The four towers of the Cuatro Torres Business Area of Madrid

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Abstract

The Cuatro Torres Business Area complex is formed by four tall buildings in which each one them of them gives a different answer to the same problem and the same situation. In this study we look forward to describe and discuss, through a comparative analysis, the different structural solutions used to solve the problem of the construction of a tall building, as well as the conditions to which it responds in the decision-making process.

Despite that the general scheme of each tower it is completely different, we can differentiate between the three towers placed on the north of the site -the Espacio Tower, the Cristal Tower and the PwC Tower- and the Bankia Tower, as the first three of them were designed with a central communications core as the main element of the tower, versus the separated communications cores placed at the boundaries with which the Bankia tower was designed.

Figure 1: Overall view of the complex

1 Introduction

The Four Towers Business Area (CTBA) is located in the extension of the axis of Paseo de la Castellana, on the site of the former Real Madrid Sport Complex. The complex consists of four tall buildings 250 meters high that have become the new tallest buildings in Spain. The previous highest building in Madrid was the Picasso Tower, 100 meters shorter, and in Spain it was the Gran Hotel Bali, from Benidorm, that is 65 meters shorter than the towers of the CTBA. As the four of them are located on the same site and are devoted mostly to offices, they show us different ways of facing the same problem.

The specificity of tall buildings

Tall buildings have the particularity that, from a certain height, the horizontal forces play a much more important role than the gravity loads in the design of the structure. The behavior of a tall building against the wind forces could be resembled to the behavior of a cantilever fixed on the ground, with the flexural moments produced by the wind load as the main stresses to resist.

In tall buildings, the critical condition of the structure is the movement that the wind produces in the top of the tower. Not just for the damage that the horizontal movements can produce to the tower, if not because of the accelerations, because of the discomfort that could mean for the users the perception of the movements of the building. Thus, to optimize the structure of a tower the structural mass should be located on the boundaries, so that the tower gains more inertia against the horizontal bending forces. At the same time, the elements in charge of resisting the horizontal stresses should receive enough gravity load so they could work better in flexo-compression. The basic optimal shape of a tower would be like the shape of a chimney, with all its structural mass in the boundary and receiving all the gravity loads.

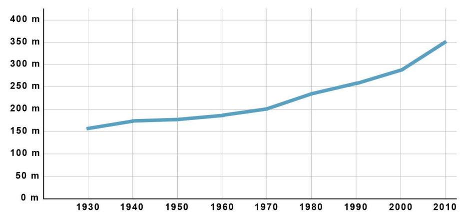

Figure 2: Average height of the 100 tallest buildings in the world

Structural context

The first tall buildings were built in the United States in the 19th century as an answer to the need of space in the center of the cities. Since then, the construction of tall buildings has increased significantly, both in number and height (Figure 2). After the first buildings, built with structural walls, came the rigid metal frame structures, the use of outrigger structures and the tube in tube structure, with a central core and boundary columns working as one. In the 1950, Fazlur Kahn defined the different structural types, and established their optimal inferior and superior theoretical height limits for each one of them. From the simple ones, for reduced heights, to more complex ones, like the trussed tube, or the use of damping mass for heights bigger than 450 meters. Parallel to the evolution of the typology, the materials have also being improved, moving from the steel structures of the first constructions, to composite structures of concrete and steel, and to the very frequent use of high strength concretes.

Currently, the tallest building built it is the Burj Dubai which is 829 m high,and already exist designs of skyscrapers taller than a kilometer, thus the construction of 250 m high tall buildings, like in this case, has become an usual situation in international context.

2 Four Towers Business Area (CTBA)

Espacio Tower

The Espacio Tower is located in the North-East corner of the site, is 223 m high and has 57 floors above grade. It was designed by the architects Pei, Cobb, Freed & Partners, and, with an office use, it has a square floor plan at base level of 42 m x 42 m. The tower has a height to width ratio of 5.3. It was conceived as an element rising from the ground, as a living thing, which evolves from a square to become the intersection of two quarter-circles.

The structure, which was designed by the engineering studio MC-2, leaded by Julio Martínez Calzón, had a determining condition imposed by the promoter group: the main material for its development had to be concrete.

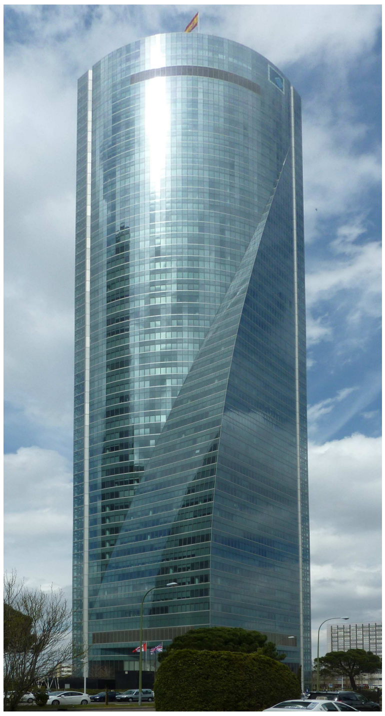

Figure 3: Espacio Tower. General view.

Foundations

The foundation of the Espacio Tower consists of a 4 meter post-tensioned reinforced concrete slab with a surface bigger than the projection of the tower. The pos-tensioned was placed in the central area, parallel to the two directions of the slab, receiving the loads from its communications cores (Figure 4).

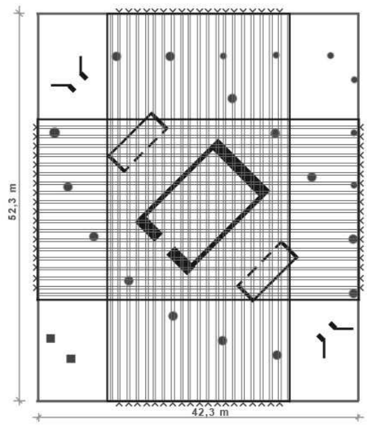

Figure 4: Torre Espacio foundations plan.

General scheme of the structure

The Espacio Tower is composed by a continuous central reinforced concrete core, two C-shaped laterals cores placed on the major axis of the oval, and two groups of columns located on the buildings boundaries (Figure 5a). The central core which, despite of being perforated to allow the passage to the elevators and of the facilities, works as a continuous box-shaped rigid element, being the main stiffness elements against the forces of wind, flexion and torsion (caused this last ones because of the asymmetry of the floor). The quality of the concrete decreases with the height, moving from high-strength concretes HA-70 in the ground floor to HA-40 and to HA-30 in the top levels of the tower. The lateral cores, with less rigidity because their shape, collaborate against the wind stresses thanks to the stiffness of the two-way reinforced concrete slabs which work as connectors. When the use of the elevators in the C-shaped lateral cores ends, the cores are substituted by two separate columns in their corners (Figure 5b).

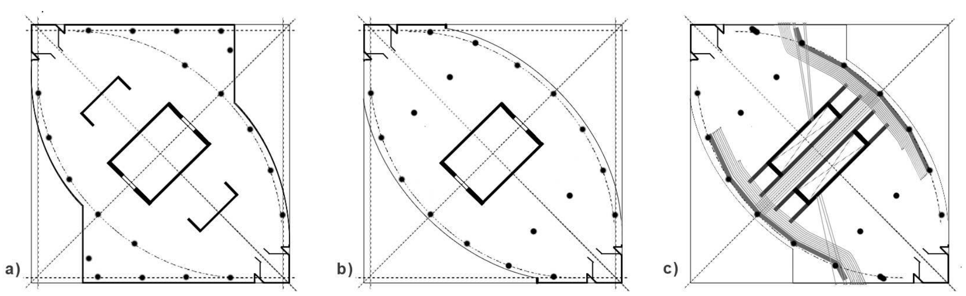

Figure 5: Espacio Tower floor plans at different heights: a) Lower section b) Top section c) Outrigger structure with stiffness belt.

At 2/3 of the total height, in order to gain a better resistance against wind loads, an outrigger structure is placed connecting the central cores with the columns that follow the shape of the final oval. The outrigger structure is composed by two boundary walls which, working as a belt, connect the perimeter columns, and four walls which prolong the sides of the core and connect it with the belt (Figure 5c). It is made with prestressed concrete HP-80 and it is a whole floor high, taking the top and bottom floors, 43 cm thick, as their chords, being therefore strengthen with more density of reinforcements and prestressed bars.

Structural elements

In the Espacio Tower we can differentiate between two groups of columns, on one side are the ones which form the perimeter of the oval of the top of the tower, which are continuous in the height of it, and on the other side are the ones that form the perimeter of the square of the base of the tower. The ones on the perimeter of the oval receive a big amount of gravity load and collaborate also against the horizontal forces, thanks to the stiffness of the slabs and to the outrigger structure that connects them with the core. Because of the big loads they have to resist they are made with high-strength concrete in the lower part and, as happened at the cores, they reduce the strength of the concrete with the height to HA-40 and to HA-30. Looking after to stay in diameters of 120 cm in the underground levels, 100 cm in the base and 60 cm in the middle and upper levels, they use big quantities of reinforcements, with a 3 % of reinforcements in the base, disposed in two circles. In the access levels, to avoid excessive dimensions a HEM steel profile is embedded in the column surrounded by a circle of reinforcements bars. The reinforcements of the middle and upper levels are disposed in one circle and take from 2 % to 5 % of the total section of the column (Figure 6). The columns placed on the perimeter of the square of the base, which disappear as the height increases, take less amount of gravity loads. They go parallel to the exterior cladding and following it, they lean in two of the faces of the tower. As a consequence of the polar symmetry of the floor, the inclination of the columns does not affect negatively as they compensate each other.

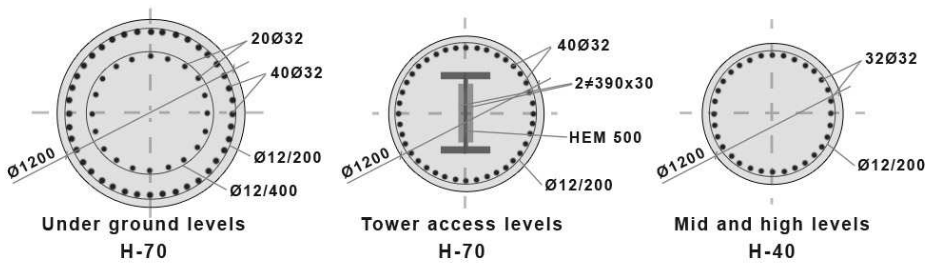

Figure 6: Typical columns cross-sections: below grade, tower access areas and mid and high levels.

Figure 7: Iew of the entrance to the Espacio Tower.

The slabs, which span up to 12 meters, were designed in a 28 cm thick reinforced concrete slab, occasionally with a depth of 35 cm in special areas. The rigidity of the slabs allows the transmission of the horizontal stresses that, collaborating with the outrigger structure, guarantee the joint work of all the structure against the wind loads.

The joint detail between the HA-30 reinforced concrete slabs and the heavily loaded columns made with high-strength concrete HA-70 is made through a confinement of the slab with 5 circulars Ø25 bars which increase its strength.

With the aim of adapting to the variations in the geometry of the floors an horizontal displacement is produced in some columns through solid rigid blocks of reinforced concrete from the initial to the end position, at the height of the technical floors M1 and M2, in the base and at the level of the outrigger structure respectively. The horizontal forces that appear are compensated with prestressed reinforcements and passive steel reinforcements in the upper and lower slabs.

Looking after providing a greater importance to the entrance of the Espacio Tower, the perimeter columns of its South and West elevations are removed, with the exception of the one in the corner (Figure 7). To make it possible is used a big truss 8 meter high which spans 27.8 meters and which is connected to the upper and bottom, and using them as composite chords.

Cristal Tower

The Cristal Tower was designed by the architects Cesar Pelli & Associates, it rises 250 meters high with 52 storeys. It is located South of the Espacio Tower in the West end of its plot and it is completely devoted to the use of offices. It has a rectangular base floor plan with dimensions 40 x 33 m, and a global slender of 7.6. The volume of the building answers to the sculptural concept that the building goes folding towards itself with the height, resulting in that all the floors are different between themselves.

Already since the first drafts it was insinuated the design of the structure as a big central services core which released the exterior cladding and allowed to assimilate the shape of the tower to a gemstone. The structure will be finally solved by the structures engineering team of OTEP International.

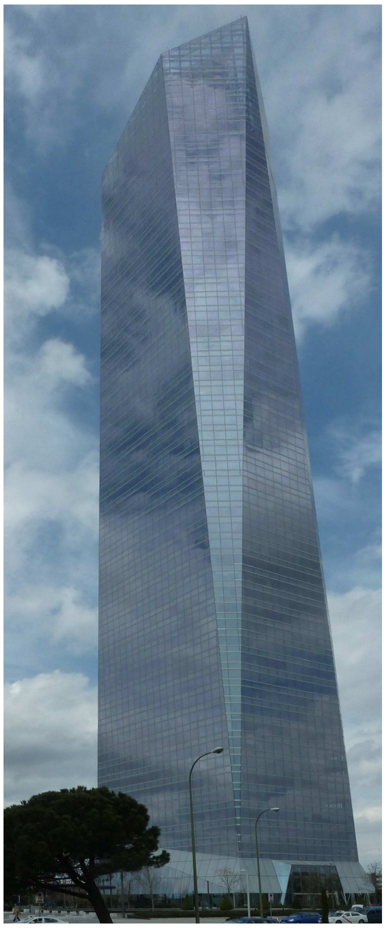

Figure 8: Cristal Tower. General view

Foundations

The foundations of the Cristal Tower are solved with a deep foundation with bearing walls 20 m long and 120 cm thick. Acting as a global unity, it has a 150 cm thick shallow concrete slab on top of the bearing walls, which are located under the columns and the central core. The bearing walls, connected between themselves to work as a unit, transmit loads to the terrain across the toe and by friction along the shaft.

General scheme of the structure

The Cristal Tower was designed with a big central core that contains all the services and communications, and a group of columns in the perimeter that holds the structure of the floor framing and go along with the exterior cladding (Figure 9). The big central core has its thickest walls, 120 cm thick in the base and 70 cm thick on the top of the tower, parallel to the side with bigger facade to equilibrate the bigger wind loads that receives. In the other direction the transversal walls are 50 cm thick.

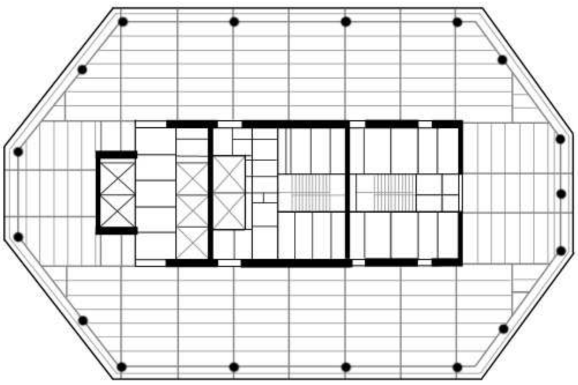

Figure 9: Standard Cristal Tower structural floor plan.

Despite it has a perimeter structure, the core is the element in charge of resisting almost all the wind loads, as a consequence of the low stiffness of the floor framing and the absence of an outrigger structure which would bring together the whole structure.

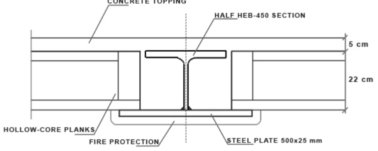

Figure 10: Cross-section of standard beam outside the core

Structural elements

The Cristal Tower has its 18 composite columns placed in the perimeter. They are made of a HD steel section embedded in the concrete surrounded by a circle of reinforcement bars. They go from diameters of 95 cm in the base levels to 70 cm in the top of the tower. Due to the inclination of the exterior cladding some of the columns lean slightly following the slope of the facade. The forces that appear because of the deviation are resisted by active reinforcements between the column and the central core.

Despite its non-orthogonal and variable geometry, the floor framing is solved through a precast hollow-core planks of 22 cm with a 5 cm in-situ concrete topping supported by steel beams. Over the beam which goes along the perimeter through the columns rests another group of beams, which start in the central core and go perpendicular to the facade. These secondary beams lean alternatively in a column and in the center of the beam of the perimeter, when they rest on the beam they continue and have 110 cm cantilever till the exterior cladding, supporting the floor framing in cantilever with an edge beam at the end that acts as a confinement to the slab. The hollow-core planks are supported by the beams perpendiculars to the facade, which are made of half of an HEB-450 steel section and a steel plate of 50 cm as its bottom flange, so that it guarantees a correct support of the planks (Figure 10). Within the core, because of the number of holes through the floor, it is decided to make a composite metal deck floor where the steel deck act as permanent formwork of a light weight concrete slab with a depth of 20+7 cm which leans on steel beams fixed to the walls of the core.

In the entrance to the tower, in this case, there is not any variation in the structure. To mark the entrance it is designed a small change in the geometry of the exterior cladding and taller ground floor.

Figure 11: PwC Tower. General view.

PWC Tower

Devoted mostly to the use of hotel, the PwC Tower (former Sacyr-Vallehermoso Tower) it is the only one that only uses one third of its space to offices. Located South of the Cristal Tower, the tower was designed by the Spanish studio of architecture of Enrique Álvarez Sala and Carlos Rubio Carvajal. With its 236 meter high, 52 storeys and a slender ratio of 5.9, the tower is divided in its floor plan in 3 different sectors, which show up to the exterior through cracks in the exterior cladding that allow the light to illuminate the three-lobed central core. Both its plant and its structure are marked by a maximum exploitation of its hotel use.

The Engineering Studio MC-2, which had previously designed the structure of the Espacio Tower was also the team in charge for designing the structure of the PwC Tower.

Foundations

In the PwC Tower is used the same system that was used before in the Espacio Tower: a 5 meter post-tensioned reinforced concrete slab with a surface bigger than the projection of the tower. And, as in the previous case, they see themselves in the need of strengthen the connection between the columns and the slab. Because of the size of the slab, the concreting is made in several phases, separating the slab in two of 2 meters thick each, where it was necessary to put shear connection reinforcements between themselves. The columns and the core, for being able to transfer conveniently the tension stresses that appear under extreme wind situations, are anchored to the bottom of the slab. The stressing of the prestressed cables was completed before the onset of the construction of the columns and the core.

General scheme of the structure

The reinforced concrete central core of the PwC Tower has a three-lobed shape (Figure 12). It has the stiffness concentrated at its end positions, on the buttresses, with several layers of reinforcements, in order to provide a greater inertia to the ensemble. The thickness is reduced in its radial walls, and it is finally reduced to the minimum in the triangle that has in the center, decreasing to a thickness of 30 cm. As it happened in the Espacio Tower, the core has holes to allow the passage of people and facilities, so the lintel over the hole is designed so that the whole core works as a unity. The central core is the main element to resist the wind loads. Its interior form is continuous in all the height of the building, containing the elevators and services, varying only its thicknesses and the strength of the concrete of its walls, ranging from HA-45 to HA-30 in the last third of the height of the tower.

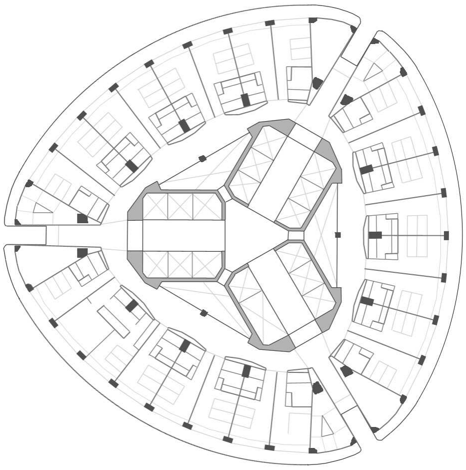

Figure 12: Standard PwC Tower hotel floor plan.

To stiffen the structure, tying together the columns with the central core, the PwC Tower has an outrigger structure in the last floor, which links the central columns with the core through a structure of radial concrete walls 80 cm thick and 5 meters tall, with the upper and bottom floor as chords. The outrigger belt, apart from unifying the structure against the wind forces also, because of its high stiffness, reduces the differential shortenings between the core and the columns caused by the creep and the shrinkage of the concrete. In this case its design was very conditioned by the long-term gravity loads that transfer from the columns to the core.

Structural elements

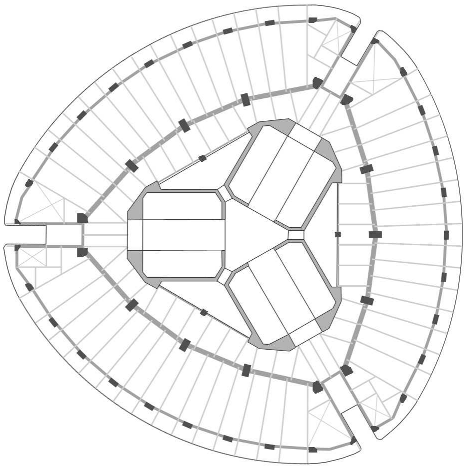

Figure 13: Standard PwC Tower structural floor plan.

In the PwC Tower the columns are placed attending to the partition of the hotel. They are disposed in three rings: one in the perimeter, a central one in the corridor of the hotel and the other ones adjacent to the core. The shape of the columns changes adapting itself to the floor plan, varying between rectangular, circular and other special shapes in the end columns in the encounter with the stairs (Figure 13). From the foundations to the access floors, because of the heavy loads, they are made of high-strength concrete HA-70 with diameters ranging from 150 cm to 120 cm with a double circle of reinforcements. Above the fourth level, to reduce the size of the columns in the hotel and to allow a fastest construction of the floor framing, columns with a steel column embedded in the reinforced concrete were designed. To simplify the connection between the steel sections, they were designed so that once spilled the concrete, the steel column does not receive any tension, resisting only the ones produced by the wind during the construction process, as the steel construction goes 3 floors ahead of the concreting. The perimeter reinforcements will be the ones in charge of resisting the tensions that could appear in the columns.

Because of the higher loads, the location of holes, and columns with a larger distance between them, the floors under level N04 are made with a solid reinforced concrete slab. Upwards level N04 the floor framing consists a composite structure of steel and concrete. It is designed a composite metal deck slab supported by composite beams of steel profiles provided with shear studs. There are three rings of beams, bolted to the three rings of columns respectively. The radial joists rest over the exterior ring of beams and have a cantilever that supports the two layers of the exterior cladding. The exterior curved perimeter is solved with a border stiffness element which acts as an edge beam at the end of the slab, shaped like a steel coffin, is supported by the radial joists and acts as composite formwork of the concrete of the slab.

Figure 14: Bankia Tower. General view.

Bankia Tower

The Bankia Tower (former Caja Madrid Tower), designed by the architecture studio Foster + Partners, is the one which closes the compound in its South-East corner. With its 250 meters high and 42 storeys, is the tallest building in Spain and the tenth of Europe. With a height to width ratio of 11, and dimensions in its plan view of 53 x 43 m, it is completely dedicated to the use of offices. The main idea of the design was, already from the first drafts, to create a column free office space as flexible as possible, which will be the concept that will mark all the decisions in the project.

It was developed from the very beginning in a close collaboration between the architectural team and the engineering studio of Halvorson & Partners, who were in charge of the design of the structure. The tower is designed as a "mega-frame" where the core, which is divided in two and which becomes the columns of the "mega-frame", are tied together in four points by two groups of big trusses, supporting blocks of 11, 12 and 11 floors between the two cores.

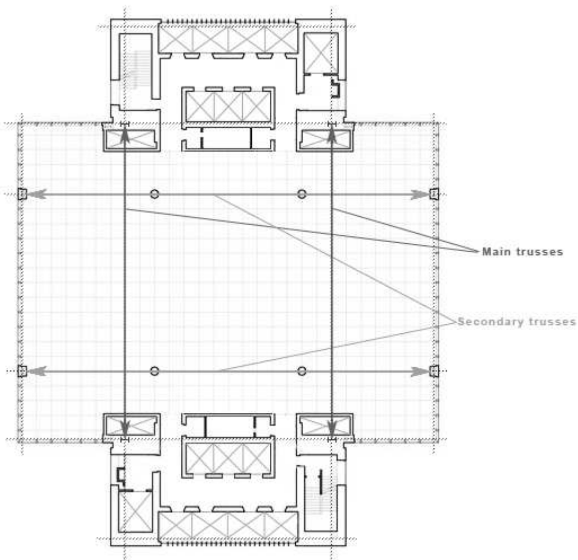

Figure 15: Standard Bankia Tower floor plan with the projection of the trusses.

Foundations

The Bankia Tower transfers all its loads to the terrain through the two main cores, as they are the only elements of the tower that arrive to the ground floor and to the foundation plan. The foundation is solved with a 5 meters thick reinforced concrete

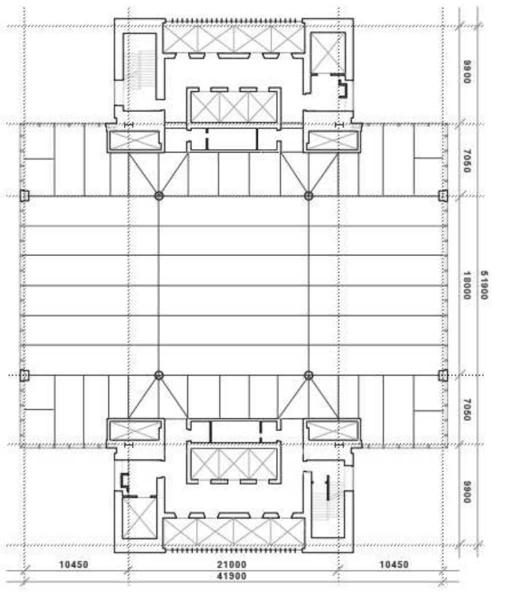

Figure 17: Standard Bankia Tower structural floor plan.

slab bigger than the projection of the tower. For its construction the concreting was made in two different phases of 2.5 meters thick each one.

General scheme of the structure

In the Bankia Tower the two cores take a special importance as they are continuous in all the height of the tower and as they are the elements in charge of transferring all the loads to the foundations. The three office blocks of 11, 12 and 11 storeys transfer their gravity loads to the cores through two groups of perpendicular trusses. The cores are also the elements that resist the wind forces, either in the East-West direction, where, united by the trusses act like a "mega-frame" with a big resistance, or, in the North-South direction, where they work as a double cantilever in which each core takes its part of the wind load. Its walls are made with concretes HA-55 and HA-40 and thicknesses ranging from 30 cm to 120 cm.

Figure 16: View of the Bankia Tower column-free access.

Three groups of trusses are placed under each block of offices, and two plate girders are located in coronation, to transfer all the gravity loads from the offices floors and to tie and unify the cores. This groups of trusses are formed by two main trusses that spans between the cores, and two secondary that, perpendicular to the main ones, receive the loads of the 8 columns and transfer it to the main trusses (Figure 15). The stress of tying the cores together against the wind loads it is the most critical one for its sizing, so that the top chord of the main trusses it is over dimensioned against the gravity loads.

Structural elements

The Bankia Tower is a particular case as none of its columns arrives to the ground floor (Figure 16), but all deliver their load to the two big vertical cores through the trusses. In the floor there are only 8 columns, 4 interiors and 4 in the exterior cladding, separated by maximum distances up to 15 and 18 meters. All of them are steel columns to reduce their size to the minimum. The columns are continuous in their height, they were designed so they could work in habitual state in compression resting over the inferior trust or, in the case that this one fails, work in tension hanging from the top truss through a special connection detail.

The floor framing is solved with a composite metal deck slab, of a 7.5 cm depth deck of 1 mm thick, with 7.5 cm of light weight concrete of 18 kN/m^3. Because of the large distances between columns that the slab has, the deck rests on steel wide flange beams which are provided with shear studs that assure the ensemble work of the slab. Towards North and South the slab has a 9 meters cantilever respect the cores, with a cantilever also in each corner as it does not have any columns, just the 8 interiors in its central area (Figure 17). As a special case, over the technical floors and to ensure a better acoustic insulation, the light weight concrete is substituted by normal dense concrete and the layer of concrete is increased to 15 cm. In the facade of each office block, to improve its behavior, a Vierendeel frame is formed with the exterior columns and the edge beams.

3 Comparison of the four solutions

Foundations

The foundations of the four towers are made on the same soil of Tosco formation (clayey soil with some fine sand) that started in depths from 15 to 25 meters below grade. It has a maximum soil bearing pressure of 715 kPa. Ground water was only encountered in some points between 13 and 16 meters below grade in the south area of the site.

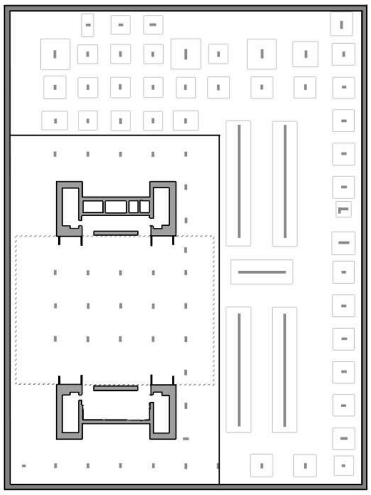

Figure 18: Bankia Tower foundations plan.

The Cristal Tower is the only one that makes a deep foundation through bearing walls, with a 150 cm thick shallow slab as a pile cap. The bearing walls are 20 m depth and 120 cm thick.

In the rest of the towers a deep foundation by bearing walls or drilled piles was discarded, despite that the expected settlements would be lower, because of the excessive thickness that the pile cap would take. Resulting the pile cap almost of the same size of a single shallow slab.

In the Espacio Tower and in the Pwc Tower, designed by the same engineering studio MC-2, a 4 meters thick post-tensioned reinforced concrete slab was employed. The post-tensioned cables helped to reduce the amount of steel reinforcements in the slab, as well as ensure a better durability, avoiding the appearance of cracks in the concrete in contact with the soil.

In the Bankia Tower the possibility of making an isolated foundation for each core separately was studied, but, to avoid the possible appearance of differential settlements between the cores, it was finally decided to make a single combined slab.

General scheme of the structure

Stairways and elevators play a determinant role in the design of tall buildings. They usually take up to a third of the surface of the floor, therefore, their location becomes one of the main issues of the design of a tower. As the vertical communication cores need a structure that goes with them all the way up, usually it is increased the

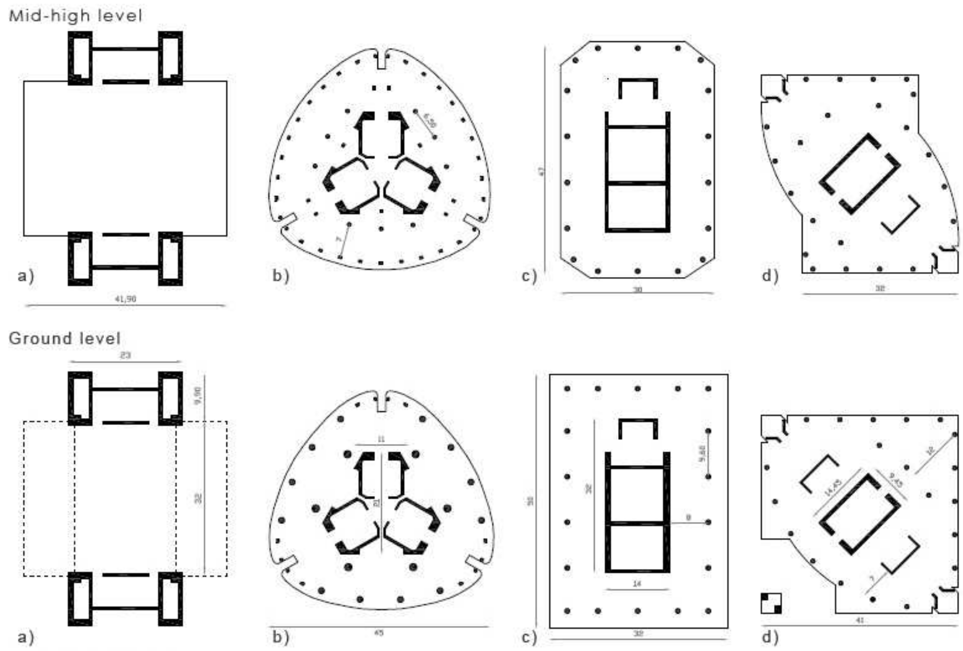

Figure 19: Compared cross-sections of the towers, a) Bankia Tower, b) PwC Tower, c) Cristal Tower, d) Espacio Tower.

load that this structure receives, increasing also its thicknesses, and giving it enough importance as to become the main resisting element against the lateral wind loads, and the element in charge of transferring much of the loads to the foundation. Thereby it is usually avoided to make a secondary structure for the vertical communications and a principal one to resist the forces.

In the Espacio Tower, the Cristal Tower and the Pw Tower, the communications are solved with a central communications core, which becomes the main element in the design of the tower. Although in each one of them plays a different role in the general scheme of the structure, they are clearly different from the solution that is made in the Bankia Tower, with two separated communications core placed on the boundaries.

In the Espacio Tower the communication cores are disposed, by functional reasons, along the longitudinal axis of the oval of the top of the tower. To compensate the reduced inertia existing against the wind forces upon the bigger side of the facade the thickness of the end walls of the core is increased considerably up to 150 cm thick, with a big density of reinforcements.

In the Cristal Tower the communications core, quite large in relation with the surface of its floor, is the element in charge of resisting almost all the horizontal forces. As it happened in the Espacio Tower, the end walls of the short side of the core are thicker to compensate the less distance existing between them and to increase the inertia of the tower for the more adverse axis.

In the PwC Tower, with a three-lobed shaped central core, to avoid complications in its design and to facilitate the circulations of the facilities, because of their size, it is made a hole outside the core, where the facilities could go. This decision implies a big reduction in the gravity loads that the central core receives, as the floor beams are not able to go throw the utility shaft. Thereby, against the approximately 52 % of gravity load that received the core of the Espacio Tower, the one of the PwC Tower just takes a 32 % of the gravity loads despite it is in charge of resisting the 90 % of the horizontal forces, against the 50 % of the horizontal forces that takes the core of the Espacio Tower. This is reflected in the design of the core, that not only implies a less resistance to flexural stresses because of its reduced compression loads, if not that part of it could even reach to work in tension for a determined situation of horizontal forces.

The fact that the core of the PwC Tower takes so much weight in the resistance against the horizontal forces compared to the one of the Espacio Tower (been both structures designed by the same engineering team MC-2), is determined also by the location of the outrigger structure in the top level of the tower, versus its location at 2/3 the height of the tower, its optimal position, that they have previously made in the Espacio Tower. Although the contribution against the horizontal forces that the outrigger structure makes in the PwC Tower is just of a 10 %, against the 19 % that takes the one in the Espacio Tower, as all the plants are equal, and to avoid stopping the constructive process, in the PwC Tower was decided to place it in its top floor.

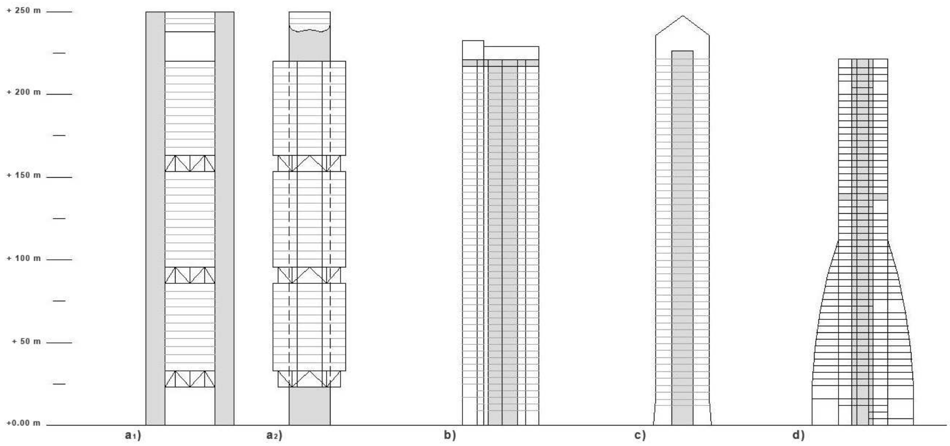

Figure 20: Schematic section of the towers comparing their resistance against horizontal forces, a1) Bankia Tower South elevation, a2) Bankia Tower North-South longitudinal section, b) PwC Tower longitudinal section, c) Cristal Tower longitudinal section, d) Espacio Tower longitudinal section.

In the Bankia tower, by separating the core in two and placing them on the boundaries it is reached an optimal resistance against the lateral wind forces coming from the East-West direction as the structural mass is located in both ends of the tower. But, on the other hand, it complicates the transmission of the gravity loads, and the North and South orientations, with a larger elevation, do not offer a bigger resistance to the wind action. To compensate this, the most part of the structural mass of the cores is placed in the South and North ends of each cores, as separated as possible.

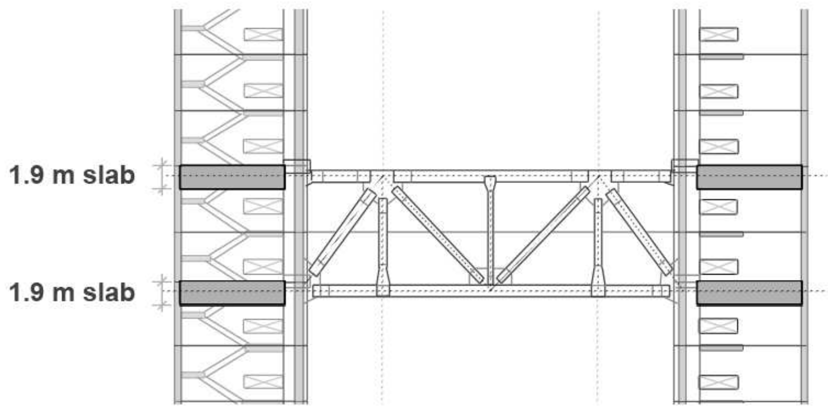

Figure 21: Scheme of the location of the 1.9 meters thick slabs in the cores of the Bankia Tower

The structural typology, used generally for higher types of towers, answers to the architectural will of creating a flexible and column-free office floor. This type has the advantage that all the gravity loads are transferred to the cores, improving its flexural resistance. But the deviation of the loads carries a series of added problems, not only because of the deviation of the loads from their original direction, if not for its transmission to the core. To ensure the transmission it was necessary the employ of a 1.9 m thick post-tensioned concrete slab in the core at the levels of the top and bottom chords of the trusses (Figure 21). This slab had the big problem that for its construction it was necessary to stop the constructive process and to disassemble the interior climbing formwork. To reduce the excessive loads transferred by the trusses, that are designed to resist the weight of two blocks of offices floors in compression or, for safety reasons, in compression and in tension, post-tensioned reinforcements are employed at the level of the bottom chord. To minimize the flexural moment that the trusses introduce in the cores, because of the reached magnitude, the bolts in the top chord connection of the trusses to the embedded columns of the cores are not fully tightened until all the dead load has been applied to the truss.

Structural elements

Further than the general scheme of the structure, in tall buildings the structural elements also take great importance, not just because of its structural efficiency and self-weight, but because of their influence in the constructive process. Decisions like the repetition of floors, towards prefabrication, or the use of freestanding elements that avoid shoring and increase the safety on site, are really beneficial.

The Espacio Tower is the only example of floors of solid reinforced concrete slab. This kind of slab answers to the interest of the promoters to make the whole construction with reinforced concrete, but also to the complex and variable geometry of the floor, difficulting, to some extent, the prefabrication, to its constructive simplicity, that has the inconvenient of having to shore, but avoids in some way the use of cranes, and also to the possibility of transferring the horizontal forces through the slab for the joint work of the whole structure against the wind loads. For the horizontal forces, the slab, because of its stiffness, is able to carry a 31 % of this forces to the columns so that they work together with the core. In the Espacio Tower the columns play a very important role in the resistance of the building against the wind loads, so that 50 % of the wind efforts are assumed by the core, and the other 50 % is taken by columns through the outrigger structure with the stiffness belt and the solid reinforced concrete slabs.

In the Cristal Tower the composite columns are formed by steel sections embedded into the reinforced concrete. It was avoided to make the columns just in concrete because of their bigger rheological deformations and their unsuitability with the floor framing of precast hollow-core planks, but it was also avoided to make them only of steel because of their higher cost and the need of protecting them from the fire and give them a covering, that would extend the construction process. This way it was only necessary to protect from the fire the inferior steel plate of the steel beams that remain exposed between the hollow-core planks. This precast solution, even though it had the disadvantage of the variable geometry of the floors and made necessary the use of cranes, carry to a more easily and quick assembly without need of shoring.

The PwC Tower shows a clear difference from the previous ones in the repetition of the shape of its floors in all its height. This decision is very beneficial towards prefabrication and to a systematization of the assembly process. As in the Cristal Tower, but here with composite metal deck slabs, to speed the construction process, from the fourth floor upwards the columns were designed with an embedded steel profile, which allowed the assembly of the metal structure to be 3 floors ahead the concreting. The slabs were designed as composite metal decks because of their advantages to the constructive process, where, as a freestanding solution avoids shoring, and, as it is a lightest solution than the hollow-core planks, it can be assembly with light cranes. The circular geometry of the floor was not a problem as the steel coffin that played like the role of the edge beam was prefabricated and as it was used in all floor systematically. This constructive system allowed the PwC Tower to be built at a construction rhythm of 6 days per floor, in comparison to the 9 days per floor of the Espacio Tower. To protect the slabs against fire only the beams were covered with projected fire-proof mortar, as a supplementary reinforcement was placed on the bottom of the slabs ribs.

The Bankia Tower, following its architectural intentions of achieving a floor as diaphanous as possible, was designed with a slab with the less possible number of columns, resulting in distances up to 18 meters between their 8 columns. Because of this large distances between columns the composite metal deck slab only has 7.5 cm light weight concrete of 18 kN/m^3 and the steel beams are mostly designed with cambering, to compensate the self-weight of the slab. Even though this particularities to answer in an ideal way to the architectural wills could become a problem, this is minimized thanks to the repetition of all floors along the tower, allowing the prefabrication and standardization of all elements.

In relation with the importance that takes, in tall buildings, the deformations associated to the creep and shrinkage of the concrete, the towers opt for different solutions.

At the Espacio Tower and the PwC Tower, both designed with concrete columns and cores, the problem of the differential creep and shrinkage between them —which tends to create differential deflections in the slabs—, is assumed by the outrigger structure, that, because of its stiffness, avoids the appearing of differential shortenings.

In the Cristal Tower, as it has not got any outrigger structure that compensates the bigger settlements in the columns against the ones produced in the core, it is decided to anticipate to those shortenings and increase the length of the columns in each segment.

In the Bankia Tower, to equilibrate the big values of creep and shrinkage that has the concrete of the core versus the steel frames of the office blocks, relative displacements between the different blocks of offices were allowed through a special joint detail at the connection with each group of trusses, becoming the offices blocks independent and limiting the accumulation of stresses and differential movements to each block of offices separately.

4 Conclusions

The typology of towers of the Cuatro Torres Business Area, with heights up to 250 meters and height to width ratios ranging from 5.3 to 11, offers several structural alternatives. In this case, the most common choice was the central core with perimeter columns. This solution was used in the Espacio Tower, in the Cristal Tower and in the PwC Tower, although in each one of them plays a different role.

In the Espacio Tower and in the Cristal Tower the central cores, with a different behaviour in each one of them, answer to the interest of leaving free and continuous the facade, as it becomes the image of the design and of the tower. In the PwC Tower the central core answers more to the intention of allowing a maximum exploitation of the surface of the floor to the hotel use, releasing the surface of facade to this use. The Bankia Tower, looking forward to having a diaphanous office floor, was design with a completely different typology, with two cores situated on the boundaries. In all of them, whether in a greater or lesser extent, the main objectives of each tower are reflected on the choice of its structural typology.

Tied together to the election of the structural typology goes the choice of the different structural elements that will form the structure of the tower. In this case it is covered a wide range of possibilities, from composite metal deck slabs, to reinforced concrete slabs or to precast concrete hollow-core slabs, and from steel, to reinforced concrete or to composite columns. Depending on the structural typology of the tower and the role that the structural elements play on it, it can be seen the different possibilities and attributes that each one of them provides.

The different structural solutions highlight, as we have tried to point up, the absence of a unique structural solution and the direct relationship between this and all the aspects that cover the construction of a tower. The analysis of the structure of the four towers reveal the need of an interaction between the structural answer and the architectural designs wills already from the first phases of the project.

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