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# CONCEPTUAL DESIGN OF THE ITER HOT CELL BUILDING: STRUCTURAL ANALYSIS

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## ABSTRACT

The new ITER Hot Cell Building (HCB) is the second building in importance of the ITER project. During the conceptual stage, two different structural configurations are studied for the HCB, the conventional traditional approach, and the staged approach, in which the structure of the building is separated in two parts: the main structure, composed by slabs, pillars, external walls, foundation; and the secondary structure composed of partitioning walls located inside the building. This allows to reduce the construction time, impacting favorably in the schedule of the project. This paper summarizes the main results and conclusions obtained during this project, showing the feasibility of this building construction method.

## INTRODUCTION

This building is presented, together the Tokamak Complex (TKC), in Figure 1.

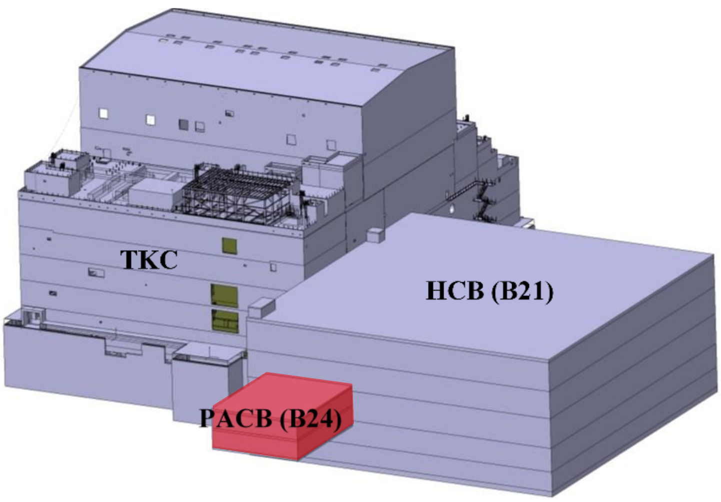


Figure 1. Location of HCB relative to TKC.

The new Hote Cell Commplex (HCC) consists of two buildings:

- A strong concrete building, called the Hot Cell Building (HCB, B21), whose size is approximately 84m×91m×36m, composed of five levels, 12m below the ground, founded on a single basemat (*Safety class*: PIC/SIC-1, *Seismic class*: SC1(S), *Quality class*: QC1).
- A steel frame building close to the concrete building, called Personal Access Concrete Building (PACB, B24) to house the non-PIC elements (*Safety class*: SR, *Seismic class*: SC2, *Quality class*: QC1).

Seismic class SC1, implies structural stability needs maintained in the event of an earthquake, whereas SC2 require only no damage in SC1 equipment. Thus, the analysis if focused in the main building, B21. For the construction of this building, it is proposed a strategy in which the concrete building is composed by the Main structure, called the skeleton, and the Secondary structure, composed of internal walls. The Main structure will participate to the global stability (with or without the secondary structure). This structure is formed by the external walls, slabs, and a grid of columns which is mandatorily plumbing on all levels. Some structural walls are defined, where needed are by stability requirements. The number of structural walls must be minimized as much as possible in order to accelerate the constructive process. Thus, two configurations are analyzed,

- Configuration 1: Main and secondary structures are modelled. This configuration is equivalent to the traditional approach.
- Configuration 2: Only the main structure contributes to stiffness. The secondary structure is implemented as equivalent masses distributed along the building, according the wall configuration.

The HCB B21 has 7 levels: B2 (0.70m) / B1 (6.58m) / L1 (12.38m) / L2 (20.33m) / L3 (27.63m) / R1 (36.45m) / R2 (42.13m). Figure 1 show the main structure (Level L1) and the secondary walls (all levels), extracted from the FE model. The following paragraphs show the design issues.

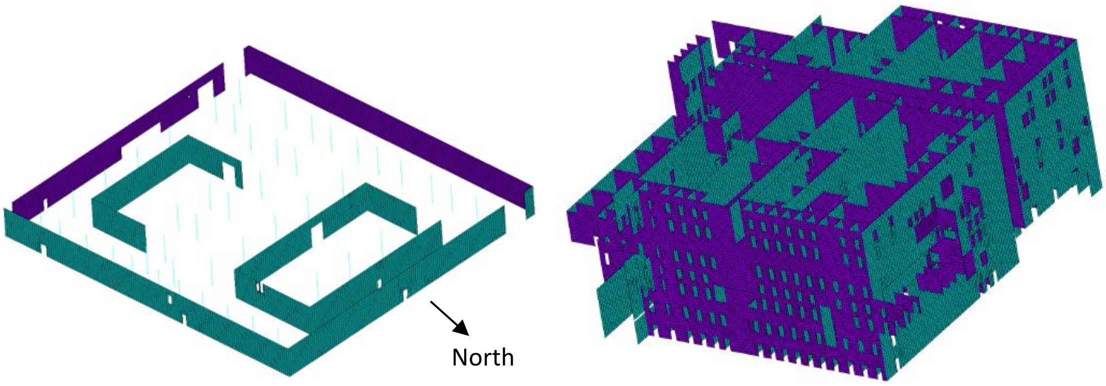


Figure 1. Main structure (L1) left, Secondary walls (all levels)

ANSYS software is used to generate the Finite Element (FE) model and dedicated macros are applied to accomplish the required checks for Serviceability Limit State (SLS) and Ultimate Limit State (ULS), according to the I-SDCB [1], and the calculation of reinforcement for columns, walls and slabs. The reinforcement steel ratios are calculated to measure the impact of the structural changes introduced by the skeleton approach. Thus, this paper summarizes the main results and conclusions obtained along the conceptual design stage of Building B21, showing the feasibility of this building construction method.

## TECHNICAL DESIGN DRIVERS

The **main technical design drivers** for the building structures are the following:

- Design a regular building as per seismic classification. Means no static descent of load to be transferred through a cantilever or beam,
- Define points of descent of loads are regularly defined (max span is 15m), from top to bottom,
- The points of descent of loads are a vertical and non-interrupted linear structure carrying the loads from top to down then to the raft slab,
- The sizing of this grid of vertical lines matches as much as possible to the thickness of the adjacent wall, but could be refined accurately at a later stage,
- Only the main structure is mandatory to maintain its integrity for bracing purpose and providing the global dynamic stability of the building

Sequencing works in 2 steps:

- Stage 1: Only main structure
- Stage 2: Secondary structure linked to interface maturities

Main advantages are:
- More flexibility with the location of penetrations and embedded plates
- More flexibility with the location of the internal walls themselves (to be built or not)
- Construction phases

**Main structure:**
- Will participate to the global stability of the building: external walls, slabs, a grid of columns and some internal walls plumbing all levels.
- Only those elements are mandatory to maintain their integrity for bracing propose and providing the global dynamic stability of the building.
- Columns are as most as possible integrated in the thickness of the wall. This implies no protrusion and quasi transparent from a process point of view.
- In a structural wall the horizontal and vertical reinforcements shall be continuous without any interruptions due to penetrations or embedded plates, as a structural wall shall contribute to transfer horizontal shear loads.
- In a structural wall, a local reinforcement is to be implemented around each penetration and each embedded plate. Difficulty/time/cost increased for the design and the construction.
- Normal reinforced concrete class C40/50.

**Secondary structure (internal walls):**
- Answers to all structural requirements except the obligation of their participation to the global stability of the building.
- Shall ensure fire zoning and fire stability, supporting of equipment's, shielding, confinement, overpressure loads, etc… but their participation to the global bracing of the building is not mandatory.
- By their presence, may change the FRS and consequently to be considered within the calculation of the FRS, but by their absence or weakness (openings etc..) the global behavior of the building shall never be impacted.
- Can be interrupted, and their loads transferred through a beam or better an embedded slab beam.
- Can be built either in first phase (at the same time than the main structure), or in a second phase if its design is not mature enough vs the process.
- Reinforced concrete class C30/37 in case of traditional approach. Another material has been studied, as the Steel Concrete (SC) composite solution, but for preliminary studies the classical traditional solution was studied.

## METHODOLOGY

**Materials**: The main structure (called the skeleton) is in normal concrete class C40/50. For the secondary structure, although the analysis takes into consideration different possible solutions, for calculation is considered classical RC walls, with normal concrete class C30/37. For reinforcing steel properties. Steel class is 500 MPa and minimum ductility is 5%.

**Soil properties**:

The soil on site is limestone [2] the best estimate properties (static/dynamic) are:
- Young's modulus is 30 GPa,
- Poisson modulus is 0.25/0.36,
- Shear modulus 12/11 GPa,
- Density 2.61 t/m$^3$.

Lower and Upper bounds are found using a factor of 1.50.

**Design life time**:

70 years. This parameter is useful for the long-term analysis (creep, shrinkage).

**Loads**:

- **Permanente loads**: This set includes the permanent loads produced by self-weight ($G_0$), equipment ($G_e$), secondary structures, liner, finishing, etc.
- **Variable loads**: This set includes the variable loads produced by normal operation (Q), equipment ($Q_e$), movement of loads (casks, Cranes) ($Q_{car}$), etc.
- **Wind loads**: extreme permanent winds 29 m/s at 10 m above ground level
- **Creep and shrinkage**: calculated according EN1992-1-1 [3].
- **Temperature**: extreme air temperatures down to -15°C up to +40°C.
- **Snow**: normal loading 80 daN/m$^2$, exceptional loading 160 daN/m$^2$.
- **Seismic loads**: Seismic loads are extracted from [4], in which the horizontal Design Spectrum is defined with a ZPA of 0.3·g (the vertical Design Spectrum is obtained by applying a factor of 2/3).
- **LOCA in PPTF area**: Overpressure in the PPTF with a value of 2 bars ($\Delta P$ = 1 bar)
- **Groundwater level**: Only the ground water level for return period of 100 years is relevant for design, as accidental load.
- **Fire**: the building must be stable by 2h.
- **External explosion**: an external pressure of 50 mbar.
- **Drop loads**: Different drop loads produced by accidents along the building are analysed [5].
- **Airplane Crash** (**APC**): The impacts of a Learjet 23 and Cessna 210 airplanes are studied.

**FE model**:

Figure 2 show the ANSYS FE model developed for the Building (B21). The model is made mainly of shell (Shel181) and beams (Beam181) elements. Punctual masses, i.e., for equipment are introduced with mass (MASS21) elements. Soil springs are introduced with spring elements (COMBIN14). The mean size of shell and beam elements is 600 mm, and the total number of elements is around 400000 when the soil springs are included.

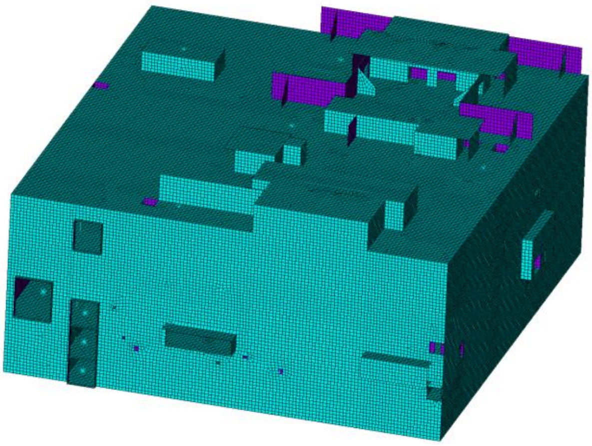

Figure 2. Finite Element Model of the HCB (B21) [6].

The FE model is developed first with all the secondary walls included (Configuration 1), and then these walls isolated from the main structure and fixed in those points in contact with the building. By conventional gravity analysis, the vertical reactions at each node can be taken to determine the

equivalent mass at each node. Once the mass is obtained, the FE model for configuration 2 is generated from the main structure and applying punctual masses at those points in which the secondary walls are in contact with the building.
The dynamic model introduces the permanent loads and the 50% of the overloads as permanent masses, by modifying the density of the elements.

**Seismic Analysis**:

The methodology for introduction of the soil impedance is based on the provisions given in ASCE standard "Seismic Analysis of Safety-Related Nuclear Structures and Commentary" [7]. According to [8], the effect of embedment may be neglected in obtaining the impedance functions for embedment with a ratio between the depth and an equivalent radius less than 0.3, as it is the case of the HCB building. It is important to note that springs and dashpots coefficients are given as discrete parameters and are valid for rigid foundations. Thus, in order to introduce the local flexibility of the foundation, these parameters are distributed along the foundation, assigning to each node a representative value that integrated along the foundation match the global parameter. The discussion about the validity of this assumption is still in process of validation, although the hypothesis is valid from global point of view, some additional flexibility can exist in the foundation slab in those zones far away from the walls (i.e. center of span). Complementary analysis with SASSI [9] will be accomplished in the next phase of design.
Once defined the impedances for the three soil configurations (Lower Bound, Best Estimates, and Upper Bound). Three dynamic models are generated for analysis of ULS.e cases and other three for the calculation of Floor Response Spectra (FRS). Response Spectrum Analysis (RSA) is accomplished to determine the internal forces, that are combined with the rest of load cases, and Modal Based Transient Analysis is used to determine the FRS. The main difference between the models is that for Transient Analysis, the technique of using a “big mass” is used, connecting the soil springs to a big mass node, by couplings. This introduce three rigid modes (displacements in the three space directions) that allows the introduction of the seismic acceleration as time histories of force (The force equals the seismic acceleration by the big mass, usually taken several magnitude order greater than the building mass). On the other hand, in the RSA analysis, soil springs are fixed connected to the ground, and thus the missing mass technique is used to introduce the “rigid” response [6].

**ULS analysis**:

All the load cases, except the seismic loads, are considered as static loads. Thus the static models are used to determine the reinforcement required in order to cover the different load combinations defined by regulation [1]. Basically the models are similar than for dynamic analysis, changing the soil impedance by Winkler springs, that represent the static properties of soil. In order to reduce the number of calculations, only Best Estimates properties are used during the conceptual phase.
In order to generate the load cases that imply seismic loads, and combine these results, a quasi-static FE model is generated. The soil properties match the dynamic soil properties, the permanent loads (self-weight, equipment…) and the 50% of the overloads introduced as permanent masses are modeled. Other seismic actions, as the earth thrust produced by seismic loads are introduced by using the Mononobe-Okabe method [10-11].
Depending the analysis is in normal operation or accidental condition, the partial safety factors for concrete $\gamma_c$ and steel $\gamma_s$ are varied: $\gamma_c$ = 1.50/1.20, $\gamma_s$ = 1.15/1.00.

**SLS analysis**:

The model dedicated to SLS analysis, is basically the same model used for static analysis, the only difference is that the elasticity modulus of concrete is reduced by the factor 0.7, in order to introduce the effects of cracking when short-term loads are analyzed. For long-term loads, it requires the implementation of the loads induced by creep and shrinkage, along the service life of the facility (70 years). Following the indications presented in [1,3], effect of creep is introduced by modifying the

elasticity modulus, $E_{c,\infty} = E_c/(1 + \chi\varphi)$, being $E_c$ the elasticity modulus of concrete, $\varphi$ the creep coefficient (obtained from Model Code 2010 formulae), and $\chi$ the ageing coefficient ($\chi \cong 0.80$).
Shrinkage is calculated according the EC-2, but Model Code 2010 formulae is proposed (this represent an improvement respect the formula of EC-2). The resultant imposed strain is introduced as equivalent temperature in the structural elements. This can be achieved by equating the effective temperature $\Delta T^* = \varepsilon_{sh}/\alpha_T$, being $\varepsilon_{sh}$ the shrinkage strain, and $\alpha_T$ the expansion coefficient of concrete, equals to $1 \cdot 10^{-5}$/ºC. The shrinkage strain depends, among others, of the element thickness.
Other parameters controlled during the SLS analysis are the tensile stress in reinforcement $\sigma_y$ and the mean compressive stress in concrete $\sigma_c$, for SLS.qp (quasi permanent) and SLS.f (frequent) combinations, $\sigma_c \leq 0.45f_{ck}$ ($\sigma_{c,max} \leq 0.6f_{ck}$), and $\sigma_y \leq 2/3f_{yk}$; whereas for SLS.c (characteristic), $\sigma_{c,max} \leq 0.6f_{ck}$, and $\sigma_y \leq 0.8f_{yk}$. Vertical deflections are defined according section 7 of EC2 [3] which gives a limit of span/250 for the deflection under SLS.qp and a limit of span/500. Additionally, soil stresses are verified under quasi-permanent load combination, controlling that stresses are below 2.50 MPa.

**Drop loads and APC analysis**:

The analysis is based in the simplified methodology proposed in Appendix B of [1], supported by CEB-187 [12] document. This allows to assess the Panel capacity against drop loads and APC events.
Drop loads are preliminary defined, only mass and drop height is available, and thus simplified calculations based in energy considerations are made. To achieve this goal, the failure energy based in the formulations that define the local behavior of the panel, are contrasted with the kinetic energy of the impactor. Additionally, to analyze the behavior of the capacity of the panels, in zones far away from the impacted zone, the yield lines methodology [13] can be used to determine the failure by bending taking advantage of the plasticity of concrete. On the other hand, to analyze shear forces in the zones close to supports, elastic shear forces distributions are determined (the ITER regulation does not allow take advantage of plasticity in case of shear failures).
For APC events, the impact force is an input data, and only the structural analysis is required. The analysis is done by using the yield line methodology, and the methodology proposed in Appendix D [1]. Impact of engines is solved using the perforation formulae provided in [1]. For more advanced stages of design, non-linear analysis following a more complex methodology is required in order to optimize the results, for example the indicated in reference [14].

## RESULTS

The total mass of the building is around 275000 tons (permanent loads + 0.50·variable load). The mass of secondary walls 58600 tons. The first modes (X: West/East, Y: South/North, Z: Vertical) for configurations 1 and 2 are presented in Table 1. As can be seen in this table, the change in natural frequencies reflects clearly the increase of flexibility of configuration 2.
Maximum accelerations obtained at each floor are shown in Table 2.1 or horizontal accelerations, and Table 2.2 for vertical accelerations. Horizontal accelerations are in general increased for configuration 2, the maximum difference is found in level L2, more than 1·g. Vertical accelerations are increased for levels between B1 and L3, but quite similar for B2 and R1. Figure 3 show the vertical displacement at level L1 for both configurations.

Table 1: First modes for configurations 1 and 2.

| Dir. | X | Y | Z | RX | RY | RZ |
|---|---|---|---|---|---|---|
| **C1** | 6.16 | 5.49 | 11.09 | 10.63 | 10.63 | 6.16 |
| **C2** | 3.90 | 3.48 | 4.41 | 4.41 | 3.90 | 3.90 |

Table 2.1: Max horizontal accelerations (·g) by levels for configurations 1 and 2.

| Dir. | B2 | B1 | L1 | L2 | L3 | R1 |
|---|---|---|---|---|---|---|
| **C1** | 0.35 | 0.55 | 0.57 | 1.03 | 0.91 | 1.10 |
| **C2** | 0.34 | 0.83 | 0.61 | 2.14 | 1.11 | 1.24 |

Table 2.2: Max vertical accelerations (·g) by levels for configurations 1 and 2.

| Dir. | B2 | B1 | L1 | L2 | L3 | R1 |
|---|---|---|---|---|---|---|
| **C1** | 0.37 | 0.48 | 0.62 | 0.71 | 0.98 | 1.71 |
| **C2** | 0.29 | 1.01 | 1.06 | 1.44 | 1.64 | 1.63 |

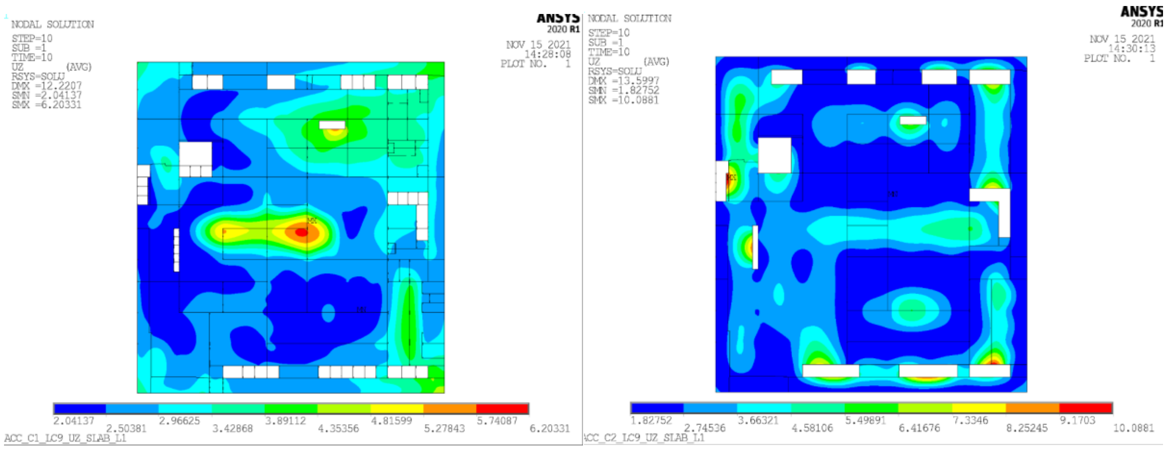


Figure 3. Vertical accelerations level L1 C1 (left) C2 (right)

For the study of drop loads and APC events, the minimum thickness required to prevent the perforation of the engine impact (mass 200 kg, impact area 0.5 m$^2$) is 210 mm, and the minimum thickness of external walls is 600 mm.

For application of formulae to local check and yield line methodologies, 4 configurations of shear reinforcement ($A_t$ = 16∅10-12-16-20mm/m$^2$) and three of bending reinforcement ($A_s$ = ∅25-32-40mm/250mm) are studied. The analysis reveals that minimum thickness for external walls is defined by APC events, equals 800mm, being the wall reinforcement ratios around 300 kg/m$^3$. The thickness of columns is affected by the APC event, when impact the roof. Columns located in level L3 must have a minimum area of 800×800 mm.

Drop load analysis identify some weak points in which the slab thickness must be increased or dissipation energy systems provided. In order to confirm these failures, a new design phase will be started soon, in which a more sophisticated methodology will be used [14-15].

Good structural performance is achieved under the case of external explosion.

Embedded plates, were calculated with TACEP program, provided by F4E [16]. After some iteration with IO, it was concluded that the design of the plates is possible only when the design seismic action is limited to 1.5·ZPA. The common practice is the use of the factor 1.5, but multiplying the maximum FRS response, but this is not possible in some cases. Thus, the equipment supports design require special attention during the following stages of design.

Soil below foundation stays below the admissible soil stress (2.50 MPa).

Regard the deflections, the results shoe that displacements are acceptable for both configurations.

Level of compression is acceptable is most of the concrete elements except in some pillars, mostly in configuration 2:

- Either the size of the pillars needs to be increased.
- Or walls shall be kept in these areas (or additional pillars should be added).

Global displacement compared to the ground are quite low (the available gap length between the Hot Cell building and the Tokamak building is 200mm in X and Y direction and 30mm is Z direction), as indicated in Table 3.

Table 3: Global maximum displacements (mm) for configurations 1 and 2.

| | **C1** | **C2** |
|---|---|---|
| **UX max/min** | 13 | 25 |
| **UY max/min** | 15 | 47 |
| **UZ max** | 13 | 13 |
| **UZ min** | -3 | -68 |

Slabs and walls are mostly designed by earthquake combinations, while pillars are more designed by normal operations, except for the pillars at L3 which are designed by the APC event.

Configuration 2 (secondary structure considered as a mass) is governing the sizing of the pillars.

Deformation of slabs are higher in configuration 2 due to the absence of walls.

Reinforcement ratios are in slabs and walls is presented in Table 4.1, and the same quantities presented in Table 4.2.

Table 4.1: Wall and slabs ratios for configurations 1 and 2.

| | **C1** | **C2** |
|---|---|---|
| **Volume** (m3) | 98660 | 98660 |
| **Kg steel** (ton) | 13351 | 14604 |
| **Ratio** (kg/m$^3$) | 135 | 148 |

Table 4.2: Wall and slabs ratios for configurations 1 and 2.

| | **C1** | **C2** |
|---|---|---|
| **Volume** (m3) | 1194 | 1194 |
| **Kg steel** (ton) | 243 | 432 |
| **Ratio** (kg/m$^3$) | 204 | 362 |

Reinforcement ratios are reasonable in slabs and walls. On the other hand, reinforcement ratios are quite significant in pillars, especially in configuration 2 when the secondary structure is not modelled.

Reinforcement ratios in external walls under APC event are maximum 300 kg/m³.

## CONCLUSIONS

This paper show a summary of the main results obtained during the conceptual design of the HCB B21. The conceptual design has passed the first CDR [17], and the future work is focused in the required work to justify the chits detected by the French Regulator (The forward action plan is detailed below).

The paper shows that global stability of the building is ensured for both configurations in case of earthquake. The solution main structure / secondary structure is working from a structural point of view. Some variants could be envisaged, and cost and schedule aspects will have to be assessed in future stages of design.

Thicknesses of concrete elements are driven by:

- the radiological shielding requirement for the slabs.
- the structural integrity for the pillars.
- the radiological shielding requirement for the internal walls (from 1000 to 1650 mm needed).

Where there is no shielding requirement:

- internal walls are 600mm thick, except for shafts, lifts and stairs where the thickness is reduced to 300mm.
- thickness of external walls is driven by the APC and set up to 800mm
- Basemat is 1400mm thick.

### Forward action plan

The structural analysis identified some points to be further investigated and refined among which the following:

- Refine/adjust the section of pillars where the compressive strength and reinforcement ratio are too high.
- Adjust the thicknesses of the slabs where the deflection is too high (mezzanines in particular).
- Check the integration of process and services against those changes.
- Integrate within the FEM used for the next design stage the changes implemented in the layout between the layout used in 2021 [18].
- The combination of fire and seismic loads is required to guarantee that no structural problems are expected during and after fire event takes place. Thus, the methodology must be improved.
- APC events will be calculated using non-linear tools, in order to determine the structural margin with more accuracy following methodologies developed previously [14-15]. It is expected that the required thickness will be reduced.
- The flexibility of the raft foundation will be determined by using SASSI methodology. In this point, we do not expect significant changes respect the calculation done, but it is required to confirm the calculations.

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