The Twist: innovative architectural and structural integrated high rise building design

Citation for published version (APA):

Document status and date:
Published: 01/01/2017

Document Version:
Accepted manuscript including changes made at the peer-review stage

Please check the document version of this publication:
• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
• You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:
www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:
openaccess@tue.nl
providing details and we will investigate your claim.

Download date: 20. Sep. 2020
The Twist
Innovative Architectural and Structural Integrated High Rise Building Design

Abstract— When city’s become more dense, the need for high rise buildings increases. However, implementation of high rise buildings in a crowded city is difficult on street level. Common high rise designs have a discrete transition between public and private area, subsequently losing interaction with the city. In this research a new high rise building concept has been developed. An integrated design approach combining architectural and structural solutions has been used. The final design consists of three slender buildings with public space between them combined through a diagrid structure. This diagrid structure ensures the lateral stiffness of the buildings. This innovative high rise building concept is a new possibility to implement high rise in a city that combines all important design criteria.

Keywords-component; high rise building; innovative design concept; architecture; structural design; diagrid; integrated design

I. HIGH RISE BUILDING DESIGN CHALLENGES

In the design of high rise buildings there are two important aspects, which need careful consideration from the start of the design process. The first aspect is building access and vertical transport. With increasing heights the capacity of the vertical transport for occupants and users needs careful consideration and planning. The amount of lifts and their systems need sufficient capacity for high numbers of people in rush hours and should keep waiting times as low as possible. However, at the same time the amount of space involved in this efficient vertical transport needs to be minimised in order to achieve a sufficiently high net floor area ratio.[1] An equally important aspect of vertical transport are the alternative escape and safety routes in case of an emergency, whenever evacuation is needed.[2]

The other important design consideration is the design for lateral stability of the structure of the building. Obviously structural safety for all vertical and horizontal loads in high rise buildings is an important design consideration. Especially the buildings sway systems, the structures that provide the lateral stiffness, become increasingly important with increasing building height. As shown in literature, the horizontal deflections due to high wind loads increase to the power of four with an increasing building height when the stiffness of the building remains constant.[3] Moreover, the risk that wind induced vibrations are perceived as significant hindrance for its occupants is an increasing concern while building in height. Therefore, the horizontal stiffness of the building is one of the most important structural challenges in high rise building design. This high stiffness is especially important at lower parts of the building and less in the higher part. This concept of design is used in the Eiffel tower and the Burj Khalifa. In literature many different types of sway structures have been described in relation to their most common applications with their building heights.[3] Shear walls and stiff building cores have the advantage that they can be integrated with lift shafts. Rigid frames have the advantage of providing an open structure that has no obstruction for the free use of floor space. However, with increasing height these systems provide insufficient lateral stiffness. Above 60m it becomes necessary to activate structures with an increased...
leverage arm, more towards the perimeter of the building.[4] So-called tube or bundled tube structures can provide this increased stiffness. Another efficient method for activating the outer columns, whenever the structure is subject to bending due to horizontal wind loading, is by introducing so-called outrigger structures.[5] Moreover, the use of mega-braced frames at the perimeter of the building are also a possibility to increase the lateral stiffness.[3] Another efficient method to activate the outer parameter of the building, and thus providing lateral stiffness, is a diagrid system. In this system diagonal crossing structural elements provide an outer grid. These can not only provide lateral stiffness, but also carry the vertical loads. Thus, there is no need for vertical columns. The Russian engineer Shukov [6] was probably the first to use this kind of engineering, which is based on engineering very slender high structures incorporating this system. Using straight elements under an angle he created many hyperboloid structures. Until this day his Moscow Radio tower is an example of such a structure. This concept is used in the design of the twist, see figure 1.

A. Initial design requirements

Obviously integrated high rise design solutions with high structural lateral stiffness and efficient vertical lift transport solutions are not the goal. These are means to design good functional solutions for high rise buildings. Combining flexible and free use of (preferably) open floor space, multiple functions and sufficient daylight access are requirements for a design with higher architectural quality.

The main starting points for the new high rise design at Eindhoven University of Technology (TU/e) started with the following requirements:

- Open unobstructed flexible floor space to create multifunctional buildings
- Possibility to combine multiple floors into office units
- Efficient high quality building structure with high stiffness of the lateral sway system
- Reduce material usage in the structure of the design
- Sufficient space/free positioning for efficient access lift systems
- Multiple safe escape routes
- Abundant daylight access to all work and living areas
- Good surrounding views
- High quality and striking architectural appearance
- Sustainable service solutions
- Smooth integration in multiple urban situations

II. ARCHITECTURAL AND URBAN CONSIDERATIONS

Currently, we are able to build more and higher buildings than before [7]. This challenge of height results in not only new technical problems, but it also changes the urban fabric of a city and the mindset of the people who use these buildings. The functionalism designers in the architecture were the first who experimented with high rise.[8] These designers were idealistic. The aim of their designs was to create an environment that results in a better society. They believed that a better society is a more social one, since the modern mind should be a social spirit.[9] In their opinion high rise and especially mechanized mass produced high rise is excellent for this purpose. Rietveld mentioned during an interview,[10] that especially the monography of the identical buildings will create beauty high rise also gave the possibility to create high density and enough open space in a city to ensure that all the inhabitants could have the joy of an outdoor space. Just as Le Corbusier already mentioned: “A normal man can have a palace in a park, provided that he is willing to share it with other people.” [8]

However, most inhabitants of these high density buildings do not react as anticipated by the experts.[11] Instead of becoming more social, people become less friendly and social if they live together with many others.[8] This is the reason why Catharina Bauer thinks that high rise is unsuitable for social housing.[8] This is not the only reason why people dislike this way of housing. The identical buildings that are a result of the mechanized mass production have led to streets with a lack of identity and anonymous streets make anonymous people [12].

Willem van Teijen brings new insights in the world of high rise[13] He explains that if you use high rise as a landmark, instead of creating a higher density, the high rise buildings become more special just as the location where the building is located. Hereby the living space of the inhabitants is not a living machine anymore, as Le Corbusier called it, but it becomes a home, connected with the sun, inhabitants and landscape.[14] People like the feeling of being special and want to live here. Creating high rise as a landmark gives it a higher standing and gives the inhabitants of this vertical city a higher status, with views (see and be seen) and sunlight than any other building could offer.

From a distance the standing of a high rise building is immediately clear, since those buildings create the skyline of a city and thereby will be seen by everybody. Closer to the building it is more challenging to create and transfer these feelings of status to persons whom are passing by. With regard to this fact the implementation of a high rise building in an urban fabric is very difficult. Alongside of this focus, the lateral stability is a decisive factor when designing a high rise structure. Due to the amount of structural elements common high rise designs often fail to create public space at ground level. The plinth of the building is the main link between the high rise building and the urban fabric, hereby the transition from public to private space is very important.[7] Most designers consider this transition. Without public space on the ground level of the building it is hard to achieve this interwoven public to private transition. This is the main reason why many high rise buildings can become “big blocks” in the urban fabric, being perceived with hardly any interaction with its surroundings.
III. DESIGN SOLUTION

One Solution to create public space at ground level is to design multiple buildings with a small ground surface, which results in space between the buildings, see fig. 2. The space between the buildings improves the quality of the buildings. There are two factors increasing the positive experience of the users of the buildings. The floors in a slender building have more windows and therefore every storey receives more daylight. Besides this effect, the users of the building can experience a 360 degrees view of the surroundings creating “pent-house” qualities on every floor. The level of perceived quality of a building is of great importance when designing a high rise structure, since people will prefer a building with high statue appearance over an ordinary building. Therefore vacancy will be lower. The fact that the buildings are slender gives the possibility for column free open floor spaces, which is positive for a developer since the building can house multiple functions.

The lateral stability of the core is large due to the big coherence of the structure. The diagrid creates triangles, which have a high stiffness. Subsequently, this big coherence of the structure has a positive effect on the response of the structure. When failure of one or more members occur, due to for example a local impact or fire, the core structure assures a secondary load path and therefore ensures safe evacuation of the buildings.

The vertical transport of the three different buildings is designed using multiple elevator systems combined in one location. In common high rise designs the amount of floor space needed for vertical transport grows to relative high levels when buildings get taller and the area of the floorplans get smaller. By integrating the access of the three buildings a more effective use of elevator capacity is achieved. Alternative fire escape routes are designed in the three buildings. Besides the escape stairs in the three buildings the fact that the buildings are connected at different levels ensures a safe escape for all users.

A. Structural models

During the design of the structure of the Twist, static calculations have been executed using Scia Engineer. Three models have been constructed increasing in complexity. Commonly simplified hand-calculations are used to verify the results of a model, because of the 3D complexity simplified hand-calculations quickly became rather time consuming. Therefore, in the initial design stage a simplified model has been created, as shown in Figure 4. This model, which excludes the buildings, consists of 16 vertical members and 5 horizontal rings representing the stiffness of the 80 inclined columns and 26 horizontal rings presented in the final design.
In this model only vertical loads of the buildings have been applied, located on three of the vertical members of the core. Using this model a first estimation of the final dimensions and behavior of the structure could be predicted. Subsequently, a more complex model, (Figure 5), has been created to simulate the behavior of the core diagrid, also for loads originating from buildings outside of the core. The core in this model consists of 30 inclined columns and 9 horizontal rings, again representing the stiffness of the final model. Figure 6 shows the final model that has been created as the actual representation of the design. This model shows that the structures of both the core and the buildings are diagrids. The final model has been used to optimize the structure of the core and the buildings. One of the results that has been compared between the models is the largest normal force in the bottom of the core. The resulting forces that have been found are 9000 kN in the first model, 9400 kN in the second model and 10300 kN in the third model. The increase in force is caused by added self weight in the models.

B. Force distribution

Due to the shape that is created out of different diagrids a specific load distribution will occur in the structure. First the load distribution in the core will be explained and afterwards the load distribution in the structure of the buildings.

The rings in the core are a vital part of the total structure and have a big influence on the coherence and subsequently the stiffness of the structure. To make this possible the in plain stiffness of the rings needs to be sufficiently high. Therefor the rings are designed as horizontal trusses where the bottom and top cords two rings with different radii. These trusses have been used as construction for the walkways in between the buildings.

Due to the inclination of the buildings, see figure 1, the gravitational loads in the buildings results in a torsional force in the core structure. The steel columns of the core structure have been positioned in two directions, the same direction as the building’s inclinations and the opposite direction. Subsequently the columns in the direction opposite of the inclination of the buildings endure a much larger normal force than the columns in the same direction as the inclination of the buildings. This difference in normal force becomes smaller over the height. When the columns in the two different directions have the same cross sections the difference in normal force results in different strains. Subsequently askew triangles occur in the structure which results in a large rotation of the core at the top. The columns in the core have been designed with different cross sections to reduce this effect, see figure 7. Where the columns with the higher normal force have been designed with a larger cross sectional area. For esthetic reasons the outer diameter of the two columns in the different is the same and the thickness of the wall is varied.

The large coherence of the diagrid structures in the buildings causes loads to be distributed over all vertical members of the diagrid. The diagrid structures of the buildings fits the structure of the core in a way that all nodes at the boundary between buildings and core are coincident. There is a significant difference in stiffness between the core and buildings. This causes most loads from the buildings to be transferred to the core. At the bottom of the buildings more force is directly distributed to the supports. This causes higher normal forces in the vertical members at the bottom of the buildings.

When designing a diagrid structure, like the core and the buildings in this design, normal forces, over bending and shear forces, are the decisive factor in the columns. Due to the fact that most members are relatively long (14.2m), buckling of the members becomes the governing failure mechanism for the design the cross sectional properties of the members. Circular columns have been used, because of three main reasons:

- Circular sections have the same stiffness in every direction.
- Connection details are simplified since all columns connect under different angles. Where cross sections with other shapes would have to be twisted upwards along their axis
- Architectural considerations make circular columns the most suitable.

C. Optimization

The optimization of the structure is done by changing the section properties of the members, using the structural model from SCIA Engineer shown in figure 6, to reduce the total weight of steel in the structure, see table 1. When designing the structure of a high rise building the maximum deflection in a preliminary design stage is set to a maximum of approximately h/900, in this case 200mm. This deflection is relatively small, but in a later design stage the foundation will have a big impact on the displacements at the top. This horizontal deflection at the top is caused by the vertical loads due to self weight, the vertical variable loads and the horizontal wind loads.

![Figure 7. Deflection of vertical members in the diagrid](image-url)
The final design as shown in Figure 8 has been elaborated into detail for a building height of 180 m. In the final design of the structure columns with five different cross sections have been used.

In the core HFCHS 611x40 and HFCHS 611x16 have been used. The thinnest cross section is used as vertical member in the top 7 layers of the core and in the other layers the as vertical members with the same inclination direction as the buildings. The thick cross section is used for the rings and for the vertical members with the opposite inclination direction as the buildings in the bottom 18 layers.

In the buildings HFCHS 4064x40, HFCHS 4064x30 and HFCHS 4064x10 have been used. All vertical members in the top 20 layers of the buildings have been designed with a wall thickness of 10mm. The vertical members in the bottom five layers of the structures of the buildings have been designed with a wall thickness of 30mm. The rings in the diagonals of the buildings have the thickest wall thickness of 40mm, emphasizing the rings as a vital part of the structure.

### TABLE I. OPTIMIZATION PROCESS

<table>
<thead>
<tr>
<th>Optimization steps (change in structure)</th>
<th>Total weight steel (reduction compared to initial step %)</th>
<th>Maximal horizontal deflection</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Initial step</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Core</td>
<td>20,421 ton</td>
<td>149.0 mm</td>
</tr>
<tr>
<td>Buildings</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Step 1**
- Core: SD 508x60, OD 508x60
- Buildings: SD 508x30, OD 508x30
- Rings: SD 508x60
- Total: 14,435 ton (29.3%) 131.2 mm

**Step 2**
- Core: SD OD 611x16, OD 611x16
- Buildings: SD OD 607x60, OD 611x40
- Rings: All
- Total: 11,231 ton (45.0%) 157.6 mm

**Step 3**
- Core: SD OD 611x16, OD 611x16
- Buildings: SD OD 611x60, OD 611x40
- Rings: All
- Total: 8,735 ton (56.3%) 191.8 mm

**Step 4**
- Core: SD OD 611x16, OD 611x16
- Buildings: SD OD 611x60, OD 611x40
- Rings: All
- Total: 9,354 ton (54.2%) 186.9 mm

**Step 5**
- Core: SD OD 611x16, OD 611x16
- Buildings: SD OD 611x60, OD 611x40
- Rings: All
- Total: 8,811 ton (56.2%) 207 mm

**D. Final design**

The final design as shown in Figure 8 has been elaborated into detail for a building height of 180 m. In the final design of the structure columns with five different cross sections have been used.

In the core HFCHS 611x40 and HFCHS 611x16 have been used. The thinnest cross section is used as vertical member in the top 7 layers of the core and in the other layers the as vertical members with the same inclination direction as the buildings. The thick cross section is used for the rings and for the vertical members with the opposite inclination direction as the buildings in the bottom 18 layers.

In the buildings HFCHS 4064x40, HFCHS 4064x30 and HFCHS 4064x10 have been used. All vertical members in the top 20 layers of the buildings have been designed with a wall thickness of 10mm. The vertical members in the bottom five layers of the structures of the buildings have been designed with a wall thickness of 30mm. The rings in the diagonals of the buildings have the thickest wall thickness of 40mm, emphasizing the rings as a vital part of the structure.
E. Parametric alternatives

Figure 9 and 10 show that by changing the design parameter, such as height and the inclination of the columns in the diagrid, the building design can change its shape. This change in shape can be seen as using different diameters and different rotations of the top and bottom circle of the core that connect the straight columns, thus twisting them into inclined columns. A large rotation results in a narrow waist in the middle, a small rotation results in a wider waist. Also, a different cut-off point at the top of the building (or a smaller diameter of the top circle) can result in a building that is no longer symmetrical in width around mid-height (same diameter top as bottom), but becomes more wide at the bottom and less wide at the top. The same counts for the three twisted buildings that rotate around the central core structure. By choosing different diameters the size of the floor surface area changes. In this way the design concept can be adapted into different designs with different areas and dimensions depending on the requirements and the program of demands from the developers.

IV. CONCLUSION

Despite the challenging initial design requirements, the design team has succeeded in finding a new integrated architectural and structural high rise building concept. This design handles the entanglement of the various necessities using an integrated design approach. The design concept has been successfully elaborated for a 180 meter high building and proves to be a very stiff, multi-functional and architecturally elegant design.

REFERENCES


Iris van Weersch BSc. is a combined master student Structural Design and Architecture at the University of Eindhoven. She received the bachelor’s degree in September 2014 and will finalize the master in 2017. The final thesis of her combined master is a design of a water purification center. The structure of the roof and facades is solely built up out of a biocomposite. The master project the Twist was a collaboration with another student and is presented at the Dutch Design Week and at the UPPD in Singapore.
Dirk Ploegmakers BsC. is a master student Structural Design at the University of Eindhoven. Received the bachelor’s degree February 2014 and finalizing the master January 2017. The final thesis of the master structural design is a research to develop a design rule for the lateral torsional buckling resistance of a spreader beam using an experiment and FEM. The master project the Twist was a collaboration with another student and is presented at the Dutch Design Week and at the UPPD in Singapore. The reason to become a structural engineer follows from interest in physics in general.

Rijk Blok is a Structural Designer at W5A Structures and an Assistant Professor at Eindhoven, University of Technology, in the chair of Innovative Structural Design. Among his structural designs are the Dutch Pavilion on the Shanghai 2010 World-Expo and more recently the structural design for the Dutch BiesBosch Museum in the Netherlands (2016). Also in 2016 he was the project leader of the Light-house research project on a fully Bio-based pedestrian bridge. This bridge has been realized in October 2016 of last year.