A Place To – Esbjerg Towers

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Jens Fussing has over 28 years of experience in the design and documentation of a wide range of structures throughout 24 countries, from seismic retrofit in Nepal and Iran, towers in Europe, Africa and the Middle East, spot stadiums in Azerbaijan, arenas in Europe, and large scale commercial and residential developments in the GCC countries. Jens has particular expertise in high-rise structures, precast building systems and building physics. He also has experience with examination as well as mentoring master and PhD students at university level in relation to research and development projects. He holds an unlimited license in Dubai Municipality.

Abstract

A place To in Esbjerg is a truly unique, affordable student accommodation project, located in Esbjerg on the west coast of Denmark facing the strong winds from the North Sea.

At first glance the buildings are inspired from cactus trees challenging the build ability. The buildings consist predominantly of apartments for students. At the lower levels there are common facilities such as bicycle parking, storage facilities and landscape breakout spaces. There are no basements in the towers. The project is currently under construction and is planned to be taken into use end of 2021.

The article will predominantly demonstrate innovative solutions within the structural system, facades, MEP and the practical use of industrialization, transforming a highly complex looking building into buildable towers.

Because of the round floor plates, prestressed “cake-shaped” slabs were developed, columns are double high without corbels, the integrated ring beams ties the perimeter and inside the cast the cast in-situ jump-formed cores stairs and MEP shafts are prefabricated. The outer balconies rotate from one another in plan however only 4 different façade/balcony types were fabricated. The structural system has been developed for towers up to 100m, the taller ones

are tube in tube structures.

As an add on the contractor chose to 3D print the cores so that the labors could get acquainted with them before starting building.

By using highly repetitive customized technical solution material waste was limited and demonstrates that it is possible to build tall and affordable.

A Place to – Esbjerg Towers

The Project

The site A Place To is located between Esbjerg city's coast, university and city center. The site itself is surrounded by a wide range of sports facilities, the Tovværk Park, a high school and an array of residential courtyard blocks in the fifties, making it an ideal location for student housing. BIG lifts the ground to accommodate the common program on street level, while defining the circulations throughout the plot. The resulting dunes are carved and scooped according to the alignment parameters defined by the local regulations, allowing daylight and people inside. The landscape provides a wide range of open-air areas for recreation and relaxation. The three towers offer a total of 431 units out of which 122 are hotel apartments. The floor plans are typically divided into 16 modules, and each floor is approximately 440 m^2. Floor plans including the balconies are approximately 595 m^2**.** By rotating every other terrace while keeping the core in place, the residential units achieve a variety of generous balconies and a characteristic profile. The result provides a myriad of residential units with views to the surrounding nature, the city center and the sea, see figure 1.

Figure 1. A Place To – Areal view © A Place To

The Vision.

The original vision was to develop a building system which would be attractive for students to live in and to be affordable, the ambition for the building system is to be re-used on sites and plots around Europe. BG&E's role in the project team was to participate with the development of a tailormade structural building system with a height limit of up to 100m, for the A Place To project the EOR was BIG Engineering and the third party checking was carried out by INGENIØR'NE. The student apartments are uniformly distributed over the floors plates with large window views out into nature, the views are without visible drops or downstands, see image figure 2, all apartments to be alike however with a variety of the balconies' layout, see figure 3. The ambition to implement flexibility for future changes of use was also part of the scope of works. Sustainability i.e. minimize material use and waste. A Place To is an example of how a complex looking building has been broken down into simple construction solutions with the high use of prefabrication, that is the structural system, the facades and balconies and the core wall structures.

Because the buildings are one use only and symmetrical the repetition factors are evident i.e. all apartments are alike hence industrialization and prefabrication of tailor-made solutions was a logical conclusion for the development. Inspiration and synergies of construction techniques from around the world was part of the innovative solutions.

Figure 2. A Place To – “The View” view through the apartments © A Place To

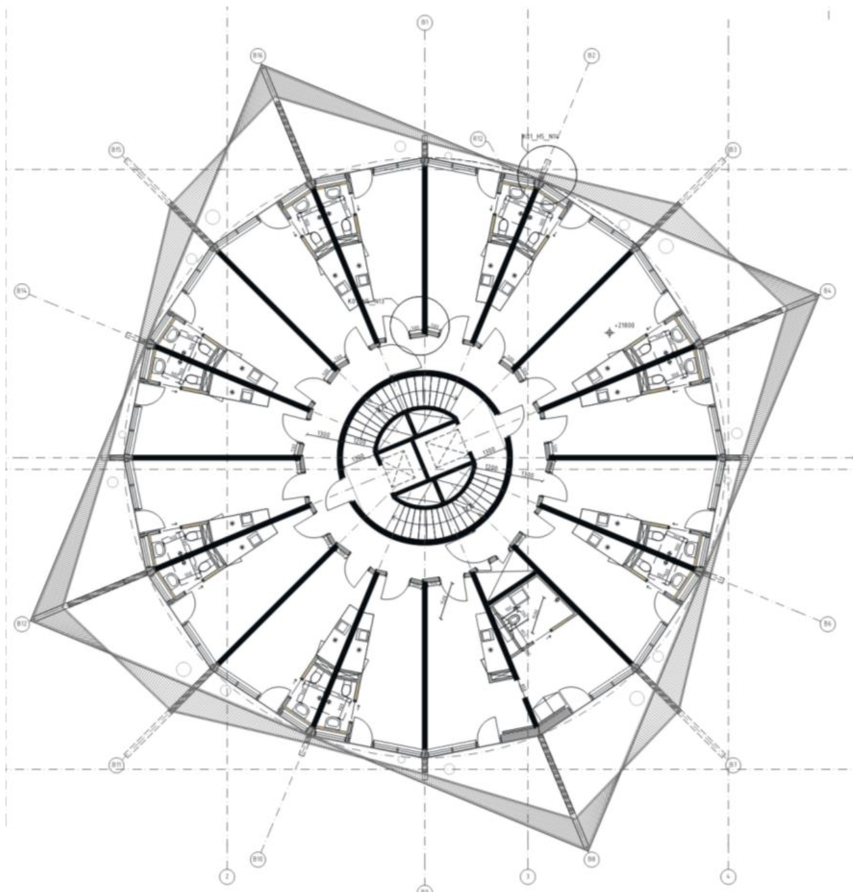


Figure 3. A Place To – Architectural impression, typical floorplates © BIG

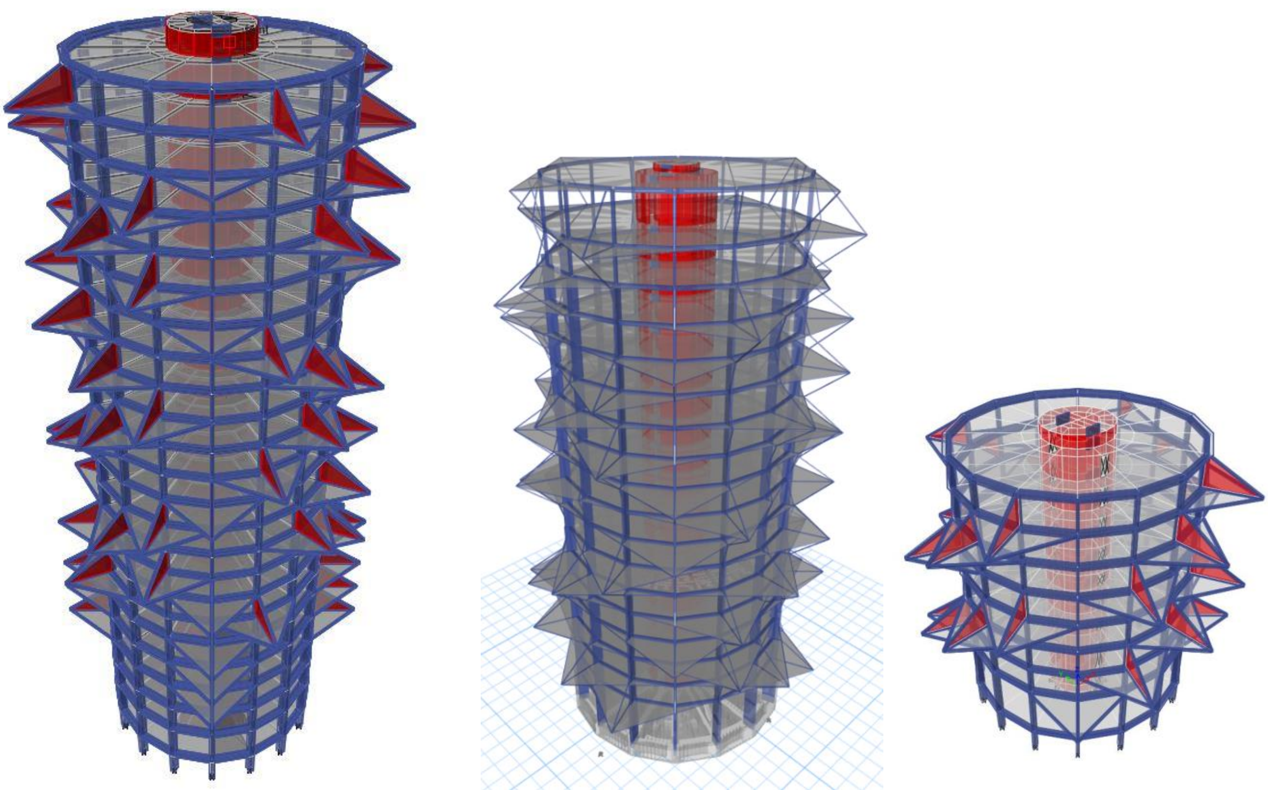


Figure 4. A Place To – ETABS model © BG&E and BIG Engineering

The Structural System.

As the aim was high repetition and to use cast in-situ concrete and precast concrete where it was most cost effective, 4 individual ETABS models were created, G+7 (33m height), G+9 (40m height), G+17 (65m height) and G+24 (80m height) with the same footprint and structural system and the only variable would be the member sizes, see figure 4. The tower structures are isolated from the podium structures with expansion joints thus no lateral interaction between them. The floors plates consist of simply supported precast prestressed trapezoid slabs resting on the central circular cast in-situ core wall and on a composite concrete ring-beam in the perimeter. The verticals are evenly spaced rectangular precast columns along the perimeter and a central core wall. The lateral load resisting system was a tube in tube structure, stiffness of the slabs is ignored, the tube in tube action becomes more pronounced for the taller towers than for the lower towers where most of the lateral stability is taken by the core, the ring beams dimensions (stiffness) also play a role especially for the taller towers. The core wall has a diameter of 7.2m thus the slenderness ratio varies from 4.5 for lowest tower up to 11 for taller towers looking at the core alone, which explains why the tube in tube action is more pronounced for the taller structures. There are no outriggers or transfer structures in the towers. It was the ambition to avoid outriggers due to flexibility and the structurally open floorplates, see figure 22. The substructure was for the smaller tower a strip footing in the perimeter and an isolated foundation underneath the central core whereas for the taller towers the foundation was raft foundations, bearing on sand. The benefit of the open floor plans structurally with a flat slab solution was that larger apartment sizes could be re-arranged in the future without having to interfere with the structure. The structural design is carried out as per Eurocodes including local annexes and placed in consequence class 3 called CC3 and CC3+ for buildings with more than 15 floors.

Prestressed Slabs

Five different floor systems were developed in the concept phase and analysed with one another, due to the building shape the optimum solution was found to be a custom-made solution. A traditional prefabricated solution would be carried out with radial beams spanning from the core out to the perimeter columns with hollow slabs spanning as floors which mean many on site work activities and drops interfering with the mechanical strategy. Instead a prefabricated 270mm flat slab solution was developed by custom-made prestressed slabs – the cake-shaped slab, spanning form the core to the perimeter ring-beam, the 270mm SL-slabs rests on post fixed steel corbels onto the core walls, see figure 5. The prestressing technology saves on material consumption as opposed to conventional construction and had very limited material waste because slabs are fabricated in steel molds see figure 6. The SL-Slabs have a high fire rating performance, up to 4 hours, the fire rating for the towers was 2 hours. The high fire rating performance for the SL-Slabs is ideal for tall buildings as opposed to hollow core slabs which have much lower fire performance and may need extra fire protection. SL-Slabs is structurally a prestressed rib slab similar to T-slabs, the arch shaped ribs are formed by lightweight concrete, the lightweight concrete is a special mix which provides good fire protection thus the high fire rating. The perimeter the ring beam was integrated as part of the slab and due to transportation and lifting restrictions (maximum panel sizes) there are two slabs in each apartment, the connection at mid-span of the ring beam is carried by a welded steel plate connection recesses into the slab thereby not being visible, the welding is done from above, see figure 7, and notice the prop location on figure 22. Openings for MEP risers are fully integrated see figure 8. In addition conventional top and bottom mesh can be built into the slabs in case of high diaphragm forces or if bending stiffness would be required for building stability, this would be evident to explore for the 100m tall version, say for example in the upper 30% of the floors, this is still to be researched. The idea about prestressing slabs with complex geometry originates to the Towers construction boom in Dubai back in the 00's, because even though many floor plates had complex geometry the repetition factors were high up through the towers enough to become a cost effective solution, i.e. partial elliptical custom-made prestressed balcony slabs were mass produced lifted up in place and tied into the more regular conventional cast in-situ floor slabs.

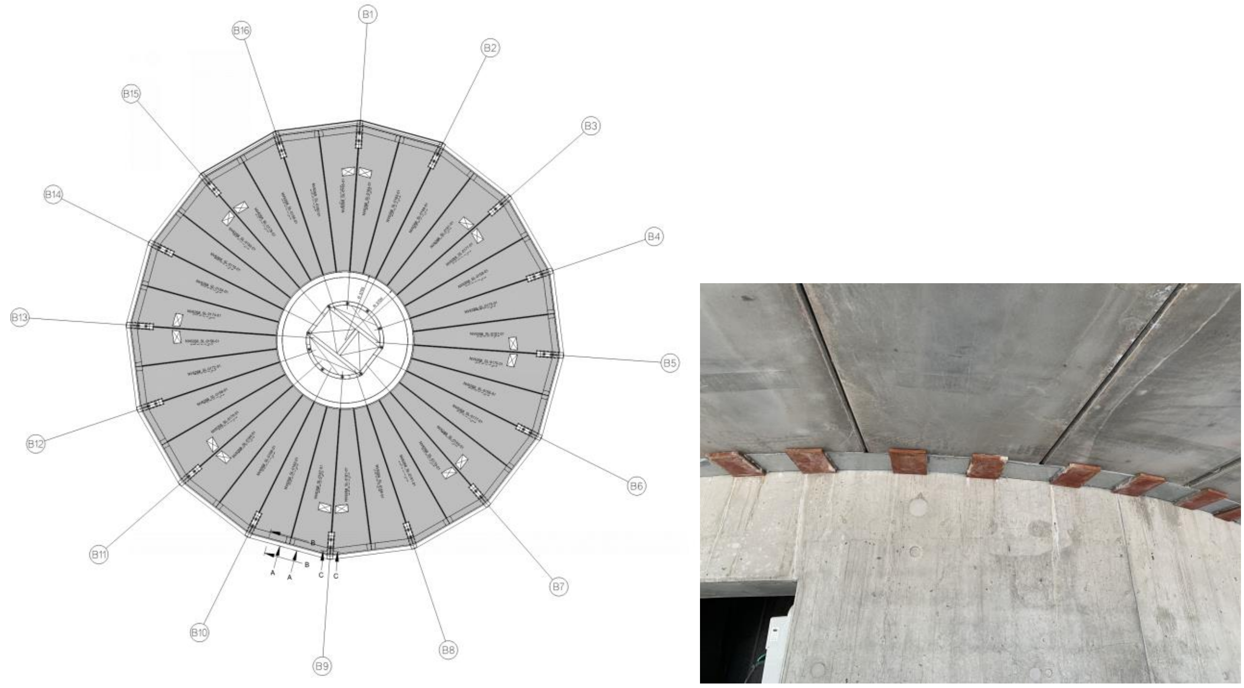


Figure 5. A Place To – Typical Floors of SL-slabs and steel corbel connection © Abeo / A Place To

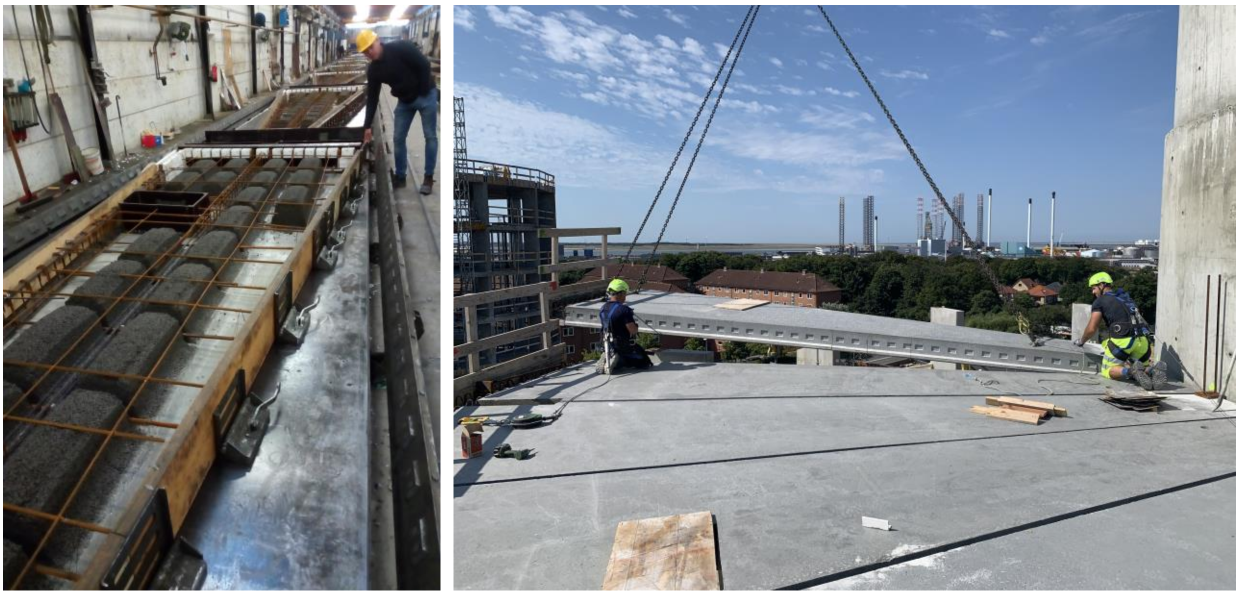


Figure 6. A Place To – SL-slabs during fabrication and installation © Abeo / A Place To

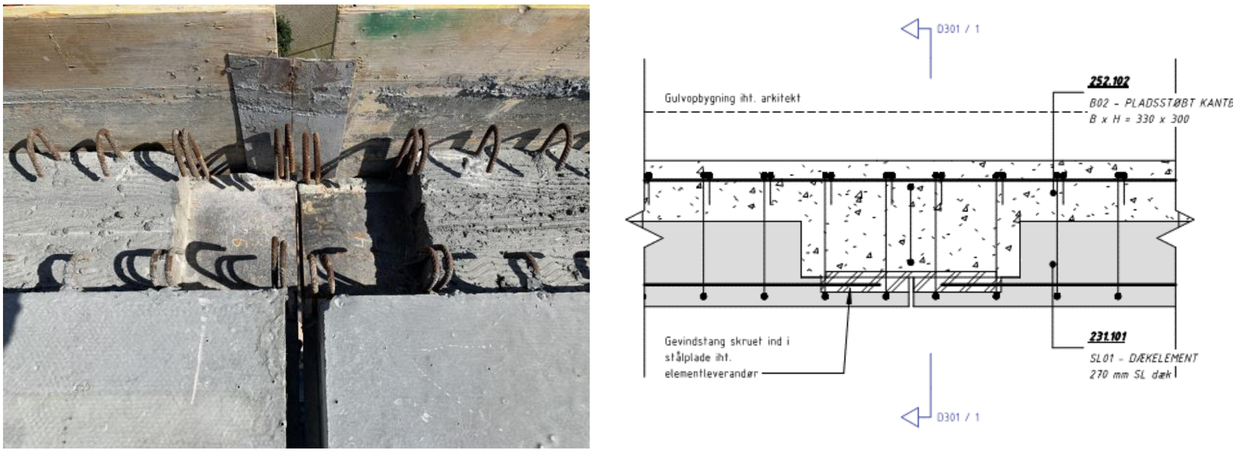


Figure 7. A Place To – Steel plate splice in integrated composite ring beam © Abeo / BIG Engineering

Figure 8. A Place To – MEP riser integration © Abeo / A Place To

Columns

The columns are evenly spaced along the perimeter of the floorplate, and shapes are rectangular and orientated in the same direction as the partitions. The columns have the same widths as the partition walls, and columns sizes increases due to loads only occurring in the long direction of the columns. The columns are tied in both directions in the perimeter by the ring beam and with ties parallel to the slabs located in the joint between the floor planks anchored into the core. Columns are designed continuously therefore column to column connections are also designed as moment stiff and with use of dowels and standard columns shoes are used. Also the connection between columns and the slab ring beams have been designed as full moment connections, see figure 9 and 10. The builder as such is free to decide between the use of single, double high or triple high columns. Because the columns are rectangular, corbels could be avoided as the ring beam rests on a simple recess on the outer side of the column, this solution also ensures that no visible structural elements interfere with the original architectural intent of having the large window view from floors to ceiling, see figure 2. Column recesses are also more cost effective due to a more direct load path as opposed to corbels and other bracket systems.

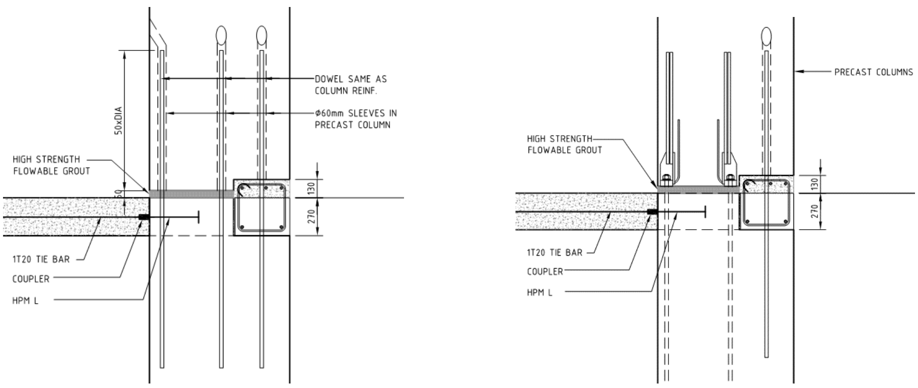


Figure 9. A Place To – Columns splice and ring beam support, to the left a traditional propped doweled solution and to the right a Peikko solution un-propped © BG&E / Peikko / A Place To

Figure 10. A Place To – Columns / SL-slab / Ring beam connection © A Place To

Ring beam

Because the floor heating system is integrated into the floor build up layer consisting of a lightweight concrete layer on top of the SL-Slabs the height of the ring beam can vary from 270mm – 400 mm beneficial for the tube in tube action for the taller towers. The ring beam is integrated within the floorplate build up and is not visible taking into account the original architectural intention with the full window view, see figure 2.

The ring-beam serves many purposes, firstly carrying vertical loads working as a continuous beam, secondly taking part of the tube and tube system, thirdly working as a tie in combination with the radial column ties as significant tie forces are generated from balcony overhang, see figure 11. In terms of robustness the towers are designed for progressive collapse assuming a column failure, because of symmetry the perimeter tie forces generated from the catenary action gets cancelled out as the top reinforcement absorbs the tension forces, see figure 9 and figure 11.

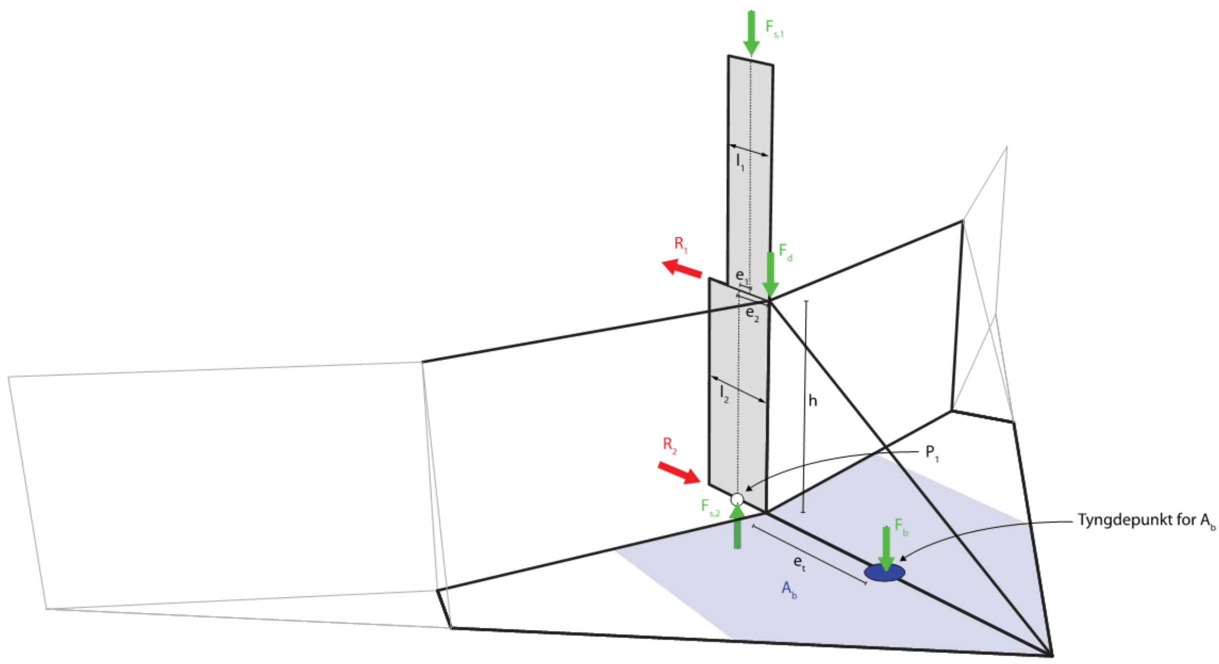


Figure 11. A Place To – Balcony Overhangs © BIG Engineering

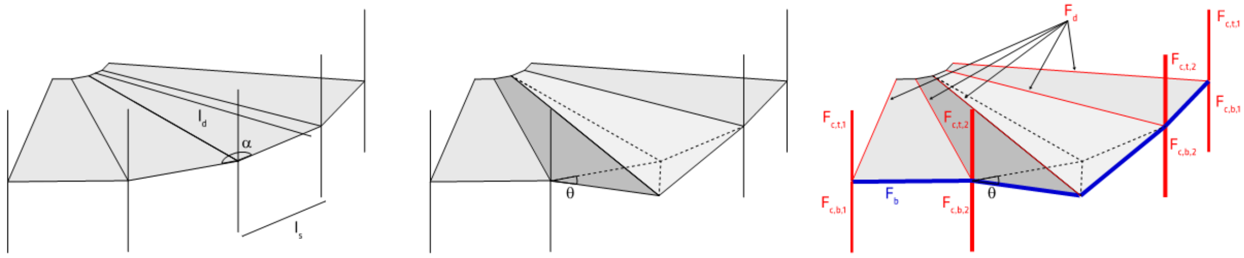


Figure 12. A Place To – Catenary action © BIG Engineering

Core walls

The core wall consists of an outer and inner core. The external core wall takes part of the lateral stability system and has wall thickness of 300-400mm varying down through building. Over door openings, rigid link beams are integrated. The inner core wall contains the MEP services shaft and the lift; while the precast spiral stairs are supported by the inner and outer core walls. All stair flights, landings and partition walls, MEP shafts are alike, suitable for prefabrication. The philosophy is that the inner core follows the movements of the tower because the entire inner core is fully prefabricated, connections are as such studied and detailed for the inter-story drifts and building deflection, see figure 13.

The central circular outer core wall was designed as cast in-situ concrete partly due to constructability, but also because of its suitability to withstand the magnitude of the shear forces, especially in cold joints, as opposed to precast concrete which require vertical and horizontal stitching connections or in some cases post tensioning. The construction of the core wall was accomplished by use of two independent custom-built form climbing systems. In fact, in accordance to PERI the specific formwork is with the smallest diameter they have ever experienced. As typically for towers the core wall construction is on the critical path therefore in terms of construction sequence the core jumps are up to 5-10 floors ahead of the floor plate construction, see figure 14. When the core has reached its final level, the climbing system is removed, and the inner core stands like a hollow chimney. Partition walls, stairs, stair pressurization shafts and mechanical shafts are all prefabricated and installed from the top, see figure 13, this work is happening at the same time as the floorplate construction on the outside of the core. In the preplanning construction phase the core wall with all its components inside was 3D printed in a small scale so that workers could get acquainted with the sequence in advance, see figure 15.

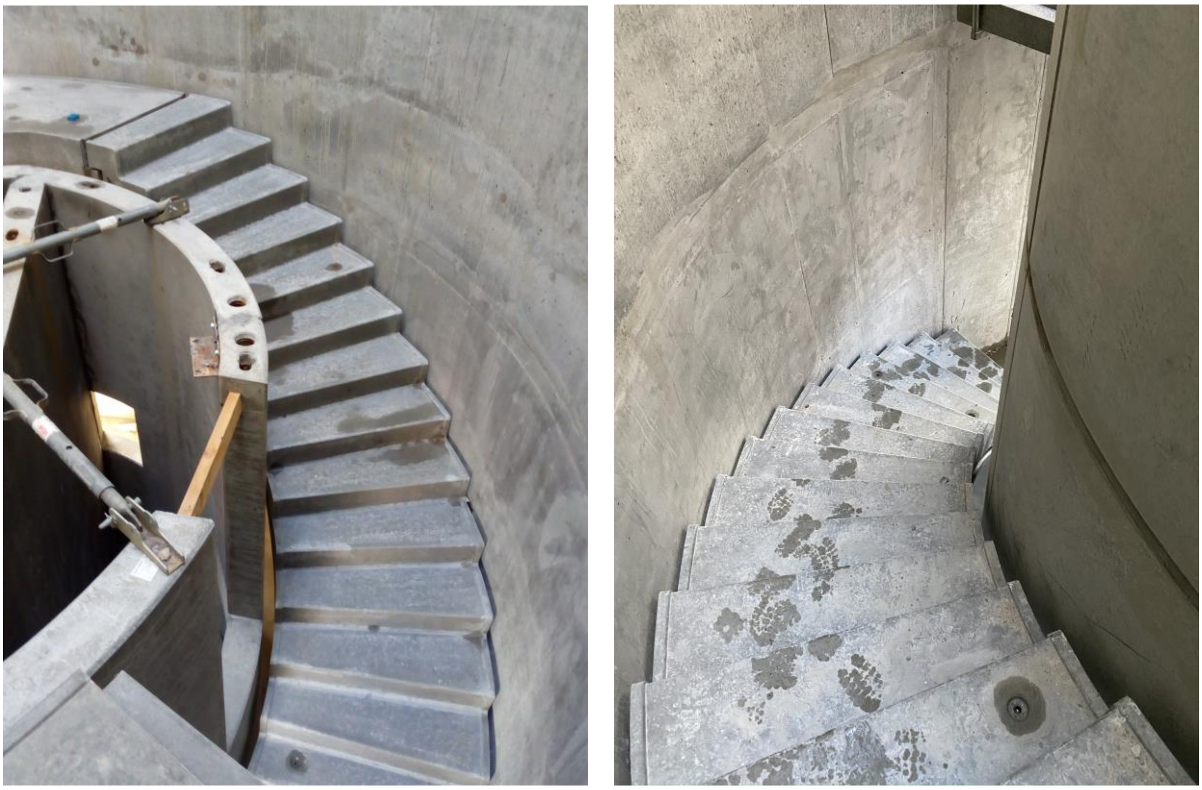


Figure 13. A Place To – Inner core © NCC / Industribeton

Figure 14. A Place To – Outer core © NCC / Industribeton / PERI

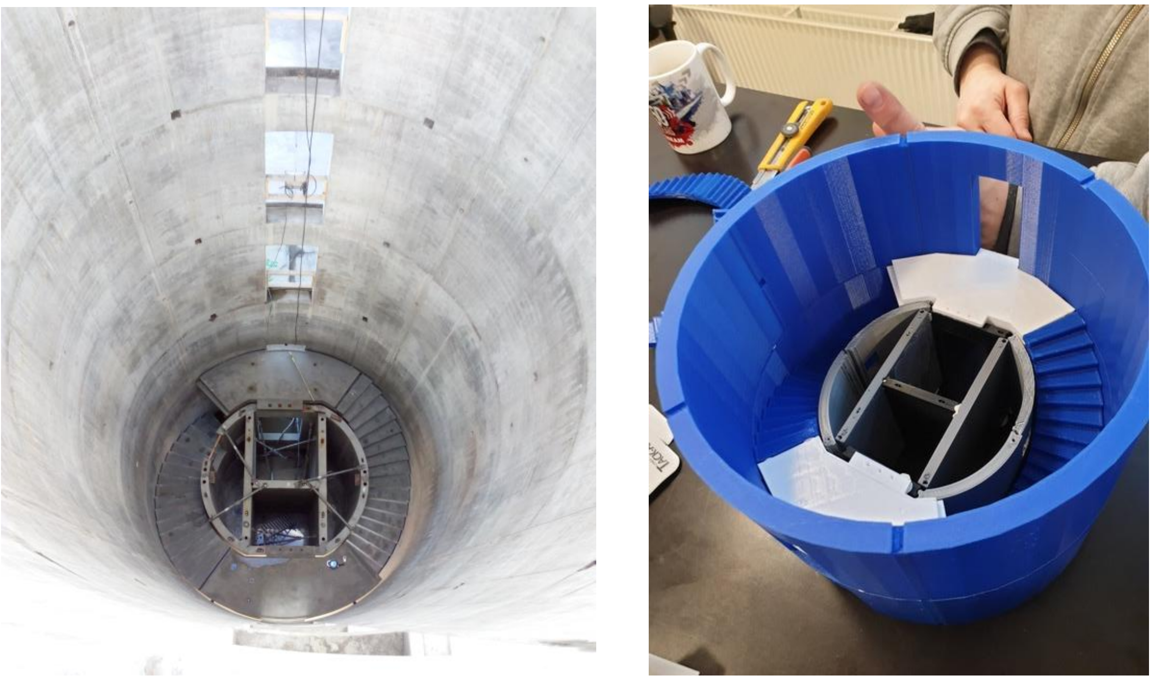


Figure 15. A Place To – Core wall as built and 3D printed © NCC / Industribeton

Wind Engineering

The site is located on the west coast of Denmark close to the North Sea, where the highest wind speeds in the nation are observed. The governing wind direction is west with the highest wind speeds. Up along the west coast the wind almost always blows, storms are a common phenomenon, the trees in the landscape are tilted towards the easterly direction because of the constant blowing from the west. Because of the shape of the building and its geographical location, wind tunnel testing was carried out, see figure 16. Perhaps, intuitively at first glance one might have concerns about torsional effects of the building due to the overall shape from the façade protrusions, however it was found that the circular shape introducing only a minor torsion from wind actions were dominant. Furthermore, the façade protrusions did reduce vortex shedding by confusing the wind. The torsional moments from the wind tunnel test were found to be small and the third mode shape from Finite Element Modelling FEM modelling was in fact torsion with highest natural frequency. In terms of building acceleration's, the proposed tube in tube structural system works for building height up to 100m. The wind study included statically equivalent floor plate loads from 12 independent directions, building acceleration study, wind pressures on facades and balconies and a study of the local wind environment at ground level, and on the balconies. The highest wind speeds found at the pedestrian level were in fact from the easterly wind direction. For the determination of the wind loads on the building, a peak velocity pressure in the reference height 60.9 m equal to the height of the building above terrain is used. An orography factor of 1.0, an air density 1.25 kg/m^3, and a fundamental basic wind velocity of 27 m/s are applied in accordance with the Eurocode specifications. This gives a maximum peak velocity pressure of approx. 1.65 kN/m^2 for the building.

Figure 16. A Place To – Wind tunnel testing © Svend Ole Hansen ApS

Substructures.

The geology in western Denmark is of interest as a significant part of Jutland where Esbjerg is located the soils were formed during in the late to post glacial geological time age. During the last ice age a great portion of western Denmark was not fully covered by glaciers as opposed to the rest of the country. Roughly speaking in the areas where glaciers were covering the land good ground conditions can be found today as they are un-organic and well compacted from the load of glaciers, even in some locations good limestone ground conditions are near to the surface because the glaciers scraped away soil when moving back and forth in the interglacial periods. However, in the part where Esbjerg is located the soils are sandy because the soil layers were created in front of the glaciers and thus also un-compacted. The phenomenon of where the glaciers stopped under the last ice age is today still visible in the landscape as the change in ground conditions can be seen because the sand is visible. The older glacial soil layers are located 16 m below the existing ground level, the Danish landscape was impacted by a least 5 ice ages.

As a result, hereof due to these ground conditions and the magnitude of the loads a geotechnical investigation report was developed to categorize the soil parameters for calculating the soil bearing capacity. Therefore, the design of the foundation was carried out by taking into account the raft stiffness, soil stiffness with the associated soil bearing capacities, see figure 17, the stresses are all in compression. The soil bearing capacity is between 1,59MPa and 2,62MPa, depending on the pressure distribution, and has been design according to Eurocode 7.

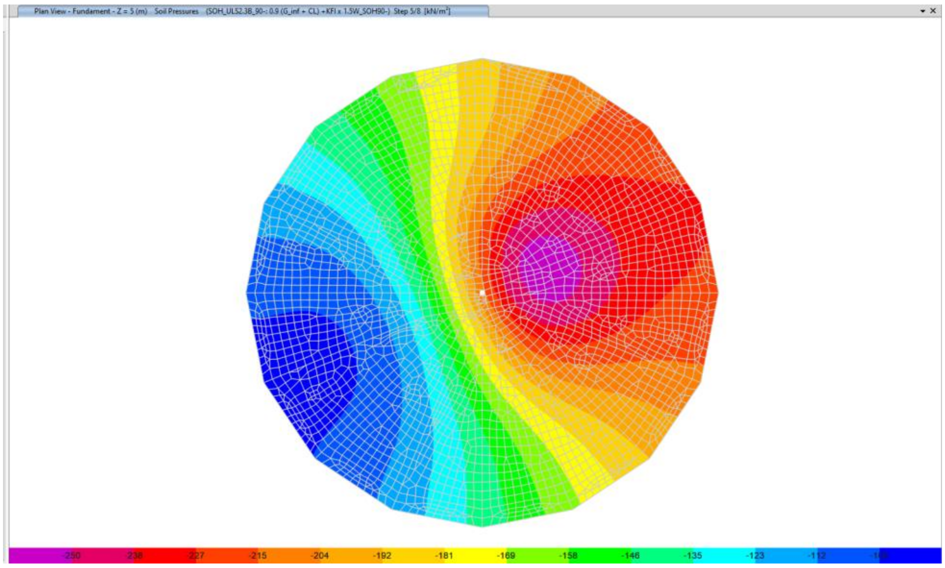
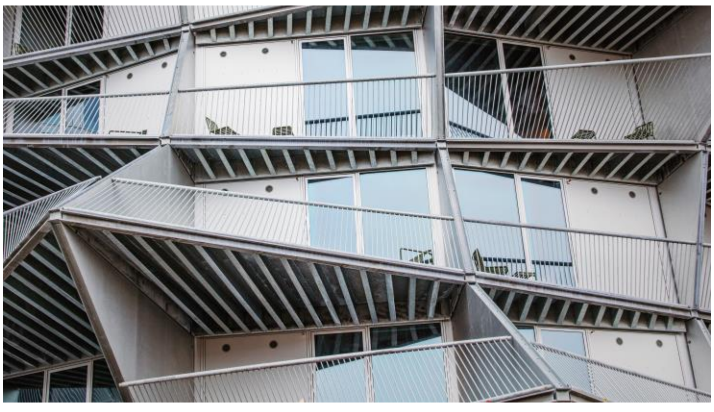


Figure 17. A Place To – Soil pressures max wind + minimum self weight [250 kN/m^2] © BIG Engineering

Facades / Balconies

Imagine the towers without the balconies, they would stand like cylinders. A cylindric shape is the optimum shape when it comes to the lowest façade/floorplate ratio i.e. as opposed to a rectangular box shape. In other words, a cylindric shape generates less façade area than a rectangular box shape per horizontal floors area. In addition to this the circular looking building is in fact faceted into 16 individual straight façade panels on each floor, thus a significant amount of repetition factors for the fabrication and installation, panels are prefabricated unitized façade panels. There are 4 different panel types in the project and all panels have the geometrical sizes, the erection sequence of the facades are two days per floor, see figure 18 and 19. In such harsh weather conditions getting the envelope sealed and closed off is of significant importance allowing building internal finishes work to proceed. The floorplates rotate 22.5° from one another up through building. The balcony structure is a segmented prefabricated steel structure with cladded slab and wall parts, there are 4 different balcony types split up into an outer wall part which support the slab system. It is predominantly the balcony that creates the spectacular looks of the buildings, without them the towers would be plain, notice the skewed railing in figure 18 and 19. The sequence of construction is first to install the bearing brackets for the balconies onto the concrete super structure, then the façade panels are installed and finally the balcony units, see figure 19 and 20. The erection of the balconies will take 2 days per floor and can occur in parallel to work activities inside the towers. Thermal bridges are limited to the connection points between super structure and the balconies, see figure 20.



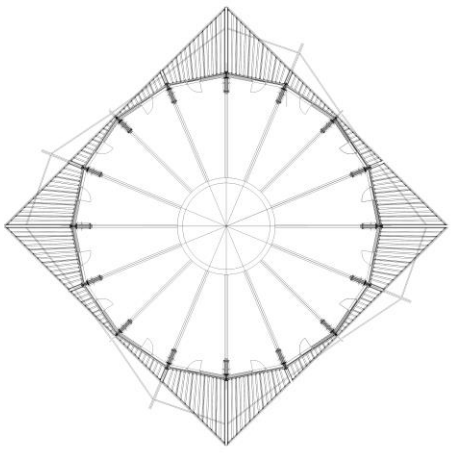


Figure 18. A Place To – Façade / Balcony © A Place To

Figure 19. A Place To – Façade / Balcony installation © HSHansen / A Place To

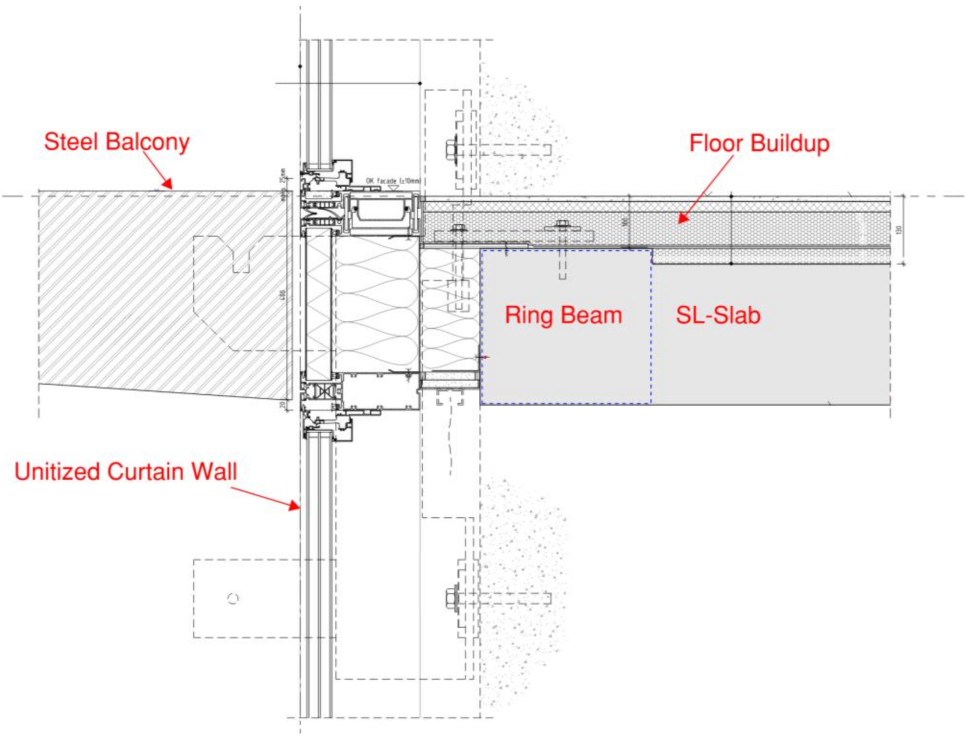


Figure 20. A Place To – Façade / Balcony connection © BIG

The future of prefabrication.

In addition, interiors such as kitchens and bed nieces are partially prefabricated and in the future the use of lightweight build up floors will eliminate the needs for floor recess allowing the use of pods in which kitchen and toilets will be integrated in the design.

As a thumb rule, high-rise buildings are more expensive than low-rise to construct and unusual shapes only add to the construction cost as opposed to more regular buildings – working against the business case. By applying highly industrialized construction methods it is in fact possible to create tall affordable and sustainable housing projects. The main explanation is high repetition factors meaning repeating the same work processes over and over whereof a great deal of work is carried out in an indoor environment in factories with quality control and limited delay due to bad weather. The benefit with construction time is evident because with prefabrication it is possible to fabricate multiple components at the same time i.e. floors and double high columns are produced while or even in advance of the foundation works being done. This would be impossible for conventional construction methods as each work activity is dependent on another. On the other hand, it would not make sense to prefabricate heavy and rigid core wall systems when sophisticated "vertical factories" like jumpform systems are more feasible. Labor forces on site are reduced significantly when compared to conventional construction methods which increase safety measures. The superstructure, that is the concrete works, workforce at A Place To was 12 labors per tower with a floor to floor cycle of 4-5 days – working hours in Denmark is 37 hours per week. For example, in the Middle East some countries encourage the use of prefabrication because it counts positively in the green building score systems as it is seen as being good for the environment and the society. The success for projects involving large amounts of prefabrication is lead time, coordination, consensus, allowing time for planning through the whole supply chain of stakeholders is the key, every single detail must be pre-planned a process where BIM technology has shown to be of great use. The future for high-rise buildings may perhaps be hybrids meaning combining the best from prefabrication and conventional construction and explore the synergies, combining the best from the two worlds.

Figure 21. A Place To – Construction © A Place To / Abeo / PERI

Figure 22. A Place To – Construction © A Place To / Abeo

Figure 23. A Place To – Construction © A Place To