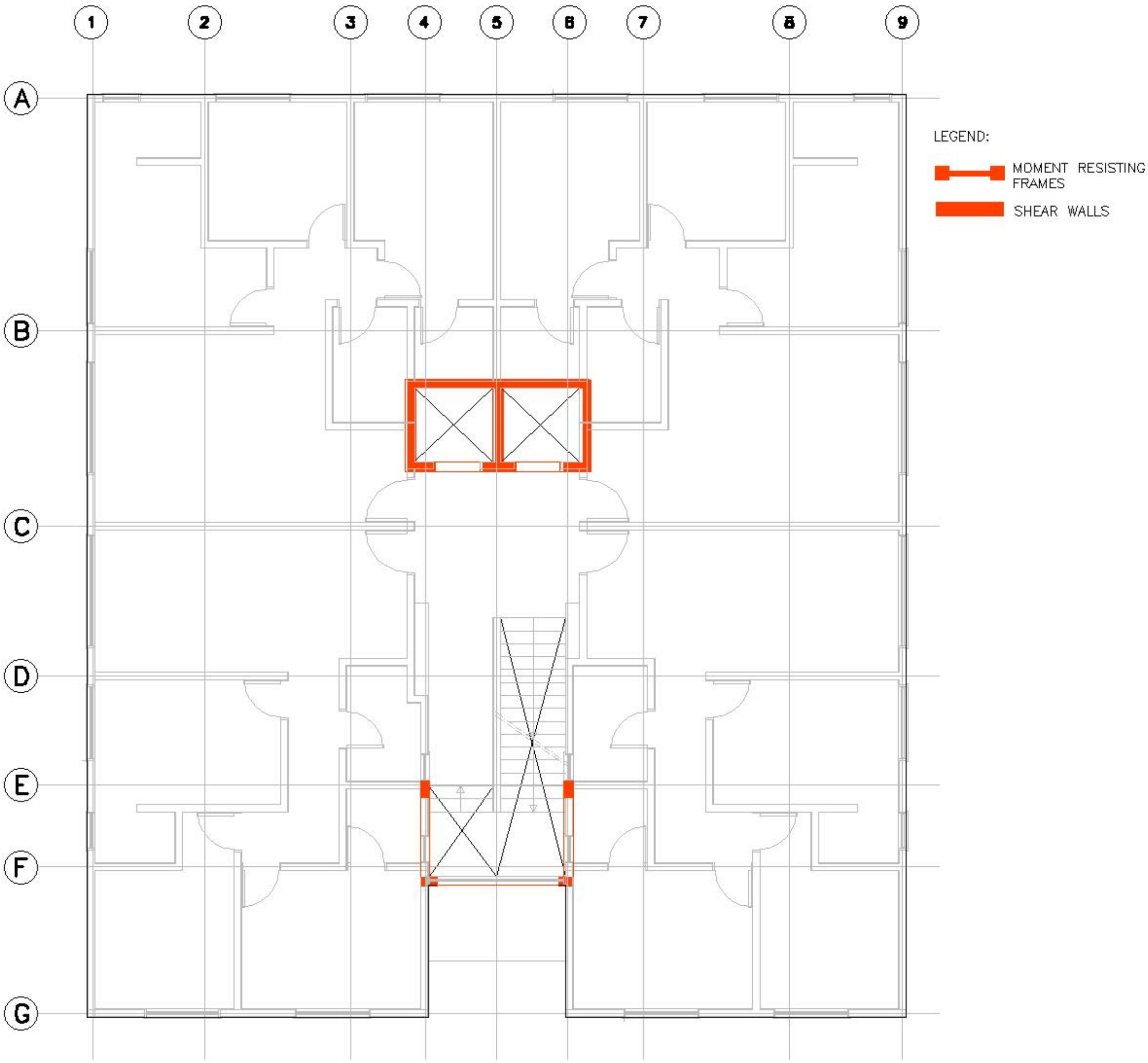


Figure 4.7. Timber with shear walls structural layout.

4.5.2 Structural fire design

Fire resistance is one of the most important requirements to address for a structure. Just like for the other framing solutions the required fire resistance for the studied building is R60. Timber is actually a material with good fire resistance since it burns in a controlled way and dependent on the charring rate which generally can be considered as 0.7 mm/min. For large cross-sections, the slow charring rate can ensure that the required fire resistance is met. However, for the studied building the cross-sections are relatively small, consequently, to meet the required 60 minutes of fire resistance, some kind of protection is needed. Just like for the other framing solutions the selected wall systems comprise gypsum boards that ensure that the structure is able to fulfil the requirements in terms of fire resistance (R60).

4.5.3 Foundations

Foundations for the timber building are similar than assumed for CFS Buildings, as the reactions on supports have the same magnitude. However, for the concrete core, rectangular footings were included, as the reaction forces on the walls are higher.

For the geotechnical design, the same characteristics were assumed for the soil.

4.6 SUMMARY

The structural solutions presented in the previous sections were designed in accordance with the Structural Eurocodes. The loads are determined in accordance with EN 1991 [15] for the gravity loads and EN 1998-1 [4] for the seismic action. Additional information can be consulted in Annex B of this document. The design of the studied structural solutions is performed following the recommendations of:

- EN 1990 for the basis of structural design [16];
- EN 1991-1 for the definition of the actions on structures [15];
- EN 1992-1-1 for the design of reinforced concrete structures [17];
- EN 1992-1-2 for the structural fire design of concrete structures [8];
- EN 1993-1-1 for the design of the hot-rolled steel solution [18];
- EN 1993-1-3 for the design of the cold-formed structure [19];
- EN 1993-1-2 for the structural fire design of steel structures [9];
- EN 1994-1-1 for the structural design of composite structural members [20];
- EN 1994-1-2 for the structural fire design of composite structural elements [10];
- EN 1995-1-1 for the timber structure [21];
- EN 1995-1-2 for the structural fire design of timber structures [11];
- EN 1997-1-1 for the geotechnical design [13];
- EN 1998-1-1 (CEN, 2004) for the design of structures under seismic action [4];
- EN 1998-5 for the design of structures for earthquake resistance, namely foundations [22].

As a major objective here, the optimum dimensions for each structural solution were sought. Nevertheless, the specifics of the different materials were taken into account as they are usually applied in practice.

Each structure was designed assuming the three different levels of seismic action considered in this study, namely no seismic action, low, medium and high seismic action.

5. COMPARATIVE STUDY

5.1 BILL OF MATERIALS

In the following, the summary of the results obtained for the various structural solutions is presented. They are presented as a Bill of Materials (BoM). The comparison is based solely on the load bearing members, such as columns, beams, walls, floor systems, roof materials and foundations. The BoM does not include non-structural items such as internal finishes, doors, windows, etc, as their quantities do not vary between the cases and are not influenced by loads applied to the structure.

The overall weight of the buildings was grouped into different categories, namely, superstructure, foundations, roof and floor, allowing for a clearer comparison between all tested solutions.

The structural area per floor is approximately 364 m^2.

Greater attention is paid to how the light steel framing solution compares to the more traditional structural solutions such as hot-rolled steel, reinforced concrete and timber. In the following sub-sections, a brief summary of the results obtained for each alternative is presented.

5.1.1 Light-steel framing solution

The structural analysis was based on the conceptual design presented in Section 4.2. The dimension of the profiles used is given in Annex C.

For the other cases studied (medium and high seismic zones), the concrete slab and steel deck weight were not affected.

In order to have a similar basis of comparison, the quantities are divided into the following categories:

- **Cold-formed steel:** includes the quantities of all cold-formed profiles needed for the load-bearing system (vertical and horizontal)
- **Hot-rolled steel:** includes the quantities of the hot-rolled profiles required for the moment resisting frames;
- **Concrete:** includes the concrete for the composite slabs at each floor and for the foundations;
- **Reinforcement:** includes the reinforcement used in the foundations;
- **Steel deck:** includes the quantity of steel sheeting required for the composite slabs at each floor.

Table 5.1 summarizes the BoM per material for the CFS solution with high strength steel (G550) for the all seismicity level cases studied considering the initial modifications to meet European requirements. The differences to the reference case are due to the consideration of the seismic action in this comparison.

Table 5.1. Bill of structural materials – cold-formed steel solution (G550).

Category	Seismicity Level		
	Reference	Medium Seismic	High Seismic
Cold-Formed Steel	45.5	55.2	55.2
Hot-Rolled Steel	6.4	12.3	15.5
Concrete (slabs)	226.1	226.1	226.1
Reinforcement (slabs)	6.1	6.1	6.1
Concrete (foundations)	296.3	296.3	296.3
Reinforcement (foundations)	8.9	8.9	8.9
Steel Deck	12.9	12.9	12.9
Simpson	0.6	0.8	0.8
Total	**602.8**	**618.6**	**621.8**

Table 5.2 summarizes the BoM per group (superstructure, foundation, floors, roof) for the CFS solution for all seismicity levels tested.

Table 5.2. Bill of structural materials (ton) according to the defined categories – cold-formed steel solution (G550).

Category	Seismicity Level		
	Reference	Medium Seismic	High Seismic
Superstructure	52.5	68.3	71.5
Foundations	305.2	305.2	305.2
Floors	181.0	181.0	181.0
Roof	64.1	64.1	64.1
Total	**602.8**	**618.6**	**621.8**

In Table 5.3 the bill of materials for the cold-formed steel solution with S320GD+Z steel is presented. Increasing the seismicity level was followed by an increase in the weight of the superstructure. For the cold-formed steel building no modifications were required for the foundations or floors due to the seismic levels considered.

Table 5.2 summarizes the BoM per group (superstructure, foundation, floors, roof) for the CFS solution for all seismicity levels tested for the S320GD+Z steel.

Table 5.3. Bill of structural materials – cold-formed steel solution (S320).

Category	Seismicity Level		
	Reference	Medium Seismic	High Seismic
Cold-Formed Steel	52.5	62.1	62.1
Hot-Rolled Steel	6.4	12.3	15.5
Concrete (slabs)	226.1	226.1	226.1
Reinforcement (slabs)	6.1	6.1	6.1
Concrete (foundations)	296.3	296.3	296.3
Reinforcement (foundations)	8.9	8.9	8.9
Steel Deck	12.9	12.9	12.9
Simpson	0.6	0.8	0.8
Total	**609.8**	**625.5**	**628.7**

Table 5.4. Bill of structural materials (ton) according to the defined categories – cold-formed steel solution (S320).

Category	Seismicity Level		
	Reference	Medium Seismic	High Seismic
Superstructure	59.4	75.1	78.4
Foundations	305.2	305.2	305.2
Floors	181.0	181.0	181.0
Roof	64.1	64.1	64.1
Total	**609.8**	**625.5**	**628.7**

The adopted concrete was the C30/37 for both foundations and composite slabs with steel deck. Based on the selected concrete composition (see Table 1.2) it is possible to estimate the quantities for each one of the materials. In Table 5.5 the estimated quantities are presented, assuming a 5% waste. The same overall concrete quantity was used for both steel grades considered.

Table 5.5. Estimated quantities based on the C30/37 concrete composition.

	Ref [ton]	MS [ton]	HS [ton]
Concrete C30/37	**530.7**	**530.7**	**530.7**
Cement	88.7	88.7	88.7
Plasticizer	2.6	2.6	2.6
Aggregate1	133.1	133.1	133.1
Aggregate2	71.2	71.2	71.2
Sand	104.2	104.2	104.2
Fine Sand	51.0	51.0	51.0
Filler	44.4	44.4	44.4
Water	35.5	35.5	35.5

5.1.2 Hot-Rolled Solution

The structural analysis was based on the conceptual design presented in Section 4.3. The sizes of the profiles vary depending on the initial assumptions for the loading. For columns, the selected cross-sections ranged from a HEB 200 to a HEB 450. For beams, the selected cross-sections ranged from IPE 220 to IPE 450. For the tested cases the selected steel grades were the S355 and S460. The height of the composite slab is 140 mm.

Additional information regarding all cross-sections used, including its length and number of pieces is available in Annex D for the different seismicity levels.

In order to have a similar basis of comparison, the quantities are divided into the following materials:

- **Hot-rolled steel:** includes the quantities of the hot-rolled profiles required for the moment resisting frames;
- **Concrete:** includes the concrete for the composite slabs at each floor and the concrete of the foundations;
- **Reinforcement:** includes the reinforcement of the foundations and composite slabs.
- **Steel deck:** includes the quantity of steel sheeting required for the composite slabs at each floor.

The design did not include details for all connections or similar items.

Table 5.6 summarizes the BoM per material for the HRS solution for the all seismicity levels.

Table 5.6. Bill of structure materials - HRS solution

Material	Structural Weight [tons]		
	Ref.	MS_q=6.5	HS_q=6.5
Hot-rolled steel	54.7	59.6	64.1
Concrete (Foundations)	365.8	425.8	425.8
Reinforcement (Foundations)	9.2	9.6	9.6
Concrete (slabs)	332.0	332.0	332.0
Reinforcement (slabs)	4.0	4.0	4.0
Steel deck	12.9	12.9	12.9
Total	**778.6**	**843.9**	**848.4**

Analysing the obtained results, the weight increased 8.4% and 8.9%, respectively for the medium and high seismicity levels, when comparing with the reference case. The seismic action had a significant impact not only in the superstructure but also on the substructure. The weight of the hot-rolled steel elements (both gravity and lateral resisting force systems) increased 9.3% and 17.2%, respectively for the medium and high seismicity levels, when comparing with the reference case. For the foundations the total weight increase was 16.1%

when comparing with the reference case. The composite slabs were the same for all tested scenarios.

Table 5.7 summarizes the BoM per group (superstructure, foundation, floors, roof) for the HRS solution for all seismicity levels tested.

Table 5.7. Bill of structural materials according to the defined categories – HRS solution.

Category	Structural Weight [tons]		
	Ref.	MS_q=4	HS_q=6.5
Superstructure	54.7	59.6	64.1
Foundations	375.0	435.4	435.4
Floors	257.2	257.2	257.2
Roof	91.7	91.7	91.7
Total	**778.6**	**843.9**	**848.4**

The adopted concrete was the C30/37 for both foundations and composite slabs with steel deck. Based on the selected concrete composition (see Table 1.2) it is possible to estimate the quantities for each one of the materials. In Table 5.8 the estimated quantities are presented, assuming a 5% waste. The same overall concrete quantity was used for both steel grades considered.

Table 5.8. Estimated quantities based on the C30/37 concrete composition.

	Ref [ton]	MS [ton]	HS [ton]
Concrete C30/37	**710.0**	**770.0**	**770.0**
Cement	118.7	128.7	128.7
Plasticizer	3.4	3.7	3.7
Aggregate1	178.1	193.1	193.1
Aggregate2	95.3	103.3	103.3
Sand	139.5	151.3	151.3
Fine Sand	68.3	74.0	74.0
Filler	59.4	64.4	64.4
Water	47.5	51.5	51.5

5.1.3 Reinforced Concrete Solution

The structural analysis was based on the conceptual design presented in Section **Error! Reference source not found.**. The dimensions of the structural members are summarized in Table 5.9. For the reinforced concrete building the adopted concrete class was C30/37 and the steel grade of the reinforcements bars was A500. Additional information is available in Annex E.

For this structural solution comprising reinforced concrete shear walls, moment resisting frames and flat slabs the estimation for both concrete and reinforcement bars is provided.

In order to have a similar basis of comparison, the quantities are divided into the following categories:

- **Superstructure:** includes the quantities of concrete and reinforcement required for the moment resisting frames (columns and beams) and shear walls;
- **Concrete Foundations:** includes the quantities of concrete and reinforcements required for the foundations;
- **Concrete Slabs:** includes the quantities of concrete and reinforcement required for the floor slabs.

Table 5.9. Dimensions of the structural elements.

Scenario	Structural Element	Sections (m)			Area (m^2)	Unit
		Width	Height / thickness	Length (m)		
RC_Ref.	Columns	0.3	0.3	12.8		32
	Beams	0.2	0.5	80.1		4
	Slabs		0.18		339.7	4
	Walls		0.2		45.5	4
	Stairs		0.2		11.6	4
RC_LS	Columns	0.3	0.3	12.8		30
	Beams	0.2	0.5	71.8		4
	Slabs		0.18		339.7	4
	Walls		0.2		60.2	4
	Stairs		0.2		12.9	4
RC_HS	Columns	0.4	0.4	12.8		30
	Beams	0.2	0.5	69.9		4
	Slabs		0.2		339.7	4
	Walls		0.2		60.2	4
	Stairs		0.2		12.9	4

Table 5.10 summarizes the BoM per material for the RC solution for all seismicity levels. From Table 5.10 the weight increase was 9% and 19.6%, respectively for the medium and high seismicity level when compared with the reference case. The most significant increase was observed for the concrete frames and reinforced concrete shear walls. It is worth mentioning that for the high seismicity level the thickness of the concrete slabs increased from 18 to 20 cm. Hence, the weight increase was about 11% for the reinforced concrete flat slabs when comparing the high seismicity level scenario with the medium seismicity and reference scenarios. The impact on the foundations is also worth noting. When considering the seismic action, the total weight of the foundations (concrete plus reinforcement) increased by 24.5%.

Table 5.10. Bill of structure materials - RC solution

Material	Structural Weight [tons]		
	Reference	Medium Seismic	High Seismic
Concrete Frames	205.8	191.5	264.0
Concrete Shear Walls	95.0	125.1	126.3
Concrete (Foundations)	419.5	523.2	523.3
Reinforcement (Foundations)	5.7	6.3	6.3
Concrete (slabs)	584.4	584.4	649.3
Reinforcement (slabs)	18.3	18.3	20.2
Total	**1328.7**	**1448.8**	**1589.4**

Table 5.11 summarizes the BoM per category for the RCS solution for the all seismicity level cases.

Table 5.11. Bill of structural materials - reinforced concrete building.

Category	Structure weight [ton]		
	Reference	Medium Seismic	High Seismic
Concrete Frames	205.8	191.5	264.0
Shear Walls	95.0	125.1	126.3
Concrete flat slab	442.0	442.0	491.1
Roof	160.7	160.7	178.5
Foundation	425.2	529.5	529.5
Total	**1328.6**	**1448.7**	**1589.3**

The adopted concrete was the C30/37 for both substructure and superstructure. Based on the selected concrete composition (see Table 1.2) it is possible to estimate the quantities for each one of the materials. In Table 5.8 the estimated quantities are presented, assuming a 5% waste.

Table 5.12. Estimated quantities based on the C30/37 concrete composition.

	Ref [ton]	MS [ton]	HS [ton]
Concrete C30/37	**1317.4**	**1436.8**	**1573.2**
Cement	220.3	240.2	263.0
Plasticizer	6.4	7.0	7.6
Aggregate1	330.4	360.3	394.5
Aggregate2	176.8	192.8	211.1
Sand	258.8	282.2	309.0
FineSand	126.6	138.1	151.2
Filler	110.1	120.1	131.5
Water	88.1	96.1	105.2

5.1.4 Timber solution

For this structural solution, a C24 timber was selected. For the timber posts the cross-section selected was 150 × 150 mm and for the timber joists, the section was 150 × 250 mm. The timber framing was designed to resist the gravity loading, whereas the reinforced concrete walls were designed to resists the lateral forces. For the reference case, the thickness of the shear walls was 15 cm whereas for the medium and high seismicity cases the thickness was 20 cm. The concrete class considered for the shear walls was the C30/37 and the steel grade for the reinforcement bars was A500.

In Table 5.13 the bill of materials for the timber building considering a high seismicity value is presented.

Table 5.13. Bill of structure materials – timber building.

Category	Structure weight [ton]		
	Reference	Medium Seismic	High Seismic
Timber	69.3	69.3	69.3
Shear Walls	53.1	67.4	68.7
Composite slab	203.2	203.2	203.2
Roof	72.5	72.5	72.5
Foundation	357.5	357.5	357.5
Total	**755.6**	**769.9**	**771.2**

Analysing the obtained results presented in Table 5.13 it is clear that no impact on the timber structure was observed when considering different seismic scenarios. The Timber building was designed using the similar principle adopted for the cold-formed steel building. Hence, the timber framing was designed to resist the gravity loading whereas the reinforced concrete shear walls were designed to resist the lateral forces. This strategy proved to be very efficient since the seismic action had no significant impact on the timber framing system. Considering the high seismicity level led to an increase of about 30% in the weight of the reinforced concrete shear walls when comparing with the reference case (no seismic action). Comparing the overall weight of the timber buildings designed, the increase was about 1.9% and 2.1%, respectively for the medium and high seismicity level, when comparing with the reference case.

The adopted concrete was the C30/37 for both the foundations and composite slabs. Based on the selected concrete composition (see Table 1.2) it is possible to estimate the quantities for each one of the materials. In the estimated quantities are presented, assuming a 5% waste.

Table 5.14. Estimated quantities based on the C30/37 concrete composition.

	Ref [ton]	MS [ton]	HS [ton]
Concrete C30/37	**614.9**	**614.9**	**614.9**
Cement	102.8	102.8	102.8
Plasticizer	3.0	3.0	3.0
Aggregate1	154.2	154.2	154.2
Aggregate2	82.5	82.5	82.5
Sand	120.8	120.8	120.8
FineSand	59.1	59.1	59.1
Filler	51.4	51.4	51.4
Water	41.1	41.1	41.1

5.1.5 Weight comparison

In summary, a weight comparison for the assessed structural alternatives is proposed. In this section, it is solely based on the weights obtained for the reference cases, i.e. without the consideration of seismic action. Its impact is discussed in a separate paragraph (see Section 5.2).

The comparison, analysis and discussion are conducted on the basis of the results obtained from the structural analysis. The total weight estimated and the total weight per square meter for each structural solution is summarized in Table 5.15 and Table 5.16 and graphically in Figure 5.1. For the estimation of the weight of the materials an area of 1384 m^2 was considered.

From the analysis of Figure 5.1 it is clear that the total weight of the reinforced concrete building is 2.21, 2.18, 1.71, 1.72 and 1.76 times (120.7%, 118.2%, 71.4%, 72.15 and 75.8%) higher than the weight of the cold-formed steel (G550 and S320GD+Z), hot-rolled steel (S355 and S460) and timber buildings, respectively. The estimations presented are only for the structural elements of the building.

Table 5.15. Comparison of total structural materials weight.

Structural solution	Superstructure					Found. [ton]	Slabs	
	Gravitational loads resisting elements				Lateral resisting elements			
	CFS [ton]	HRS [ton]	RC [ton]	T [ton]	MRF/shear walls [ton]		Slabs [ton]	Steel Deck [ton]
CFS_Ref._G550	46	0.5			5.9	305.2	231.2	12.9
CFS_Ref._S320	52	0.5			5.9	305.2	231.2	12.9
HRS_S355_Ref.		45.4			9.3	375	336.0	12.9
HRS_S460_Ref.		39.8			8.3	375	336.0	12.9
RC_Ref.			205.8		95.0	425.2	602.7	
T_Ref.				69.3	53.1	357.5	275.7	

Cold-formed steel buildings are the lightest, however, it worth mentioning their hybrid character since the lateral force resisting system was mainly based on hot-rolled steel frames.

For the foundations, and once again taking advantage of the reduced weight of the superstructure the lightest ones are the ones for the cold-formed steel buildings. For the reference case, the weight of the foundations of the reinforced concrete building is 39.1%, 13.4% and 18.9% higher than the weight of the foundations for the cold-formed steel, hot-rolled steel and timber buildings.

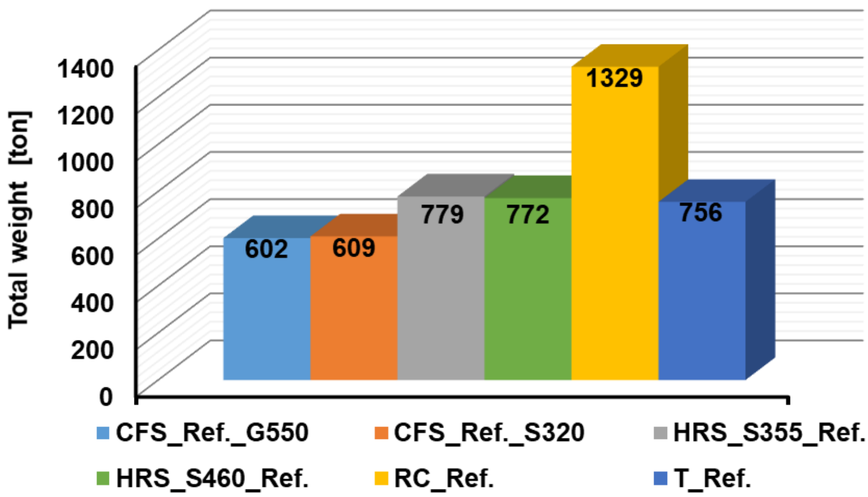


Figure 5.1. Total weight comparison between all tested structural solutions, for the reference case (without seismic action).

It is worth mentioning that for all buildings the overall weight of the floors and foundations represent a significant part of its weight. Consequently, in some of the following comparisons, the different structural categories will be individualized, and the more relevant ones compared, so that the overall impacts on the weight estimations may be clearly assessed.

Table 5.16. Comparison of structural materials weight per sqm.

Structural solution	Superstructure					Found. [kg/m²]	Slabs	
	Gravitational loads resisting elements				Lateral resisting elements			
	CFS [kg/m²]	HRS [kg/m²]	RC [kg/m²]	T [kg/m²]	MRF/shear walls [kg/m²]		Slabs [kg/m²]	Steel Deck [kg/m²]
CFS_Ref._G550	33	0.5			4.3	220.5	166.9	9.3
CFS_Ref._S320	38	0.5			4.3	220.5	166.9	9.3
HRS_S355_Ref.		32.8			6.7	270.9	242.8	9.3
HRS_S460_Ref.		28.7			6.0	270.9	242.8	9.3
RC_Ref.			148.7		68.6	307.2	435.5	
T_Ref.				50.1	38.4	258.3	199.2	

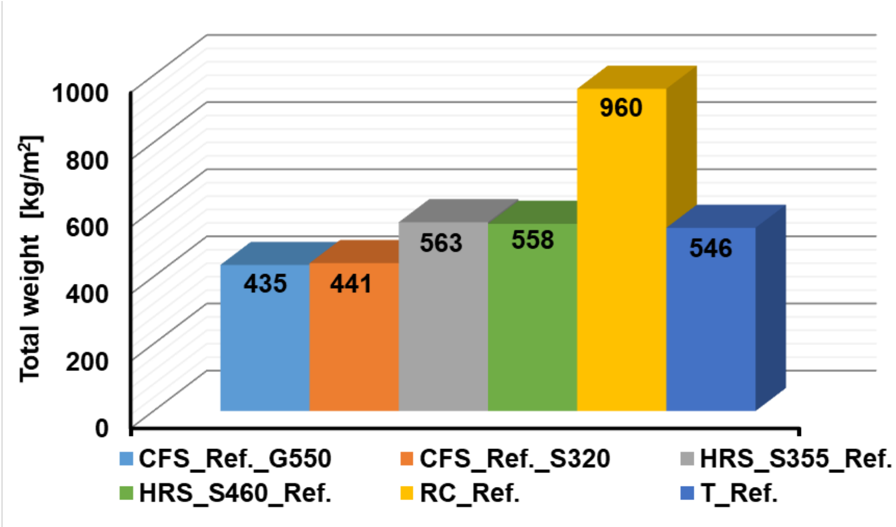


Figure 5.2. Total weight (per sqm) comparison between all tested structural solutions, for the reference case (without seismic action).

From the analysis of the obtained results, the major findings can be summarised as follows:

- Cold-formed, hot-rolled steel and timber solutions provide structural solutions with a much lower weight per unit area in comparison to the reinforced concrete building. This has a direct impact on the foundation where lower loads are transmitted in the case of the steel solutions;
- For the cold-formed steel buildings, the use of a normal strength steel was translated in a slight increase in terms of weight, as expected. Using S320GD+Z steel the total weight of the building increased approximately 1.2%. In terms of the total weight of the cold-formed steel material, reducing its steel grade led to an increase of about 13% in terms of weight;
- For cold-formed steel buildings, the vertical resisting structure (gravitational loads) can be considered as internal partitions and external facades, representing significant cost savings with materials and labour and consequently faster construction time.

5.2 INFLUENCE OF THE SEISMICITY LEVEL

5.2.1 Introduction

In this section, the different seismicity levels are assessed. The different structural solutions are firstly compared separately, which is followed by a global comparison between the various alternatives.

In the assessment, it was assumed that the building is situated in two different locations:

- Medium Seismicity level (MS) – Faro, Portugal

- High Seismicity level (HS) – Bucharest, Romania

In addition, for some cases, a Low Seismicity (LS) location was also considered: Low seismicity level – Coimbra, Portugal. Moreover, different behaviour factors were also considered in this study for the reinforced concrete building (q=3 and q=3.9) and for the hot-rolled steel building (q=4 and q=6.5).

In the previous section, it was shown that the concrete slabs are responsible for more than 80% of the total structural weight. Although this is a major part, it is not affected by the seismic loads. Following the objectives of this section, the weight of the slabs is not included in the comparisons of this section. It is noted that the RC solution has increased the slab width for the HS level.

5.2.2 CFS solution

In Figure 5.3 a comparison is established between the overall weight estimation for the Cold-Formed steel building, considering the high strength steel G550, for the different seismicity levels considered. The materials used are compared. This is a hybrid building, incorporating cold-formed steel strengthened in specific areas by hot-rolled steel frames which resisted the lateral loading (wind and seismic action).

It is clear that the weight of the foundations and slabs/roof is very significant when compared with the weight of the cold-formed steel members. Consequently, in

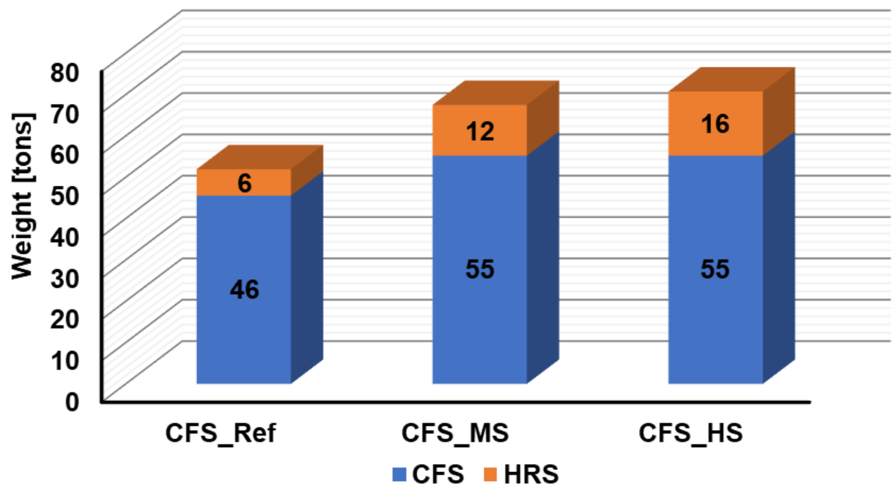


Figure 5.4 only the cold-formed and hot-rolled steel are presented and compared. The hot-rolled steel frames were used to resist the horizontal loading, ensuring that the cold-formed steel structure can resist only the gravity loading.

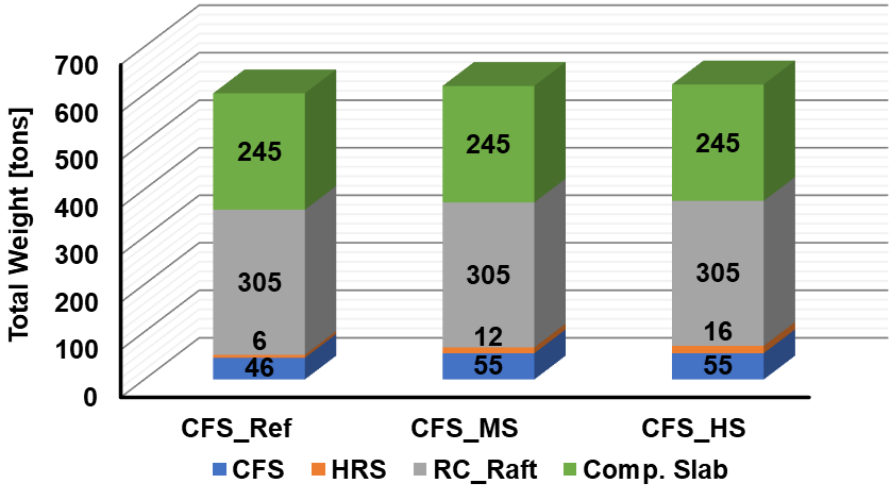


Figure 5.3. Total weight comparison between all tested seismic scenarios (G550).

Observing the obtained results, the total weight increase from the reference situation to a medium seismic location was about 2.5%, whereas comparing the reference case with the high seismicity scenario the weight increase was 3.12%. Regarding the hot-rolled steel (lateral resisting frames) the weight increased by 100% when comparing the reference case with the medium seismicity level and 166% when comparing the reference case with the high seismicity level. The results show clearly that the hybrid solution considered is effective and that each framing system is performing correctly and as expected. Based on the results presented in

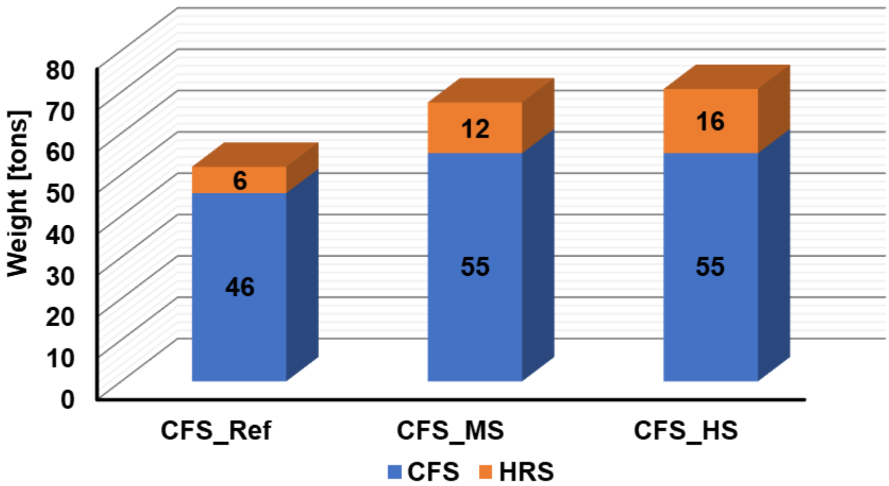


Figure 5.4 the weight of the cold-formed steel structural elements increased approximately 21% when comparing the reference situation with the medium and high seismic scenario. Comparing the medium and high seismicity the impact was only observed in the lateral force resisting elements.

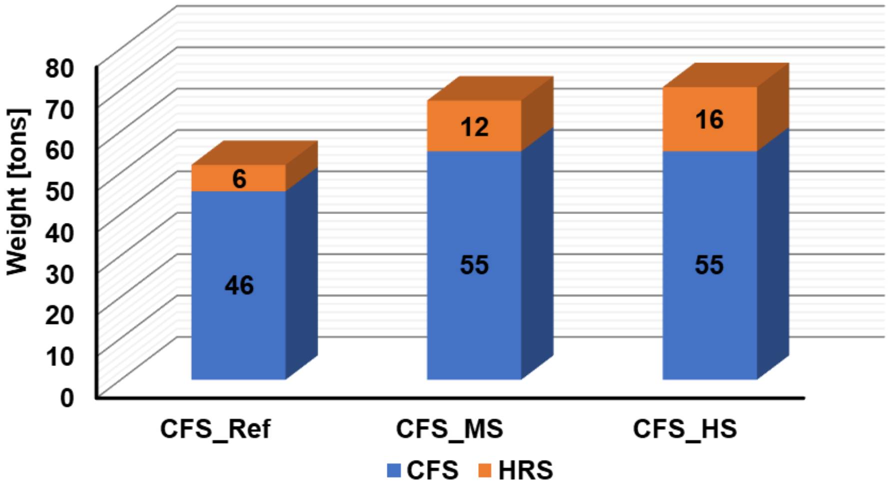


Figure 5.4. The weight of the superstructure for the different seismic scenarios (G550).

The same type of analysis was also undertaken, assuming a normal strength cold-formed steel, namely the S320GD+Z. In this case, no changes were prescribed to the foundations and floor systems as observed in Figure 5.5.

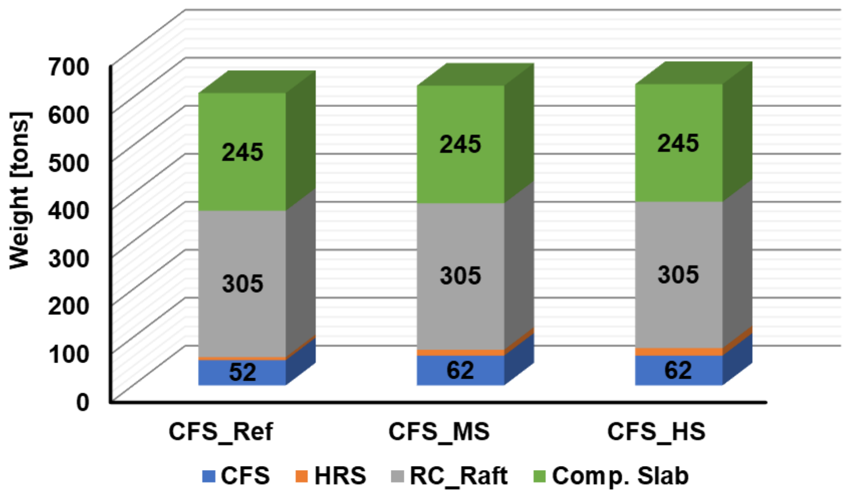


Figure 5.5 - Total weight comparison between all tested seismic scenarios (S320).

In Figure 5.6 only the obtained results for the superstructure are presented. It was observed that using the S320GD+Z cold-formed steel the overall weight of the superstructure increased approximately 13% for the reference case when comparing directly with the building where the high strength G550 steel was used. Establishing a comparison between the different seismicity levels tested it was found that the superstructure weight increased 26.2% and 31.7%, respectively for the medium and high seismicity levels, when compared with the reference case.

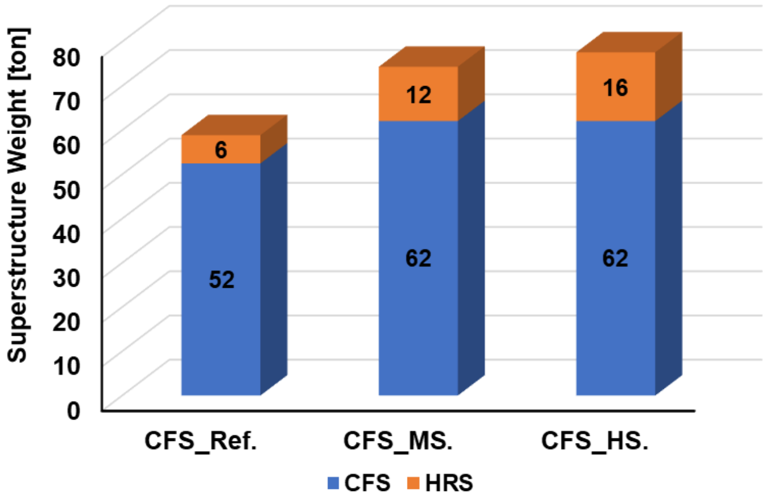


Figure 5.6 - Weight of the superstructure for the different seismic scenarios (S320).

From Figure 5.6 the weight increase of the lateral force resisting system is significant when the seismicity level increases. For the medium seismicity level, the weight of the lateral force resisting system increased 92.4% and for the high seismicity level, it has increased by 143.5% when compared with the reference case. From the medium to the high seismicity level no significant weight increase was observed for the cold-formed steel structure. Hence, the hot-rolled steel structure can withstand all the lateral forces and the cold-formed steel resists the gravity loading.

5.2.3 HRS solution

In Figure 5.7 and Figure 5.8 a comparison is established between the overall weight estimation for the Hot-Rolled Steel building for the different seismicity levels and steel grades considered. The defined structural categories are compared. It is clear that the weight of the foundations and slabs/roof is very significant when compared with the weight of the hot-rolled steel members. For the reference case, both foundations and floors represent approximately 92.9% of the total weight of the buildings, whereas for the medium and high seismicity level the percentage is approximately 92.9% and 92.4%, respectively.

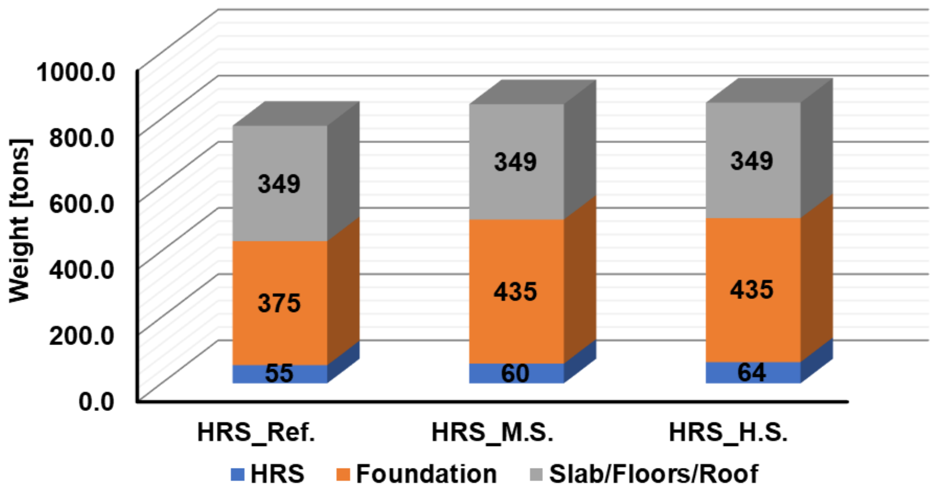


Figure 5.7. Total weight comparison between all tested seismic scenarios, considering the S355 steel.

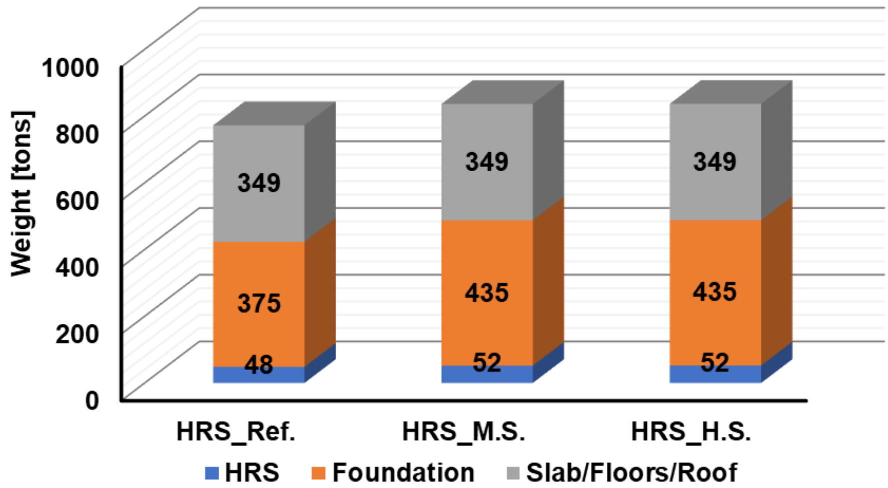


Figure 5.8. Total weight comparison between all tested seismic scenarios, considering the S460 steel.

To overcome this limitation a new comparison is presented, detailing the hot-rolled steel weight for each tested condition (Figure 5.9). Observing the obtained results, the weight increase is clear with increasing seismicity level. For instance, comparing the reference building (no seismic location) with the same building in a Medium Seismic location (MS) the HRS weight increase was 8.9%, whereas for the High Seismic location (HS) the weight increase was 17.2%.

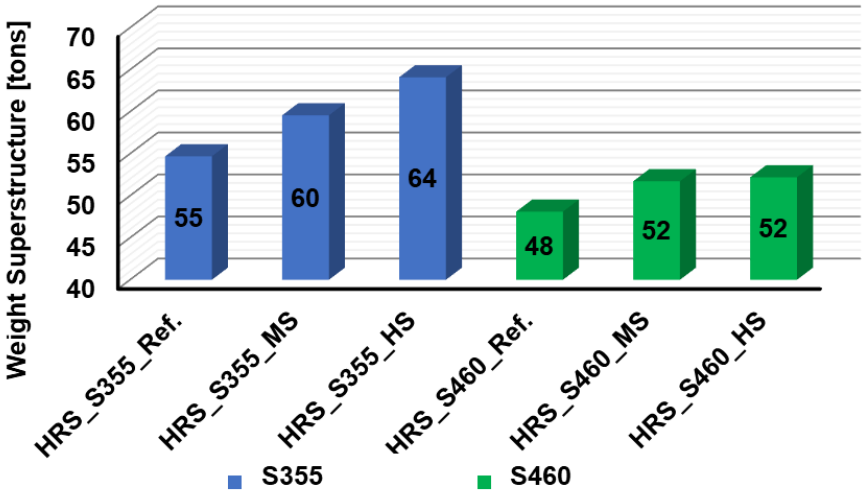


Figure 5.9. Total weight comparison between tested seismicity levels, considering both S355 and S460 steels.

Comparing the results depicted in Figure 5.9, increasing the steel grade led to a reduction of the steel weight used in the superstructure. For the reference case, the reduction was 12.7%, whereas for the medium and high seismicity levels the reduction was 13.3% and 18.75%, respectively.

Complementary, some additional studies were undertaken only considering the S355 steel, focusing mainly on the overall impact of the seismic action on the total weight of the hot-rolled steel superstructure. To do this, an additional seismic location was selected, namely Coimbra, which is a low seismic location, and two behavior factors were considered, namely q=4 (Ductility Class Medium - DCM) and q=6.5 (Ductility Class High - DCH). In Figure 5.10 the obtained results for the hot-rolled steel superstructure are depicted. Analyzing the obtained results, the weight increase is clear for the hot-rolled steel superstructure with increasing seismicity level. For this specific building, it is clear that considering a DCH may provide some benefits for the high seismicity level, whereas for the low seismicity level the need to consider Class 1 cross-section led to an increase in terms of weight when comparing with the DCM situation.

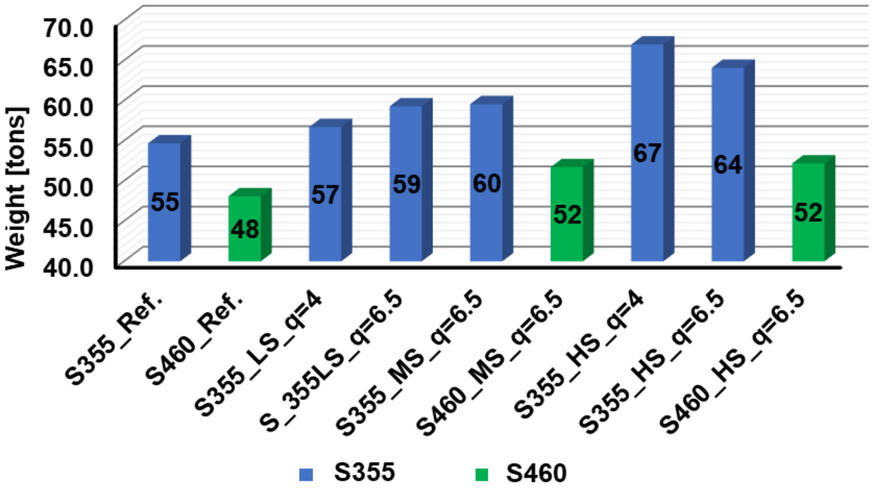


Figure 5.10. Hot-rolled steel weight comparison for the tested scenarios, considering both DCM and DCH, with the correspondent behaviour factors q=4 and q=6.5.

In Figure 5.11 and Figure 5.12 the structural weight per square meter for the superstructure are presented. Specifically, the superstructure elements responsible for resisting the lateral loads and the ones responsible for resisting the gravitational loads are individualized.

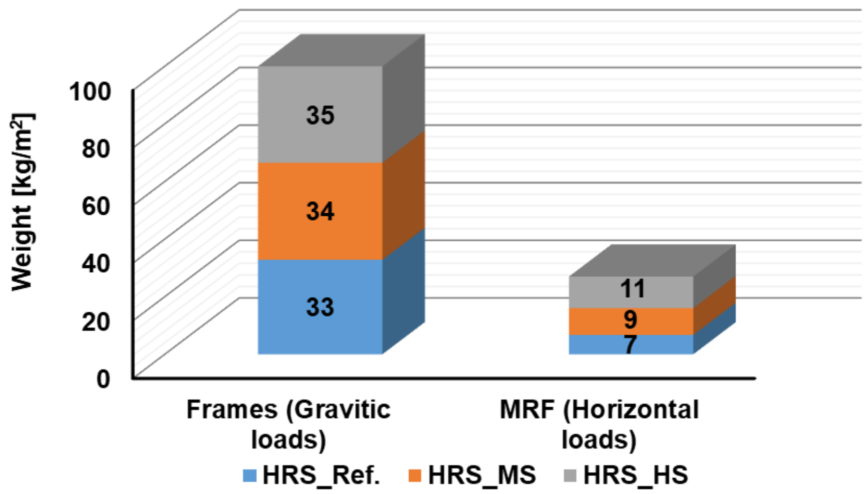


Figure 5.11. Weight comparisons for all tested cases – Hot-Rolled Steel building [kg/m^2], considering the S355 steel.

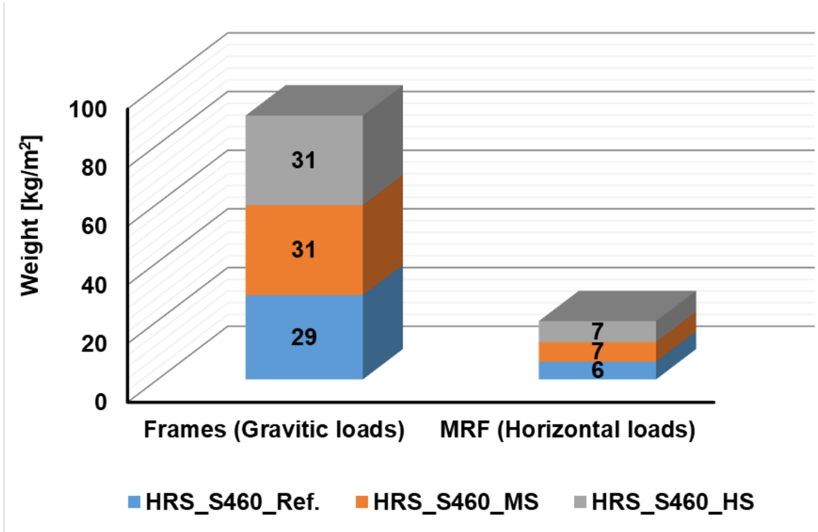


Figure 5.12. Weight comparisons for all tested cases – Hot-Rolled Steel building [kg/m^2], considering the S460 steel

5.2.4 Reinforced concrete solution

In Figure 5.13 a comparison is established between the overall weight estimation for the Reinforced Concrete building for the different seismicity levels considered. The defined structural categories are compared. It is clear that the weight of the slabs/roof is very significant when compared with the weight of the reinforced concrete columns and beams.

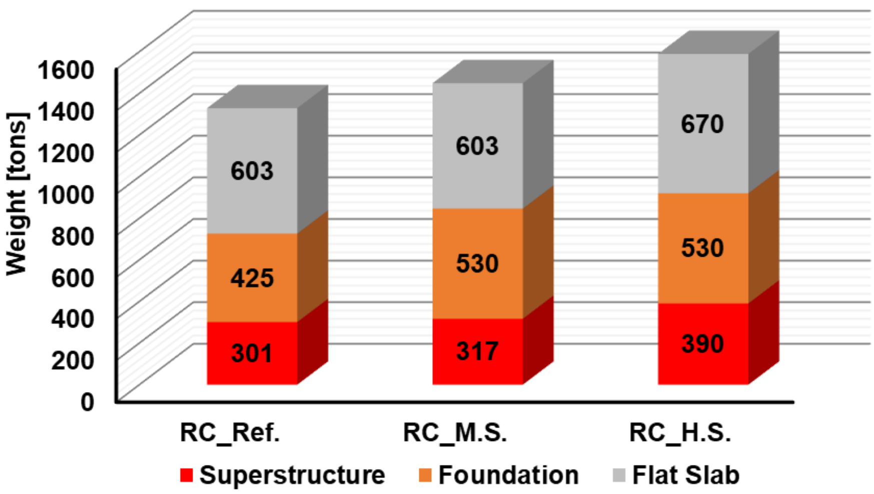


Figure 5.13. Total weight comparison between all tested scenarios for the reinforced concrete building.

For the investigated scenarios the foundations and floors represent approximately 77.4%, 78.2% and 75.5% of the total weight, respectively for the reference case, medium seismic and high seismic location. Comparing the obtained results, the building located in a high seismic area weights approximately 19.6% more than the reinforced concrete building in a non-seismic location.

In Figure 5.14 a comparison is established between all tested solutions for the superstructure and slabs, in order to assess the impact of the considered seismicity levels in the reinforced concrete structure. For the High Seismicity level, the total weight of the slabs also increased since its thickness increased from 18 to 20 cm. The weight increase was approximately 11%.

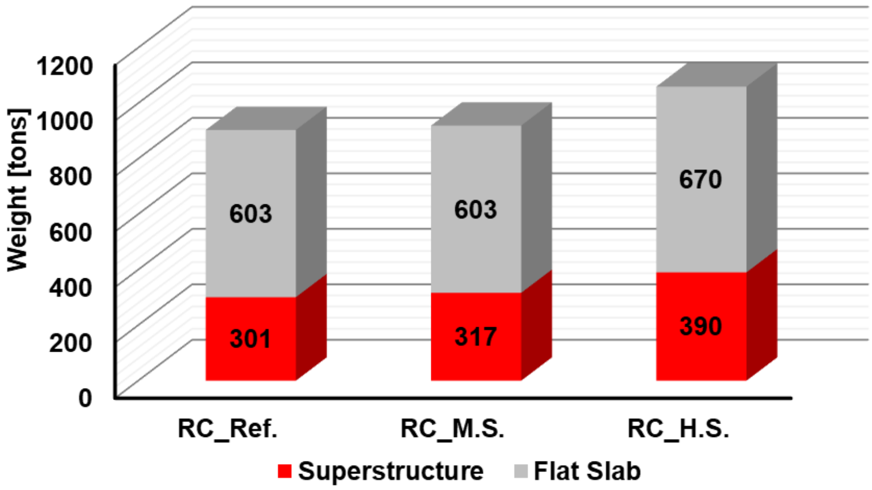


Figure 5.14. Comparison between all tested scenarios for the superstructure and flat slabs.

In Figure 5.15 the comparison is made only considering the weight of the superstructure. For the superstructure, the weight increase, when compared with the reference case, was 5.2% and 29.7%, respectively for the medium and high seismicity level.

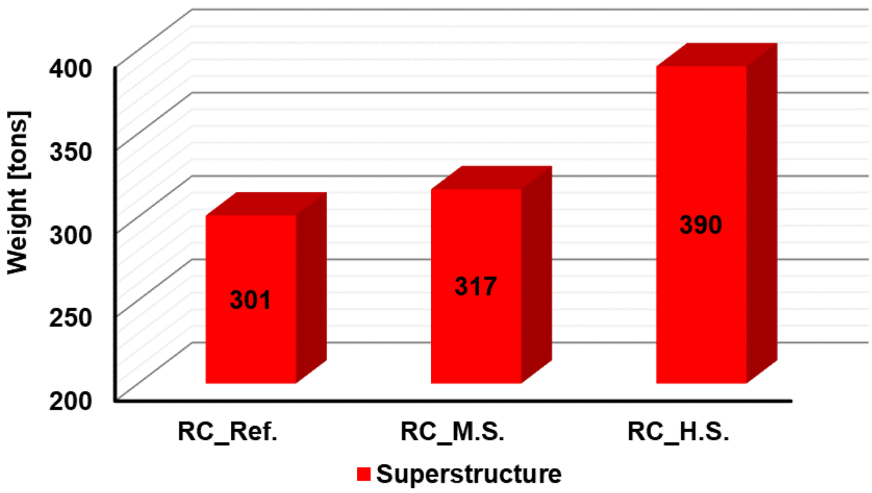


Figure 5.15. Comparison between all tested scenarios for the superstructure.

In Figure 5.16 a more specific comparison is established. The structural weight per square meter for the superstructure is presented. Specifically, the elements responsible for resisting the lateral loads and the ones responsible for resisting the gravitational loads are individualized. It is observed that the structural weight increases proportionally with seismic loads intensities.

As mentioned earlier, for the HS level, the columns sections and slab thickness increased due to the higher demand of punching shear resistance.

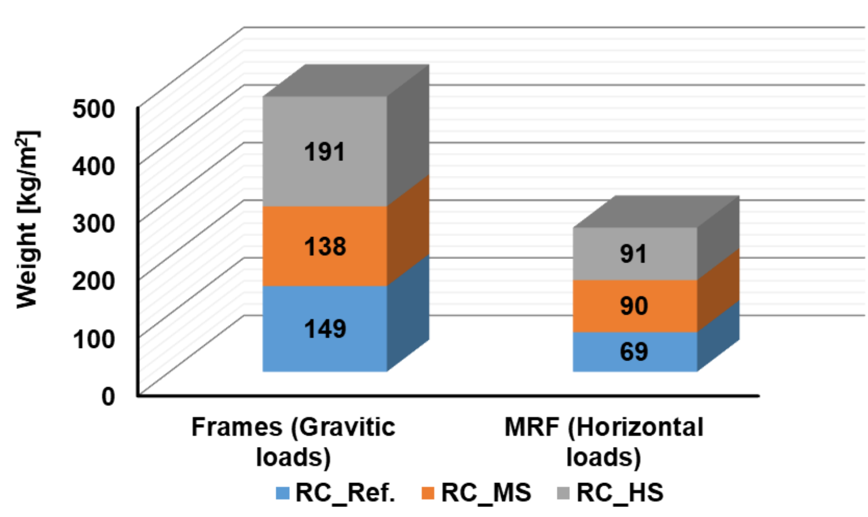


Figure 5.16. Weight comparisons for all tested cases – Reinforced concrete building [kg/m^2].

Complementary, some additional studies were undertaken, focusing mainly on the overall impact of the seismic action on the total weight of the reinforced concrete superstructure. In Figure 5.17 the obtained results for the reinforced concrete superstructure are depicted. To do this, an additional seismic location was selected, namely Coimbra, which is a low seismic location, and two behavior factors were considered, namely q=3 and q=3.9 (Ductility Class Medium – DCM).

Analyzing the obtained results, the weight increase is only significant for the High Seismicity level scenario. The behaviour factors selected for comparison did not influence significantly the weight of the superstructure of the reinforced concrete buildings for the tested seismic locations. For instance, for the low seismic location, comparing the adopted behavior factors it was found that weight increases 1.13% when the behavior factor was reduced from 3.9 to 3. For the high seismic location, the obtained difference between the adopted behavior factors is negligible.

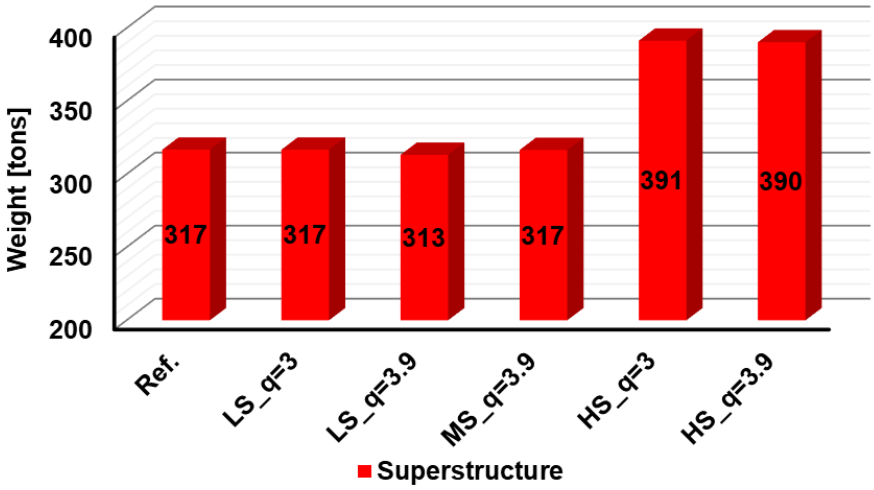


Figure 5.17. Reinforced concrete weight comparison for the tested scenarios, considering DCM, with the following behaviour factors q=3 and q=3.9.

5.2.5 Timber solution

In Figure 5.18 a comparison is established between the overall weight estimation for the Timber building for the different seismicity levels considered. The defined structural categories are compared. It is clear that the weight of the slabs/roof and foundations is very significant when compared with the weight of the superstructure elements.

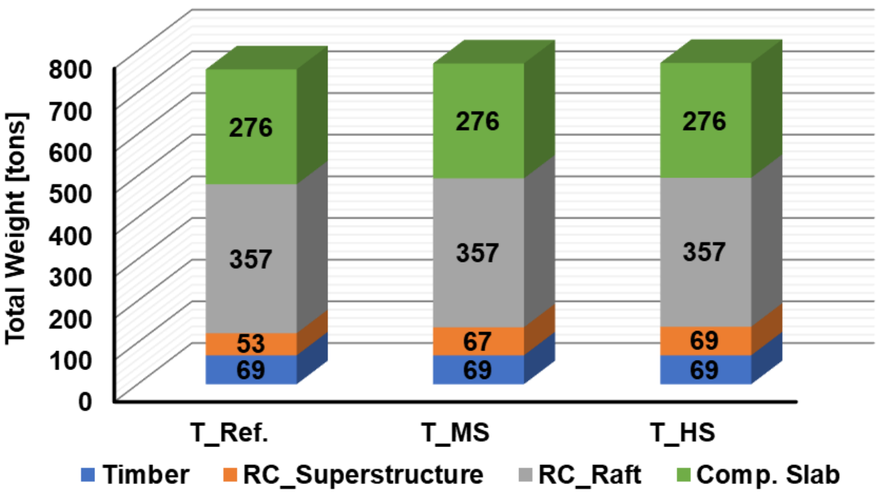


Figure 5.18. Total weight comparison between all tested seismic scenarios.

In a more detailed comparison, the superstructure weight is compared for the tested seismic levels, as depicted in Figure 5.19. Just like as for the cold-formed steel building a hybrid structural solution was also considered for the timber building. The lateral force resisting system comprised reinforced concrete shear walls, whereas the gravity force resisting system comprised the timber structural system. Increasing the seismicity level was translated in a significant impact on the weight of the reinforced concrete lateral force resisting structural system. The efficiency of this lateral force resisting system almost mitigated completely the impact of the seismic loading on the gravity force resisting system. Hence, no impacts on the timber structure were observed when the seismicity level increased. The total weight of the reinforced concrete shear walls and frame increased by 26% when comparing the reference case with the medium seismicity level and 30% when comparing the reference case with the high seismicity level considered.

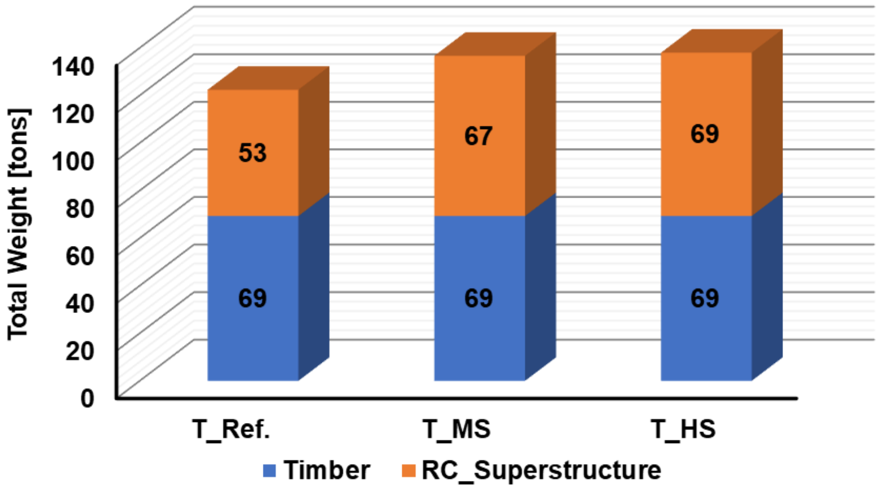


Figure 5.19. Total weight of the superstructure for all tested seismic scenarios.

In Figure 5.20 the weight per square meter for the superstructure elements is presented, individualizing the timber frames designed to resist the gravity loading and the reinforced concrete shear walls and frames designed to resist the horizontal forces.

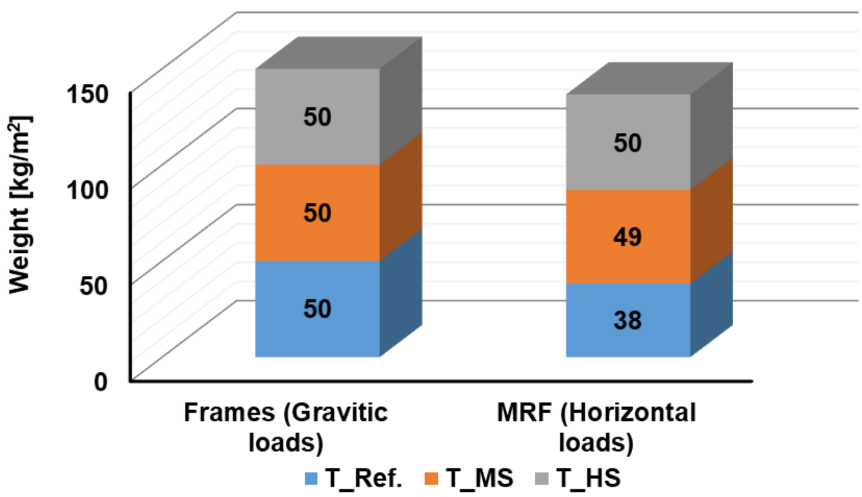


Figure 5.20. Weight per square meter of the superstructure for all tested seismic scenarios.

As previously mentioned, the impact of the seismic action on the gravity resisting frame was eliminated. The weight of the lateral force resisting system increased proportionally, according to the seismicity level considered.

5.2.6 Comparison between all different structural solutions

Finally, in this section comparison between the structural alternatives is carried out on the basis of increasing level of the seismic action. The comparison, analysis and discussion are conducted on the basis of the results obtained from the structural analysis.

Seismic loads are directly related to some factors. The two main factors that impact its intensity are the mobilized mass (that depends directly on the structural weight as other masses remain constant in all cases) and the structural behaviour factor. Regarding the first aspect, cold-formed steel has advantages as its weight is usually much lower than other structural solutions.

After analysis of all structural systems considering the established seismic scenarios, some variations were observed in terms of the seismic loads.

In Table 5.17 the total weight estimated for all studied scenarios, as a function of the used materials and structural function is presented.

Graphically, in Figure 5.21 all the information, for all investigated scenarios, is depicted. The impact of the seismic location was more relevant for the total weight of the reinforced concrete buildings.

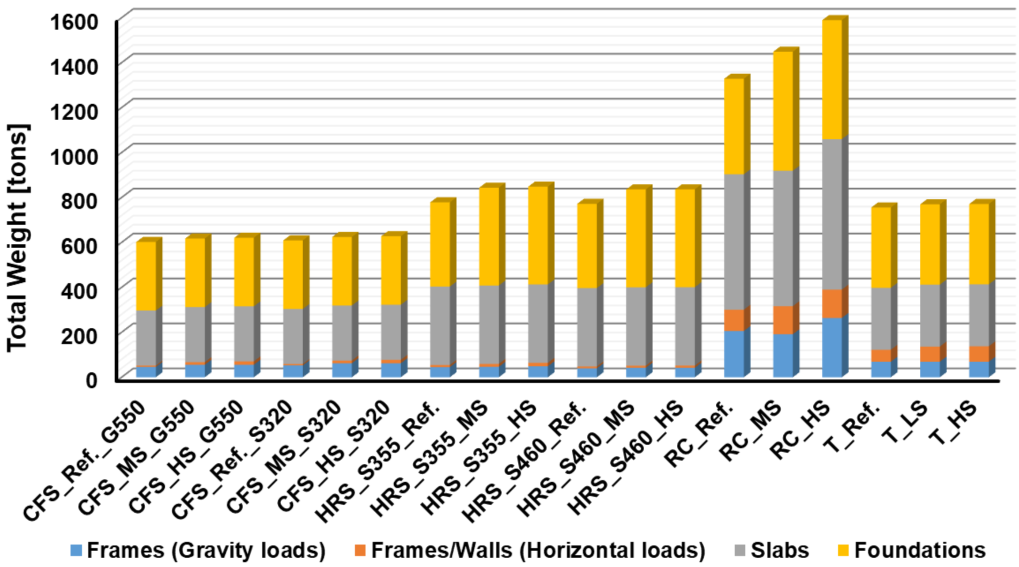


Figure 5.21. Total weight comparison between all tested structural solutions.

Table 5.17. Comparison of the total structural materials weight.

Structural solution	Superstructure					Found. [tons]	Slabs	
	Gravitational loads resisting elements				Lateral resisting elements			
	Light-Steel framing [tons]	Hot-rolled steel [tons]	Concrete Frames [tons]	Timber [tons]	MRF or shear walls [tons]		Slabs [tons]	Steel Deck [tons]
CFS_Ref._G550	46	0.5			5.9	305.2	232.2	12.92
CFS_MS_G550	55	0.5			11.8	305.2	232.2	12.92
CFS_HS_G550	55	0.5			15.1	305.2	232.2	12.92
CFS_Ref._S320	52	0.5			5.9	305.2	232.2	12.92
CFS_MS_S320	62	0.5			11.8	305.2	232.2	12.92
CFS_HS_S320	62	0.5			15.1	305.2	232.2	12.92
HRS_S355_Ref.		45.4			9.3	375.0	336.0	12.92
HRS_S355_MS		46.7			12.9	435.4	336.0	12.92
HRS_S355_HS		48.9			15.2	435.4	336.0	12.92
HRS_S460_Ref.		39.8			8.3	375.0	336.0	12.92
HRS_S460_MS		42.4			9.3	435.4	336.0	12.92
HRS_S460_HS		42.3			9.9	435.4	336.0	12.92
RC_Ref.			205.8		95.0	425.2	602.7	
RC_MS			191.5		125.1	529.5	602.7	
RC_HS			264.0		126.3	529.5	669.5	
T_Ref.				69.3	53.1	357.5	275.7	
T_MS				69.3	67.4	357.5	275.7	
T_HS				69.3	68.7	357.5	275.7	
CFS_Wind – Light steel framing building subject to wind loading;								
CFS_MS / HS – Light steel framing building subject to low seismic action / high seismic action;								
HRS_LS / MS / HS – Hot-rolled steel building subject to low seismic action / high seismic action;								
RC_LS / MS / HS – Reinforced concrete building subject to low seismic action / high seismic action;								
T_LS / HS – Timber building subject to low seismic action / high seismic action.								

Since the weight of the foundations and slabs represent a significant part of the overall weight a new comparison is established in

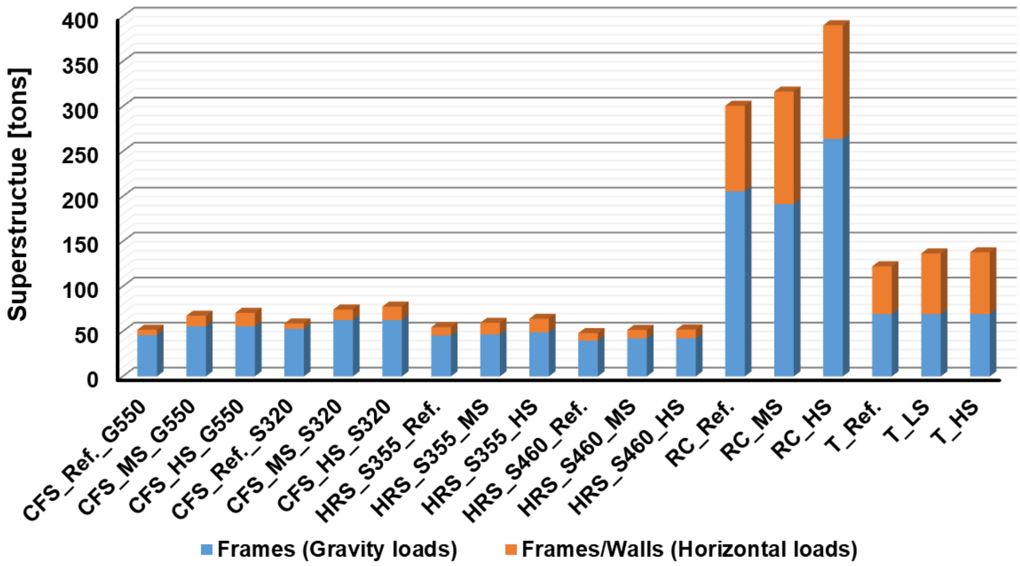


Figure 5.22 only for the vertical superstructure elements, disregarding the weight of the foundations and slabs.

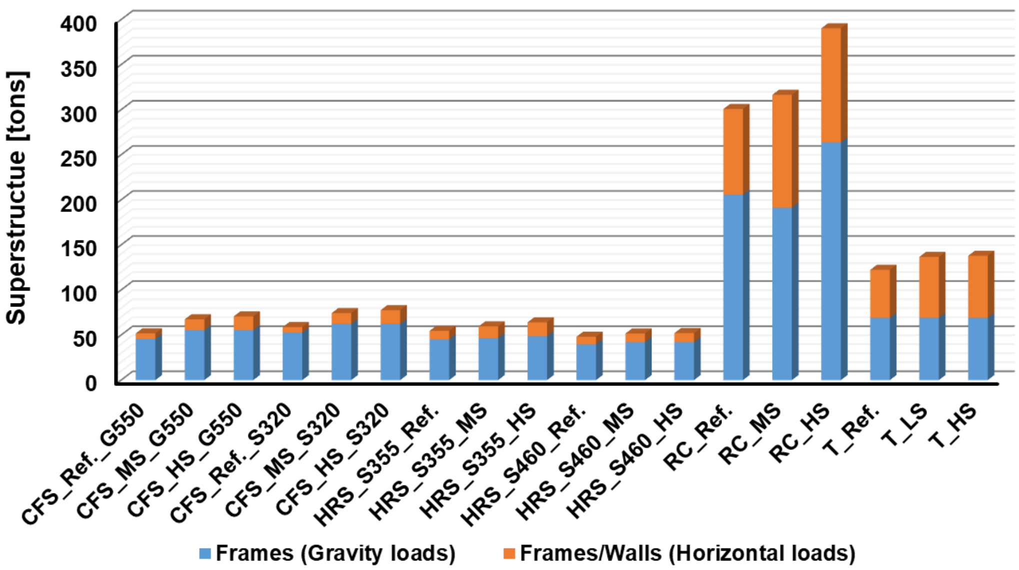


Figure 5.22. Total weight comparison for the superstructure elements between all tested structural solutions.

Finally, in Figure 5.23 the overall impact of the seismic loading in the superstructure in percentage is presented.

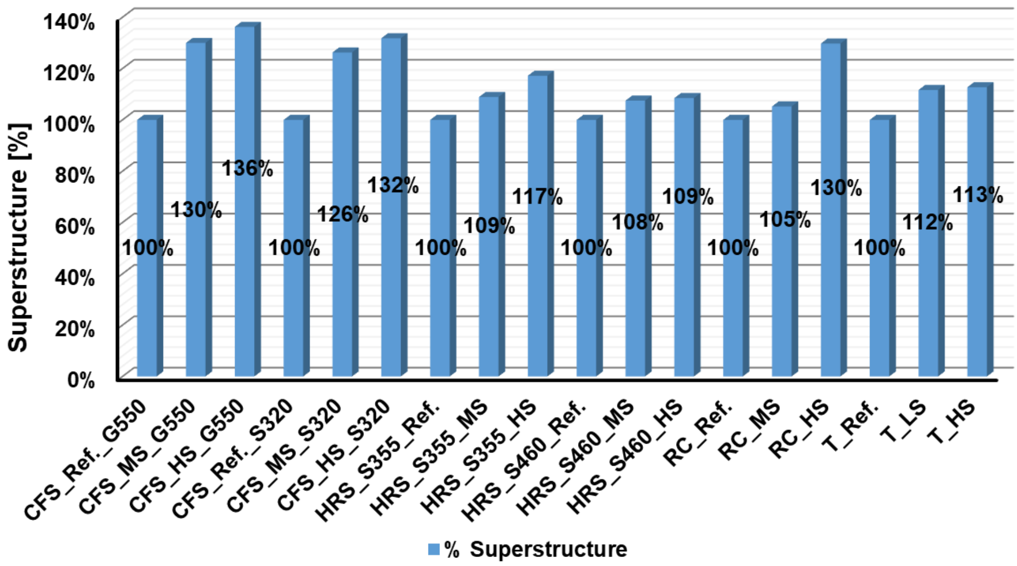


Figure 5.23. Comparison of the superstructure elements between all tested structural solutions.

Once, again it is possible to individualize the different elements of the superstructure and compared them to clearly assess the impact of the seismicity level in the overall weight of the structure (Figure 5.24). Since for the cold-formed steel and timber buildings a hybrid solution was adopted it is important to clearly understand if the lateral force resisting systems work adequately.

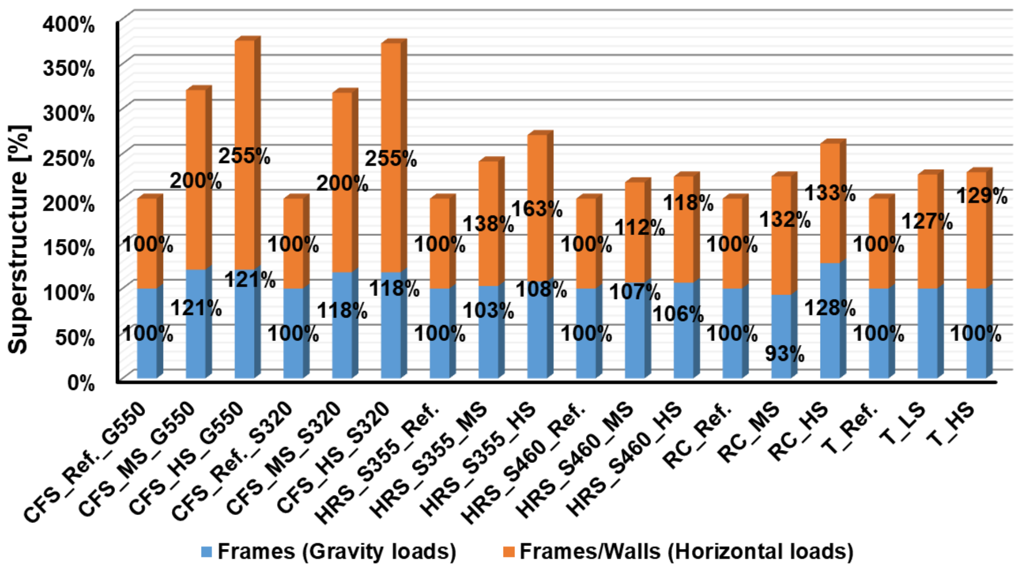


Figure 5.24. Comparison of the individualized superstructure elements between all tested structural solutions.

Observing the obtained results, the impact of the seismicity level is clear on the lateral force resisting systems. For instance, for the cold-formed steel building, the impact on the lateral force resisting system is high, but it is worth noting that the actual weight of the hot-rolled lateral force resisting system is relatively low.

Furthermore, the estimated total weight per square meter (total area of 1384 m^2) for each structural solution is summarized in

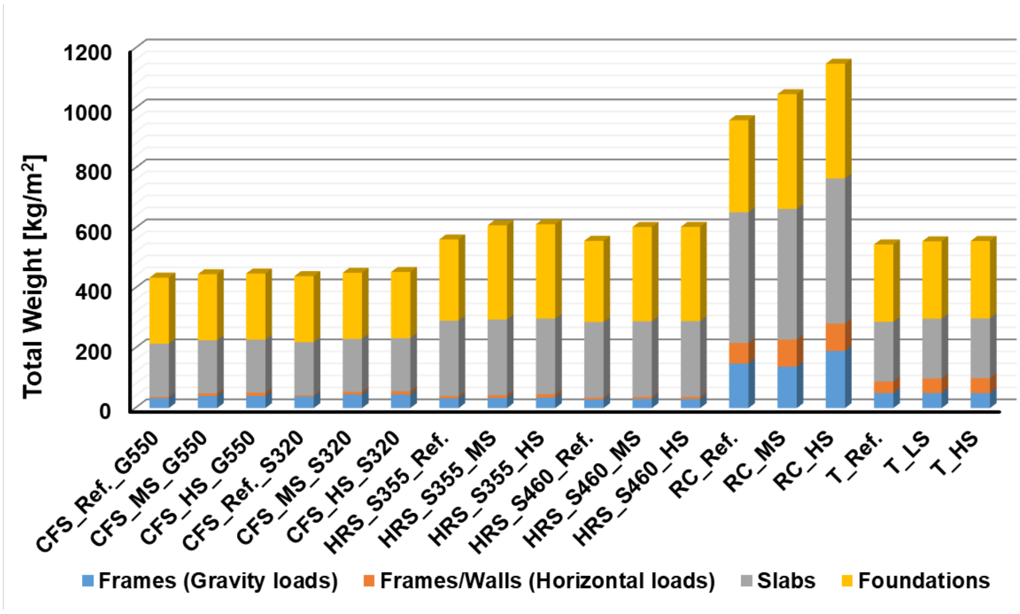


Figure 5.25. Total weight per sqm comparison between all tested structural solutions.

Table 5.18 and graphically in Figure 5.25.

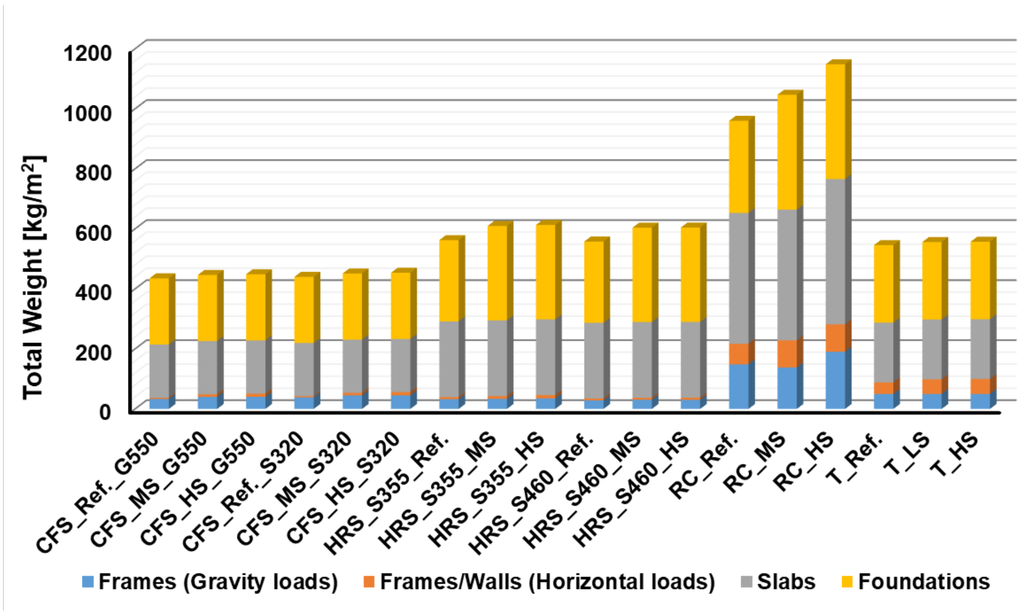


Figure 5.25. Total weight per sqm comparison between all tested structural solutions.

Table 5.18. Comparison of structural materials weight per sqm.

Structural solution	Superstructure					Found [kg/m2]	Slabs	
	Gravitational loads resisting elements				Lateral resisting elements			
	Light-Steel framing [kg/m^2]	Hot-rolled steel [kg/m^2]	Conc. Frames [kg/m^2]	Timb [kg/m^2]	MRF or shear walls [kg/m^2]		Slabs [kg/m^2]	Steel Deck [kg/m^2]
CFS_Ref._G550	33	0.5			4.3	220.5	167.7	9.3
CFS_MS_G550	40	0.5			8.5	220.5	167.7	9.3
CFS_HS_G550	40	0.5			10.9	220.5	167.7	9.3
CFS_Ref._S320	38	0.5			4.3	220.5	167.7	9.3
CFS_MS_S320	45	0.5			8.5	220.5	167.7	9.3
CFS_HS_S320	45	0.5			10.9	220.5	167.7	9.3
HRS_S355_Ref.		32.8			6.7	270.9	242.8	9.3
HRS_S355_MS		33.7			9.3	314.6	242.8	9.3
HRS_S355_HS		35.4			10.9	314.6	242.8	9.3
HRS_S460_Ref.		28.7			6.0	270.9	242.8	9.3
HRS_S460_MS		30.6			6.7	314.6	242.8	9.3
HRS_S460_HS		30.6			7.1	314.6	242.8	9.3
RC_Ref.			148.7		68.6	307.2	435.5	
RC_MS			138.4		90.4	382.6	435.5	
RC_HS			190.8		91.2	382.6	483.8	
T_Ref.				50.1	38.4	258.3	199.2	
T_MS				50.1	48.7	258.3	199.2	
T_HS				50.1	49.6	258.3	199.2	
CFS_Wind – Light steel framing building subject to wind loading;								
CFS_MS / HS – Light steel framing building subject to low seismic action / high seismic action;								
HRS_LS / MS / HS – Hot-rolled steel building subject to low seismic action / high seismic action;								
RC_LS / MS / HS – Reinforced concrete building subject to low seismic action / high seismic action;								
T_LS / HS – Timber building subject to low seismic action / high seismic action.								

Further comparison is shown in Figure 5.26, where the weight of the slabs is disregarded in order to show the direct impact of the weight increase of the vertical structural members. Here, only the superstructure elements are used for comparison purposes.

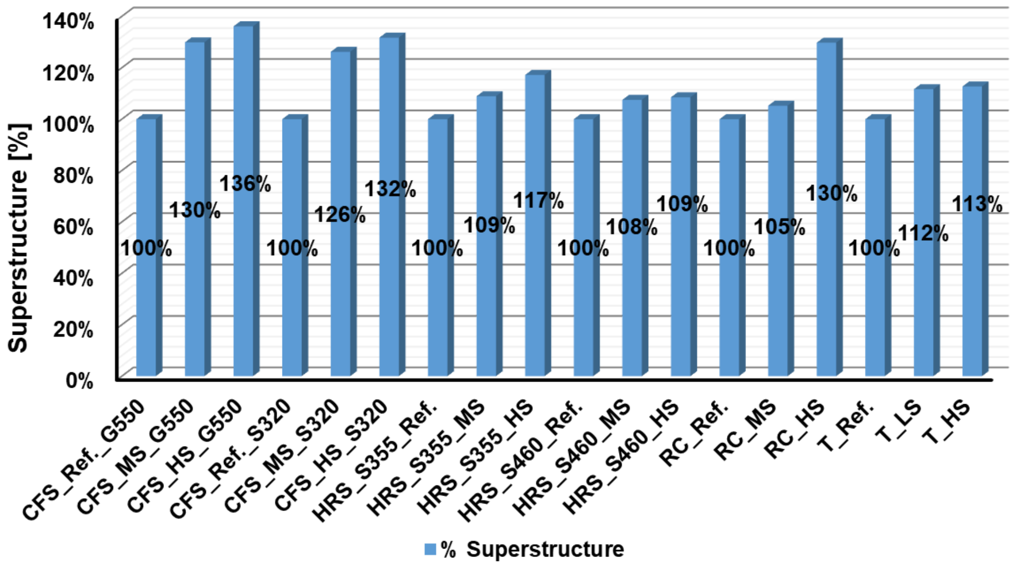


Figure 5.26. Frames and walls´ weight increase in % between all tested structural solutions.

From the analysis of the results the following conclusions may be drawn as follows:

- Cold-formed and hot-rolled steel solutions present much lower structural weight per square meter comparing to reinforced concrete buildings. This has a direct impact on the design of the foundations;
- For cold-formed steel buildings, the vertical resisting structure (gravity loads) can be considered as internal partitions and external facades, representing cost savings with materials and labour and faster construction time.
- For the hot-rolled steel solutions, the central core is responsible for resisting a great portion of horizontal loads, what was expected. The hot-rolled steel profiles weight from core had increased by more than 100% related to reference building, without seismic loads. On the other hand, the weight of other columns and beams remained the same, as they were designed to resist basically vertical loads.
- For the reinforced concrete solution, the percentage weight increase for locations with seismic hazards was higher than other solutions. This is due to the fact that this solution has a much higher mass, besides greater rigidity, which increases the seismic load applied to the base. In addition, concrete solutions have generally lower behavior factor than steel solutions, i.e., less capacity to absorb energy. Thus, this type of solution presents disadvantages in locations with high seismicity levels.
- It can be observed that the horizontal base reactions vary depending on several factors, such as the total seismic mass and the rigidity of the building. Considering this aspect, light steel framing has some advantages over the other solutions, since they have much lower mass.
- Hot-rolled steel building does not require formwork or a significant amount of shoring but has extra costs with secondary structures for facades and internal walls.

- The reinforced concrete building has additional costs with formwork, shoring, reinforcement processing (cutting and folding), a secondary structure for facades and internal walls
- The comparison in terms of material costs is not relevant. This should be analysed using a life-cycle cost assessment.

5.3 Impact on foundations

The different structural schemes tested, and the seismicity levels considered influenced significantly the overall design of the foundations. The impact of the structural system on the foundations was assessed and compared between all tested structural solutions and seismicity levels.

Foundations shall be checked against failure by sliding and against bearing capacity failure. Failure by sliding shall be resisted trough friction and lateral earth pressure. For the bearing capacity failure, load inclination and eccentricity arising from the inertia forces in the structure as well as the possible effects of the inertia forces in supporting soil itself shall be taken into account.

As expected, seismic loads have a great impact on horizontal base reactions and are much higher than wind reactions for medium and high seismicity level locations, as can be seen on the graphics below (Figure 5.27 to Figure 5.29). Seismic loads have also impact on vertical reactions as it increases the overall structural self-weight.

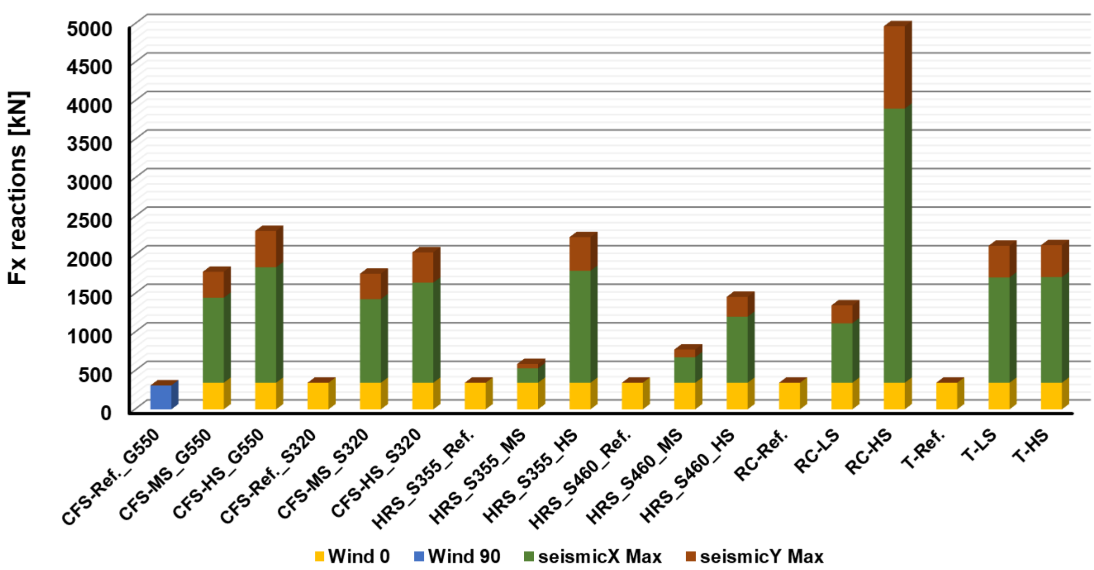


Figure 5.27. Total base reaction in the X direction.

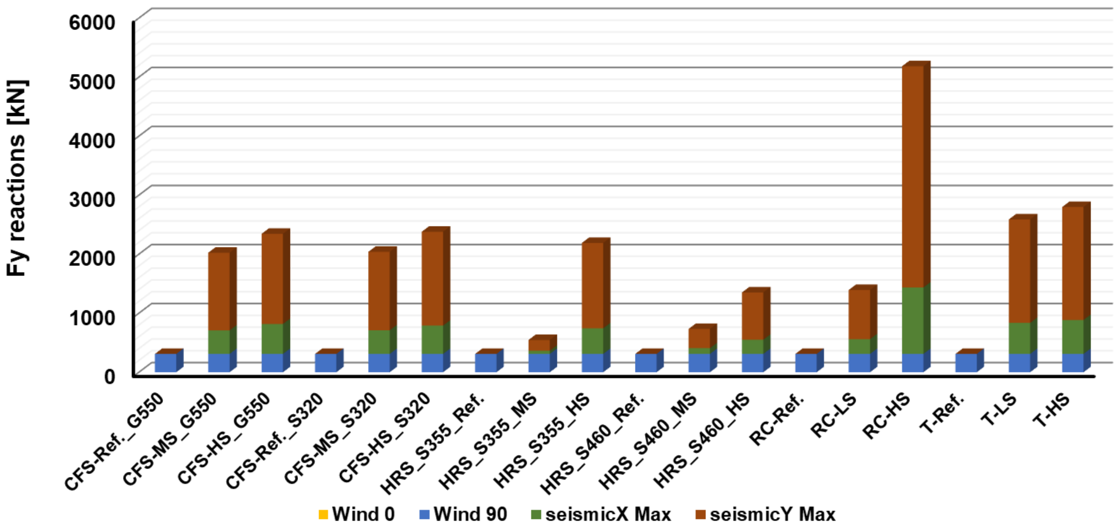


Figure 5.28 - Total base reaction in the Y direction.

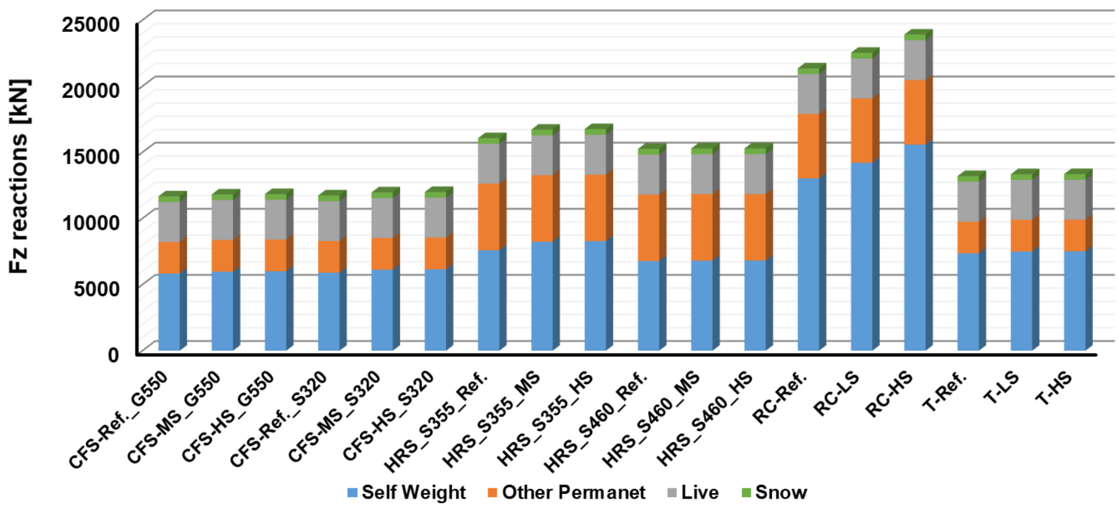


Figure 5.29. Total base reaction in the Z direction.

As shown on previous figures, the impacts on foundations are more relevant for the reinforced concrete buildings, as they have higher masses and stiffnesses, increasing base shear forces on all directions. For this structural solution, seismic actions can be responsible for more than 90% the characteristic total base reaction.

Lightweight solutions, as cold-formed steel and hot-rolled steel buildings, have advantages related to this aspect, as they mobilize lower seismic masses and have better response under these scenarios. These advantages become more significant as the seismicity level of the construction site increase.

Another important factor that must be taken into account is that steel structures, generally, can have a higher behaviour factor in seismic scenarios, as their energy dissipative capacity is often greater than concrete structures. This fact leads to lower design seismic actions applied to these solutions.

Regarding the adopted foundation systems for each one of the structural solutions, the estimated weights for the foundations are presented in Table 5.19 and depicted in Figure 5.30 as a function of the seismicity levels investigated. As expected, the foundations for the cold-formed steel and timber buildings are the lightest, and the foundations for the reinforced concrete solution the heaviest. It is worth noting, and as previously mentioned, that in this comparison different foundation systems were adopted. For both cold-formed steel and timber buildings, a raft foundation was adopted whereas for the hot-rolled steel and reinforced concrete buildings a pad foundation system with equilibrium beams and suspended ground floor slab was adopted.

Table 5.19. Weight estimation for the foundations according to the investigated scenario.

Structural solution	Foundation [ton]		Structural solution	Foundation [ton]
CFS_Ref._G550	305.2		**HRS_S355_Ref.**	375.0
CFS_MS_G550	305.2		**HRS_S355_MS**	435.4
CFS_HS_G550	305.2		**HRS_S355_HS**	435.4
CFS_Ref._S320	305.2		**RC_Ref.**	425.2
CFS_MS_S320	305.2		**RC_MS**	529.5
CFS_HS_S320	305.2		**RC_HS**	529.5
HRS_S355_Ref.	375.0		**T_Ref.**	357.5
HRS_S355_MS	435.4		**T_MS**	357.5
HRS_S355_HS	435.4		**T_HS**	357.5

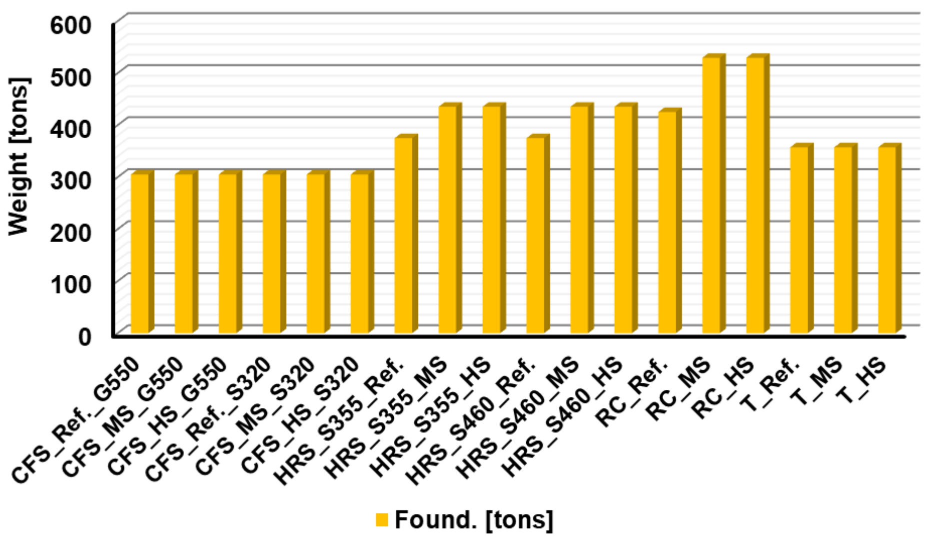


Figure 5.30. Weight comparison for the different foundation systems adopted for each type of building as a function of the seismicity level.

In Figure 5.31 a comparison in terms of percentage is established using as base value the weight of the foundation for the reference building for each structural material.

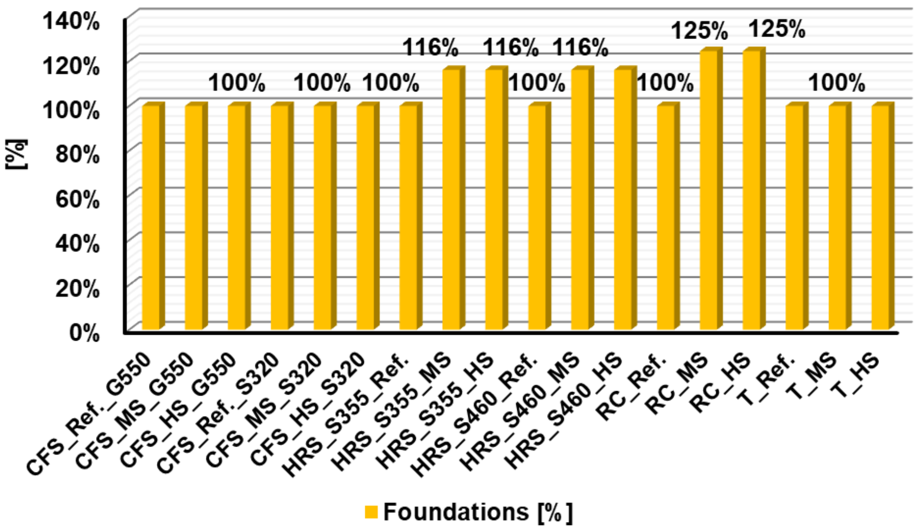


Figure 5.31. Comparison between the different foundation systems adopted for each type of building as a function of the seismicity level.

In Figure 5.32 a more global comparison is established. For this specific comparison, the lightest foundation was used as a reference to assess the weight increase for the others. The lightest solution is the one used for the cold-formed steel buildings (100%). Observing the obtained results, it can be stated that the foundation's weight is about 39% higher for the reference reinforced concrete building when compared with the reference cold-formed steel building, and 23% higher for the hot-rolled steel building when compared with the cold-formed steel building.

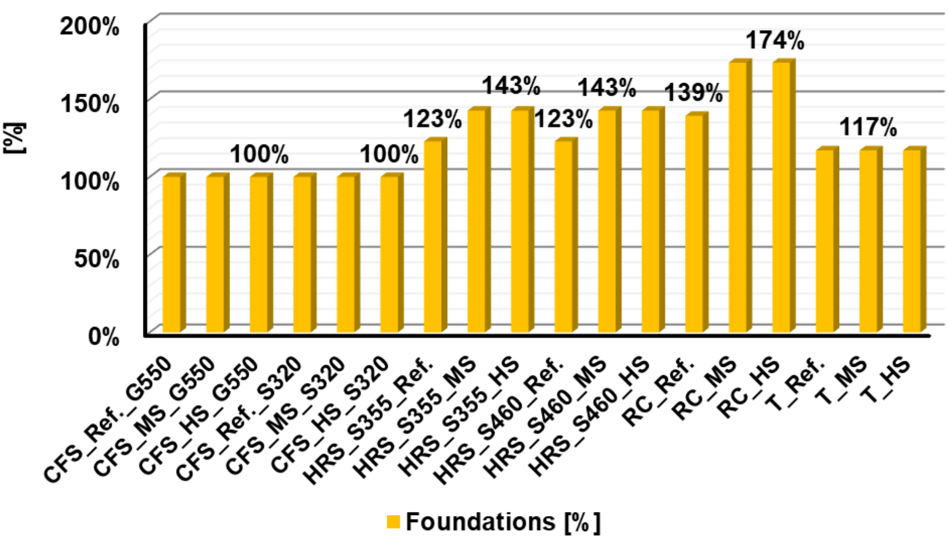


Figure 5.32. Variation of the weight of the foundations for the different studied scenarios.

As some global comments, it was observed that the weight of the foundations for the reinforced concrete solution was 43% higher than the cold-formed steel building and 13% higher than the hot-rolled steel foundations for the reference case (without seismic action). For the high seismic location, the overall impact is even greater, since for the reinforced concrete the weight of the foundation was 74% higher than the cold-formed steel building and 22% higher than the hot-rolled steel building. The weight of the timber foundation is 17% higher than the weight of the cold-formed steel foundation.

5.4 Concrete consumption

Concrete is still one of the most used materials in construction, however, it is recognized that despite all the undertaken efforts in the last few years is still considered an environmentally unfriendly material. In this Section, a comparison is established between all tested solutions in terms of concrete consumption. As previously mentioned the adopted concrete class was the C30/37, and an appropriate concrete composition was prescribed, detailing all the materials involved in the mix as well as the corresponding quantities.

In this study, it was assumed that all studied solutions would incorporate concrete foundations and slabs (flat reinforced concrete slabs and composite slabs comprising steel deck or timber deck and reinforced concrete). In Figure 5.33 the concrete weight and the weight of the materials in the concrete mix are presented for each one of the studied structural solutions for the reference situation (no-seismic action).

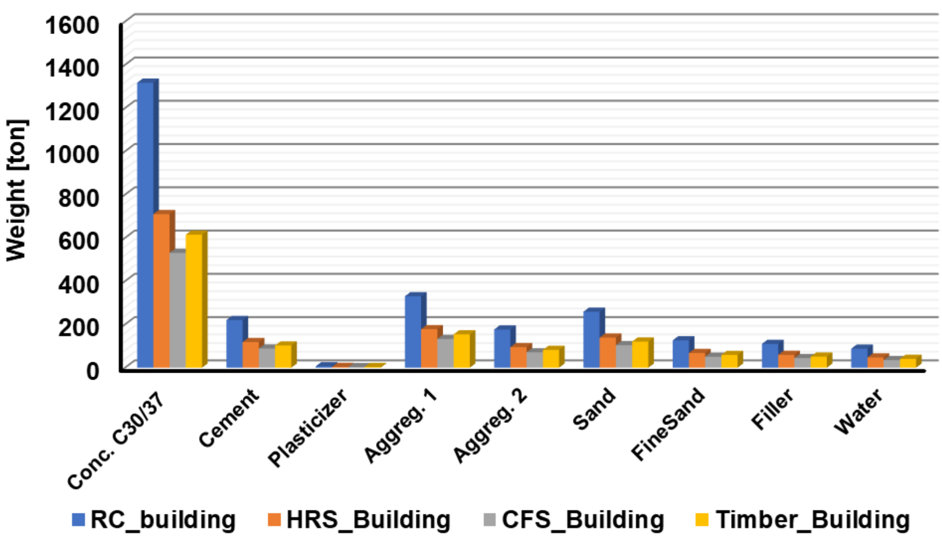


Figure 5.33. Concrete weight per building type and weight of the materials in the concrete mix for the reference cases.

For the reference, case studied and for each one of the framing solutions, the reduction in concrete consumption was assessed. Comparing reinforced concrete and hot-rolled steel cases the reduction in concrete consumption is 46.1%. Comparing the reinforced concrete solution with the cold-formed steel one, the concrete consumption decreased 59.7%, and comparing the reinforced concrete solution with the timber one, the reduction in concrete consumption is 53.3%.

In Figure 5.34 the concrete weight and the weight of the materials in the concrete mix are presented for each one of the studied structural solutions for the high seismic situation.

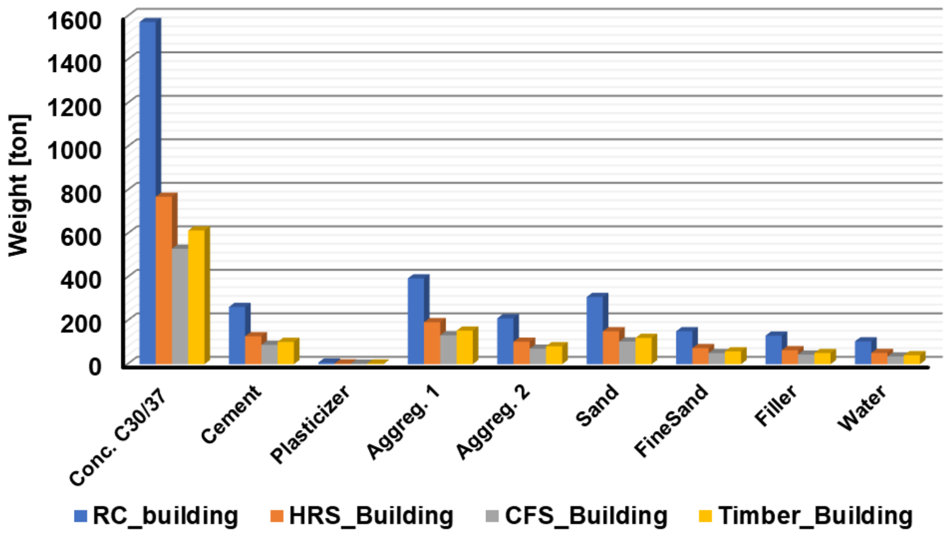


Figure 5.34. Concrete weight per building type and weight of the materials in the concrete mix for the high seismic cases.

For the reference case and for each one of the framing solutions, the reduction in concrete consumption was assessed. Comparing reinforced concrete and hot-rolled steel cases the reduction in concrete consumption is 51.1%. Comparing the reinforced concrete solution with the cold-formed steel one, the concrete consumption decreased 66.2%, and comparing the reinforced concrete solution with the timber one, the reduction in concrete consumption is 60.9%. The consumption reduction of the materials selected for the concrete mix is the same. For instance, the reduction of water consumption, when comparing the reinforced concrete framing solution with the cold-formed steel framing solution is 66.2%

The higher concrete quantity used in the reinforced concrete solutions will be translated as well in higher waste (excess material). The presented values and comparisons don’t include waste allowance. Usually, waste (excess material) for foundations is assumed as 5% and for superstructure as 2%. The excess material shall be properly handled, and proper planning is required to tackle this problem, hence while planning the construction programme the possibility of reuse the excess of concrete or recycle the excess material should be considered.

6. CONSTRUCTION SCHEDULE

6.1 Introduction

The construction schedule is a very important parameter that may influence the selection of the framing material to be adopted. Faster construction programmes will lead to an earlier use/exploitation of the building which can be translated into earlier use/rental income. A detailed analysis of each framing option was undertaken, aiming to establish a comparison between the estimated construction durations for the different structural materials. In this estimation, both frame and whole building construction durations were considered. In this analysis, the construction schedule is not dependent on site location.

For the cold-formed, hot-rolled steel and timber solutions it is assumed that all parts to be fabricated in a workshop will be available in the construction site as soon as needed. Hence, with proper planning, the fabrication in a workshop of the structural elements for the cold-formed, hot-rolled and timber building will not impact the planning of the construction site. The possibility of pre-fabrication brings some inherent advantages, such as:

- prefabrication techniques will allow the development of more technologically advanced solutions (depending on the workshop equipment and manpower);
- industrialization of the fabrication process will ensure faster execution times and safer working conditions (depending on the workshop equipment and manpower);
- increased productivity using prefabricated elements;
- higher overall quality of the final product (quality control is easier to implement in a controlled environment such as a workshop);
- reduction of site activities for frame erection, increasing safety levels;
- lower on-site work is translated into lower on-site construction waste, and even some of the steel waste can be recycled and reused;
- prefabricated solutions such as steel and timber buildings, generates flexible solutions, and specifically for residential buildings, the possibility to easily reshape the interior of the building can be an important advantage;
- Prefabricated solutions and specifically the cold-formed and hot-rolled steel ones may present an enhanced future-proofing (longer life for the building) due to its better adaptability and possibility for expansion which allow for easier changes in the future in order to address new service requirements;
- within the prefabricated solutions (cold-formed, hot-rolled steel and timber) steel presents some advantages when comparing with timber, namely, non-combustibility, termite-proof and rot proof, straightness, the accuracy of cutting and profiles. Steel will not shrink, split, warp, crack and creep;

For the concrete solution, it is assumed that all frame elements will be built on site. No pre-fabricated elements were considered for the reinforced concrete building. The reinforced concrete building will require a higher number of on-site activities, leading to additional risks for the workers, more construction waste and higher disruption to the surrounding area.

The construction is phased for all the structural solutions tested. For the cold-formed, hot rolled steel and timber buildings the construction starts with excavation, drainage, foundations, ground slab floor and erection of the cold-formed, hot-rolled and timber frame. The erection of the cold-formed, hot-rolled and timber frame with the floor slab will occur in four stages (each stage corresponding to one storey). It is worth mentioning that for the hot-rolled steel building the foundation system comprises isolated pad foundations with equilibrium beams and ground slab, whereas for the cold-formed steel and timber building a raft foundation was selected. The overall tonnage of reinforced concrete for the foundations is lower for the CFS building. Moreover, it is worth mentioning that the cold-formed steel solution is the lightest one and that the construction system, just like for the timber building, does not require the installation of additional non-loadbearing studs (the structural ones are used for this purpose) for the facade system. This can also be considered as an advantage for the cold-formed steel and timber buildings in terms of execution time. Both hot-rolled steel and reinforced concrete buildings require the installation of the studs to fix the facade gypsum boards and insulation.

Both cold-formed steel and timber buildings may be considered as hybrid ones since in these buildings different structural materials are combined. For the cold-formed steel building, hot-rolled steel elements are used to resist lateral loading, whereas for the timber building reinforced concrete walls and frames were used to resist the lateral loading. In terms of the construction schedule, the reinforced concrete shear walls will have a negative impact on the overall duration of estimated for the timber building.

For the reinforced concrete building the construction sequence comprises the excavation, drainage, foundations, ground floor slab, reinforced concrete columns, formwork and propping for the flat slabs for the 4 storeys. A seven days period was adopted for concrete curing between floor levels for the reinforced concrete building. The foundation system adopted for the reinforced concrete building is similar to the one adopted for the hot-rolled steel building, however, due to the higher tonnage of the reinforced concrete building the foundations require higher reinforced concrete quantity, hence the execution time will be higher than the one estimated for the hot-rolled steel foundation system.

For all framing solutions, the construction schedule was assessed, and the duration of each task estimated. Then according to the different phases defined for each framing solution the overall construction time was determined. In Figure 6.1 a representative construction schedule is presented. From the construction site to the end of the superstructure all tasks were assumed to be conducted sequentially, whereas for the external facades, internal partitioning and ceilings, finishes and installations it was assumed that some tasks could occur simultaneously but in different levels in the building. For instance, fitting the internal partitions will start when the external facades are fitted up to the third storey of the building. The same assumption was adopted for the remaining tasks and for all framing solutions investigated.

Hence, it is assumed that overlapping activities will not be advantageous for any of the tested solutions.

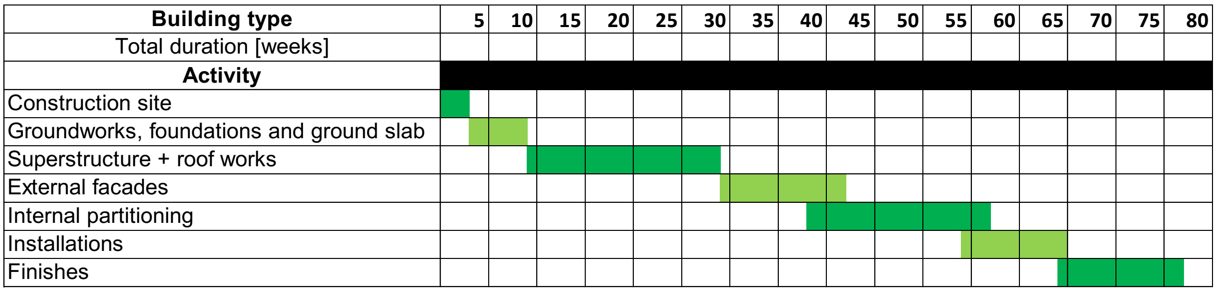


Figure 6.1.Representative construction schedule.

6.2 Comparison of the construction schedules

To understand and detail the main differences between the 4 tested framing solutions the estimated execution programmes were compared by activity. As depicted in Figure 6.1 the construction schedule was divided into 7 main activities, namely: (i) construction site; (ii) groundworks, foundations and ground slab; (iii) superstructure and roof; (iv) external facades; (v) internal partitioning and ceilings; (vi) finishes; and (vii) installations. In Table 6.1 andTable 6.2 the estimated construction schedules are compared for each major activity. Graphically the obtained results are presented in

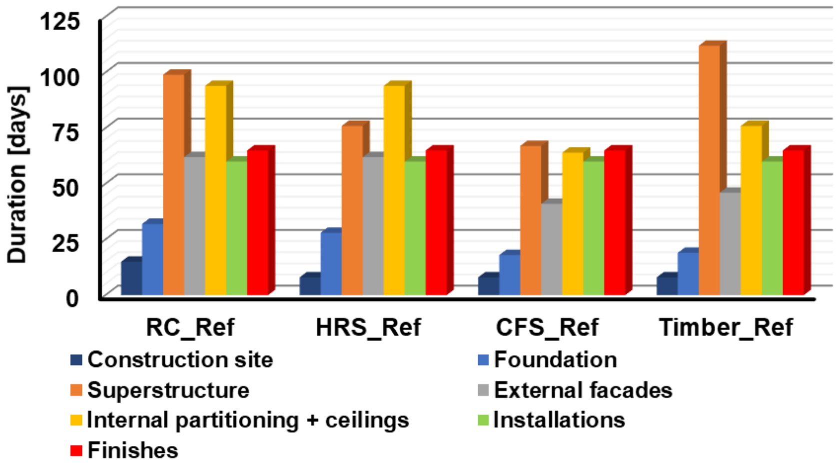


Figure 6.2 and Figure 6.3

Table 6.1. Detailed construction schedule for all tested framing solutions and the reference situation.

Activity	RC_Ref	HRS_Ref	CFS_Ref	Timber_Ref
Construction site [days]	15	8	8	8
Foundation [days]	32	28	18	19
Superstructure [days]	99	76	67	112
External facades [days]	62	62	41	46
Internal partitioning + ceilings [days]	94	94	64	76
Installations [days]	60	60	60	60
Finishes [days]	65	65	65	65

Table 6.2. Detailed construction schedule for all tested framing solutions and high seismic situation.

Activity	RC_HS	HRS_HS	CFS_HS	Timber_HS
Construction site [days]	15	8	8	8
Foundation [days]	34	31	18	19
Superstructure [days]	111	86	84	114
External facades [days]	62	62	41	46
Internal partitioning + ceilings [days]	94	94	64	76
Installations [days]	60	60	60	60
Finishes [days]	65	65	65	65

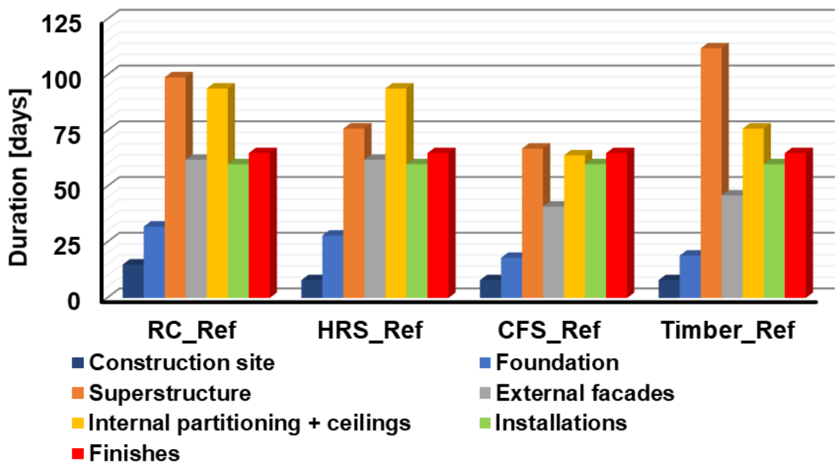


Figure 6.2. Comparison of the construction schedule per activity, for the reference case.

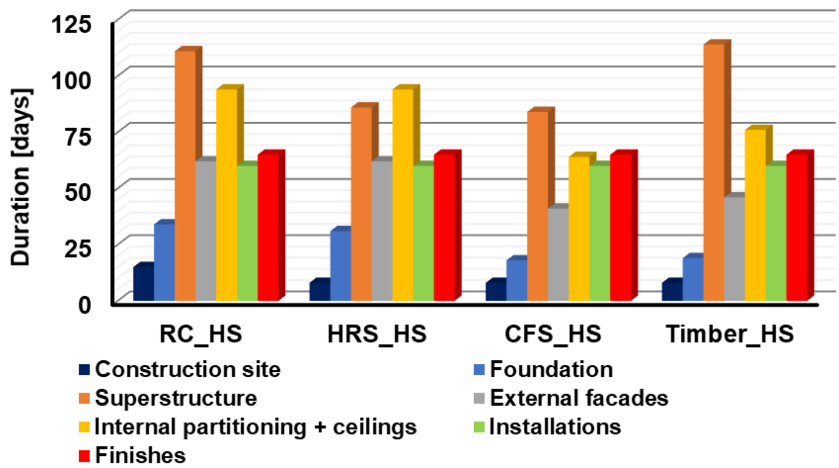


Figure 6.3. Comparison of the construction schedule per activity, for the high seismic case.

In terms of percentage, the obtained results are detailed in Table 6.3 and Table 6.4

Table 6.3. Percentage of reduction/increase in the construction time for each framing type considering the reinforced concrete solution.as reference – Reference case - no seismic action.

	Reference case		
Activity	**RC / HRS [%]**	**RC / CFS [%]**	**RC / Timber [%]**
Construction site	47	47	47
Foundation	13	44	41
Superstructure	23	32	-12
External facades	0	34	26
Internal partitioning + ceilings	0	32	19
Finishes	0	0	0
Installations	0	0	0

Table 6.4. Percentage of reduction/increase in the construction time for each framing type considering the reinforced concrete solution.as reference – High Seismicity location.

	High-Seismic case		
Activity	**RC / HRS [%]**	**RC / CFS [%]**	**RC / Timber [%]**
Construction site	47	47	47
Foundation	9	47	44
Superstructure	23	24	-3
External facades	0	34	26
Internal partitioning + ceilings	0	32	19
Finishes	0	0	0
Installations	0	0	0

Comparing the reinforced concrete framing solution with the hot-rolled steel one (Ref. – no-seismic action; HS – high seismicity level) it was found that:

- the foundation system for the HRS building takes 13% (9% for the high seismic case) less time to be built;
- the superstructure for the HRS building takes 23% (23% for the high seismic case) less time to be built.

Comparing the reinforced concrete framing solution with the cold-formed steel one (Ref. – no-seismic action; HS – high seismicity level) it was found that:

- the foundation system for the CFS building takes 44% (47% for the high seismic case) less time to be built;
- the superstructure for the CFS building takes 32% (24% for the high seismic case) less time to be built;
- the external facades for the CFS building take 34% (34% for the high seismic case) less time to be installed;
- the internal partitioning for the CFS building takes 32% (32% for the high seismic case) less time to be installed.

Comparing the reinforced concrete framing solution with the timber one (Ref. – no-seismic action; HS – high seismicity level) it was found that:

- the foundation system for the timber building takes 41% (44% for the high seismic case) less time to be built;
- the superstructure for the timber building takes 12% (3% for the high seismic case) more time to be built;
- the external facades for the timber building take 26% (26% for the high seismic case) less time to be installed;
- the internal partitioning for the timber building takes 19% (19% for the high seismic case) less time to be installed.

Analysing the obtained results it is clear that for the reference case (no seismic action) the longer construction time estimated for the reinforced concrete building is mainly due to the extra time needed to build the foundations, superstructure, facades and internal partitioning. The extra time needed for the foundations and superstructure is mainly due to the higher weight of the elements as well as due to the extra time required for curing purposes. It is worth mentioning that the construction of the superstructure of the timber building takes longer than the superstructure of the reinforced concrete solution. This is due to the hybrid character of the building (consideration of reinforced concrete shear walls and frames), which also impacts negatively on the overall duration of the construction of the superstructure. Moreover, it was assumed that erection of timber elements takes longer than the erection of steel ones.

The lack of prefabrication leads to a high volume of works in the construction site. Regarding the external facades and internal partitioning, the extra time, just as for the hot-rolled steel solution, is due to the fact that the non-loadbearing wall studs must be positioned first, whereas for the cold-formed steel and timber solutions the load bearing wall studs are also used to fix the wall panels.

The longer construction schedule was obtained for the reinforced concrete building, followed by the timber building and hot-rolled steel building. The faster execution time was obtained for the cold-formed steel building. For each one of the tested cases, the impact of the high seismic action on the execution programmes led to a small increase in the overall time, basically due to the higher quantities of structural materials for both foundations and frames. In Table 6.5 the total duration estimated for the construction schedule is presented for both reference and high seismic situation.

Table 6.5. Execution programme for the reference case and for the high seismic one for all tested framing systems.

	RC_Ref	**HRS_Ref**	**CFS_Ref**	**Timber_Ref**
Duration [days]	385	351	294	357
	RC_HS	**HRS_HS**	**CFS_HS**	**Timber_HS**
Duration [days]	399	364	311	359

In this study, the estimated duration for the reinforced concrete building was 77 weeks (385 working days), for the hot-rolled steel building was 71 weeks (351 working days), for the cold-formed steel 59 weeks (294 days) and for the timber building 73 weeks (357 days). The hot-rolled steel building programme is reduced by 8.8%, the cold-formed steel programme is reduced by 23.6% and the timber building programme is reduced by 7.2% when compared with the reinforced concrete building programme.

For the case where the buildings were located in a high seismic area the obtained duration for the reinforced concrete was 80 weeks (399 working days), for the hot-rolled steel was 73 weeks (364 days), for the cold-formed steel was 62 weeks (310 days) and for the timber 72 weeks (359 days). The hot-rolled steel building schedule is reduced by 8.7%, the cold-formed steel programme is reduced by 22% and the timber building programme is reduced by 10% when compared with the reinforced concrete building schedule.

In Figure 6.4 and Figure 6.5 the estimated durations for both reference and high seismic situation are depicted and compared.

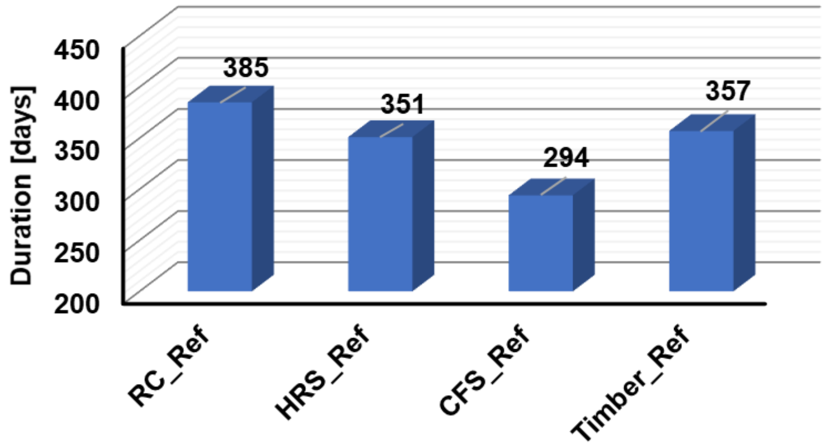


Figure 6.4. Estimated total duration for the execution programme for all framing solutions and reference case.

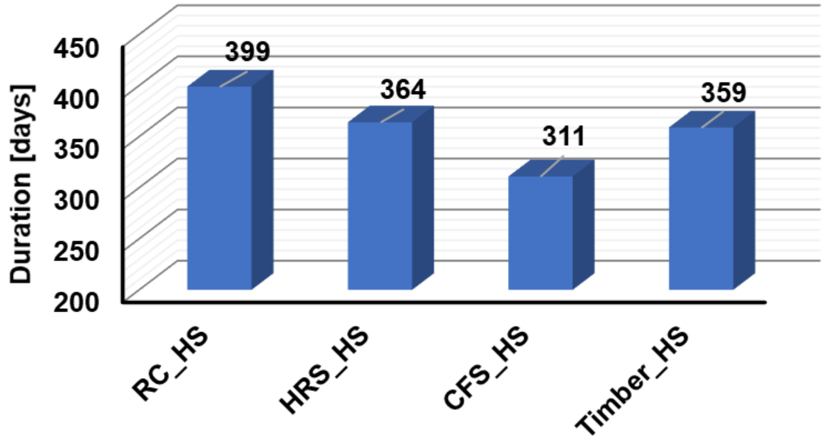


Figure 6.5. Estimated total duration for the execution programme for all framing solutions and high seismic case.

For all the tested conditions the use of cold-formed steel for framing always resulted in smaller execution programmes. This is mainly due to the lighter foundations, prefabrication of the elements allowing for a faster superstructure erection, easier and faster wall sheeting assembly, specifically taking into consideration the adopted wall systems.

6.3 Final remarks

From the conducted programming it was concluded that the reinforced concrete building is the one with the longer construction times followed by the timber building, hot-rolled steel building and finally the cold-formed steel building. On average (considering the reference and high seismic case) the construction period is reduced by about 86 days (22.2%) when the cold-formed steel framing solution is selected.

Modular construction systems are inherently faster solutions to build/erect. The construction schedule can be significantly reduced when a prefabricated, industrialized modular solution is selected for the structural framing. Reducing the overall number of activities on-site will enhance construction times. The workshop efficiency is higher as well as the accuracy and quality of the final product when compared with on-site fabrication. However, a prefabricated solution, as previously mentioned, requires proper planning ensuring that when needed all prefabricated elements can be delivered on time in the construction site avoiding delays. Hence, the construction schedule of prefabricated solutions can be highly dependent on the lead-in time required from the moment the elements are ordered to the moment they are delivered on-site. In this study, it was assumed that all elements will be delivered to the construction site in due time.

The reduced construction schedule will lead consequently to significant cost savings, enhancing the competitiveness of the cold-formed steel solution in the construction sector. Savings will be related with the manpower required, the overall material quantity, and as well with lower rental times for cranes and other types of equipment. It is worth noting that prefabricated solutions, both using steel or timber, will present high levels of precision and overall quality. This added dimension precision will also contribute to lower material waste in the construction site, reducing the overall impact of the construction site in the surrounding environment or area. For the reinforced concrete solutions, the use of the excess material must be carefully planned in order to reduce its impact on the environment.

Another important aspect that must be taken into consideration is the adaptability, and the relocation of the building. Prefabricated modular cold-formed steel solutions are inherently highly adaptable solutions allowing the building to be easily modified to address new requirements that may arise during its lifetime. Moreover, if necessary its modularity allows for future relocation of the building since this type of building is more easily disassembled. Specifically for the studied cases, relocation will require the construction of new foundations and execution of new composite slabs. The remaining framing system can be reused and relocated. The hot-rolled steel and timber solutions also share this potential for adaptability and relocation. These characteristics may ensure that the lifetime of the structure can be extended if necessary.

Finally, it is worth mentioning that using prefabricated lightweight solutions with faster construction schedules may bring additional cost savings in different construction operations. For instance, the reduced number of on-site works will lead to lower waste and lower disposal costs, as well as to increased safety levels for the workers, whereas the reduced programme will for sure lead to reduced costs and usage of elevation equipment.

7. CONCLUSIONS

A comparative study of different structural solutions for a four-storey residential building was performed. In this report, a light steel framing solution for multi-storey residential buildings was compared with other structural systems using different structural materials, including hot-rolled steel, reinforced concrete and timber. For each structural system, different seismicity scenarios were considered. Based on the same architectural layout 3D structural modelling and analysis have been performed using the software SAP2000 [3]. In this study, the bill of materials for each structural solution was determined, providing data related to the competitiveness of each material for the structural framing for residential buildings. The following conclusions can be drawn from the observations reported in this work:

(1) As expected the heaviest structural solutions are the reinforced concrete ones, for all seismicity levels tested. The lightest building is the cold-formed steel one. The weight of the reinforced concrete building is 121% higher than the weight of the G550 cold-formed steel building, 71% higher than the hot-rolled steel building and 76% higher than the timber building (for the reference scenario – no seismic action);

(2) In terms of percentage weight increase, the lateral force resisting system prescribed for the cold-formed steel building is the one where the seismic action has a more significant impact. Increasing the seismicity level, the weight of the lateral force resisting system increases up to 155% when compared with the reference situation. The percentage weight increase was up to 63%, 33% and 29%, respectively for the hot-rolled steel, reinforced concrete and timber buildings (high seismicity level);

(3) The foundations for the cold-formed steel and timber buildings were the lightest, and the foundations for the reinforced concrete solution the heaviest, as expected. The reinforced concrete foundations are 74% heavier than the cold-formed steel ones for the high seismic case;

(4) The seismic location plays a significant role in the estimation of the overall weight of the substructure and superstructure of a building. The weight of the foundations increased up to 25% for the reinforced concrete solution when the high seismicity level was considered;

(5) Hot-rolled steel building does not require formwork or a significant amount of shoring but has extra costs with secondary structures for facades and internal walls. Also, the material may be more expensive and steel structures require fire protection. Steel solutions are faster to erect, with higher quality and narrower tolerances. Moreover, steel solutions are highly adaptable, reusable, expandable an recycled.

(6) The reinforced concrete building has additional costs with formwork, shoring, reinforcement processing (cutting and folding), a secondary structure for facades and internal walls. However, the reinforced concrete building is more durable, requires less maintenance, has a very good fire behavior

(7) Light steel framing buildings usually present a good fire resistance but at the expense of fire protection with two layers of gypsum boards or calcium silicate boards (for fire resistance rate of 60 minutes), which is more expensive.
(8) The bigger the concrete consumption the bigger the waste (excess material). The excess material shall be properly handled, and proper planning is required to tackle this problem.
(9) The cold-formed steel solution is the fastest to be erected, taking advantage of its overall lightness and possibility of prefabrication. On average (considering the reference and high seismic case) the construction period is reduced by about 90 days (22.8%) when the cold-formed steel framing solution is selected.

8. REFERENCES

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ANNEX A. FACADES AND INTERNAL PARTITIONS

A1. Facade System

As previously mentioned, for the external wall facade system three climatic areas were selected as well as two performance levels. The proposed solutions are suitable for residential use and can be adapted for different structural solutions. Table A.1 specifies and details the adopted facade systems.

Table A.1. Facade solutions adopted according to climatic areas and performance level.

Facade system	**Climatic areas**		
	Csa-Csb	**Cfb**	**Dfa-Dfb**
Standard performance	External wall with Direct Render System	External wall with ETICS system	Double external wall with Direct Render System
High performance	External wall with ETICS system	Double external wall with Direct Render System	External wall with Cladding system

The wall facade systems are based on the high performance Glasroc X sheathing board specifically designed for external use. The Glasroc X is ideal for external use, with high impact resistance, high fire resistance (up to 120 minutes), Euroclass A1 non-combustible reaction to fire performance and great resistance to mould growth and water penetration.

In Figure A.1 to Figure A.3, a schematic representation of the different external wall systems is depicted.

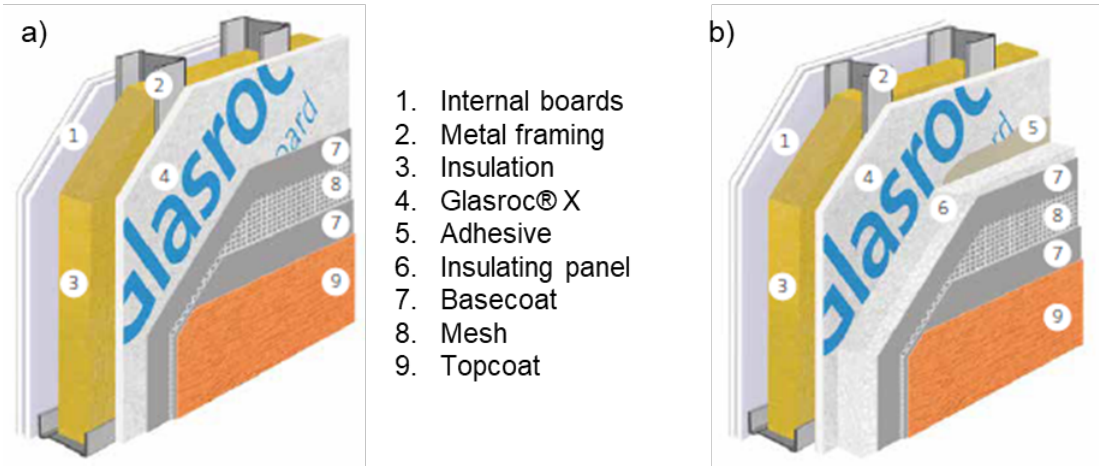


Figure A.1. Schematic representation of the Direct render (a)) and ETICS system (b)).

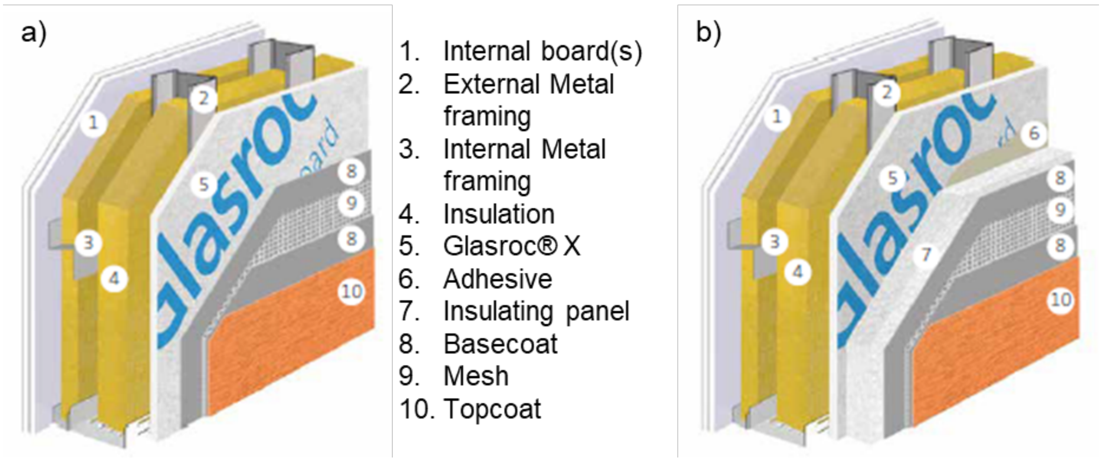


Figure A.2. Schematic representation of the Double external wall with Direct Render System (a)) and the Double External wall with ETICS system (b)).

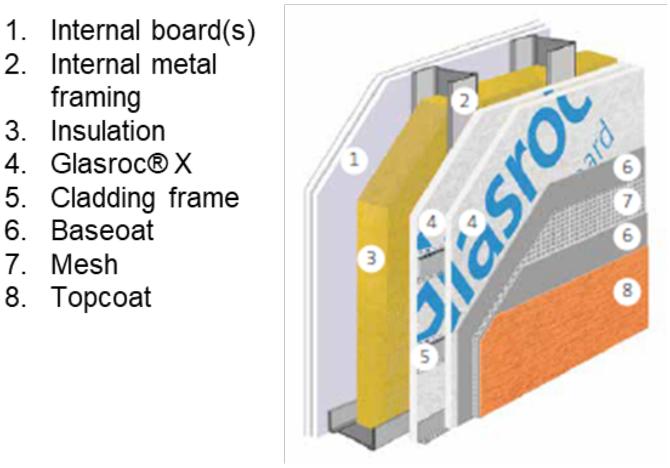


Figure A.3. Schematic representation of the External wall with Cladding system (Glasroc ® X).

A2. Elevators and Stairs

To protect the elevator shaft introduced in the building the ShaftWall special partition system is prescribed for all different building typologies investigated. The ShaftWall system is a lightweight, fire resistant solution to protect elements in confined spaces. As for the external wall systems two performance levels were considered and consequently two product lines will be prescribed. The difference in performance is mainly related with the inherent fire resistance (EI – Integrity and Insulation criteria) and acoustic insulation. Two systems are prescribed, namely the PLACO® ShaftWall EI120 and PLACO® ShaftWall EI180.

The ShaftWall system comprises a metal framing and two types of gypsum boards, namely the Coreboard ® (19 mm thickness) and a different number of PLACOFLAM ® boards, PPF BA 15 (15 mm thickness), depending on the desired performance level. The PLACOFLAM® is a board used mainly in constructive systems where high fire resistance requirements must be fulfilled. The Coreboard® gypsum board also presents good fire resistance performance, high thermal and acoustic inculation.

In Table A.2 the details of the adopted solutions are presented.

Table A.2. Definition of the most relevant properties of the ShaftWall partitioning system

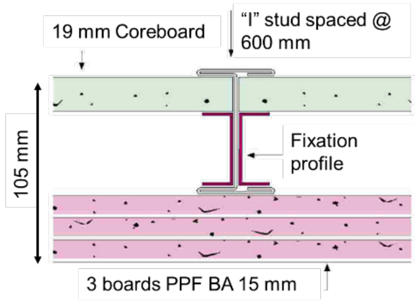
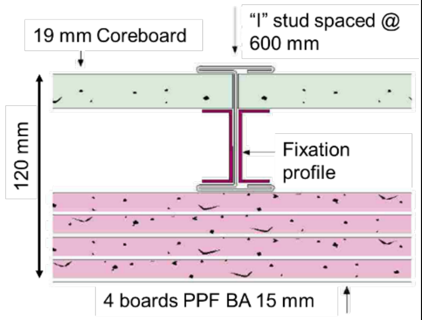
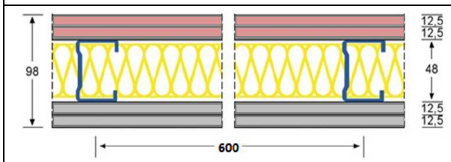
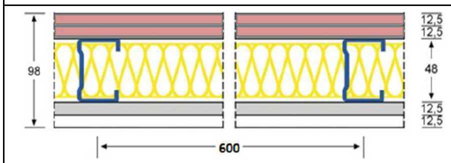
Schematics	Total thickness	Maximum height	Fire resistance	Acoustic insulation
Standard solution				
	105 mm	4.5 m	EI 120 min	53 dB
High performance solution				
	120 mm	4.5 m	EI 180 min	48 dB

Table A.3. Definition of the most relevant properties of the Stairs partitioning system.

Schematics	Weight	Thickness	Height	Fire Resistance	Acoustic insulation
Standard solution					
	45 kg	98 mm	3.05 m	EI 60 min	52 dB
High performance solution					
	47 kg	98 mm	3.05 m	EI 60 min	53 dB

For the stairs the prescribed solutions are presented in Table A.3. The standard solution comprises two PPF 13 gypsum boards and two STD BA 13 gypsum boards. The high-performance solution uses a HABITO® gypsum board, replacing one of the STD BA 13. The HABITO® gypsum boards present enhanced mechanical behaviour with high load bearing capacity, effective acoustic insulation, high thermal insulation, fire reaction classification A2 s1 d0 and resistance to impacts. Both partitioning systems are able to guarantee a 60-minute fire resistance in terms of integrity (E) and insulation (I) criteria. The studs are spaced at 600 mm and PV ACUSTIVER 50 mineral wool is used.

A3. Internal Partitioning

For the internal partitioning the architectural layout was carefully analysed and the most adequate solutions proposed. Dry areas, wet areas and compartmentation between different apartments and common areas were identified (see Figure 3.2). Hence, for partitioning according to the type of use of each compartment the solutions were selected. The types of partitioning identified were as follows:

- partitioning between different apartments and apartments to common areas;
- partitioning between dry areas within each one of the apartments;
- partitioning between dry and wet areas within each one of the apartments;
- partitioning between wet and wet areas within each one of the apartments;
- false ceiling for wet and dry areas.

Again, two performance levels were adopted and the correspondent solutions selected accordingly.

For internal partitioning solutions between apartments and apartments and common areas the Placo® PRIMA PLUS with 5 boards 159/48 system (standard solution) and the Placo® PRIMA PLUS with 5 boards (3 HABITO® boards) 159/48 (high performance solution) system were selected. The partitioning system comprises two gypsum boards in both faces and one internal one, between the two steel studs. For both standard and high-performance solution mineral wool PV ACUSTIVER 50 is used. The difference between the two systems is the incorporation of 3 HABITO® boards, replacing 3 STD BA13 ones. The studs are spaced at 600 mm. The prescribed solutions are presented and depicted in Table A.4.

For internal partitioning solutions between dry areas the Placo® PRIMA 100/70 system (standard solution) and the Placo® HABITO 100/70 system were selected. The standard solution uses STD BA15 boards whereas the high-performance solution uses HABITO® boards. The studs are spaced at 600 mm. The prescribed solutions are presented and depicted in Table A.5.

Table A.4. Definition of the most relevant properties of the partitioning system between apartments and apartments and common areas.

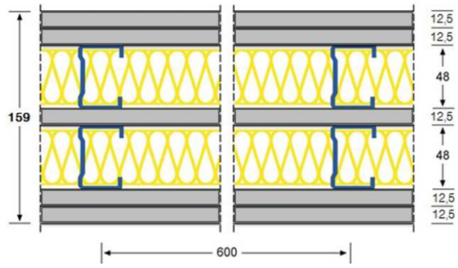
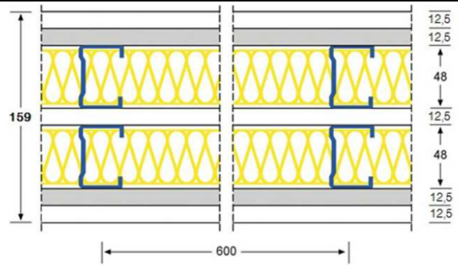
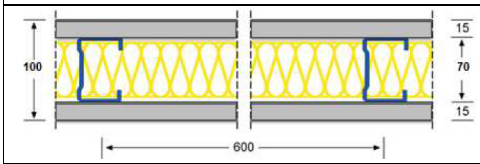
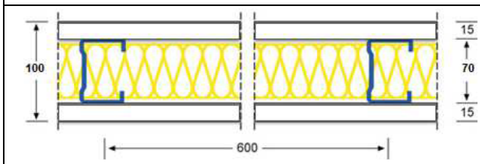
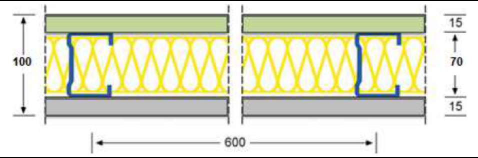
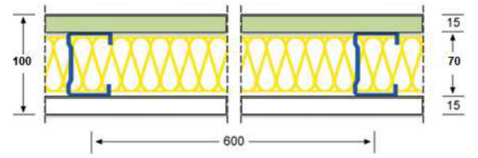
Schematics	Weight	Thickness	Height	Fire Resistance	Acoustic insulation
Standard solution					
	58 kg	159 mm	2.8 m	EI 60 min	62 dB
High performance solution					
	65 kg	159 mm	2.8 m	EI 60 min	63 dB

Table A.5. Definition of the most relevant properties of the partitioning system between dry areas.

Schematics	Weight	Thickness	Height	Fire Resistance	Acoustic insulation
Standard solution					
	29 kg	100 mm	2.8 m	EI 45 min	48 dB
High performance solution					
	33 kg	100 mm	2.8 m	EI 60 min	48 dB

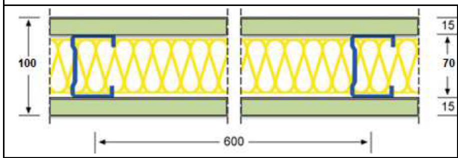
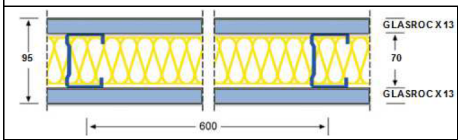
For internal partitioning solutions between dry and wet areas the Placo® HYDRO 100/70 system (standard solution) and the Placo® HYDRO with HABITO® gypsum board 100/70 system were selected. Tha standard solution Placo® HYDRO 100/70 comprises a PPM 15 and and STD BA 15 gypsum board. For the high-performance solution, the STD BA15 board is replaced by a HABITO® 15 one. The studs are spaced at 400 mm. For both standard and high-performance solution mineral wool PV ACUSTIVER 60 was used. The prescribed solutions are presented and depicted in Table A.6.

Table A.6. Definition of the most relevant properties of the partitioning system between dry and wet areas.

Schematics	Weight	Thickness	Height	Fire Resistance	Acoustic insulation
Standard solution					
	29 kg	100 mm	2.8 m	—	48 dB
High performance solution					
	31 kg	100 mm	2.8 m	—	48 dB

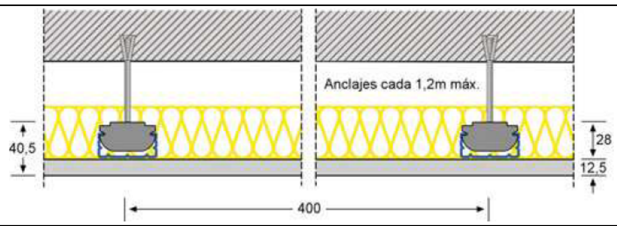
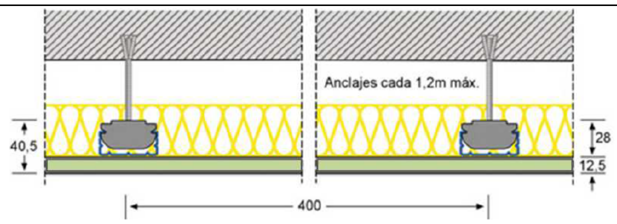
For internal partitioning solutions between wet areas the Placo® HYDRO 100/70 system (standard solution) and the Placo® HYDRO with HABITO® gypsum board 100/70 system were selected. Tha standard solution comprises two PPM 15 gypsum boards, whereas the high performance one comprises two GLASROC® X 13 gypsum boards. The studs are spaced at 400 mm. For both standard and high-performance solution mineral wool PV ACUSTIVER 60 was used. The prescribed solutions are presented and depicted inTable A.7.

Table A.7. Definition of the most relevant properties of the partitioning system between wet areas.

Schematics	Weight	Thickness	Height	Fire Resistance	Acoustic insulation
Standard solution					
	30 kg	100 mm	2.8 m	—	48 dB
High performance solution					
	27 kg	95 mm	2.8 m	—	48 dB

For the false ceilings the proposed solutions will be used either in dry or wet areas. For both dry and wet areas the Placo® PRIMA F-530 system was selected, however the gypsum board is different. For the dry areas a STD BA 13 4PRO gypsum board was used whereas for wet areas a PPM gypsum board was selected. The prescribed solutions are presented and depicted in Table A.8.

Table A.8. Definition of the most relevant properties of the false ceiling systems for both dry and wet areas.

Schematics	Thickness	Fire Resistance	Acoustic Abs.
Dry areas			
	41 mm	EI 15 min	0.1
Wet areas			
	41 mm	—	0.1

ANNEX B. ACTIONS AND LOAD COMBINATIONS

B1. GENERAL SAFETY CRITERIA, ACTIONS AND COMBINATION OF ACTIONS

The classification of action considering their variation in time according to EN 1990, is presented as it follows: a) permanent actions (G) (e.g. self-weight), b) variable actions (Q) (e.g. imposed loads on buildings floors, wind loads, snow loads) and c) accidental actions (A) (e.g. explosions). The considered actions for this study case are described in the following paragraphs. The actions were calculated accordingly to the relevant parts of EN 1991-1.

B2. PERMANENT ACTIONS

The permanent actions include the selfweight off the structural elements and also of the non-load-bearing layers or elements of the structure. All the different cases are presented in Table B.1**Error! Reference source not found.**

Table B.1. Permanent loads considered.

Element	Permanent loads [kPa]
Roof	0.42
Floor	2.25
External wall	0.50
Internal wall	0.50

For the case of partitioning walls their weight can be taken as a distributed load q_k together with the live loads as it follows:

- partioning wall load ≤1.00 kN/m, q_k =0.50 kN/m^2;
- partioning wall load ≤2.00 kN/m, q_k =0.80 kN/m^2;
- partioning wall load ≤3.00 kN/m, q_k =1.20 kN/m^2.

For the cold formed steel structures, the partitioning walls have also a structural contribution so their loads will be taken into account as permanent loads.

B3. IMPOSED LOADS

The characteristic value of the imposed load depends on the building type of occupancy and also the category of the loaded area part of the building. For a residential type of building, according to Table 6.1 of EN 1991-1-1, the category of the loaded area is A, the corresponding characteristic values being given by $q_k = 1.5$ to $2.0\ kN/m^2$ and $Q_k = 2.0$ to $3.0\ kN$. The corresponding charcateristic value q_k is used to obtain the global effects and Q_k for local effects. According to the EN 1991-1-1, the characteristic value of the imposed load is given by the National Annexes; however, the recommended values are underlined. The imposed loads for this type of building are presented in Table B.2 together with the underlined recommended values.

Table B.2. Imposed loads

Categories of loaded areas	q_k [kN]	Q_k [kN]
Category A	___	___
Floors	1.5 – 2.0	2.0 – 3.0
Stairs	2.0 – 4.0	2.0 – 4.0
Balconies	2.5 – 4.0	2.0 – 3.0

B4. WIND ACTIONS

B3.1 Wind forces

The quantification of the wind actions on the building follows EN 1991-1-4 (CEN, 2005e). Two main directions are assumed for the wind: θ=0º and θ= 90º. According to clause 5.3(3), the wind forces are calculated by the vectorial summation of the external forces, $F_{w,e}$, and the internal forces, $F_{w,i}$, given by expressions (1) and (2), respectively

$$F_{w,e} = c_s c_d \sum_{surfaces} w_e A_{ref}$$

and,

$$F_{w,i} = \sum_{surfaces} w_i A_{ref}$$

Where $c_s c_d$ are the structural factors, A_{ref} is the reference area of the individual surfaces, and we and wi are the external and internal pressures on the individual surfaces at reference heights ze and zi, respectively for external and internal pressures, given by the following expressions:

$$w_e = q_p(z_e) c_{pe}$$

and,

$$w_i = q_p(z_i) c_{pi}$$

$q_p(z_i)$ is the peak velocity pressure, and c_{pe} and c_{pi} are the pressure coefficients for the external and internal pressures, respectively.

The structural factor $c_s c_d$ is defined in clause 6.1(1). For multistory steel buildings with rectangular plan layout and vertical external walls, with regular distribution of stiffness and mass, the structural factor $c_s c_d$, may be taken from Annex D of EN1991-1-4. For h = 12.8 m and b = 19,99 m (θ=0º), $c_s c_d$ = 1 for h<15 m, and for b = 17.75 m (θ= 90º.), $c_s c_d$ = 1.

B3.2 Reference height

The reference heights, z_e, for vertical windward walls of rectangular plan buildings depend on the aspect ratio h/b and are always the upper heights of the different parts of the walls (clause 7.2.2(1)). For θ=0º or 90º (see Figure A.1), h=12.80m ≤ b = 19.99 m respectively h=12.80m ≤ b = 19.99 m therefore the height of the building will be considered in only one part. The resulting shape of the velocity pressure profile is shown in Figure B.1.

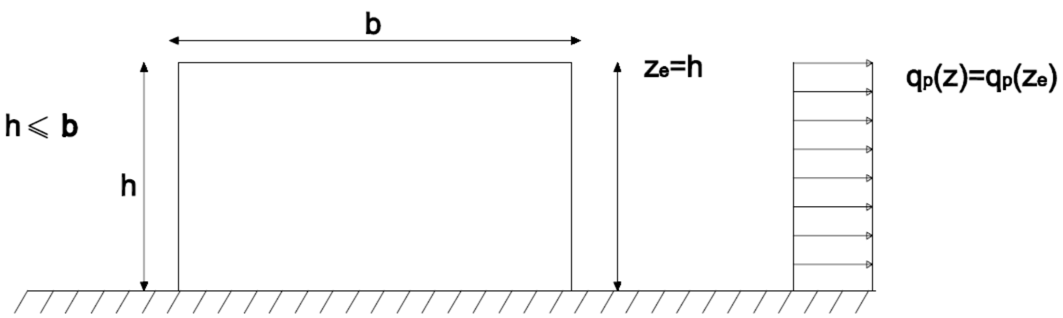


Figure B.1. Velocity pressure distribution on face D ($\theta = 0º, \theta = 90º$).

B3.3 Calculation of external and internal pressure coefficients

External and internal pressure coefficients are determined according to clause 7.2 of EN 1991-1-4. Internal and external pressures shall be considered to act at the same time (clause 7.2.9). The worst combination of external and internal pressures shall be considered. According to clause 7.2.2(2), the façades are divided in different pressure zones, defined as a function of e, where e is the lesser of b or 2h.

For wind direction θ=0º (see Figure B.2):

$$e = \min(19.99; 25.60) = 19.99 \text{ m} > d = 17.75 \text{ m}$$

and for wind direction θ=90º (see Figure B.3):

$$e = \min(17.75; 25.6) = 17.75 \text{ m} < d = 19.99 \text{ m}$$

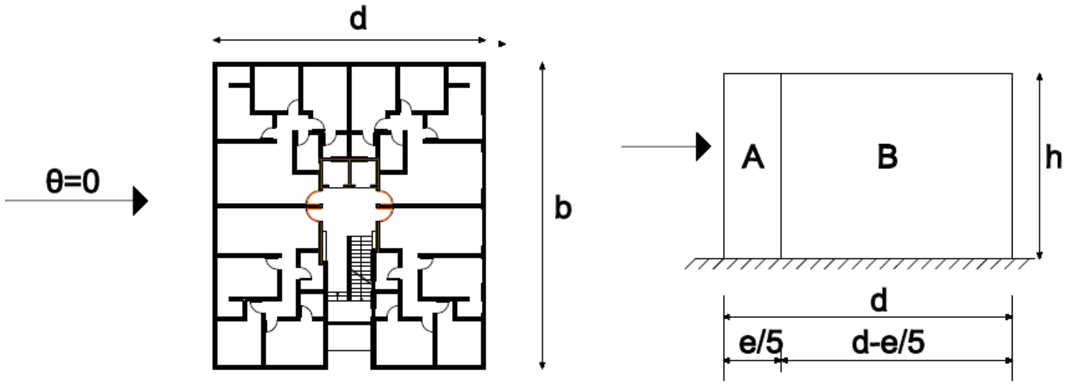


Figure B.2. Pressure zones for wind direction θ=0º

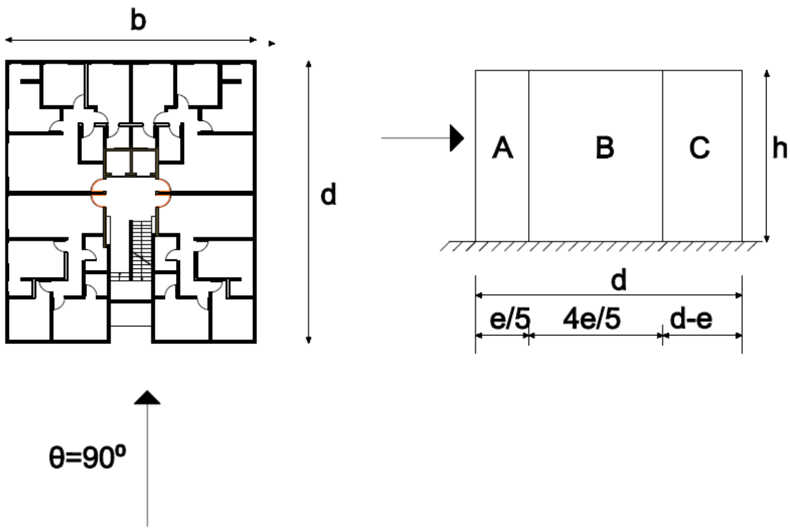


Figure B.3. Pressure zones for wind direction θ=90º.

According to clause 7.2.2(3), the lack of correlation of wind pressures between the windward and leeward sides may be taken into account by multiplying the resulting force by a factor, f, that depends on the relation h/d for each case. Therefore, by linear interpolation between f = 1.0 for h/d ≥ 5 and f = 0.85 for h/d ≤ 1, the following factors are obtained: for θ=0º, f = 0.83 and for θ=0º, f = 0.83.

Table B.3. External pressure coefficients c_{pe}

	zone	A	B	C	D	E
θ=0º	h/d=0.72	-1.2	-0.8	-	0.769	-0.438
θ=90º	h/d=0.64	-1.2	-0.8	-0.5	0.757	-0.414

The internal pressure coefficients, c_{pi}, depend on the size and distribution of the openings in the building envelope. For buildings without a dominant face and where it is not possible to determine the number of openings, then c_{pi} should be taken as the more onerous of +0.2 and -0.3.

Considering the values for external pressure coefficients from Table B.3, the external and internal pressure coefficients are represented in Figure B.4 a) and b), respectively, for θ=0º and θ=90º, according to the worst case for each face of the building.

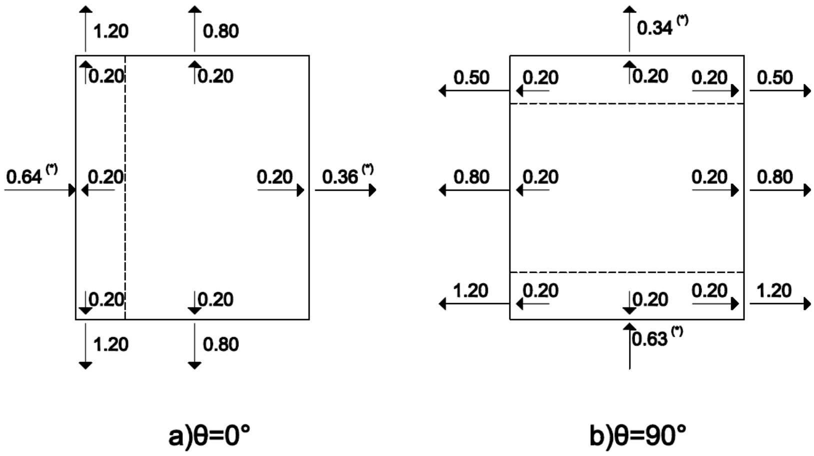


Figure B.4. External and internal coefficients.

(*) the values for faces D and E are obtained by multiplying the external coefficient by f = 0.83 for θ=0º and f = 0.83 for θ=90º.

B3.4. Calculation of the peak velocity pressure $\mathbf{q_p(z)}$

The peak velocity pressure $q_p(z)$, at height z, is given by the following equation (clause 4.5):

$$q_p(z) = [1 + 7\, I_V(z)]\frac{1}{2}\rho v_m^2(z) = c_e(z)q_b$$

where $I_V(z)$is the turbulence intensity, ρ is the air density, $v_m(z)$ is the mean wind velocity, $c_e(z)$ is the exposure factor and q_b is the basic velocity pressure.

Both options in equation (5) may be used to calculate the peak velocity pressure. In this design example only the first will be applied, because EN 1991-1-4 only provides one graph for a limited range of cases for the direct determination of the exposure factor.

The air density ρ depends on the altitude, temperature and barometric pressure to be expected in the region during wind storms. EN 1991-1-4 recommends the value 1.25 kg/m3.

B3.5. Calculation of mean wind velocity $v_m(z)$

The mean wind velocity is given by (clause 4.3.1),

$$v_m(z) = c_r(z)c_o(z)v_b$$

where $c_r(z)$ is the roughness factor and $c_o(z)$ is the orography factor, taken as 1.0 unless otherwise specified in clause 4.3.3, and v_b is the basic wind velocity. The roughness factor is specified in clause 4.3.2 and is given by:

$$c_r(z) = k_r ln\left(\frac{z}{z_0}\right) \Leftarrow z_{min} \leq z \leq z_{max}$$

$$c_r(z) = c_r(z_{min}) \Leftarrow z \leq z_{min}$$

z_{max} may be taken as 200, z_{min} is the minimum height, z_0 is the roughness length, both defined in Table 4.1 of EN 1991-1-4 as a function of the terrain category, and k_r is the terrain factor, depending on the roughness length z_0 and given by:

$$k_r = 0.19\left(\frac{z_0}{z_{0,II}}\right)^{0.07}$$

where $z_{0,II} = 0.05\ m$. The basic wind velocity v_b is calculated from (clause 4.2):

$$v_b = c_{dir} c_{season} v_{b0}$$

where c_{dir} and c_{season} are directional and seasonal factors, respectively, which may be given by the National Annexes. The recommended value, for each case, is 1.0. The fundamental value of the basic wind velocity, $v_{b,0}$, is also given in the National Annexes as a function of the regional wind maps.

Assuming $v_{b,0}$= 30 m/s, then v_b = $v_{b,0}$= 30 m/s.

Assuming a terrain of category II (i.e., area with low vegetation and isolated obstacles), from Table 4.1 of EN1991-1-4, $z_0 = z_{0,II} = 0.05$ and $z_{min} = 2\ m$, thus $k_r = 0.19$. From equations (7), with $z_{min} < z = 12.80\ m < z_{max}$:

$$c_r(12.80) = 0.19 ln\left(\frac{12.80}{0.05}\right) = 1.054$$

and from equation (6),

$$v_m(z = 12.80) = 1.054\ x\ 1.00\ x\ 1.00\ x\ 30 = 31.62\ m/s$$

B3.6. Calculation of the turbulence intensity I_v

The turbulence intensity is given by (clause 4.4(1)):

$$I_v = \frac{k_I}{c_0(z) ln\left(\frac{z}{z_0}\right)} \Rightarrow z_{min} \leq z \leq z_{max}$$

$$I_v = I_v(z_{min}) \Rightarrow z < z_{min}$$

where k_I is the turbulence factor. The recommended value for $k_I = 1.0$, thus for $z_{min} < z = 12.8 < z_{max}$:

$$I_v = \frac{1}{1 \times ln\left(\frac{12.8}{0.05}\right)} = 0.18$$

Finally, from equation (5), for $z = 12.80\ m$:

$$q_p(z = 12.80\ m) = [1 + 7 \times 0.15]\frac{1}{2} \times 1.25 \times 31.62^2 = 1281.02\ \ N/m^2 = 1.28\ \ kN/m^2$$

B3.7. Calculation of external and internal pressures

The external and internal pressures are obtained from equations (3) and (4) and are indicated in Table B.4. Note that external pressures are already multiplied by the structural factor, $c_s c_d$, from equation (1). In Figure B.5 a) and b) the resulting values are represented for θ=0º and θ=90º.

Table B.4. External and internal pressures.

$c_s c_d$		A	B	C	D	E
θ= 0º	$c_S c_d w_e$	-1.536	-1.024	-	0.98432	-0.56064
	w_i	0.256	0.256	-	0.256	0.256
θ= 90º	$c_S c_d w_e$	-1.536	-1.024	-0.64	0.96896	-0.52992
	w_i	0.256	0.256	0.256	0.256	0.256

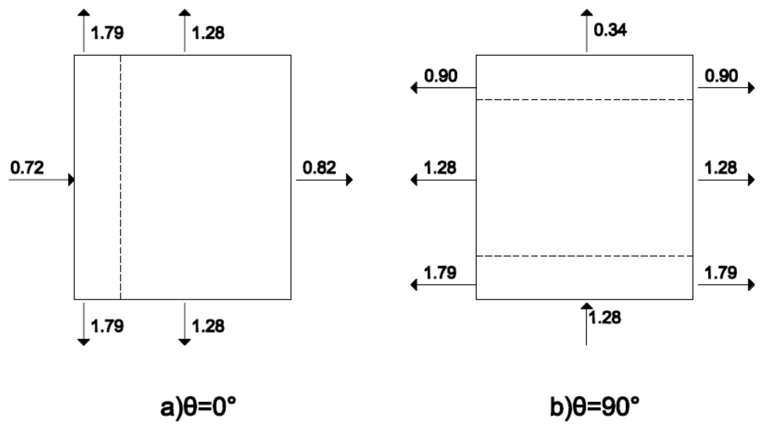


Figure B.5. Wind pressures (kN/m^2) on walls, for a) θ=0º and b) θ=90º.

B5. SEISMIC ACTIONS

B4.1. Introduction

The earthquake action was quantified following EN 1998-1 and a response spectrum response analysis was defined accordingly. The building is considered to be Class II of importance.

The design response spectrum is given by the following equations:

$$0 < T < T_B \qquad S_e(T) = a_g \cdot S \cdot \left(\frac{2}{3} + \frac{T}{T_B} \cdot \left(\frac{2.5}{q} - \frac{2}{3}\right)\right)$$

$$T_B < T < T_C \qquad S_e(T) = a_g \cdot S \cdot \frac{2.5}{q}$$

$$T_C < T < T_D \qquad S_e(T) \begin{cases} = a_g \cdot S \cdot \frac{2.5}{q} \cdot \frac{T_C}{T} \\ \geq \beta a_g \end{cases}$$

$$T > T_D \qquad S_e(T) \begin{cases} = a_g \cdot S \cdot \frac{2.5}{q} \cdot \left(\frac{T_C \cdot T_D}{T^2}\right) \\ \geq \beta a_g \end{cases}$$

The parameter β is the lower bound factor for the horizontal design spectrum, whose appropriate value should be provided by the National Annexes. EC8 recommends to assume β = 0,2.

The values to be ascribed to T_B, T_C, T_D and S for each ground type and type (shape) of spectrum (Type 1 or Type 2) to be used in a country may be found in its National Annex. Type 1 corresponds to moderate to large magnitude earthquakes, namely with with surface wave magnitude M_s larger than 5.5. Type 2 corresponds to low magnitude earthquakes with M_s less than 5.5. The recommended values for the spectral parameters are given in

Table B.5.

The behavior factor for steel structures according to EN 1998-1 design concepts is described in Figure B.6. The seismic base shear force formula is presented in (17).

$$F_b = \gamma_{I,e} S_d(T_1) m\lambda$$

Where: $\gamma_{I,e}$ is the importancy coefficient of the building, $S_d(T_1)$ is the design response spectrum, m is the mass of the structure and λ is a correction coefficient that takes into account the contributions of the fundamental modal mass.

Table B.5. EC8 recommended values of the parameters describing both Type 1 and Type 2 elastic response spectra

Elastic Response Spectra	Ground Type	*S*	T_B (s)	T_C (s)	T_D (s)
Type 1	A	1.0	0.15	0.4	2.0
	B	1.2	0.15	0.5	2.0
	C	1.15	0.20	0.6	2.0
	D	1.35	0.20	0.8	2.0
	E	1.4	0.15	0.5	2.0
Type 2	A	1.0	0.05	0.25	1.2
	B	1.35	0.05	0.25	1.2
	C	1.5	0.10	0.25	1.2
	D	1.8	0.10	0.30	1.2
	E	1.6	0.05	0.25	1.2

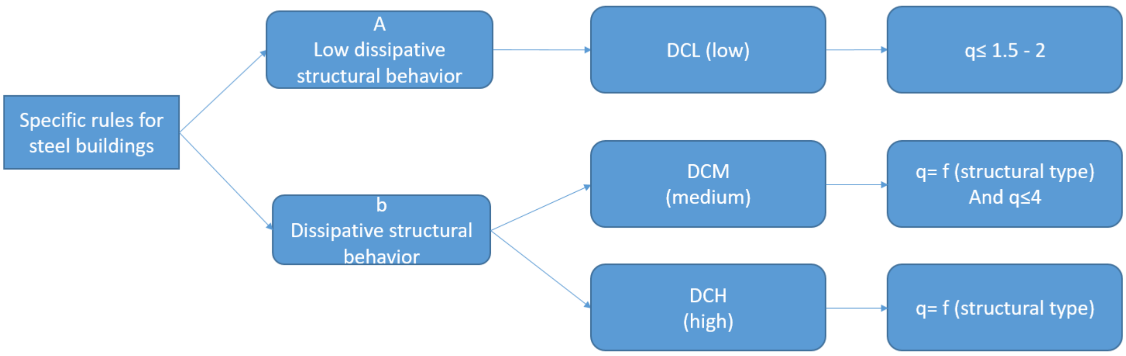


Figure B.6. Design concepts according to EN 1998-1.

B4.2. Medium seismicity area

Faro, in Portugal, was chosen as the representative location for medium seismicity. The corresponding peak ground acceleration a_{gR} (m/s^2) for Type 1 is 2.0 m/s^2 while for Type 2 it equals 1.7 m/s^2.

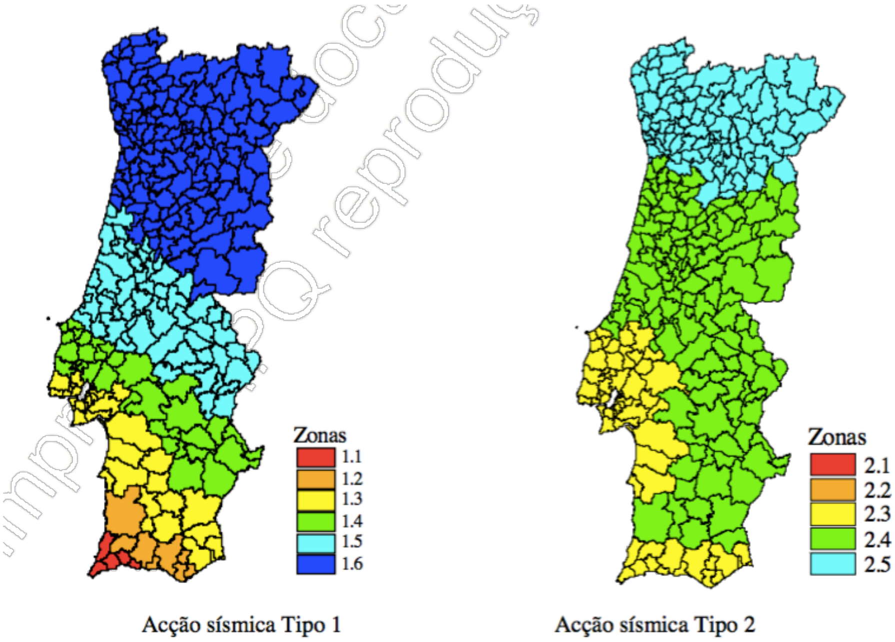


Figure A.9. Seismic zoning in Portugal

B4.3. High seismicity area

Bucharest, in Romania, was chosen as the representative location for high seismicity. In Romania, according to the National Annex of EN 1998-1, the type of ground classification (A.B,C,D,E, S1 and S2) from does not take place in the present. For design purposes, the type of ground it is being classified by the Tc spectrum period in three different zones as inFigure B.7. In Figure B.8 the design ground acceleration a_g map is presented according to the National Annex P100/1-2013:

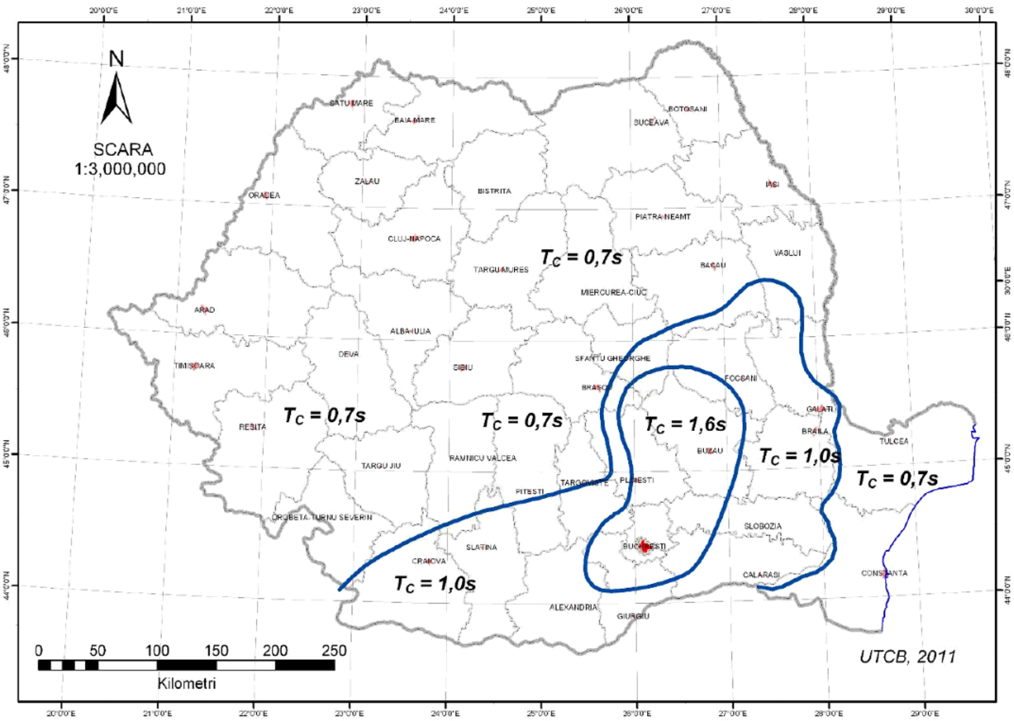


Figure B.7. Type of ground classification via the Tc spectrum period, National Annex P100/1-2013

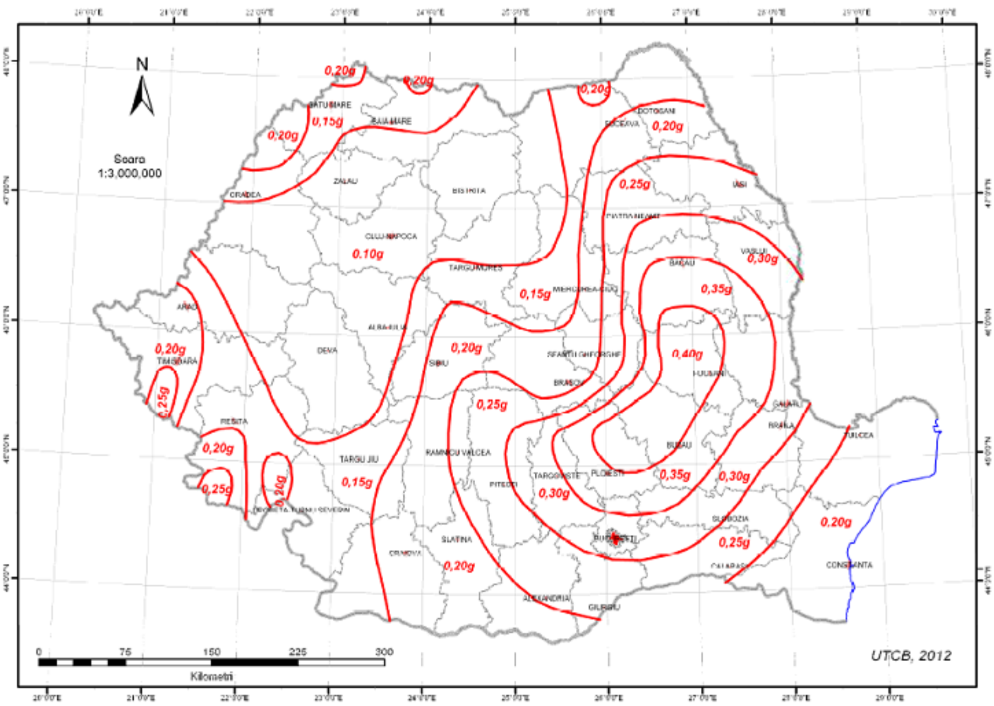


Figure B.8. The design ground acceleration a_g for an event with MRI=225 years and an exceeding probability of 20%

The normalised elastic response spectrum β(t) for the absolute acceleration of horizontal ground movement are presented in (11-14) and Figure B.9, considering ξ=5% the critical damping and the corner periods TB, TC and TD. The values of the corner periods are displayed in Table B.6.

$$0 \leq T \leq T_B \qquad \beta(T) = 1 + \frac{(\beta_0 - 1)}{T_B}\,T$$

$$T_B \leq T \leq T_C \qquad \beta(T) = \beta_0$$

$$T_C \leq T \leq T_D \qquad \beta(T) = \beta_0 \frac{T_C}{T}$$

$$T_D \leq T \leq 5s \qquad \beta(T) = \beta_0 \frac{T_C T_D}{T^2}$$

Table B.6. The corner periods T_B, T_C and T_D

T_C	0.70 s	1.00 s	1.60 s
T_B	0.14 s	0.20 s	0.32 s
T_D	3.00 s	3.00 s	2.00 s

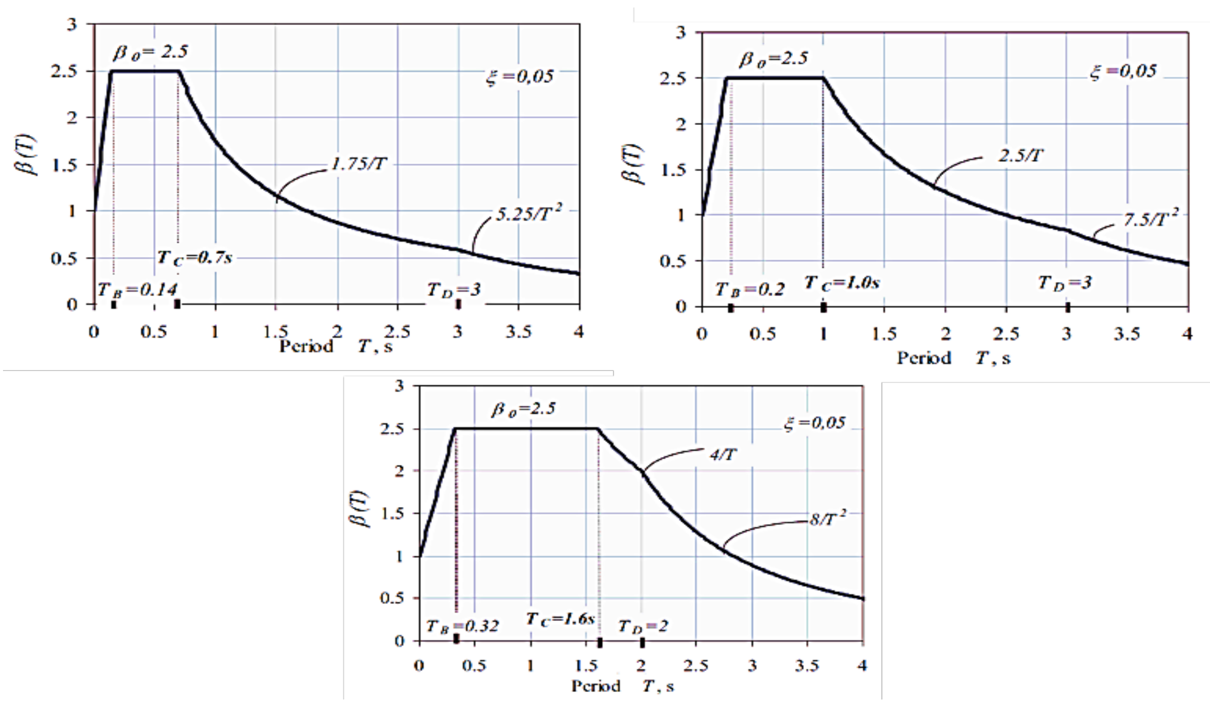


Figure B.9. Normalised elastic response spectrum $\beta(t)$ for corner periods T_B, T_C and T_D

The design spectrum as described by P10/1-2013 is defined by a function of the horizontal ground acceleration a_g, the normalised elastic response spectrum $\beta(t)$ and the behavior factor q. The relations for the design spectrum are presented in (15-16) as it follows:

$$0 < T \leq T_B \qquad S_d(T) = a_g \left(1 + \frac{\frac{\beta_0}{q} - 1}{T_B} T \right)$$

$$T > T_B \qquad S_d(T) = a_g \frac{\beta_{(T)}}{q} \geq 0.20 a_g$$

B6. LOAD COMBINATIONS

For the load combinations, the followed rules and methods are given in Annex A1 of EN 1990. According to clause A1.2.2. the following recommended values of the reduction factors ψ for the considered actions are the ones from Table B.7.

Table B.7. The reduction factors Ψ

Type of action	Ψ_0	Ψ_1	Ψ_2
Imposed loads in buildings: category A	0.7	0.5	0.3
Wind loads on buildings	0.7	0.2	0

The following combinations were taken into account for all types of buildings:

- Fundamental group of combinations where the predominant load can be the wind or live load:

$$E_d = \gamma_G G_k + \gamma_{Q,1} Q_{k,1} + \gamma_{Q,i} \psi_{0,i} Q_{k,i}$$

The characteristic combination is described by (19):

$$1.35DL + 1.5LL(WL) + 1.05WL\ (LL)$$

Where: DL is the dead load, LL is the live load and WL is the wind load:

- Special group of combinations where the predominant load is earthquake

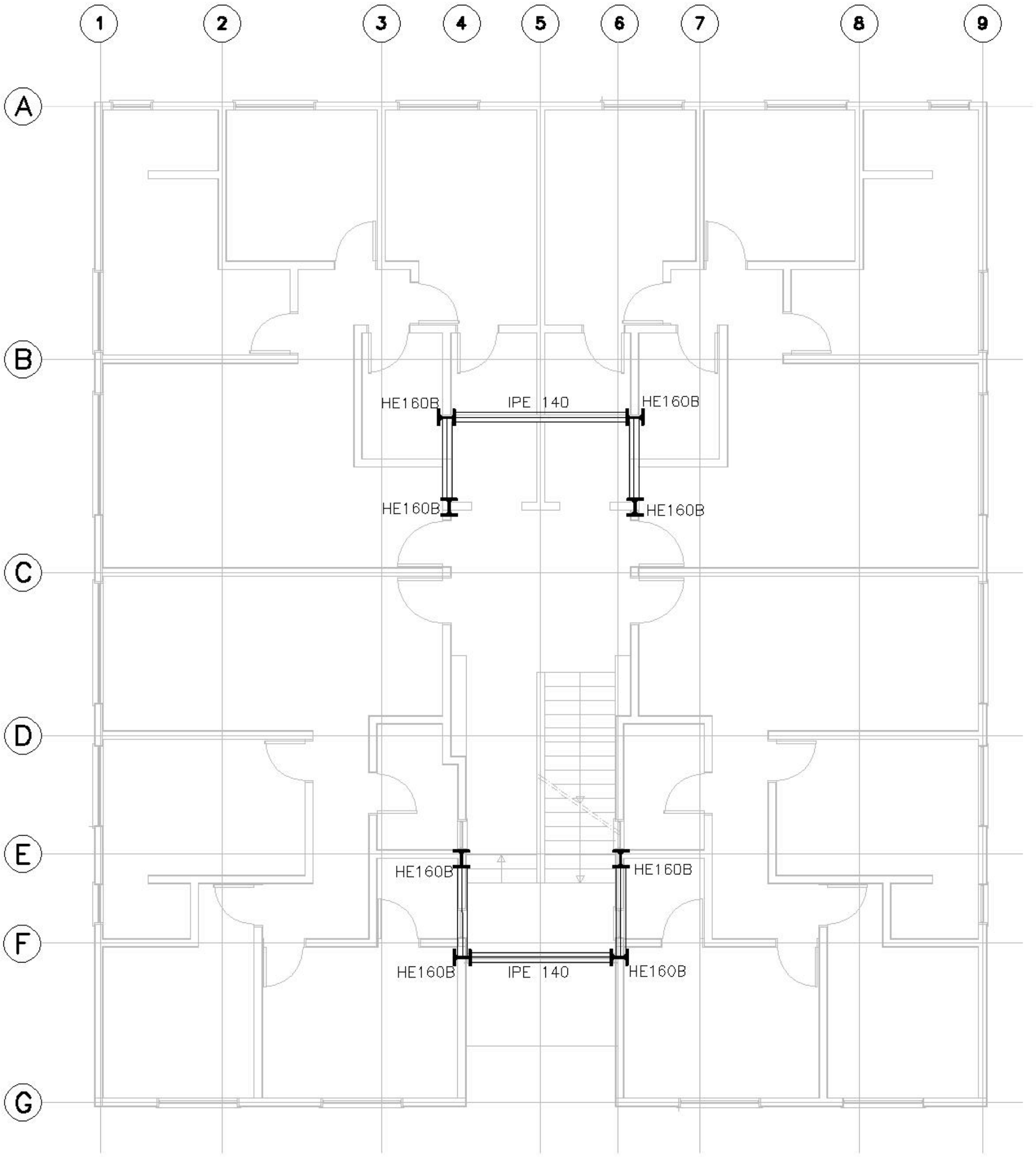
$$E_d = G_k + \psi_{2,i} Q_{k,i} + A_{Ed}$$

$$1.00DL + 0.3LL + 1.00EL$$

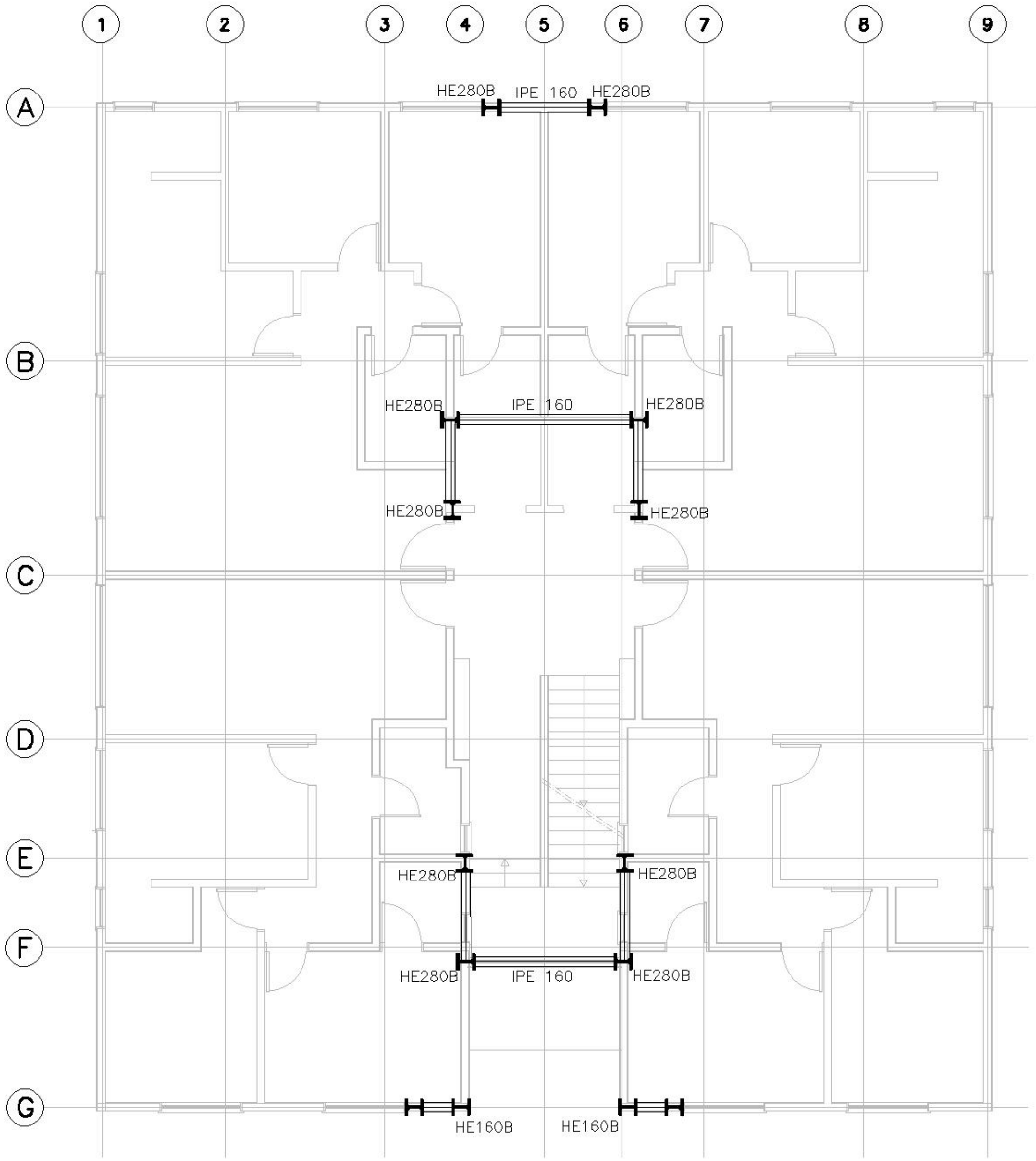
Where: EL is the earthquake load.

ANNEX C. LIGHT STEEL FRAMING

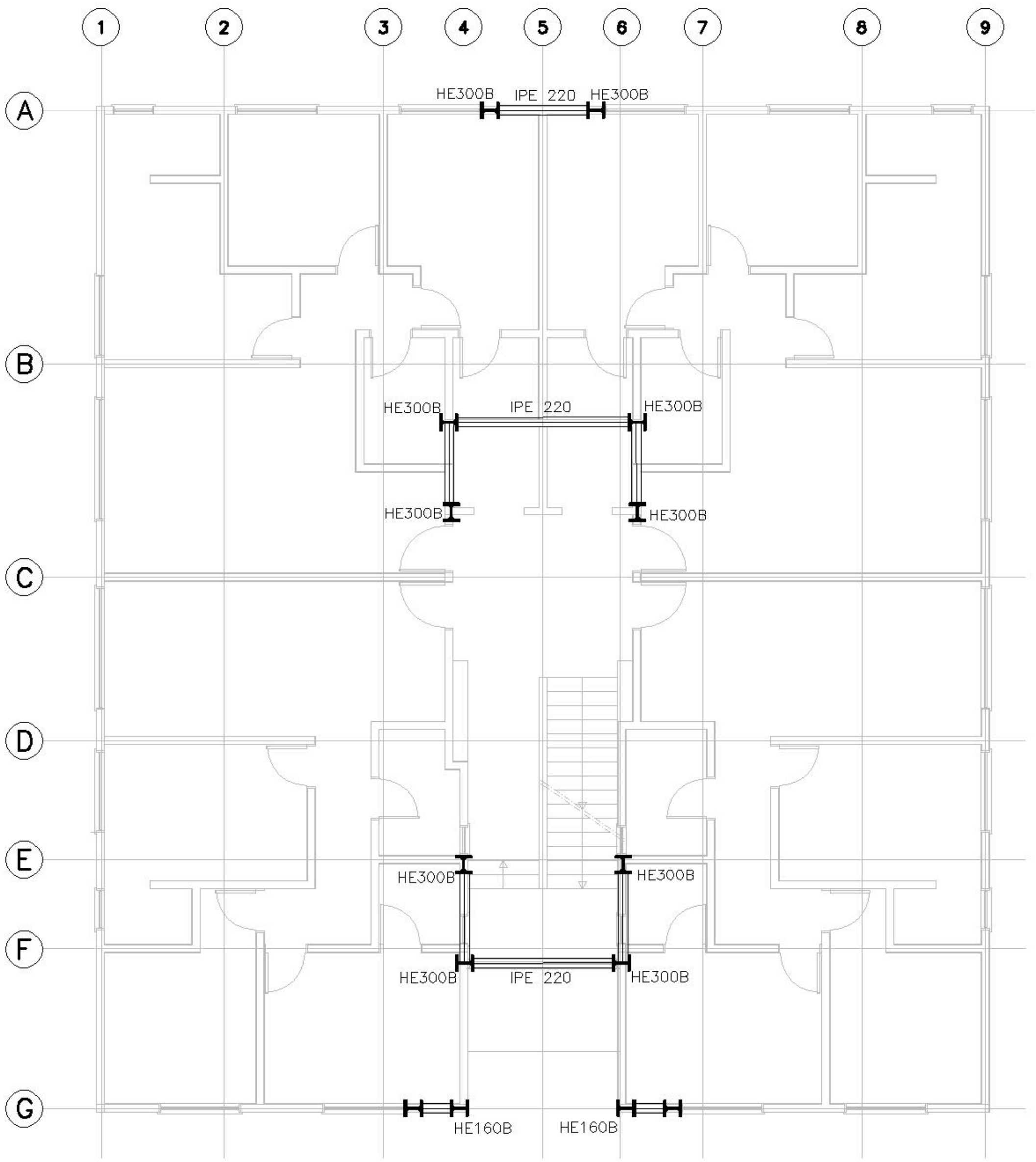
C1. SUPERSTRUCTURE - REFERENCE CASE



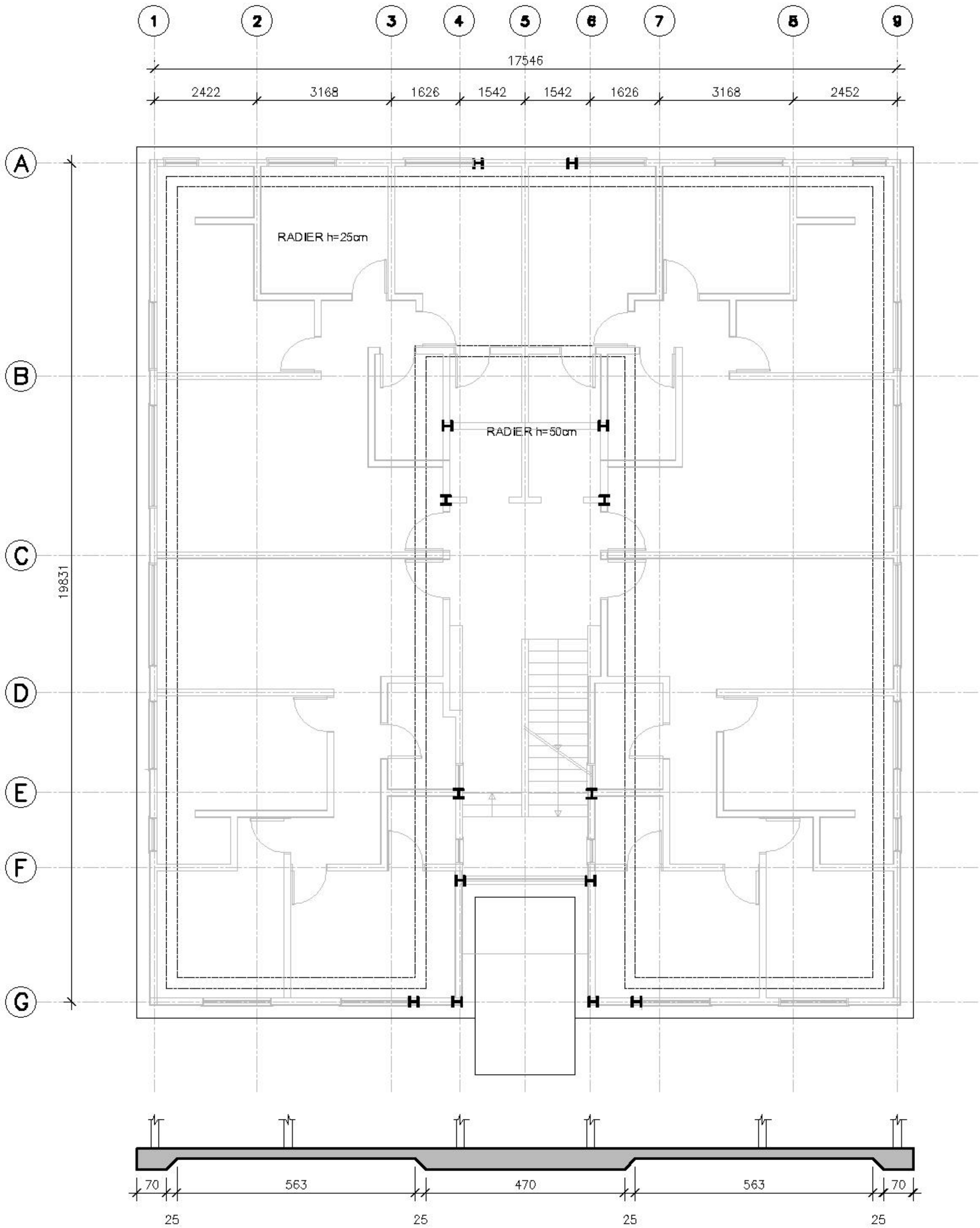
C2. SUPERSTRUCTURE - MEDIUM SEISMICITY LEVEL



C3. SUPERSTRUCTURE - HIGH SEISMICITY LEVEL



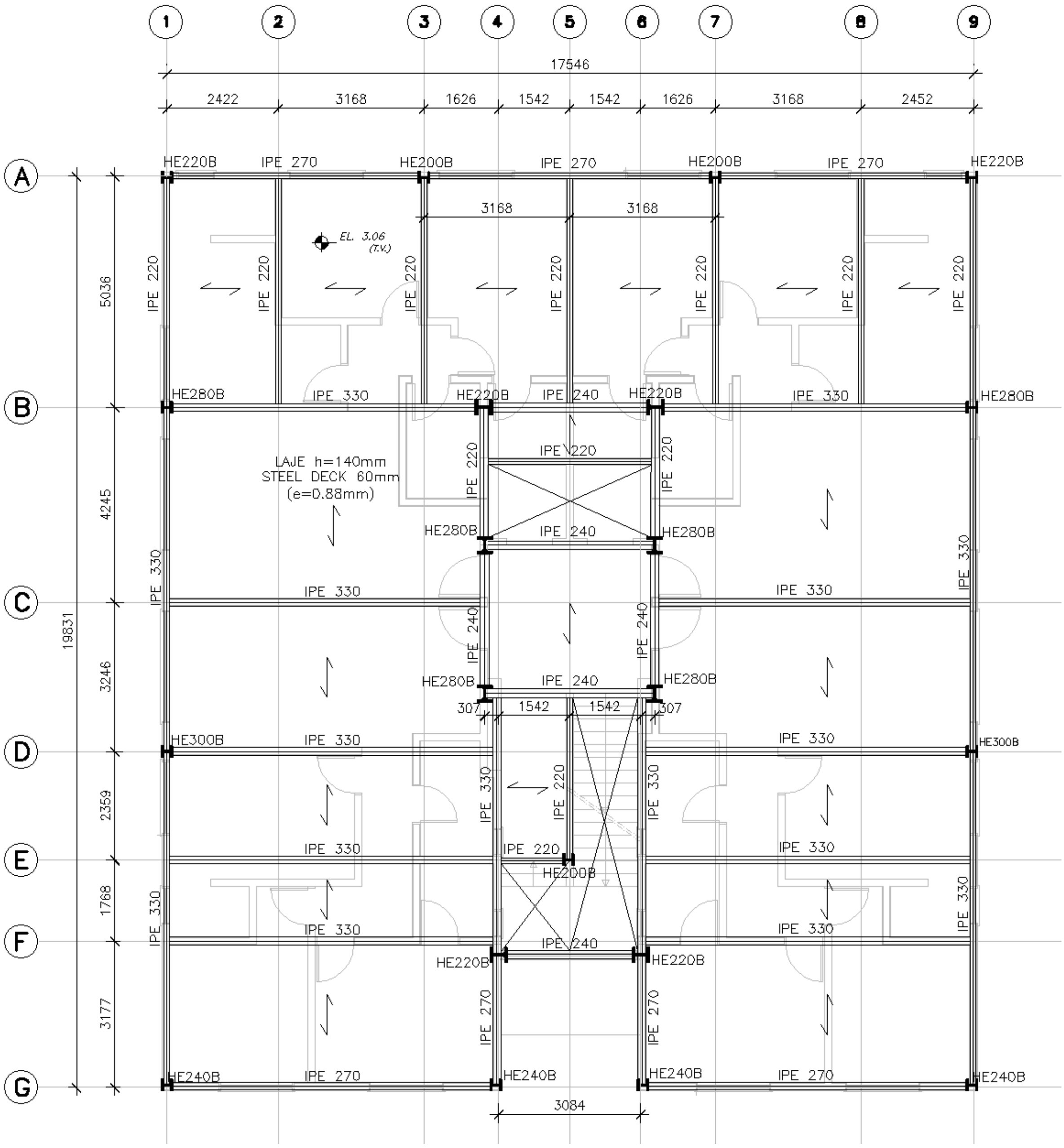
C4. FOUNDATIONS – REFERENCE



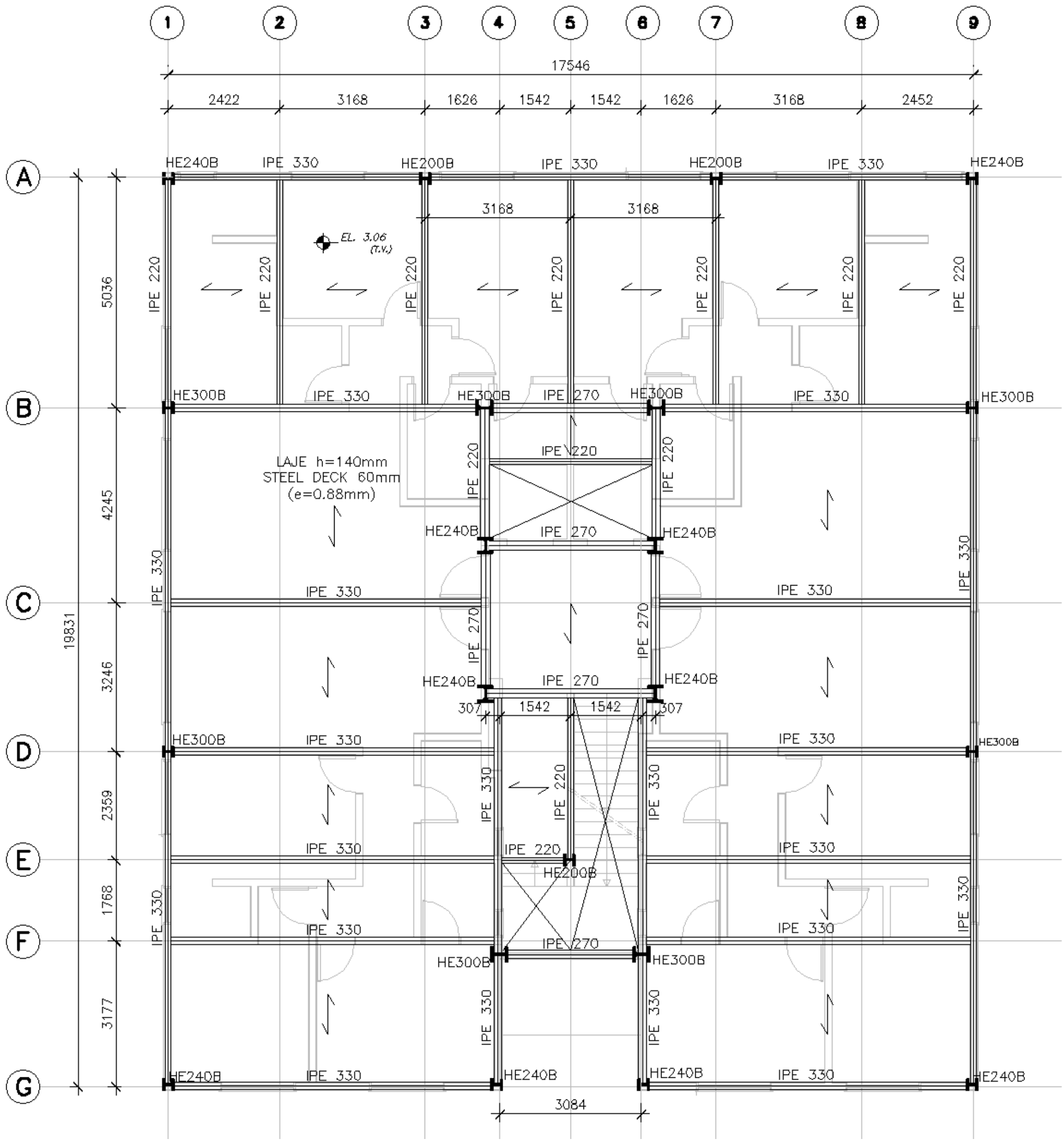
ANNEX D. HOT-ROLLED STEEL SOLUTION

D1. SUPERSTRUCTURE - REFERENCE

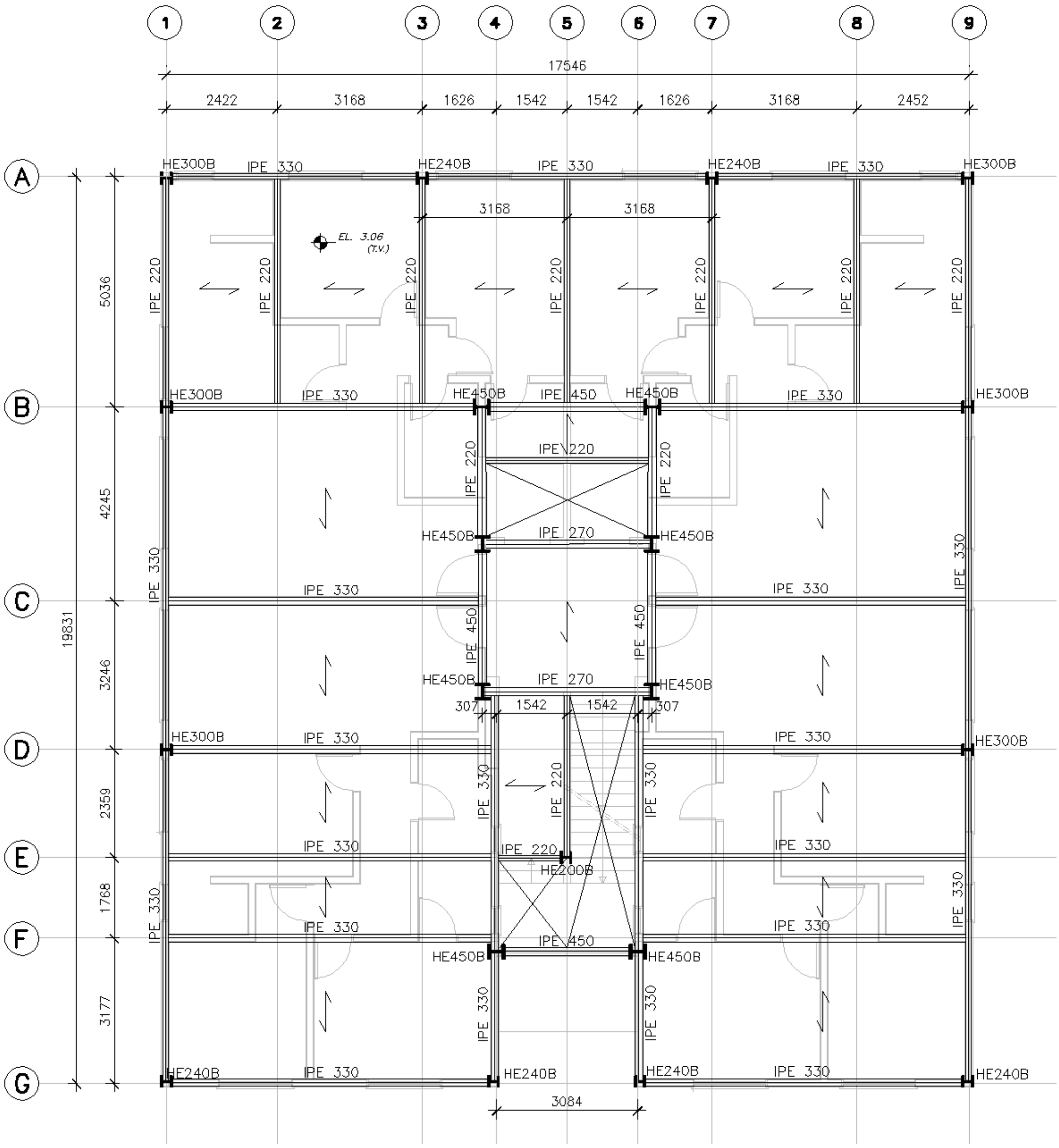
The hot-rolled steel solution consists of a moment-resisting structural system composed of hot-rolled steel sections. A detailed structural layout is presented. The structural solution consists of a composite floor system, supported on steel frames.



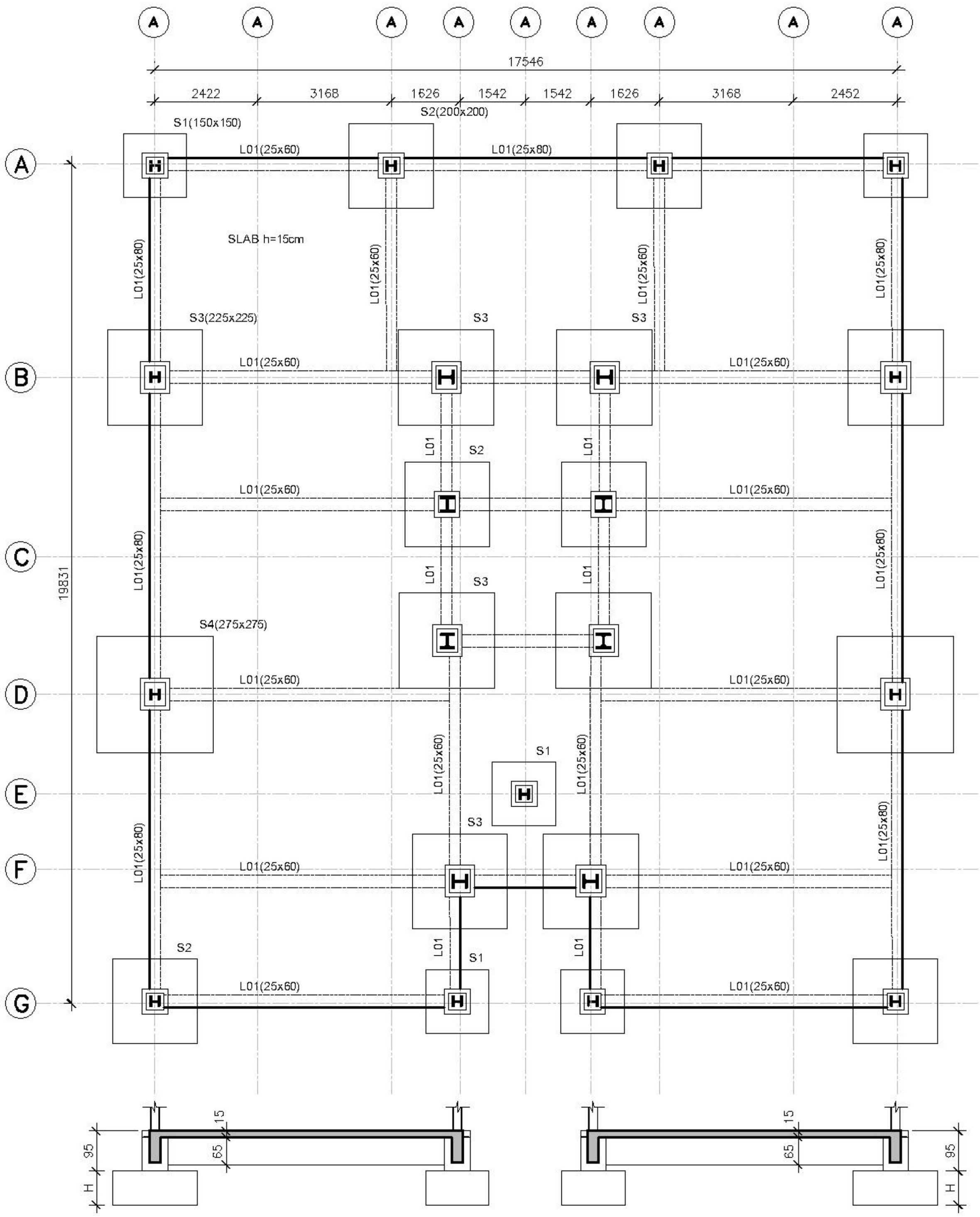
D2. SUPERSTRUCTURE - MEDIUM SEISMICITY LEVEL



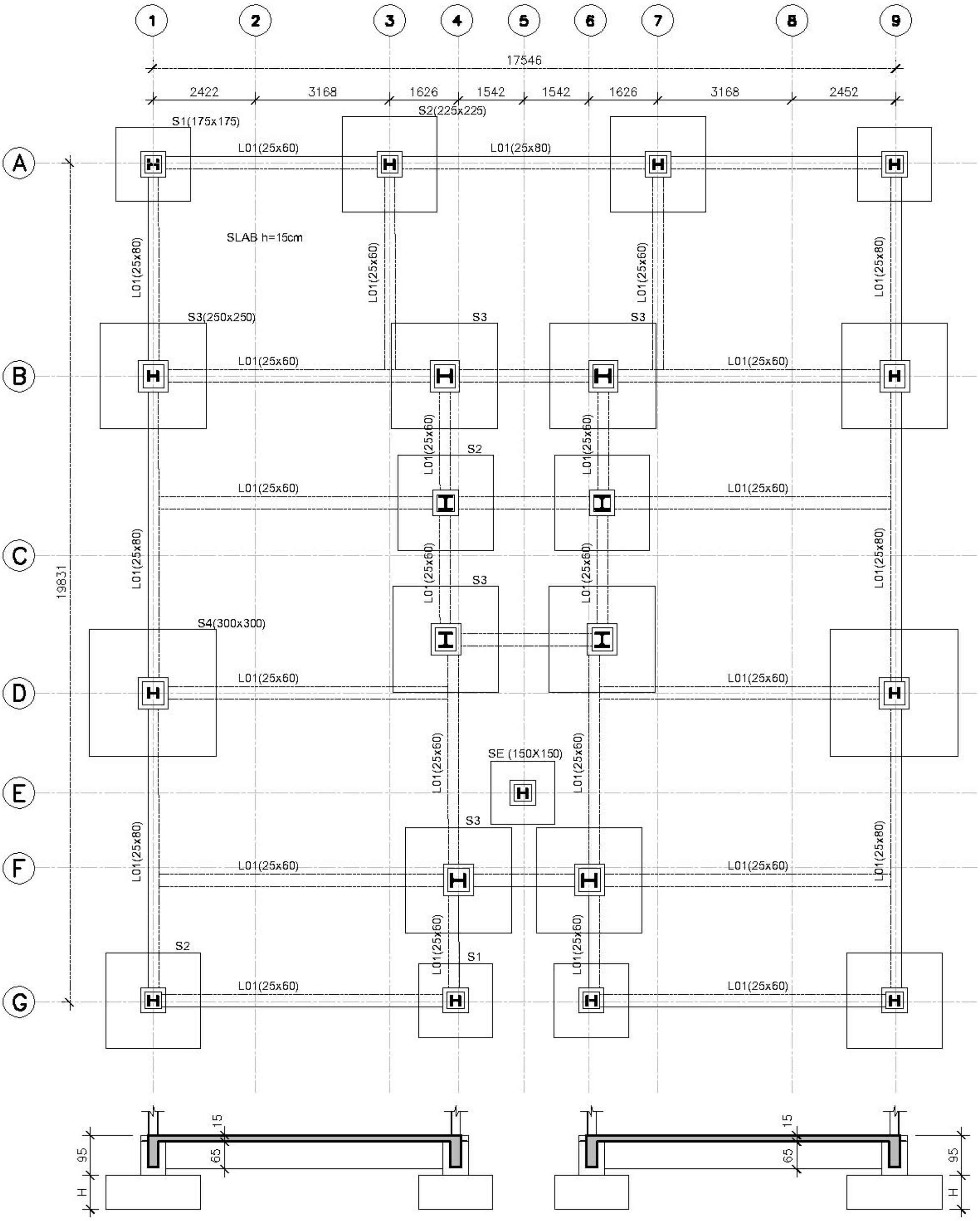
D3. SUPERSTRUCTURE - HIGH SEISMICITY LEVEL



D4. FOUNDATIONS – REFERENCE

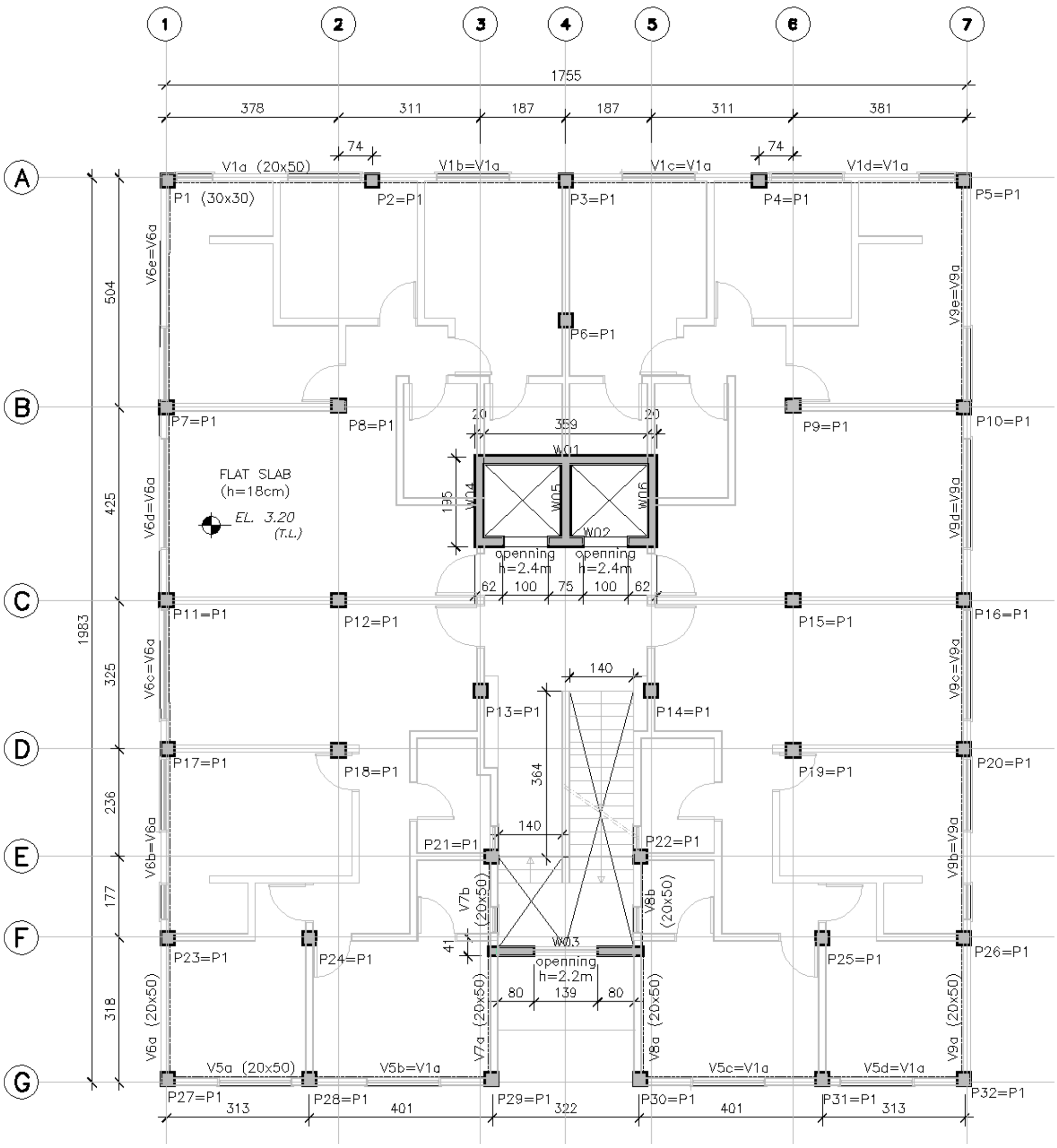


D5. FOUNDATIONS – MEDIUM / HIGH SEISMICITY LEVEL

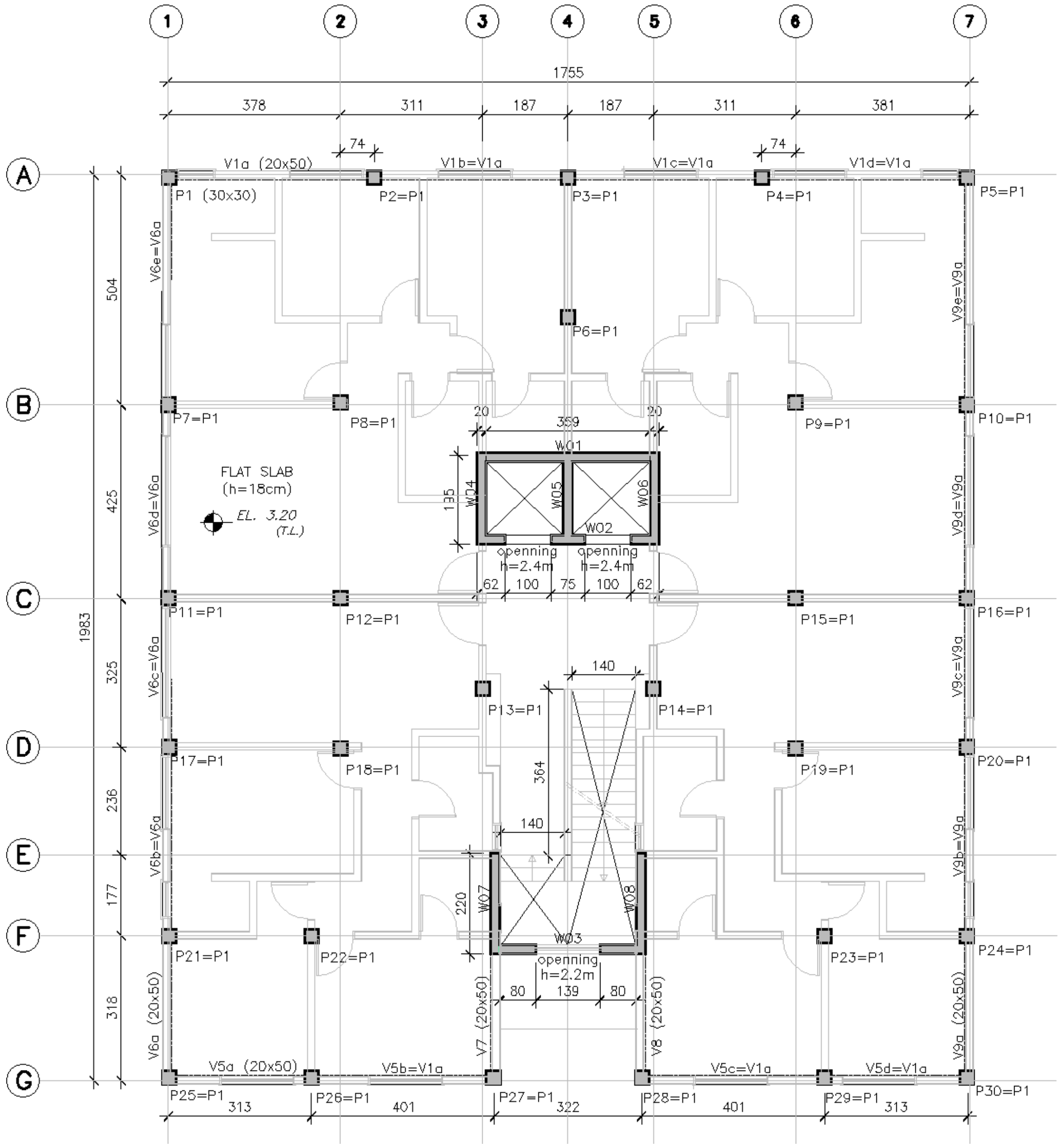


ANNEX E. REINFORCED CONCRETE SOLUTION

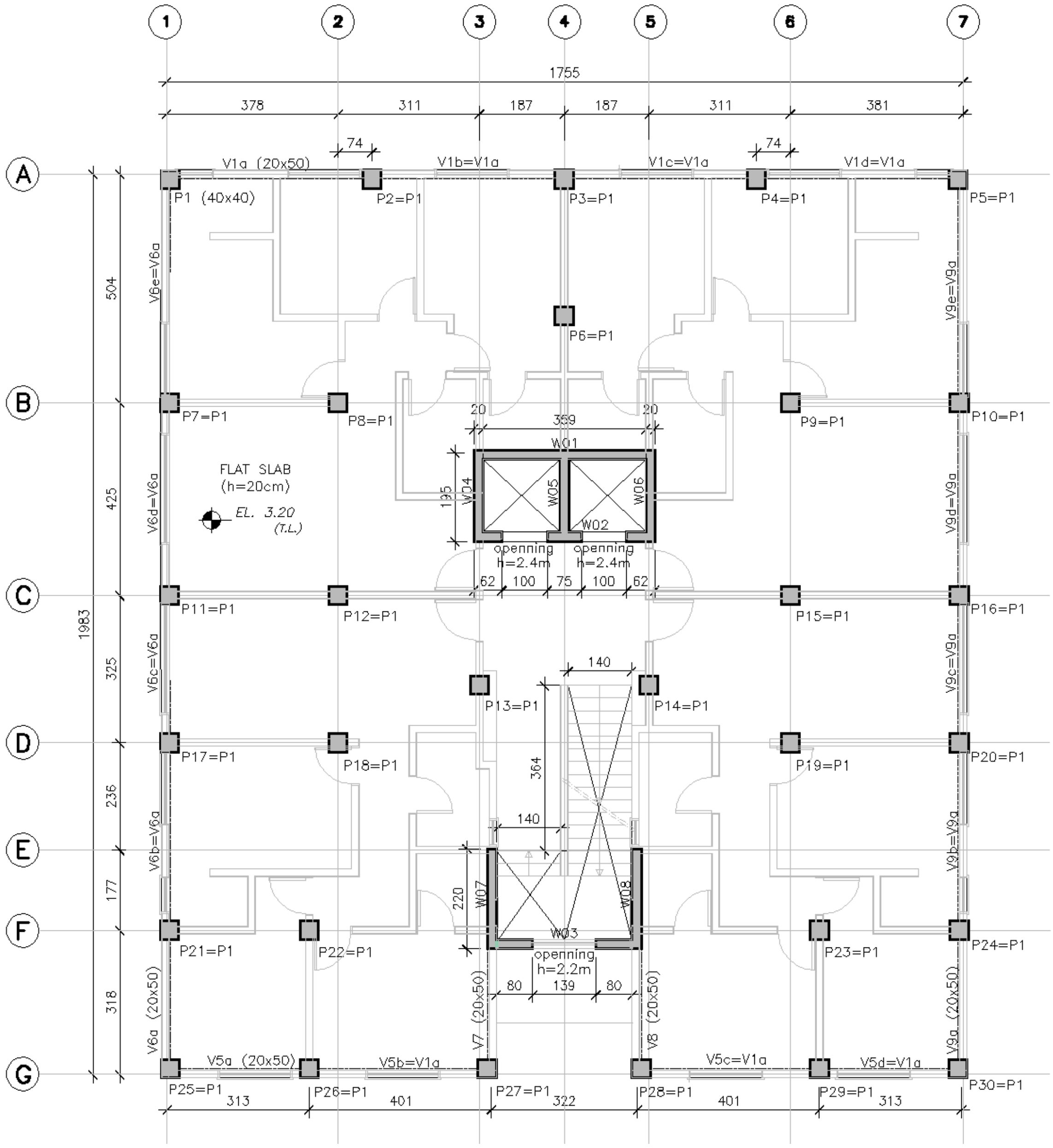
E1. SUPERSTRUCTURE - REFERENCE



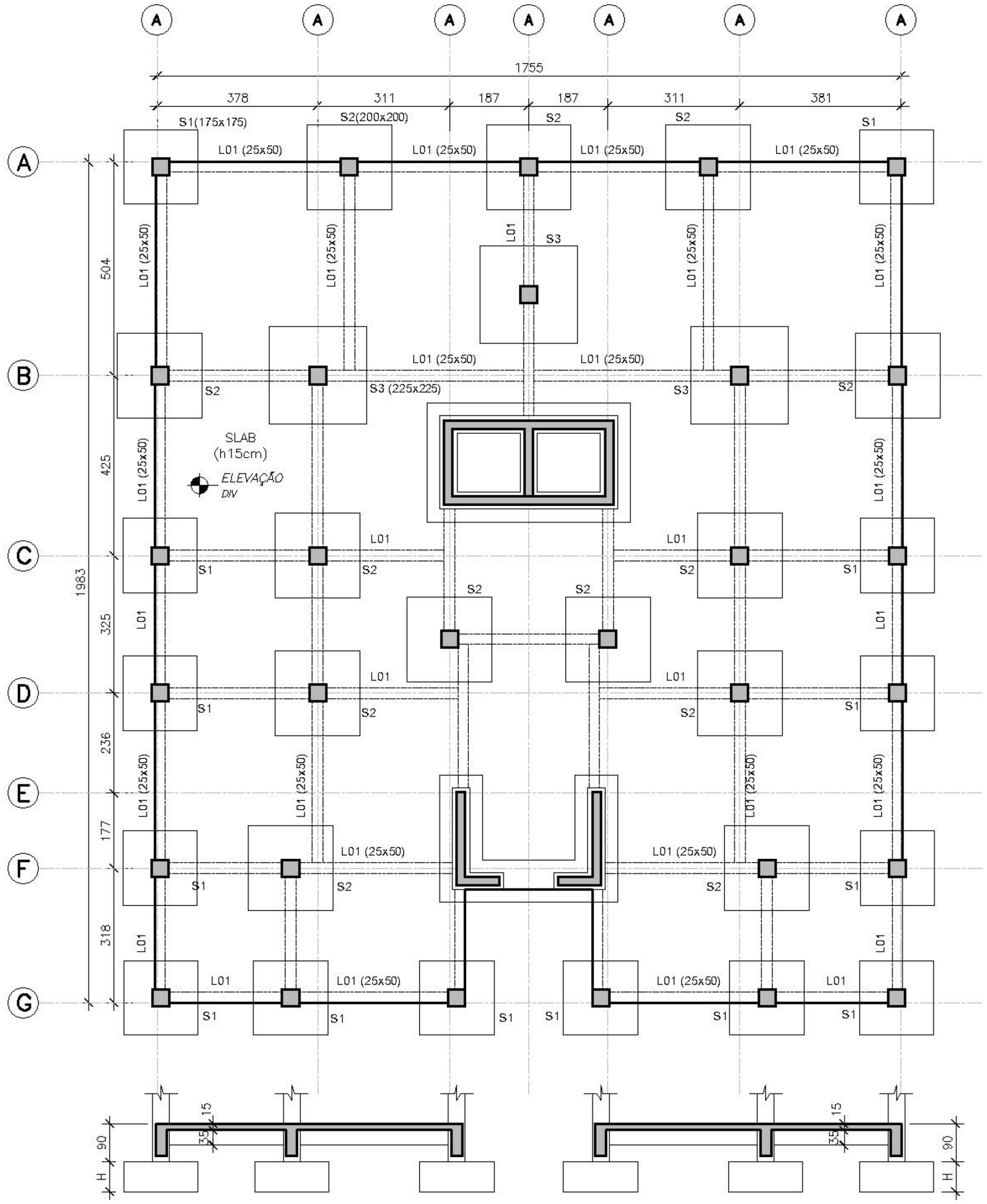
E2. SUPERSTRUCTURE - MEDIUM SEISMICITY LEVEL



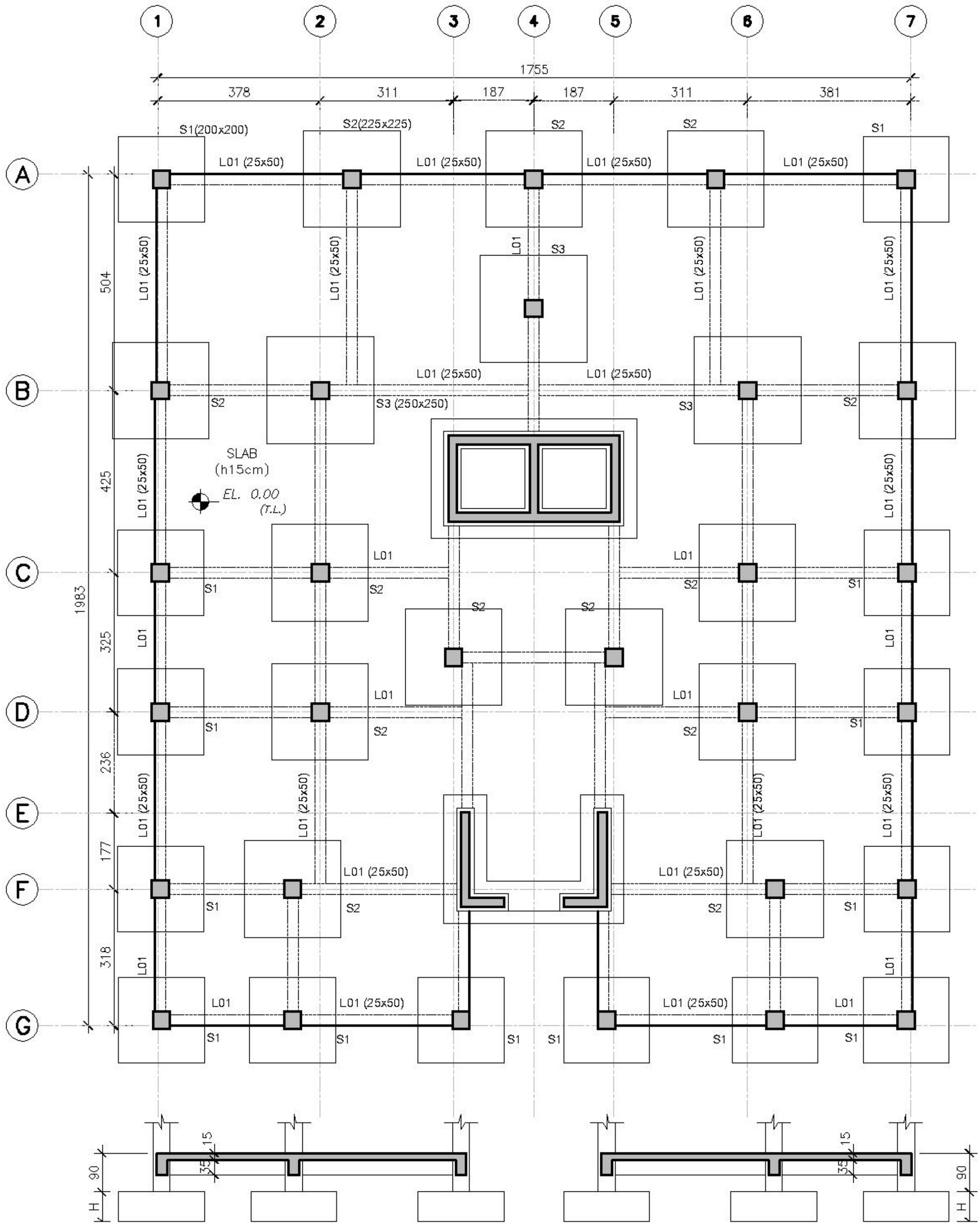
E3. SUPERSTRUCTURE - HIGH SEISMICITY LEVEL



E4. FOUNDATIONS - REFERENCE

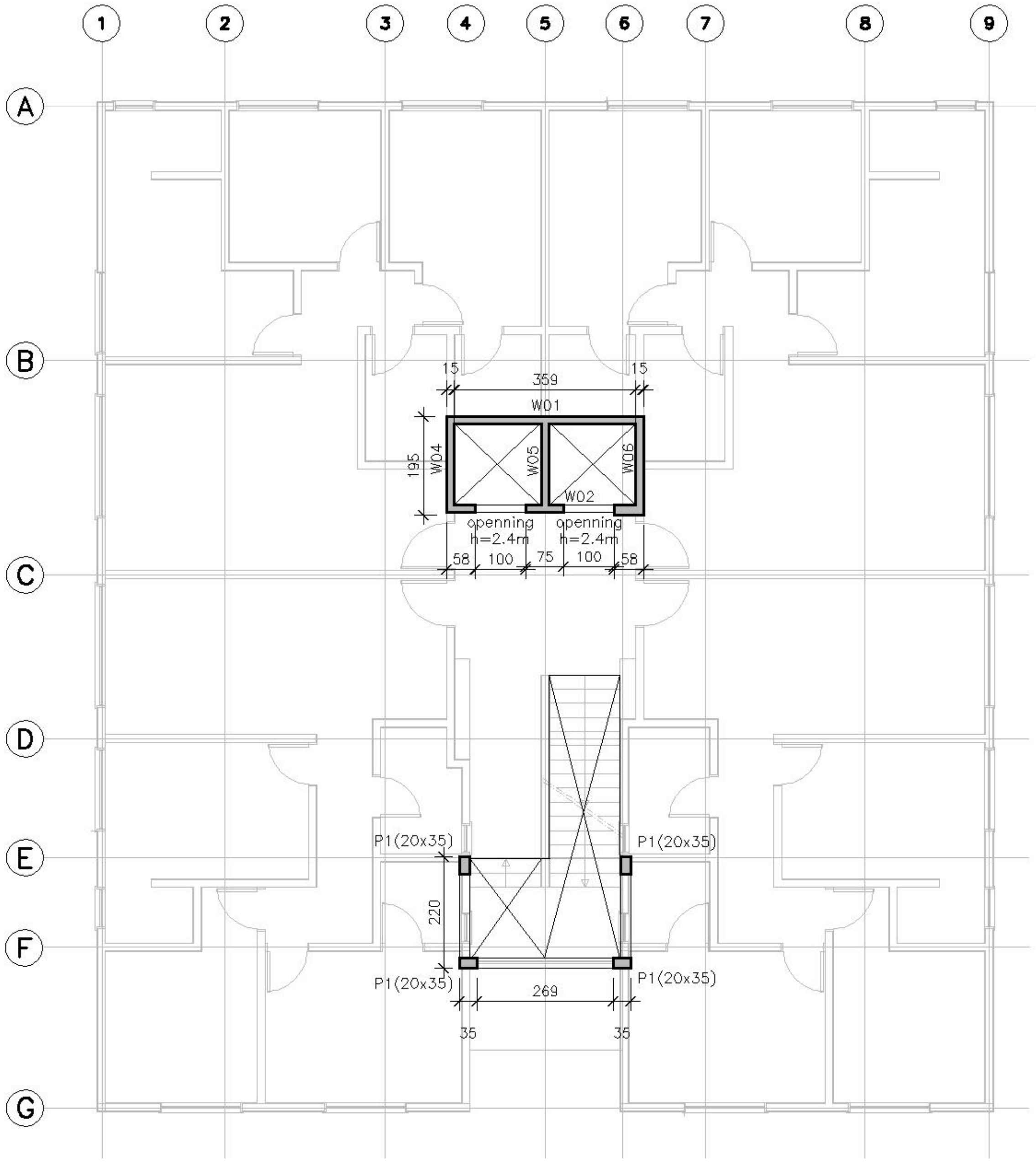


E5. FOUNDATIONS – MEDIUM / HIGH SEISMICITY LEVELS

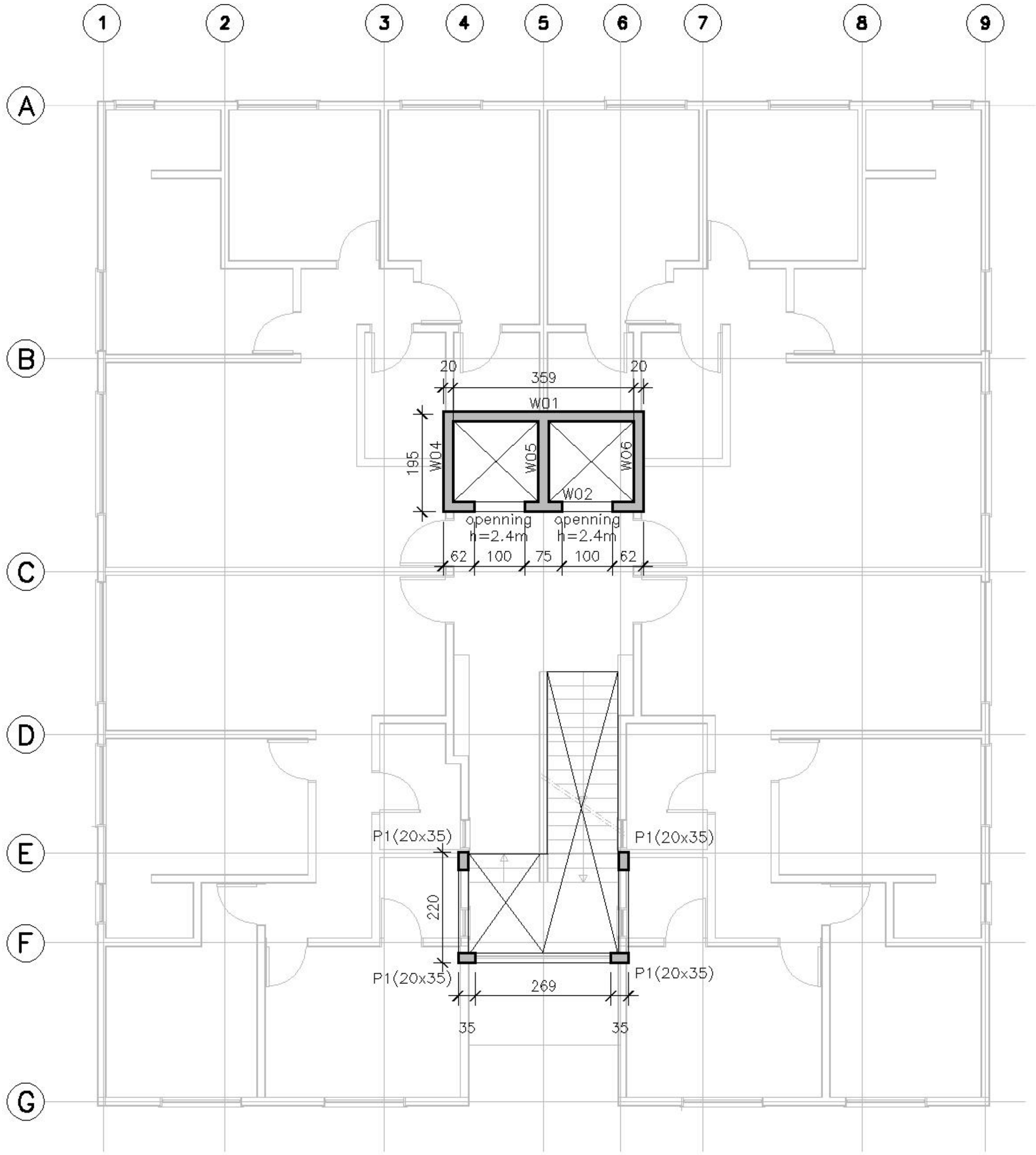


ANNEX F. TIMBER SOLUTION

F1. SUPERSTRUCTURE - REFERENCE



F2. SUPERSTRUCTURE – MEDIUM / HIGH SEISMICITY LEVEL



F3. FOUNDATIONS