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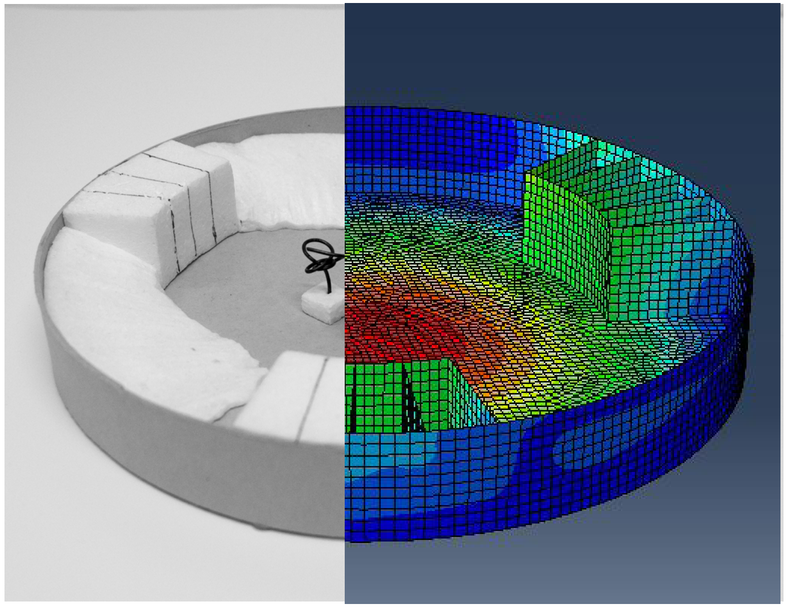

Development of innovative housing in floating structures

An interdisciplinary study between applied mechanics and architecture.

Master's thesis in Applied mechanics

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Cover:
A physical model merged with
the result from a FE analysis.

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PRELIMINARIES

I would like to give a special thanks to my supervisors Mats Ander and Mørten Lund for their continuous support and their engagement throughout the whole project.

“Whenever there is a revolution, or fast change, in architecture professional barriers break down as specialists exchange roles. Architects become sculputres, engineers become designers... If professionals do not give up their job descriptions, their trade union, there is no avant-garde, no breaking of barriers, no radical creativity.”

Charles Jencks [23]

ABSTRACT

In 1950 30 percent of the worlds total population lived in cities. Today that number has increased to almost 50 percent and UN predicts that it will continue to increase to 70 percent in the next 35 years. Finding accommodation in the cities is hence a problem and as the cities gets more densely populated it will obviously become an even bigger problem. Due to historical reasons most of the cities around the world are located close to the ocean or other waters. The rising sea level, due to climate change, is therefore a big threat. When 10 percent of the worlds population lives within 20 kilometers from the coastline and below a levitation of 10 meters a small rise of the sea level would be enough to cause devastating tragedies. Up to 1 billion people are foreseen to be forced to emigrate by the year 2050 due to the rising sea level. If the unused space along most coastlines is used for floating architecture that would help to resolve some of the problems with overpopulated cities and a rising sea level.

The project description was developed together with the supervisors with the desire of strengthening the collaboration between different departments and divisions at Chalmers. The master's thesis is therefore an interdisciplinary project between applied mechanics and architecture. And the purpose of the project is to develop and analyze innovative housing in floating structures.

Four initial rough conceptual ideas of floating dwellings are refined in an iterative process. Changes in the design, physical modeling and simple structural analyses are performed side by side in order to make sure that the concepts evolves in the right direction. The concepts are evaluated two times during the project where two concepts are disregarded during the first evaluation and the final concept is decided during the second evaluation.

The final concept is a new and an innovative way of living on water. A cylindrical structure is lower down into the water creating a dry and safe area on the inside. The structure accommodates 12 studio apartments that are placed in three sections along the inner curve, each 25 square meters. The apartments do not only challenge the way of living by the fact that they are placed in water but also by their dimensions and space. However, the relatively small apartments are expanded via the shared courtyard, in the middle of the structure, which strives to act as the living room with social activities and encounters.

Keywords: Iterative process, conceptual ideas, structural analyses, finite element analysis, applied mechanics, floating architecture, interdisciplinary

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1. CONTEXT AND CONCEPT

The building is placed in the lake Mjörn close to the outskirts of Alingsås. The lake covers an area of approximately 55 square km and the average depth is 15.7 m with a maximum of 48 m. However, the water level can deviate with up to 2 m due to the poor regulation of the lake.

Even though the lake is located in the outskirts of the city the connection between the inhabitants in the city and the lake has always been strong. The area provides a rich wildlife, recreational areas and a variety of activities.

A natural direction for expansion of the city center would be towards Mjörn, both because of the above mentioned connection but also because it is closer to Gothenburg which is favorable for commuters. ”Stadsskogen” (En: The City Forest) is an example of a newly built neighborhood in Alingsås located close to Mjörn. When the project is done there will be 1000 new houses in total and it is expected that more than 3000 people will live there. The neighborhood will also provide schools, jobs, shops, etc., which of course will contribute to making the lake become an even bigger part of the city.

As far as transportation goes there are today only small roads leading to the area. However, due to the urbanization of the area there are plans on building a new train station which will increase the mobility significantly.

The building will thus be located with proximity to nature but at the same time as a part of the city with good connections to the local transportation system.

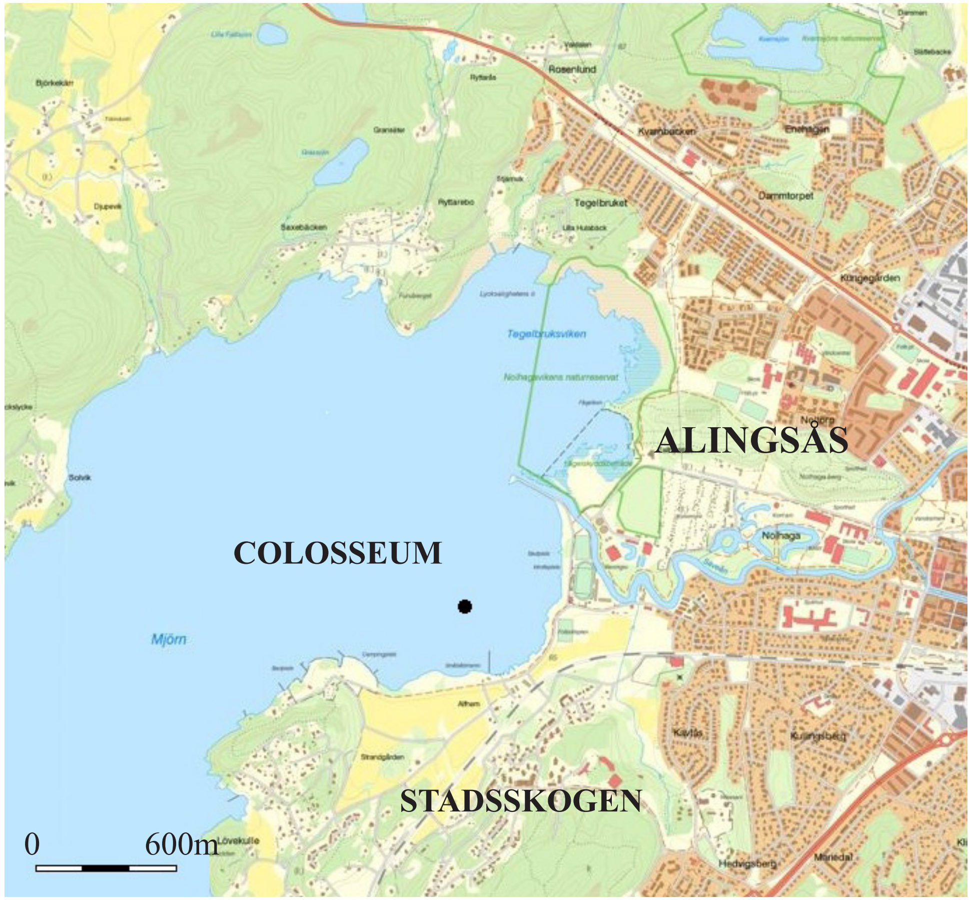

Figure 1: The final concept, Colosseum, in its context.

Colosseum, a conceptual idea of a floating structure providing a stable and secure way of living on water, both structurally and architecturally.

Colosseum represents a new and innovative way of living on water in a secluded and private neighborhood. A cylindrical structure is lower down into the water creating a dry area inside the ring. The structure accommodates 12 studio apartments dicided into three sections along the inner curve, each 25 square meters big. The apartments are laid out on two floors where the main floor is dedicated for social gatherings and dining area while the second floor is a private retreat with room for both a place to sleep and to hangout and relax.

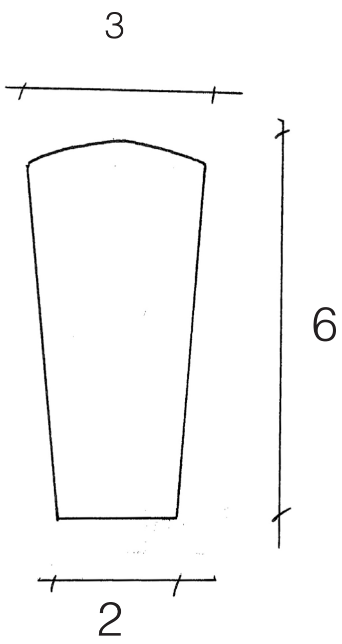

Figure 2.1: View from above.

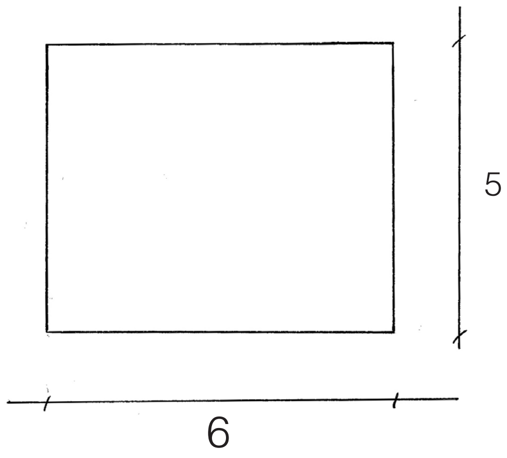

Figure 2.2: View from the side.

Figure 2: Outer dimensions of the apartments.

Figure 3: Physical model of the apartment

The building itself provides a secure and private way of living with a neighborhood feeling. Both thanks to the obvious reason that the structure is placed in a lake but also thanks to the geometry of the structure. The outer ring acts as a back that is turned to the outside which allows the inhabitants to decide when to include the outside or not. Thanks to the dimensions and shape of the apartment, it provides privacy not only from the outside community but also from the inhabitants in the building, despite the big window exposed to the courtyard. The narrow and deep structure and the fact that the width increases further into the apartment reduces the transparency of the apartment. Moreover, they are divided into an odd number of sections to assure that no apartments face each other directly across the courtyard.

Even though the plot of the apartments is small, with challenging dimensions, the occupier will most likely experience the apartment open and peaceful, thanks to the generous head room and natural lighting. The main areas in the apartment are easily lit up by the two windows and fact that no section is facing north allows the sun to reach each apartment at some point during the day. The composition of the apartment with an open plan and no inner walls allows one to experience the whole room no matter where you are which will give a sense of openness.

The fundamental element of the concept is the shared courtyard. The courtyard expands the otherwise small apartments and strives to act as the living room with social activities and encounters. The only way of entering the courtyard is through the apartments, which makes it secluded and private. The courtyard is a big and open area with places to hang out and relax. However, some space is left for the inhabitants to personalize as they like which will generate a deeper relation between the inhabitants and the courtyard. This will most likely make the inhabitants feel included in the shared space and also make them familiar with one another.

The structural elements are made out of reinforced concrete, not only due to its structural advantages but also because the exposed concrete gives a character to the apartments. The concrete gives a rustic atmosphere and highlights the warmer materials and the nature on the outside. Some elements are made out of steel in order to create a balance in the dynamic flow of the materials.

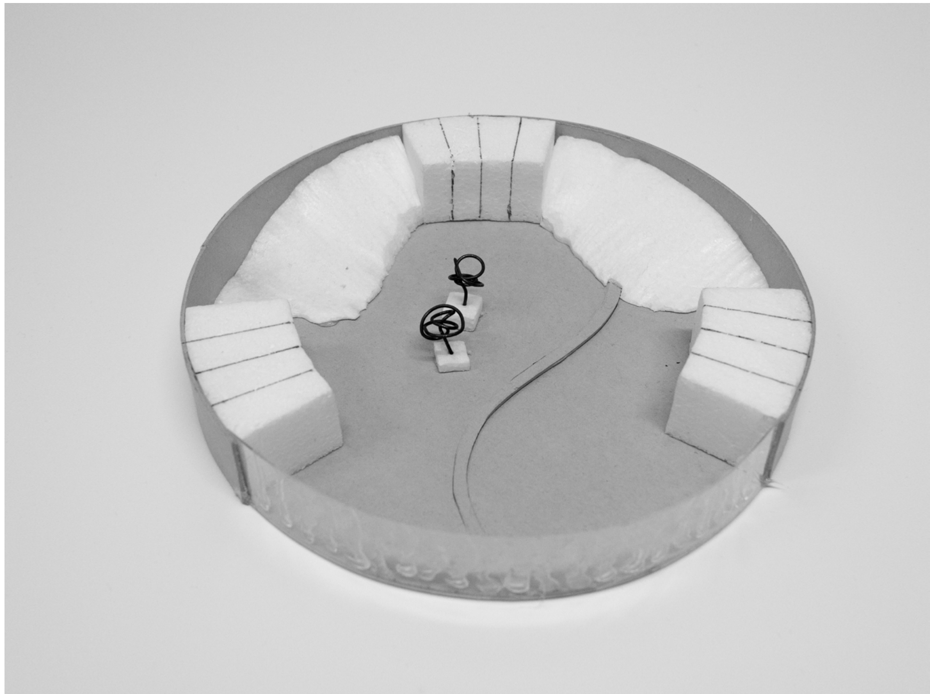

Figure 4: Physical model of the structure showing the courtyard and arrangement of the apartments.

The presence of water is left out in the apartment but one is reminded through the steep entrance. The contrast that occurs when one walks along the sea level, enters the apartment and climbs directly three meters down makes one aware of that the apartment is mainly beneath sea level.

The shape of the structure is efficient, both from an architectural point of view and also from an engineering point of view. The living space is integrated in the floating fundament, meaning that no extra lifting caisson is needed. Also the structure is axisymmetric, which is the best way of handling forces in a relatively symmetric flow and it minimizes stress concentrations. However, if one would identify the weakest spot or the most plausible failure scenario it would be failure due to bending in the main deck. Although, the relation between the floating level and the dimensions of the structure secures a small bending deflection. The bending that in fact is present will initiate cracks in the concrete. These cracks will however be initiated on the upper side of the deck, meaning that they will not be exposed to water, they can easily be detected by the inhabitants and also easily maintained if that would be needed.

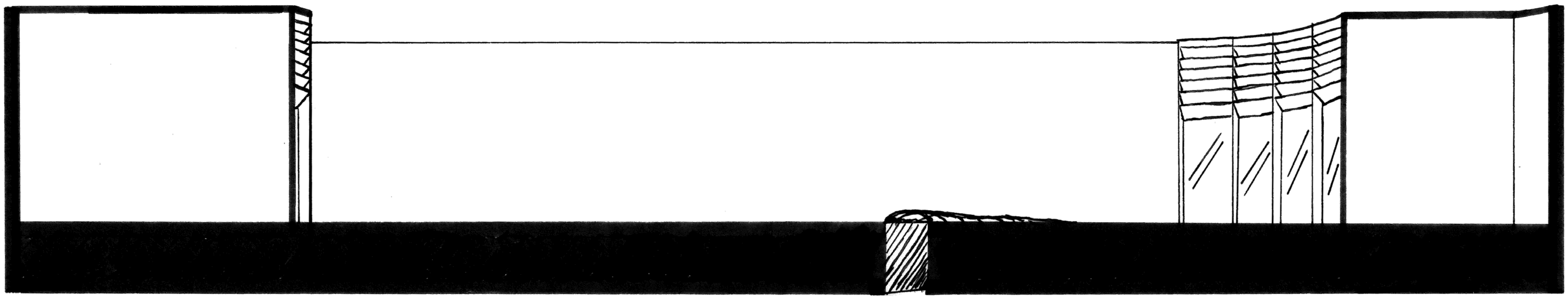

Figure 5: Section drawing 1-1 - Whole structure.

1 [m]

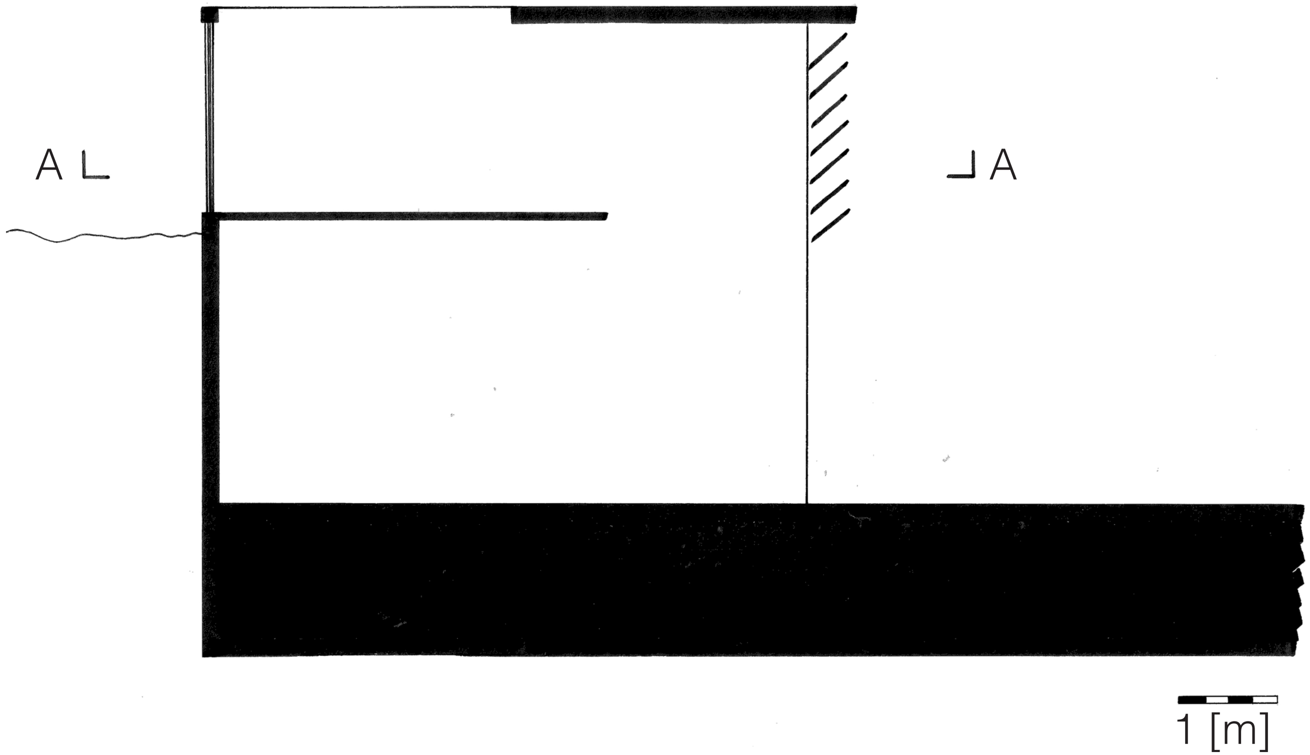

Figure 6: Section drawing 2.1 - Apartment

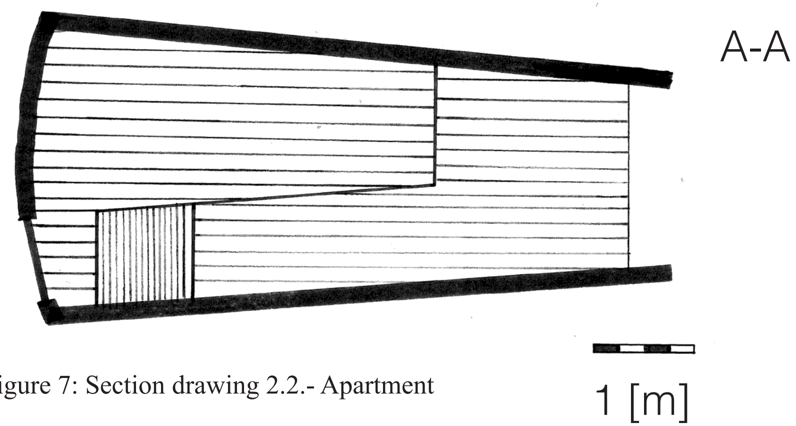

Figure 7: Section drawing 2.2.- Apartment

2. INTRODUCTION

In 1950 30 percent of the worlds total population lived in cities. Today that number has increased to almost 50 percent and UN predicts that it will continue to increase to 70 percent in the next 35 years [1]. Sweden is off course a small country in the context but the same tendencies are observed here. In 50 years (1960-2010) the inhabitants in the cities increased with approximately 17 percent and it is predicted that it will increase another 20 percent in the coming 20 to 30 years [2,3]. Finding accommodation in the cities is already a problem and as the cities gets more and more overpopulated this will obviously become an even bigger problem.

People have always chosen to live along coastlines or close to water because of its rich ecosystems and the livelihood it provides [26]. Most of the megacities around the world are therefore located close to the ocean or other waters [26, 32]. This fact both provides opportunities for innovative floating architecture but is also a threat considering the rising sea level, due to climate change. The rising sea level is mainly caused by melting of glaciers on land, e.g Greenland and Antarctica on their own consists of enough ice to increase the sea level approximately 120 meters [26]. This melting process would off course happen during hundreds of years but when 10 percent of the worlds population lives within 20 kilometers from the coastline and below a levitation of 10 meters [26] only a small sea level rise would be devastating. Sea level rise would e.g. cause inundation, saltwater intrusion, wetland loss, etc., which will make the land unusable [27]. The hundreds of millions of people populating the coastlines would then be forced to emigrate and cities further inland would have an even bigger problem with overpopulation. Forecasts of how many people that will be forced to emigrate by 2050 due to sea level rise vary from 25 million up to 1 billion [27].

A reduction of climate change and emission of greenhouse gases would obviously be the best solution to prevent a rising sea level, however that would most likely not solve the problem with overpopulated cities. If the benefits of unused space along most coastlines is instead used for floating architecture that would help to resolve the problem partly.

3. PROJECT BACKGROUND

The master's thesis is performed at the department of Applied mechanics. However, the project itself is an interdisciplinary project between applied mechanics and architecture.

The project description was developed together with the supervisors as a request from the student since he wanted to explore the possibilities for cooperation between applied mechanics and architecture.

The goal of the project is to develop floating studio apartments, where each apartment is allowed to be maximum 25 square meters.

The project is performed during an iterative process. Initially, four different rough conceptual ideas are designed. These ideas are refined somewhat before being evaluated in order to narrow the scope and focus the project on two of them. The remaining two conceptual ideas are refined further where changes in the design and simple structural analyses are performed side by side iteratively in order to make sure the concepts evolves in the right direction. Finally one concept of floating architecture is presented in sketches, drawings and physical models.

4. PURPOSE

The purpose of the project is to develop and analyze innovative housing in floating structures.

5. PROGRAM

STRUCTURE AND SAFETY
- The structure should provide studio apartments each maximum 25 square m
- The structure should be stable in water
- The structure should be floating, hence not standing on pillars on the bottom
- The material should be suitable for the situation

USAGE AND COMFORT
- The apartment should be planed in the sense of ”compact living”
- All dimensions in the apartment should fulfill a purpose

EXPERIENCE
- The apartments should be recreational and give a homey feeling
- The apartment should make the inhabitant aware of the presence of water

ATTRACTION AND EVENT
- The structure should be innovative
- The structure should be attractive and interesting.

INHABITANTS
- The inhabitants should be social and nature friendly.

6. GENERAL INTENTION

'Combining engineering knowledge and architectural creativity to design innovative floating structures that provides interesting architectural homes and celebrates the presence of water.'

7. IDEA GENERATION

Two structural ideas where given by the supervisors prior to the idea generation in order to get a starting point. One structure was laying down in the water with the apartments next to each other and the other one was standing up with the apartments on top of each other. Variations and combinations of the two given ideas together with inspiration from researching architecture in general (see Appendix B. Reference work) generated two additional ideas.

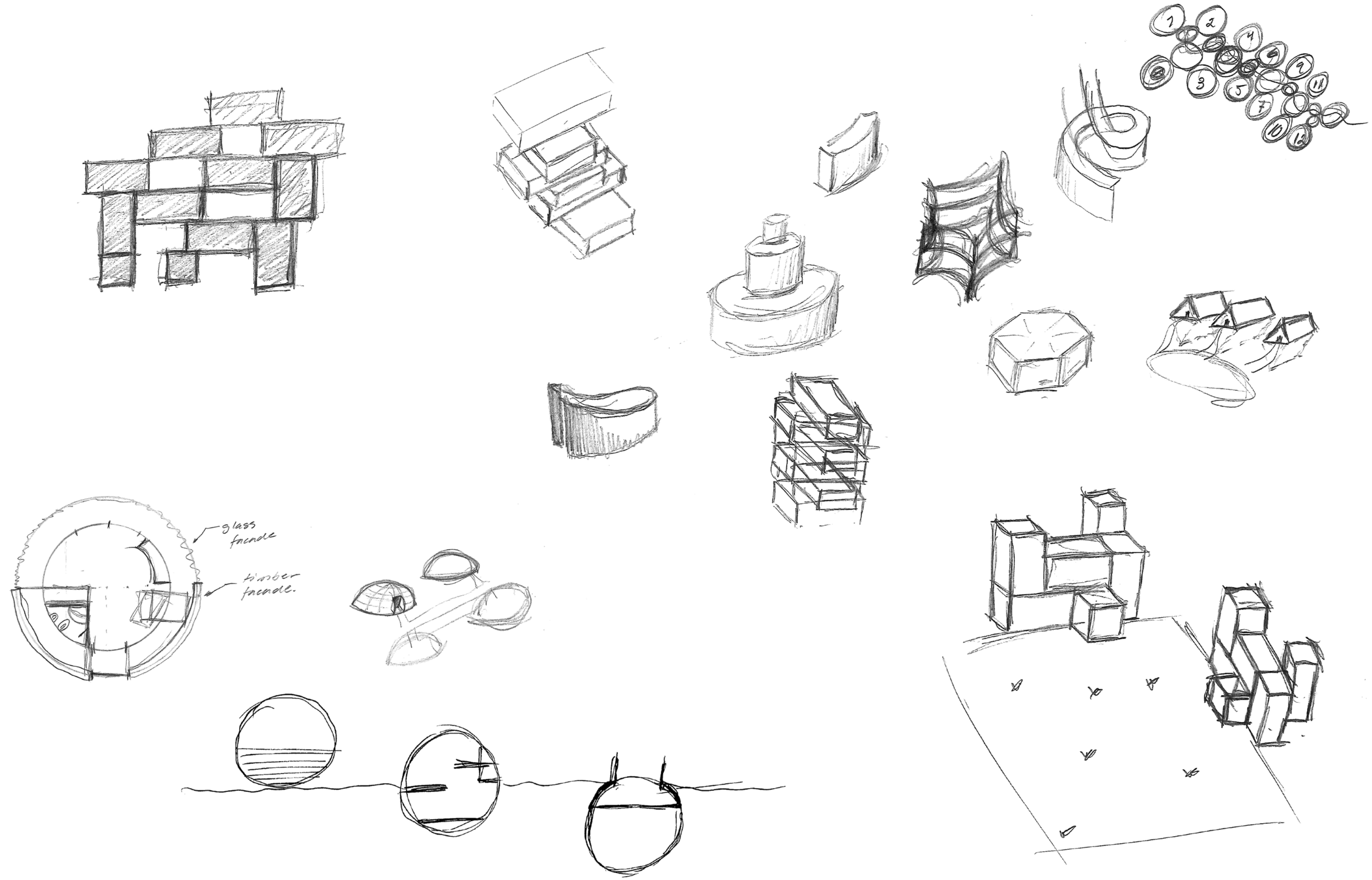

Figure 8: Sketches showing some of the idea generation.

The phrase ”floating structure” directly portrays a ship or boat and it is easy to look for nothing else. The phrase was therefore revised since the ideas started to look more or less the same.

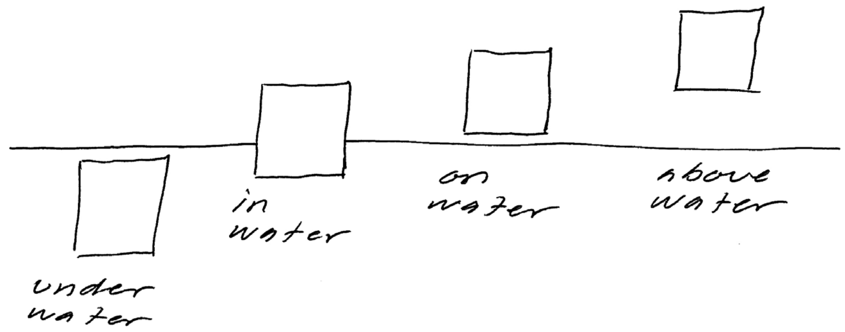

Figure 9: Different positions of a floating structure.

Different positions of a floating structure was identified and this approach gave a boost to the idea generation and new innovative conceptual ideas evolved.

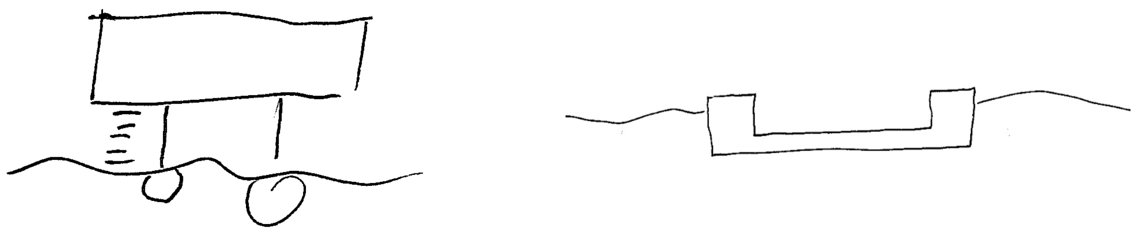
Figure 10: The first sketches of the two additional concepts.

7.1 Initial conceptual ideas

7.1.1. Concept 1

The structural idea of the first concept was predefined by the supervisors. A long and slender structure laying down in the water with the apartments next to each other.

The apartments are constructed as shell structures in a cubic shape. The structure itself acts as lifting volume and the whole space is used for living, the apartment is hence halfway under water. The placement of the apartments gives possibilities to play with the placement of windows in relation to the sea level which in turn will give the room a different impression and feeling.

That the apartments lay next to each other contributes to the feeling of a community and a neighborhood which will generate a calm way of living.

7.1.2. Concept 2

The structural idea of the second concept was also predefined by the supervisors. The initial idea was to place the apartments on top of each other. However, it was rather quickly changed to three towers due to stability problems.

The three towers covers five storages each, one entrance level and four apartments. Each floor is divided with a small gap in the exterior to give the structures a lighter appearance.

The towers was connected in a triangel in order to increse the stability even more.

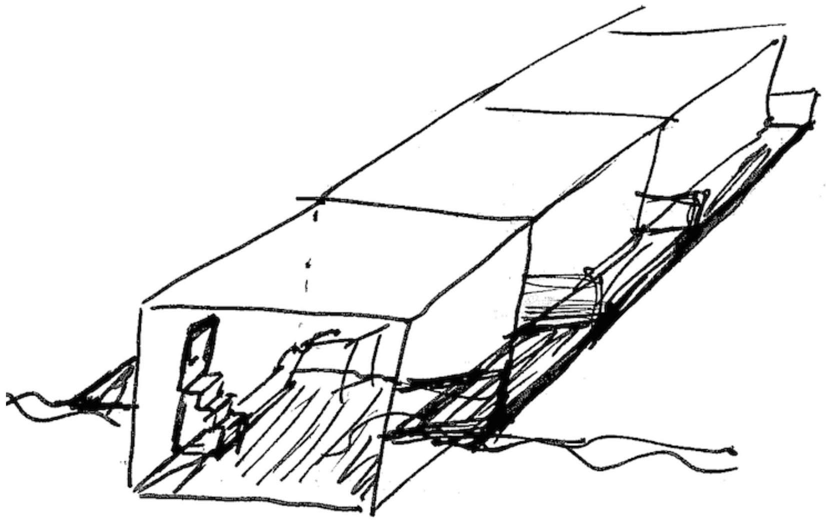

Figure 11: Early sketch of Concept 1.

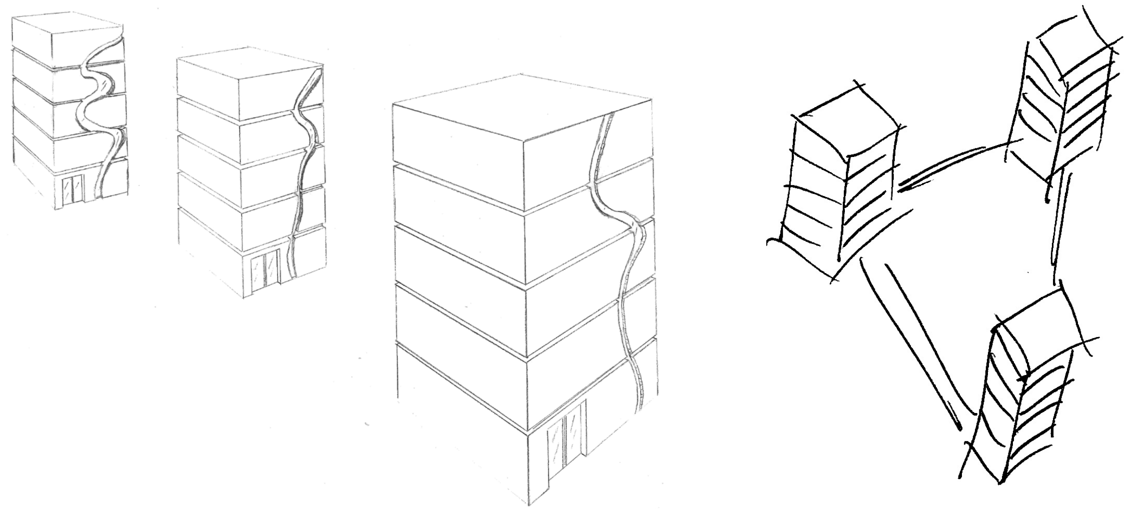

Figure 12: Early sketches of Concept 2.

7.1.3. Concept 3

The third conceptual idea is heavily influenced by Maison Bordeaux by Cecil Balmond (see Appendix B.2 Maison Bordeaux). Rectangular blocks that are standing on floating piles are forming twelve ”levitating” apartments. The structures are placed in a cluster to give a surrealistic and interesting silhouette to the viewer.

The apartments have only one window which is, however, covering a whole wall. The relatively big window allows natural light to come into the apartment and also provides a great view of the surrounding nature. The idea behind the window is to extend the relatively small apartment and to make the outside a part of the room. The headroom is therefore kept to a minimum in order to put the view in focus and not the rest of the room.

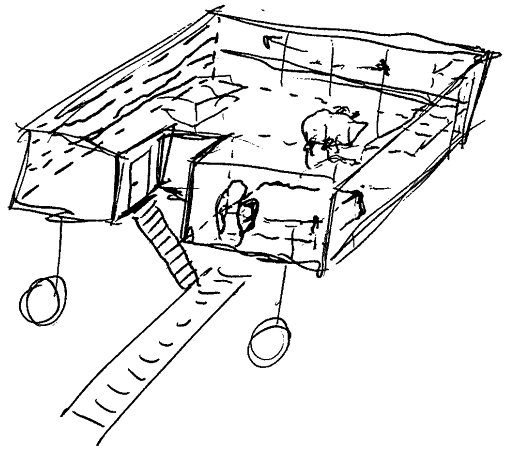

Figure 13: Early sketch of Concept 3.

7.1.4. Concept 4

A big cylindrical structure is lowered down into the water. The apartments are placed in two sections along the inner curve. A huge stair case leading to the courtyard is located in one of the spaces between the apartments and a grass slope is built in the other space to include nature in the otherwise rough area. The slope acts as an area for interaction and recreation.

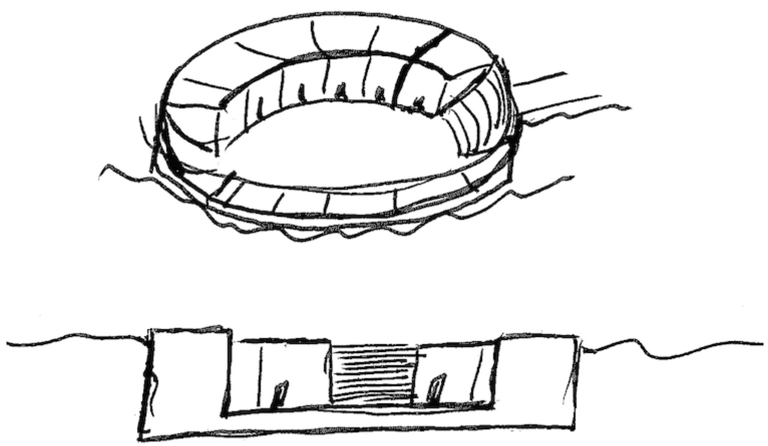

Figure 14: Early sketches of Concept 4.

8. DESIGN PROCESS

When the initial concepts where defined the iterative design process started. However, the initial ideas where first evaluated.

8.1 1st Evaluation

The four initial concepts were evaluated during the fourth week.

In structural terms were the concepts only evaluated in terms of stability since the concepts weren't very developed at the moment. This showed that the second concept stood out with worse stability. Other than that was the other concepts more or less equally stable (see Appendix D. Stability).

At the moment concepts 3 and 4 definitely stood out architectural wise. It is stated in the general intention that the concepts should provide ”interesting architectural homes” and one can argue that the two predefined concepts did not fulfill that criteria.

As a result of the first evaluation concepts 1 and 2 where disregarded and the refinement of the last two concepts went on.

8.2 Refinement phase

8.2.1. Concept 3 - Outside Inside

Silhuette

The dwellings are supposed to be put in a cluster on different heights to both secure the view for the inhabitants but also to create an interesting silhouette.

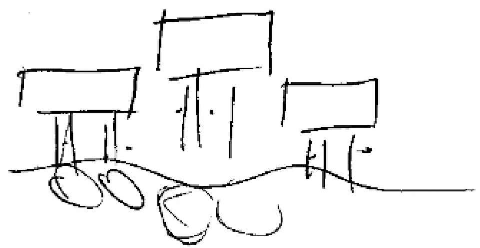

Figure 15: A rough sketch of the silhuette.

Angle of floor, ceiling and walls

In order to put the window in focus even more and to intensify the feeling of the outside becoming a part of the room the ceiling, floor and walls where inclined towards the window.

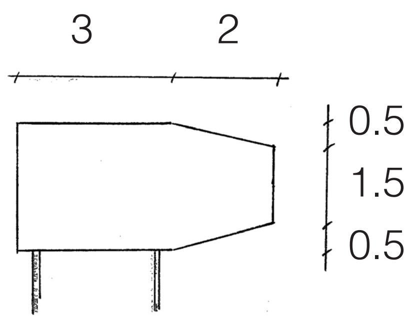

Figure 16.1: The concept seen from the side.

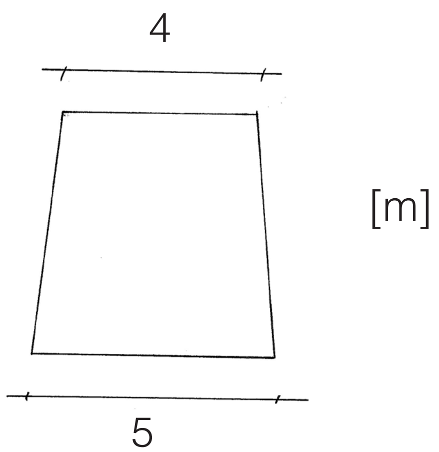

Figure 16.2: The concept seen from above.

Figure 16: Early dimensions of the concept, showing the inclination of the walls, floor and ceiling.

However, after some time it was again changed since the inclinations would most likely make the room even smaller rather than expanding the room through the window. And also because the architect thought the structure looked small and chubby in a bad way.

The walls where instead kept straight and the angle in the ceiling was decreased while the inclined part was lengthened, to create a subconscious focus on the window and view instead of being a distinct part of the room. The angle of the floor however was kept the same since the inclination was integrated as a part of the interior.

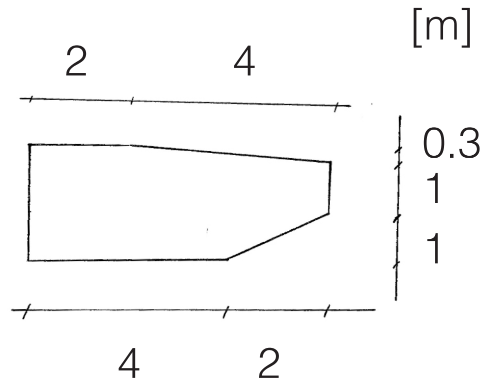

Figure 17: Showing refined dimensions and new shape of the structure.

Entrance and supports

The entrance in the initial concept was a staircase to the side. The staircase was not supposed to work as a structural element to be able to make it as lean as possible. That meant that the structure was supposed to be held up by the legs (cf. figure 18). Buckling of the supports was the most plausible and obvious failure scenario and was therefore investigated further (cf. Appendix C. - Buckling Analysis).

The entrance was rather quickly changed because it occupied too much free space and ruined the levitating feeling. It was instead replaced by a spiral staircase that was integrated in one of the supports.

However, after a while the spiral staircase wasn't considered very innovative and it didn't flow with the feeling of the rest of the room and was therefore refined again. If one instead could enter the apartment facing the window and also closer to the window that would directly put the window in focus and the whole feeling of the room would be introduced. In order to not ruin the levitating feeling the entrance should preferably also look lean and possibly be integrated in the bearing system.

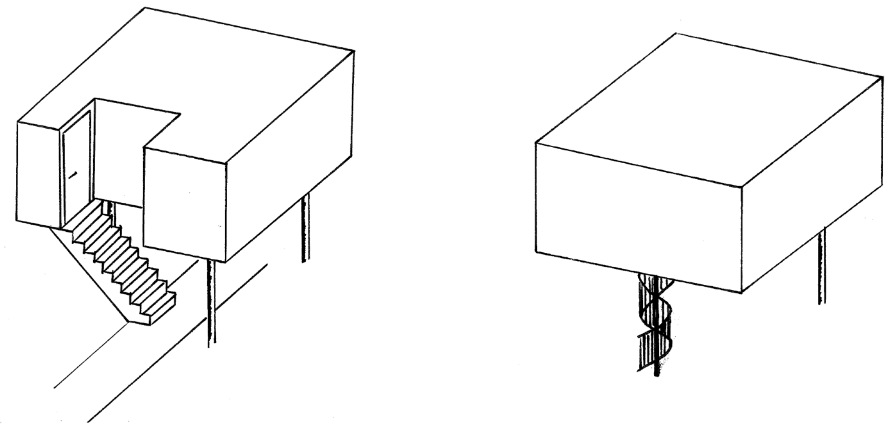

Figure 18: The entrance changed from a staircase to the side to a spiral staircase.

As a result from trying out different kinds of entrances the supports also changed. The new entrance was decided to be hidden in between two waists of a big I-beam carrying the structure and a ”corridor” was cut out of the structure to put the entrance in the middle of the room. The support was placed asymmetric to give the structure a more interesting and dangerous expression.

Thin tension wires was initially placed on the ”short side” of the support to carry the resulting bending moment from the asymmetric placement of the support. However they where removed since they ruined the looks and because the support it self was designed to be able to carry the moment.

When the structure is assumed to be made out of steel the resulting stress in the support ,caused by the bending moment, is approximately 23 [MPa], which is okey compared to the yield stress 500 [MPa] (see Appendix F. Moment in Support).

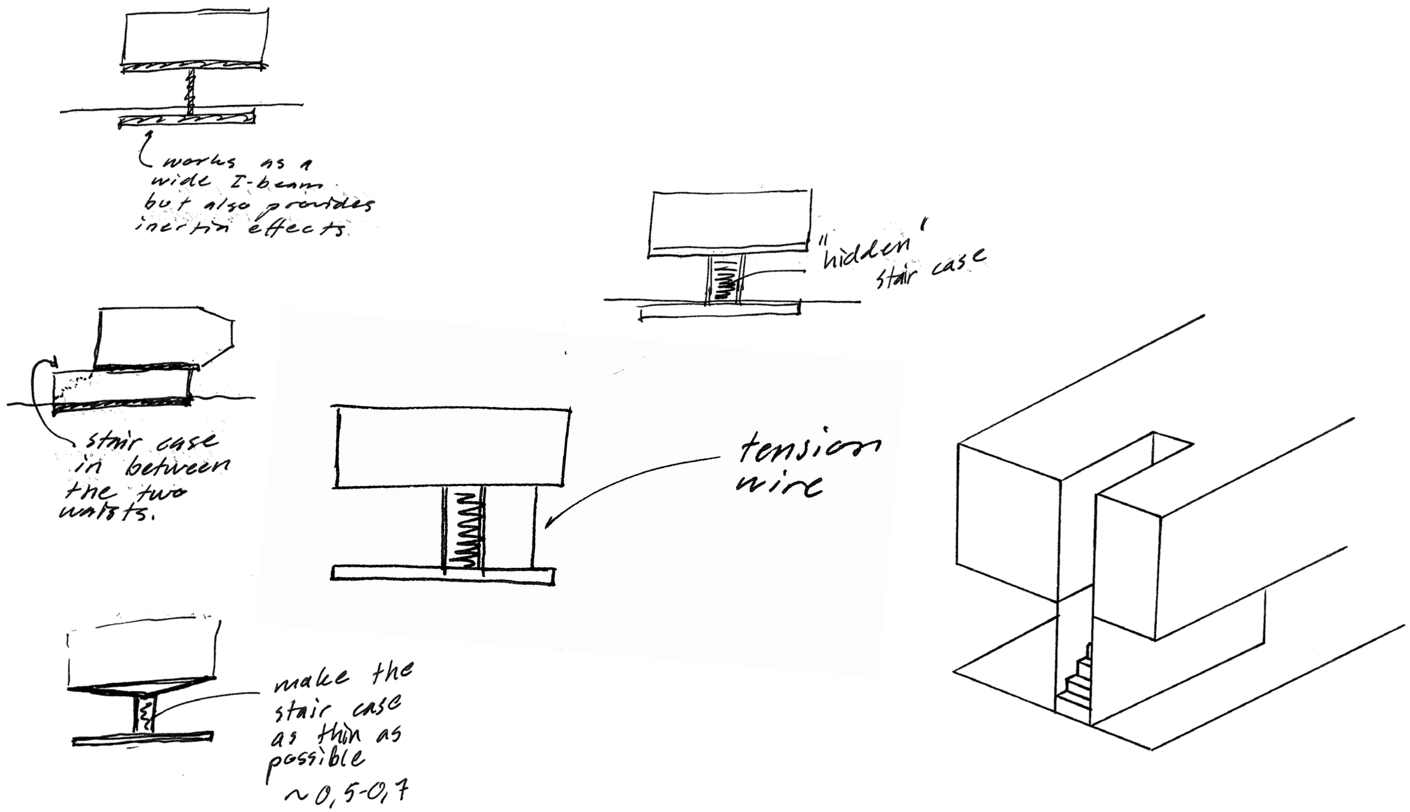

Figure 19: Showing the process of developing the final entrance and supporting element.

8.2.2. Concept 4 - Colosseum

Entrance

In the initial idea, one was supposed to enter the courtyard down a huge stair and from there enter each apartment (cf. figure 14).

The entrance was changed to a steep spiral staircase at the top of the apartment to create a distinct contrast when going directly down three meters from sea level when entering the apartment. And also to make the shared courtyard more private to the inhabitants since one would only be able to access it through the apartments.

Choice of material

The idea behind the choice of material was to create a distinct contrast to flow with the contrast of the entrance. The concrete is left exposed on the walls and ceiling to generate a rough and cold feeling, the main floor and the floor on the loft are made out of warm timber and the stair and railings are made out of steel that would work as a ”bridge” between the materials.

If one would continue out to the courtyard the journey would go from cold concrete to slightly warmer steel to warm timber and finally to the even warmer and lighter courtyard.

The fact that the walls and roof of the apartments are made out of concrete will off course also make them act as structural elements and help prevent bending in the main deck. The apartments have a significant impact on the deflection, decreasing it from *72 [mm]* to *22 [mm]* (see Appendix G. Deck analysis)

Figure 20: Showing the steep spiral staircase from the top of the apartment.

Windows

A window was originally placed in both the wall and ceiling on the loft, in order to let light to come in and also to create a nice view. The part of the window in the wall was allowing people on the outside to look inside more than it was giving a nice view to the person inside and the placement was therefore changed. The window was instead placed completely in the ceiling.

It took some time to figure out how to place the window on the other side of the apartment. At first it was placed beside the door but when the door was moved the window changed to a glass facade with a glass door to the courtyard. Since the window was placed at the very bottom of the apartment it wouldn't allow much light to enter the apartment and was therefore changed again. The glass facade was basically expanded so it instead covered the whole wall.

The wall was later moved half a meter into the room to make the room less exposed to the courtyard. However, the problem with insight still existed. The idea of solving the problem at the moment was to place a sunshade-like net-structure to prevent people to be able to see inside but still letting light pass into the room.

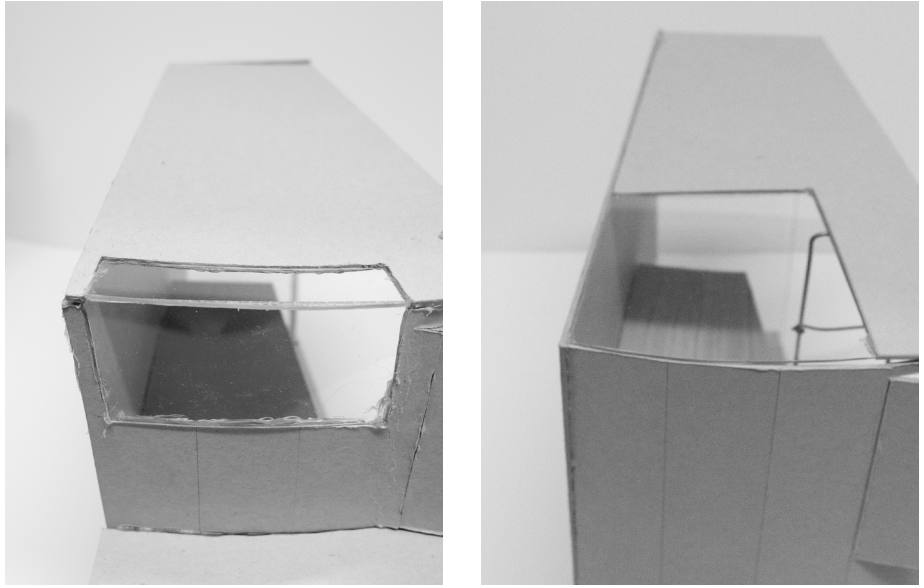

Figure 21: The placement of the back window changed from both the wall and ceiling to only the ceiling.

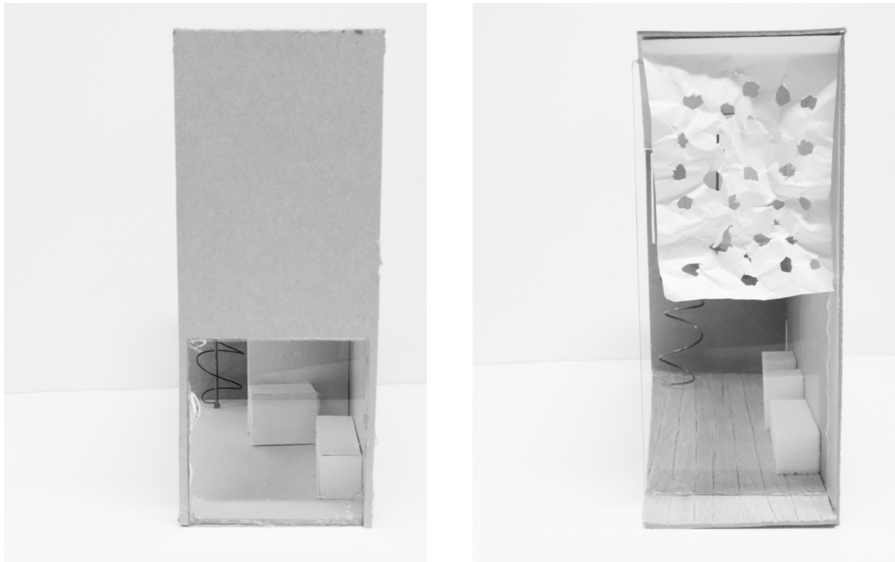

Figure 22: The main window changed from a small facade to a glass wall.

Courtyard

It is possible to forget that the structure is floating in water when one is inside the apartment, since the water isn't much integrated in the design. The idea was instead to integrate the water in the courtyard.

A river-like bench was therefore integrated in the main deck. The bench is ”cut out” directly in the deck (cf. figure 5) which allows water to flow inside the bench and create a lively and dynamic feeling to the space. The bench obviously makes the main deck weaker and more likely to bend, however this was checked in a FE analysis (see Appendix G. Deck analysis and Appendix H. Cracks in deck).

The idea was to continue the experience of rough and cold to soft and warm one has through the apartment out to the courtyard. The courtyard is therefore designed to be a calm and social place. This is accomplished by the choice of materials, curves, geometries and also by social spots. The slopes between the apartments for example has natural and smooth forms, they provide places to relax and hang out in small groups and they give a sense of nature when they are covered in grass.

Ideas about making a small section of the main ring out of glass and integrating a waterfall in the wall has come up. That would remind the occupants of the presence of water and it would definitely contribute to the calm and relaxing atmosphere.

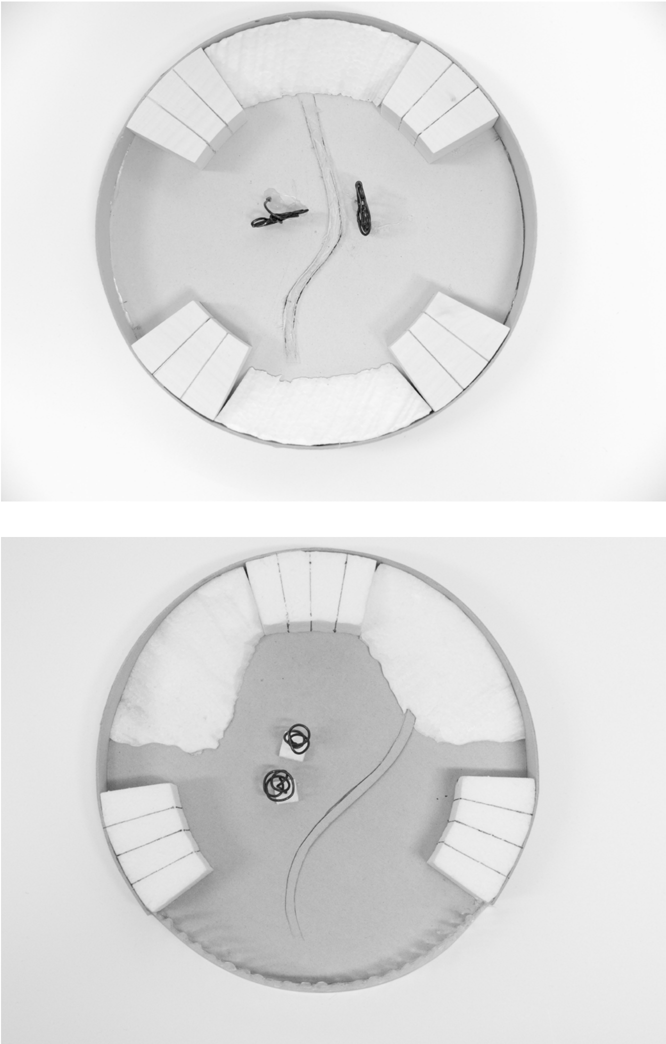

Figure 23: Showing the placement of the sections at different stages in the design proess.

Placement of apartments

The apartments where originally placed six and six along the inner ring. However this made the whole structure very small, since the dimensions of each apartment was more or less decided. The size of the structure was therefore revised in order to make the apartments more separated and the apartments was instead placed in four sections three apartments each.

When starting to work on the lighting and insight into the apartments the placement was revised again. The apartments where first of all divided into an odd number of sections in order to prevent from placing two or more apartments directly facing each other across the courtyard. The sections where then moved to one side of the structure as much as possible, to prevent apartments facing north. After some thought and experimentation the apartments where divided into three sections and placed on two-thirds of the structure.

8.3 2nd Evaluation

The second evaluation was performed three quarters into the project.

The refinement of Outside-Inside was lingering at the moment, due to lack of inspiration, whilst the work with Colosseum was moving forward. This together with architectural opinions about the two concepts was the reason why Outside-Inside was disregarded in the second evaluation. Hence, the rest of the project was focused only on refining Colosseum and summarizing the thoughts and ideas about the concept.

8.4 2nd Refinement phase

Blinds

The net-structure that was supposed to prevent people from seeing into the apartment was changed since people probably still would be able to see into the apartment during the dark hours. The net was instead replaced by big blinds (cf. Figure 6). A light sensor is supposed to be connected to the blinds so they automatically open and close depending on whether it is bright or dark outside.

Entrance

The spiral staircase was refined with the goal of making it an element of its own. However, the idea of facing the three-meter leap the first thing as one enters the apartment was kept. Due to the limited space it was pretty soon clear that a staircase wouldn't fit and instead the design started to look more and more like a ladder.

A ladder fulfilled both the desires of being steep and slender enough to fit. However, it would not be safe. Safety bars and handles was therefore added to the ladder so in the end it worked as a very steep and slender staircase after all.

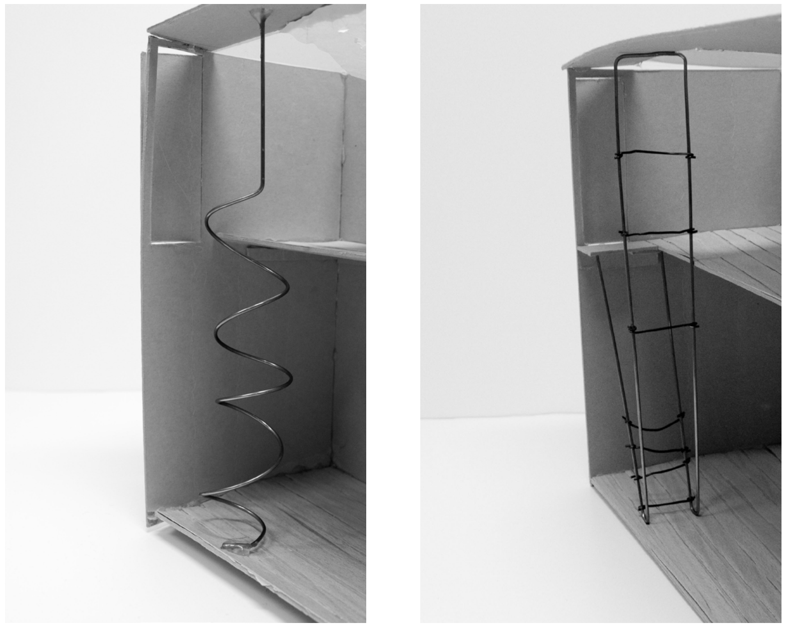

Figure 24: Showing the change from a spiral staircase to a ladder-like entrance.

9. FUTURE WORK

Making the main window in the apartments concave in order to minimize insight even more was discussed during the project. However, it was not looked into. The window would work as a mirror from the outside but still be transparent from the inside which would be an advantage although there could be problems with manufacturing, due to its big dimensions.

The final concept gives great basis for further investigations regarding the possibilities of gathering heat from the water, include wave and solar power in the structure, etc. Thus the dwellings could be more or less self-sufficient. Including more apartments in the structure or even building an up-scale version of the concept could also be possible. In other words, the concept provides sustainable and environmentally friendly dwellings for the future.

The structural analyses should be developed with exact dimensions, correct reinforcement in the concrete, a complete model of sea loads, etc. Additionally, examples on other interesting investigations are the effects from temperature differences in the main deck and effects from ice formation on the structure.

10. REVIEW OF WORK

I come from an educational background with theoretical courses on an advanced level. Most courses covers a narrow subject on a deep level which generates a mindset that assumptions and calculations should be performed extremely precise and exact. This resulted in big challenges during some parts of the project and required a change of mindset when I tried to take on the role as an architect.

The project started out with an idea generation phase which required creativity, design and patients. Complete working days could go by where the only thing I did accomplish was a couple of pages with doodles and messy sketches. At the moment it seemed as a waste of time when looking with my narrow-minded eyes but now I see that it was a part of the process. I first needed to find inspiration, absorb it and then express it in terms of my preferences. Nevertheless, after a while some material that I was able to work with started to fall out i.e. words it wasn't such a waste of time after all.

When the refinement phase started I continued to work with sketches and drawings. However, that media seemed to hold me back and the workflow was lingering. Instead I started to work with basic physical models made out of paperboard and styrofoam. This gave a whole new perspective on dimensions, light flow, etc., and the discussions they generated was inspirational and rewarding. The work progressed in an iterative process meaning that rough ideas where refined several times and that basic structural analyses was performed side by side with the changes of the design. This way of working gave a lightness to the workflow which in turn made sure that the ideas continued to develop.

I encountered again more problems with adaptation of the mindset as the project went on. I was used to analyze different material models, stress or strain-driven analyses, incompressibility, etc., i.e., advanced and complex computations, which was not the case in this project. The structural analyses performed where instead on a conceptual level. For example, rough assumptions of the dimensions and loads where used to estimate the stability, floating level, buckling load, etc. To be able to perform advanced computations as those mentioned above is off course necessary and it gives a deeper knowledge and understanding. However, simplified estimates are just as important to master in order to become a successful engineer.

APPENDICES
Appendix A. List of variables

ρ_{CLT} = 500 [kg/m^3]
$\rho_{concrete}$ = 2400 [kg/m^3]
ρ_{steel} = 7500 [kg/m^3]
ρ_{water} = 1000 [kg/m^3]
E_{steel} = 200 [GPa]
$E_{concrete}$ = 30 [GPa]
c = 30 [mm] (thickness of covering concrete layer)
k_1 = 0.8 (properties of the surface of the reinforcement)
k_2 = 0.5 (pure bending)
k_3 = 3.4 (nationell parameter, recommended)
k_4 = 0.425 (nationell parameter, recommended)
$\rho_{p,ef}$ = 0.041 (effective reinforcement content)
σ_s = 290 [MPa]
L50 - Life length 50 years
c_{pe} = 0.8
c_{pi} = 0.5
c_e = 2.8
v_b = 25
μ_i = 0.8
s_k = 2.0
C_e = 1
C_t = 1
γ_g = 1.35
γ_q = 1.5

Table 1: Exposure grades according to Euro Code [25].

Exposure class	**Description of exposure**	**Example**
XD1	Relatively wet	
XD2	Wet, rarely dry	Swimming pool
XD3	Cyclically wet and dry	Bridges, parkinglots
XS1	Airborne salt	Close to or at the shore
XS2	Constantly under water	Marine environment
XS3	Splash zone	Marine environment

Appendix B. Reference work

Inspiration was mostly found in the research where the work that influenced the structural ideas the most was the Moses bridge, Therme Vals, Maison Bordeaux and Fallingwater.

B.1 Moses bridge

The Moses bridge is a bridge submerged in a moat accessing one of many fortresses in the south-western Netherlands. The architect wanted the bridge to be invisible since the purpose of the moat back in the days was to prevent enemies to access the fortress it was guarding.

The innovative way to tackle the problem of building in water with the submerging technique was inspiring and gave a new way of looking at the situation.

Figure 25: Picture of the Moses bridge [14].

Figure 26: Picture of Maison Bordeaux [13].

B.2 Maison Bordeaux

Maison Bordeaux is a home designed by the architect Rem Koolhaas in 1994 located on a hill outside the city of Bordeaux, France. A family of a couple and their two children was supposed to inhabit the building but before the family contacted Koolhaas, the father in the family was involved in a serious car accident that paralyzed him from the waist down. Instead of designing a simple regular house the father requested “a complex house because the house will define my world” [8]. An innovative three-storey building was proposed where the top floor is almost levitating.

Koolhaas requested that the villa should ”fly” and contacted the famous engineer Cecil Balmond to help him. It’s obvious that the structure has to have some kind of supports but the way of working around it described in ”informal” [23] is fascinating. Balmond plays with the supports, in simple sketches, in an iterative process to develop a concept that generates the feeling levitation. Both the way of working and how to approach a problem as well as the design of Maison Bordeaux inspired this project.

B.3 Therme Vals

Therme Vals is a combined spa and hotel designed by the architect Peter Zumthor in 1993 and built in Vals in Switzerland. The building lays on a hillside and is partially buried within the hill. The structure is built out of Valser quarzite (a kind of stone) and the material is exposed both on the inside and outside. This gives a raw but natural look to the building and also pronounces the contrast between the raw walls and the soft water.

The feeling generated by the narrow passages, the headroom, the sharp and raw edges and the contrasts was a big inspiration to the project.

Figure 27: Picture of Therme Vals [18].

Figure 28: Picture inside Therme Vals [17].

B.4 Fallingwater

Fallingwater is the name of a famous house in Pennsylvania, USA, designed by the architect Frank Lloyd Wright in 1935. The house is built partially over a waterfall and what makes it famous, beside from that, is how Wright accomplish to integrate the waterfall with the building and by that ”redefined the relationship between man, nature and architecture” [7], or as Treiber [34] puts it ”it unites the roughness of the raw material with the smoothness that men make of all things”.

The way Wright plays with the water and makes the nature around the house present, even when one is inside, was brought into the idea generation.

Figure 29: Picture of Fallingwater [16].

Figure 30: Picture of Fallingwater [15].

Appendix C. Floating architecture now and then

C.1 Tonle Sap - Cambodia

Floating villages has been around for centuries on the lake Tonle Sap (the great lake) in Cambodia. Fishermen tribes built the villages to be more protected from enemies but also to be closer to their livelihood.

The water level of the lake changes drastically during the year. For most of the year the lake is barely one meter deep but during the rainy season when the river Mekong pushes melted water from the Himalayas into the lake the depth increases to approximately nine meters [6]. The expansion of the lake floods the surrounding fields and forests which improves the biodiversity in the lake. Furthermore it also put structural requirements on the buildings. Some houses are built on stilts high enough to handle the increasing water level and some houses float directly on water and move with it.

Figure 31: Picture of a floating village [11].

C.2 Marine city - Kiyonori Kikutake

Kiyonori Kikutake was a Japanese architect, philosopher and visionary. He together with a few other architects started the metabolism movement in Japan. Japan was at the time a country suffering from post world-war issues with a fast growing population and expanding cities. The architectural movement published ideas and concepts of huge structures that sometimes inhabited whole communities. The focus was a sustainable mindset that provided an organic and biological growth.

Marine city was, in 1958, one of the first conceived concepts by the movement. The idea was to create a floating metropolis in the ocean where the island would be sustainable and self-supporting with rich aquaculture farming.

The structure is based on huge steel rings, with a diameter of more than 3 km, floating on a bottle-like fundament. Towers, each holding 1250 modular houses, is then attached on top of the rings [5].

Even though Marine city never was built it was sure a ground breaking concept of its time and are still a current topic and an example of great architecture.

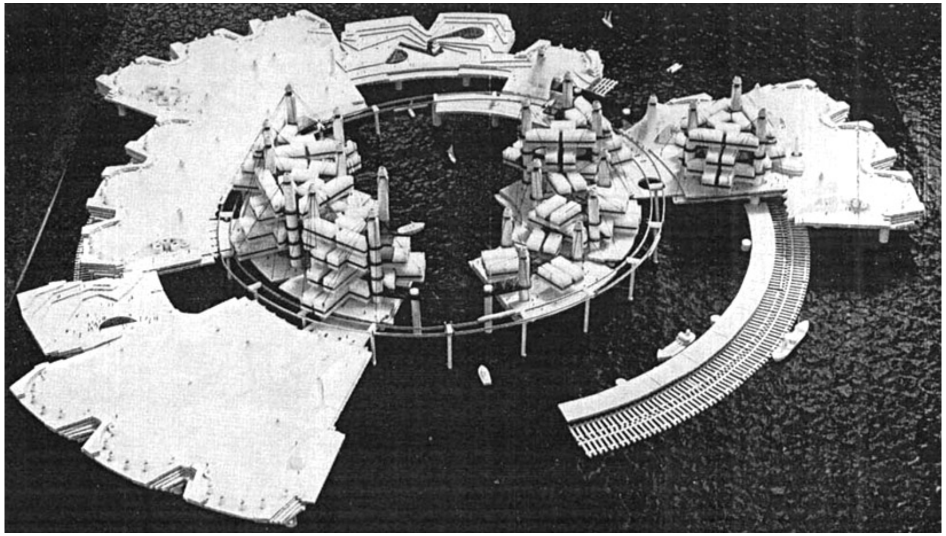

Figure 32: Picture of a physical model of Marine city [10].

C.3 Waterbuurt - Amsterdam

There are many examples of low-laying cities that has problems with flooding and Amsterdam is one of them. Houseboats have been around for a long time and it is a familiar sight when walking along the canals in Amsterdam. Houseboats provide an alternative and economical way of living but the size and lifestyle is usually limited. There has been experiments with amphibious housing, e.g., in 2005 when the architectural firm Dura Vermeer built two types of houses; one built on land but was able to float on water during a potential flooding and another that was built on water and was able adjust to the changing water levels. However, this would be a less successful example as these houses are now mainly used as holiday homes rather than for permanent living.

A more successful example would be the community Waterbuurt in the lake IJ in Amsterdam. The construction started in late 2009 and there are now a collection of more than 100 modular floating houses that forms the community. Waterbuurt is the first residential complex of its kind in Amsterdam, but it will most likely not be the last [35].

Figure 33: Picture of the residential area Waterbuurt in Amsterdam [12].

C.4 Lilypad - Vincent Callebaut

In 2008 the Belgian architect Vincent Callebaut designed the ”floating ecopolis” (Lilypad). Lilypad is a model of a sustainable solution to the rising water levels that provides housing for 50,000 possible climate refugees [4]. The residential complex would work as an artificial island with its own flora and fauna that it would develop around the central lagoon. The island would also provide work, shops and entertainment for the inhabitants.

”The goal is to create a harmonious coexistence of the couple Human / Nature and to explore new modes of living the sea by building with fluidity collective spaces in proximity, overwhelming spaces of social inclusion suitable to the meeting of all the inhabitants” [4].

Even though the project still is on a conceptual level and seams quite futuristic to some it is a great example of work being done in the field of floating architecture.

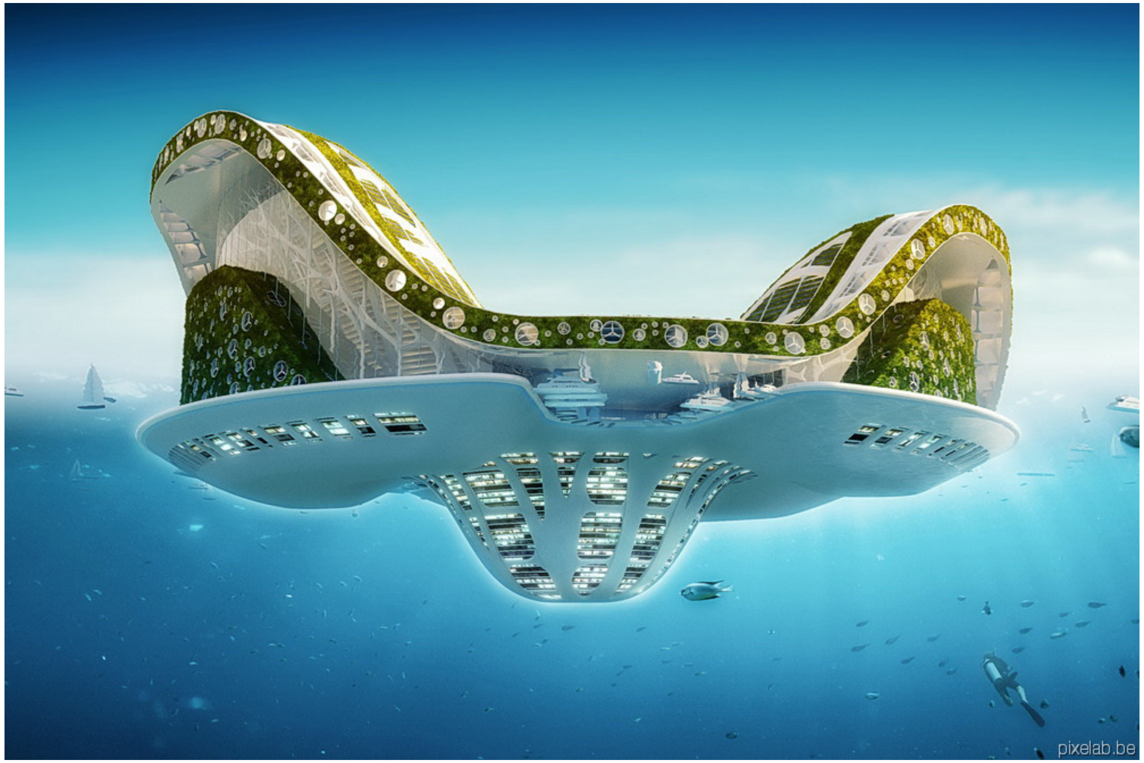

Figure 34: Animation of the conceptual idea Lilypad [9].

Appendix D. Stability

When an eccentric vertical load, a horizontal load or a moment is acting on a floating body this will result in a rotation of the body around the center of buoyancy and the body will tilt. According to Archimedes principle and hydrostatics will the part of the body that is lowered deeper into the water experience greater water pressure and also a greater buoyancy force. This buoyancy force will cause a contra action moment which will strive to put the body back into equilibrium. If however the body will tilt too far or the body has an ill-conditioned center of gravity will instead a heeling moment arise.

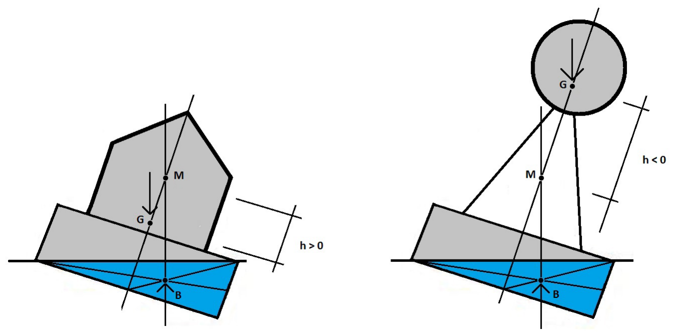

Figure 35: A stable (L) and an unstable (R) body.

The height between the center of gravity and the point where the net buoyancy force intersects the center line of the body (M, meta center) is defined as the metacentric height. A positive metacentric height results in a stabilizing moment and a negative metacentric height results in a heeling moment, i.e. the body is stable when the metacentric height is greater than zero [28, 30].

The distance between the center of buoyancy and the meta center can be calculated as:

$$BM = \frac{I_w}{\nabla}(1 + \frac{1}{2}\tan^2\alpha) \qquad [28, 30]$$

According to the formula above, the rotation plays a role when calculating the height of the meta center, however if the rotation is assumed to be small (less than 10º), which is a valid assumption, it can be neglected and the formula is reduced to:

$$BM = \frac{I_w}{\nabla}$$

where ∇ is the volume of the displaced water. The height between the keel and the buoyancy center is for a rectangular body:

$$KB = \frac{1}{2}d$$

The height between the keel and the meta center can then be calculated as:

$$KM = BM + KB$$

Assuming that the center of gravity is known the metacentric height is lastly given as:

$$GM = KM - KG$$

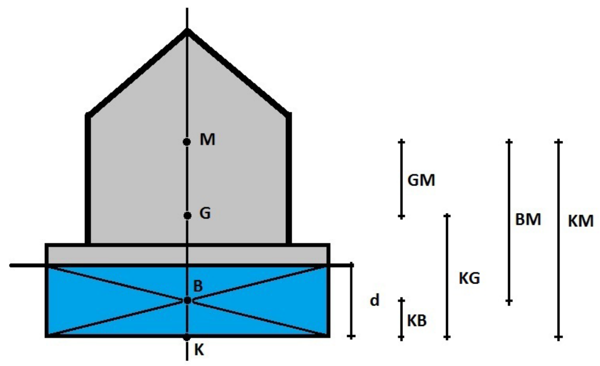

Figure 36: The points of interest of a floating body

Table 2: Metacentric height for the four different concepts. Concept 2 shows the metacentric height both when the apartments are put on top of eachother and when three separate towers are connected in a triangle.

	Metacentric height, GM [m]	
Concept 1 - Laying	3.77	
Concept 2 - Standing	-9.71	5.36 (when connected in a triangle)
Concept 3 - Outside Inside	19.05	
Concept 4 - Colosseum	5.69	

Appendix E. Buckling analysis

The buckling load of the supports in the third initial concept (cf. figure 38) was computed, both numerically and analytically in order to justify the result. The numerical analysis was performed in Matlab with the toolbox CALFEM [22]. The buckling load was computed when modeling the structure as a whole and also when just modeling one support as a beam.

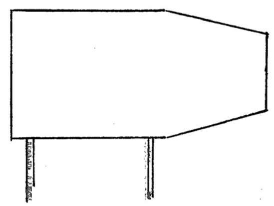

Figure 38: Showing the supports of an early version of the third concept.

The whole structure was simplified by modeling two walls as truss system and connecting them by two beams that was supposed to act as the two remaining walls in between (cf. figure 37) The supports was fixed at the bottom and one vertical and one horizontal external force was applied to the structure. The forces where ramped until buckling occurred and the resulting buckling force was decided.

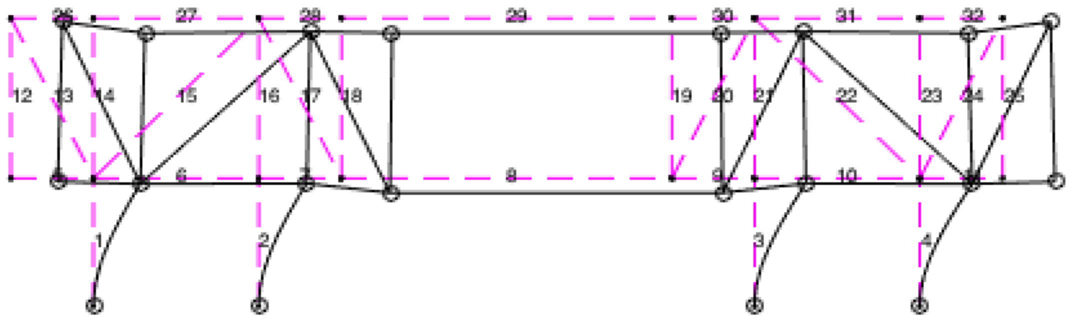

Figure 37: CALFEM model of the structure modeled as a 2D truss system.

The buckling force was also computed when modeling only one support (cf. figure 39). It was assumed to be fixed in the bottom and an external force was applied at the top. The buckling load was investigated both for an I-beam and an O-beam and the results are shown in table 3.

Figure 39: CALFEM model of one support.

The analytical buckling load, Pk, is calculated as:

$$\sigma_k = \frac{P_k}{A} = \frac{\pi^2 E}{\lambda^2} \qquad [20]$$

Where λ is defined as:

$$\lambda = \frac{L_f}{r_i}$$

L_f is here the free buckling length and r_i is the radius of gyration, defined as:

$$r_i = \sqrt{\frac{I}{A}}$$

By inserting the expressions for λ and r_i in the initial formula the buckling load is given as:

$$P_k = \frac{\pi^2 EI}{L_f^2}$$

The analytical buckling load was also investigated for both an I-beam and an O-beam and the results are shown in table 3.

Table 3: Resulting buckling force for both numerical and analytical calculations.

TYPE OF ANALYSIS	**BUCKLING FORCE**	
Numerical [MN]	1.25	
	Beam profile	
	IPE200	**KCKR200**
Numerical [MN]	2.48	5.36
Analytical [MN]	2.52	2.42

Assuming that the structure is made out of steel results in the total load acting on the legs from self weight is approximately 0.66 [MN]. Comparing the load with the results in table 2 one sees that the actual buckling load is almost four times larger.

Appendix F. Moment in support

A bending moment will arise in the support due to its asymmetric placement (cf. figure 39) and the idea is to carry the moment in the support rather than adding tension wires. In order to validate this the resulting stress in the bottom of the support caused by the bending moment,wind load and snow load is calculated and compared to the yield stress. The wind and snow loads are added in order to account for a worst case scenario.

The resulting bending moment is calculated by a simple free body diagram and equilibrium equations to approximately 20 [kNm].

The wind load is calculated as:

$$w_e = q_p(z_e)c_{pe} \quad [\mathrm{kN/m^2}]$$

$$w_i = q_p(z_e)c_{pi} \quad [\mathrm{kN/m^2}] \qquad [21]$$

w_e is the pressure on the exposed wall and w_i is the resulting drag on the back wall. c_{pe} and c_{pi} are standardized characteristic pressure constants and q_p is calculated as:

$$q_p(z_e) = c_e(z)q_b \quad [\mathrm{kN/m^2}]$$

Where c_e is a pressure constant depending on the exposure and q_b is calculated as:

$$q_b = \frac{v_b^2}{1600}$$

v_b is here the geographical wind velocity, found in tables [21]. w_e and w_i are lastly summarized and multiplied with the total area of the wall and the distance r in order to obtain the resulting moment in the bottom of the support caused by wind loads.

$$R_{wind} = (w_e + w_i) \cdot A_{wall} \cdot r = (0.87 + 0.41) \cdot 13.8 \cdot 3.15 \approx 56 \quad [\mathrm{kNm}]$$

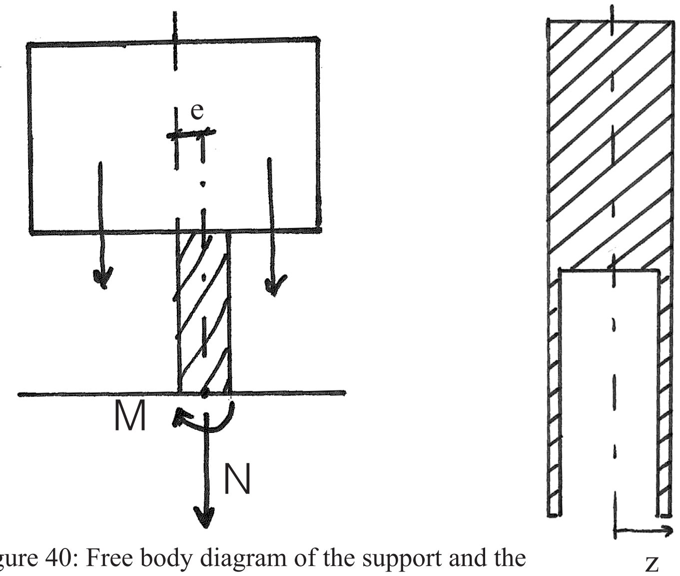

Figure 40: Free body diagram of the support and the cut through section.

The snow pressure is calculated as:

$$S = \mu_i C_e C_t s_k \quad \text{[kN/m}^2\text{]} \qquad [21]$$

Where C_e and C_t are exposure coefficient and thermal coefficient respectively. μ_i is a coefficient dependent on the shape of the roof and s_k is a characteristic snow value for the specific geographical location.

The snow pressure is multiplied with the area of the roof in order to obtain the resulting axial force caused by the snow load.

$$P_{snow} = S \cdot A_{roof} = 1.6 \cdot 24 = 38.4 \quad \text{[kN]}$$

Navier's formula is lastly used to compute the resulting stress in the support.

$$\sigma = \frac{N}{A} + \frac{M}{I}z$$

Where M is the combined moment from the eccentric placement of the support and the wind load and N is the resulting axial force from self weight and snow load combined. The loads are multiplied with different partial safety factors depending on if they are permanent (γ_g) or variable (γ_q) loads [21].

The support will be partly solid and partly hollow since the stair is hidden within it. This is accounted for by approximating the section as shown in figure 38.

$$\sigma = \frac{N}{A} + \frac{M}{I}z = \frac{(722 \cdot 1.35 + 38.4 \cdot 1.5)10^3}{1.8} + \frac{(20 \cdot 1.35 + 56 \cdot 1.5)10^3}{0.09} \cdot 0.35 \approx 1.0 \quad \text{[MPa]}$$

The resulting stress is approximately 1.0 [MPa]. Assuming that the support is made out of SS 305 and that the weld has the same material properties as the support one sees that the stress is well below the yield stress $\sigma_y > 200$ [MPa].

Appendix G. Deck analysis

When the structure is lowered down into the water a linearly varying hydrostatic pressure will arise on the outside of the ring and a constant pressure will arise on the main deck (cf. figure 40). This will result in bending of the structure and in turn initiate cracks in the main deck. This is considered the most critical scenario and was therefore analyzed for different cases using the FE software ABAQUS.

The geometry was importen from the modeling software Rhinoceros3D (Rhino). Rhino defines geometries by surfaces, hence the geometry imported into ABAQUS was also defined by surfaces. Thus, homogeneous shell elements (element type S3R and S4R - large-strain shell elements [19]) was used in the FE analysis. The total number of elements was 14962 and the performed analysis was a static linear analysis.

The structure was pinned all along the upper ring edge since in reality the structure would not move up and down in the water and also moored to the bottom of the lake to prevent it from moving in the plane.

A constant hydrostatic pressure was applied to the bottom surface of the main deck

$$\rho g h = 1000 \cdot 9.81 \cdot 4.6 = 45.1 \quad \text{[KPa]}$$

and a linearly varying hydrostatic pressure was applied to the outer surface of the main ring.

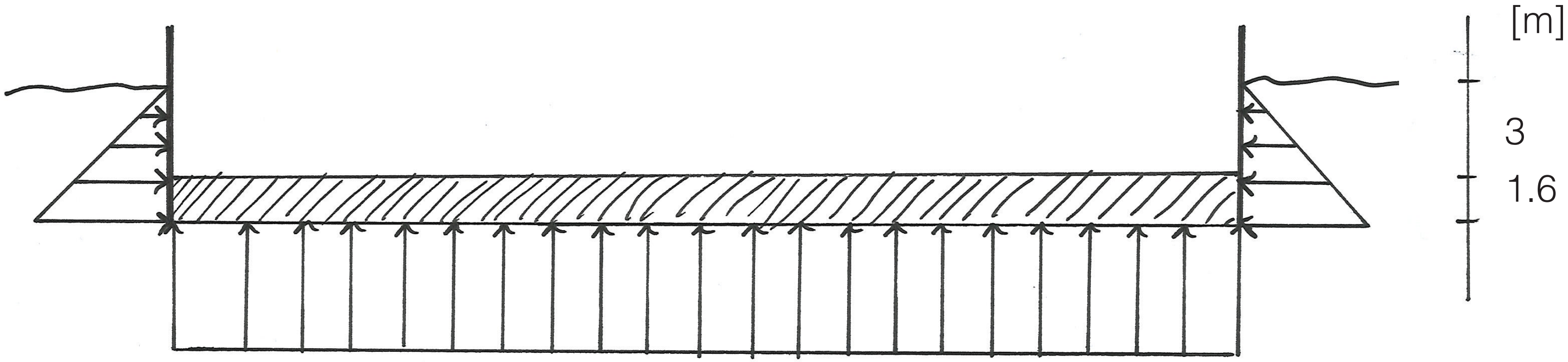

Figure 41: Showing the forces acting on the structure.

The structure was analyzed with and without the apartments (cf. figures 41 and 42) to see how it affected the structural behavior and as expected, the deflection of the deck decreased when the apartments was included as structural elements.

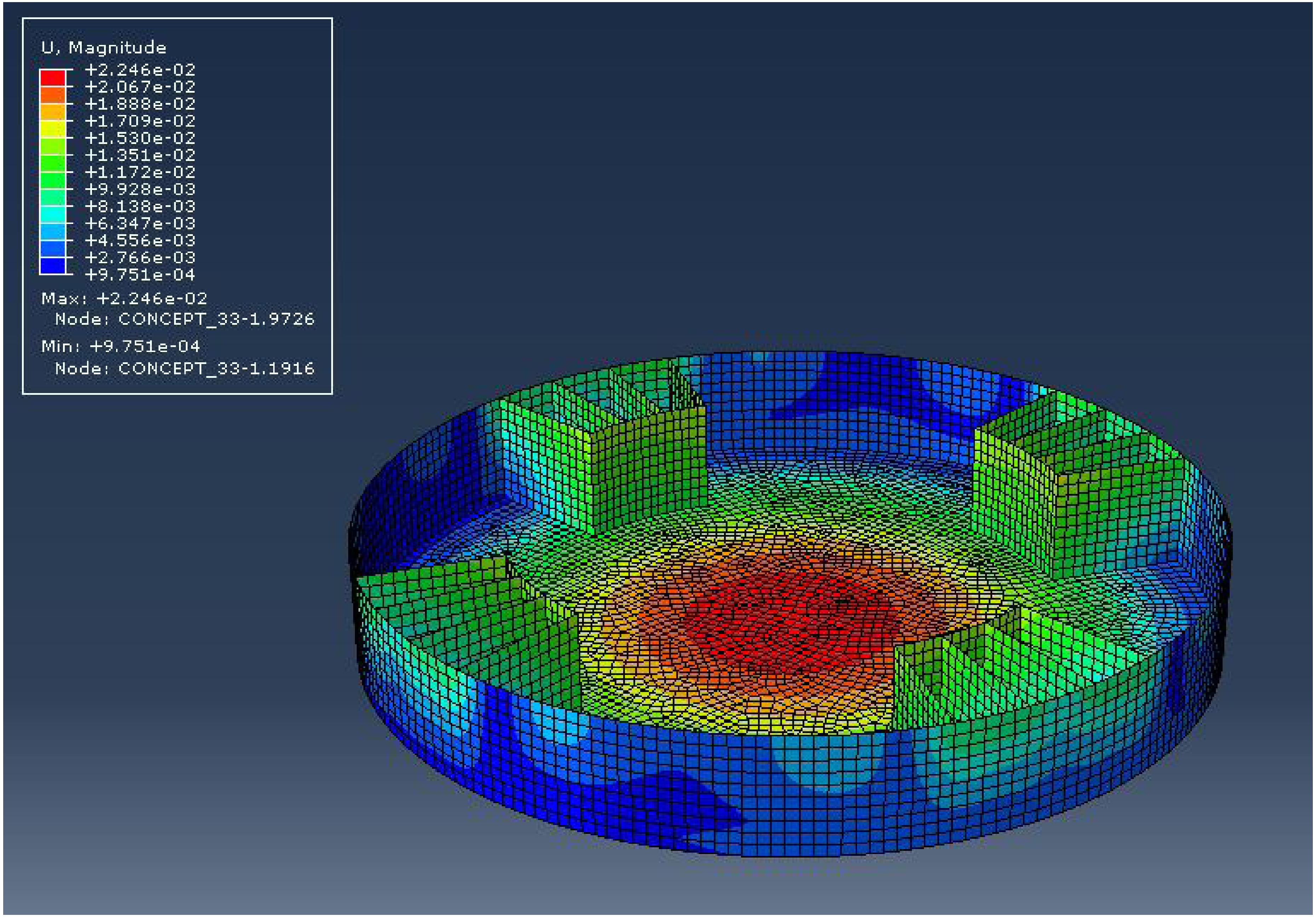

Figure 42: Showing the resulting deflection of the main deck with the apartments, 22 [mm].

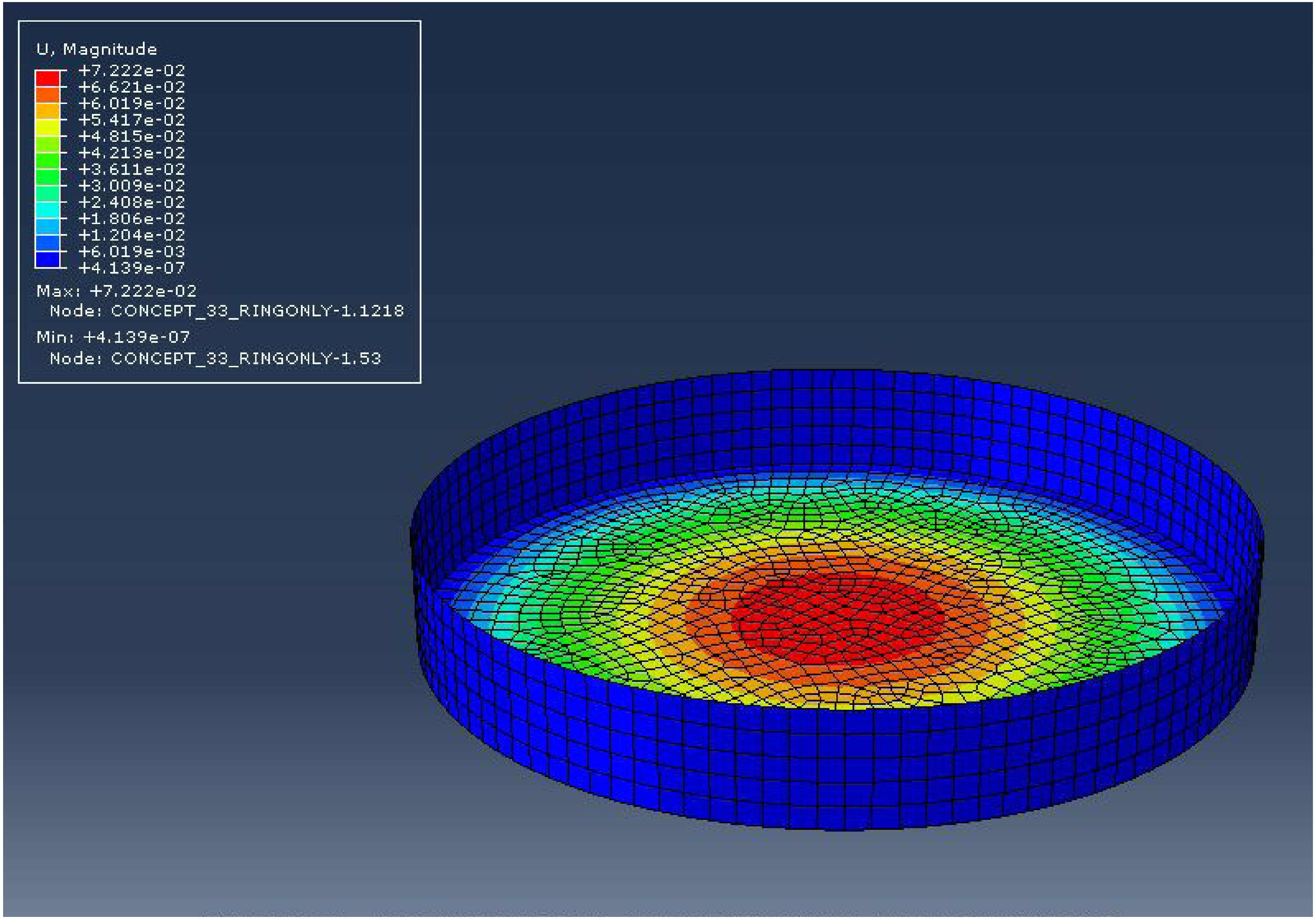

Figure 43: Showing the resulting deflection of the main deck without the apartments, 72 [mm].

A similar analysis was performed again when the design of the structure changed (cf. figures 44 and 45). The new design when the apartments was divided into three sections instead of four decreased the deflection further. However, when the bench was included in the analysis the deflection increased somewhat, although still acceptable.

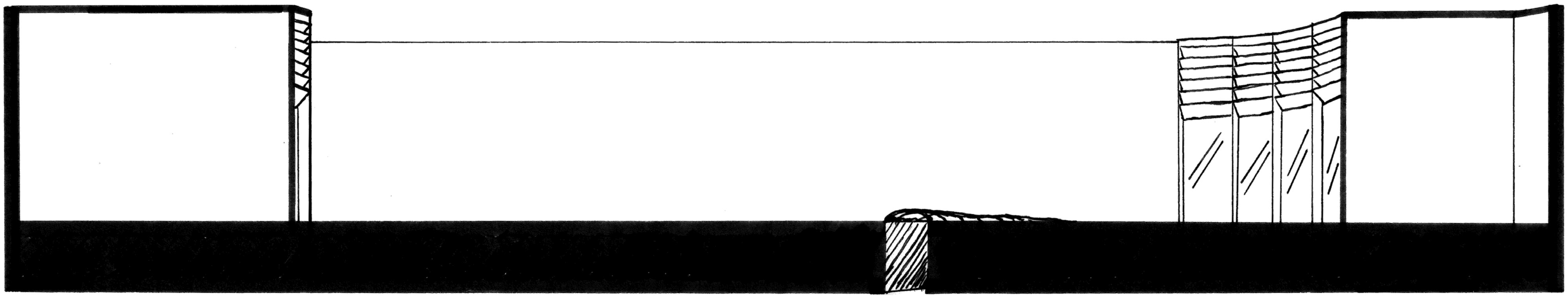

Figure 44: Showing the bench cut out directly in the main deck which will increase the deflection of the whole structure.

1 [m]

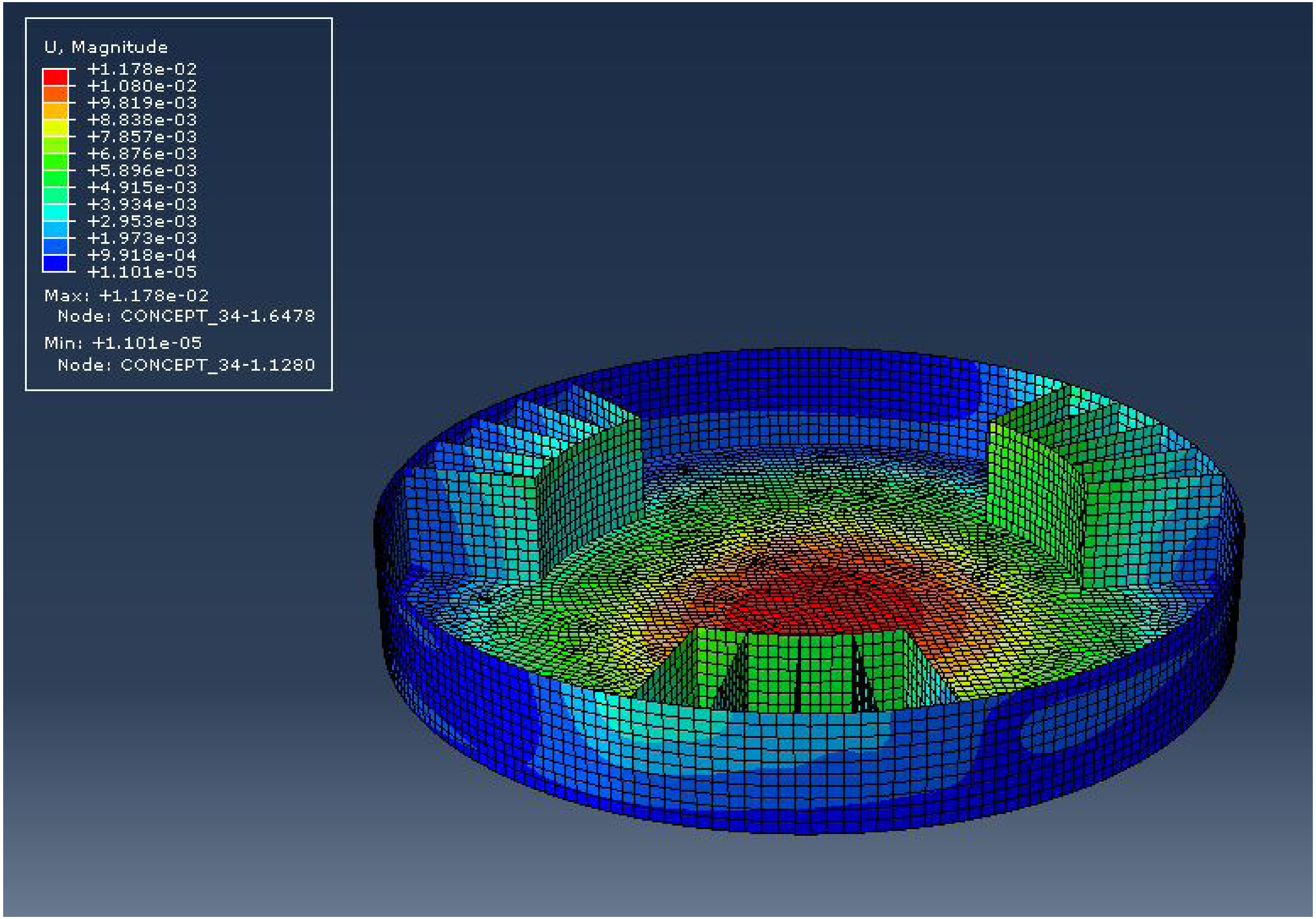

Figure 45: Showing the resulting deflection of the main deck with three sections without including the bench, 12 [mm].

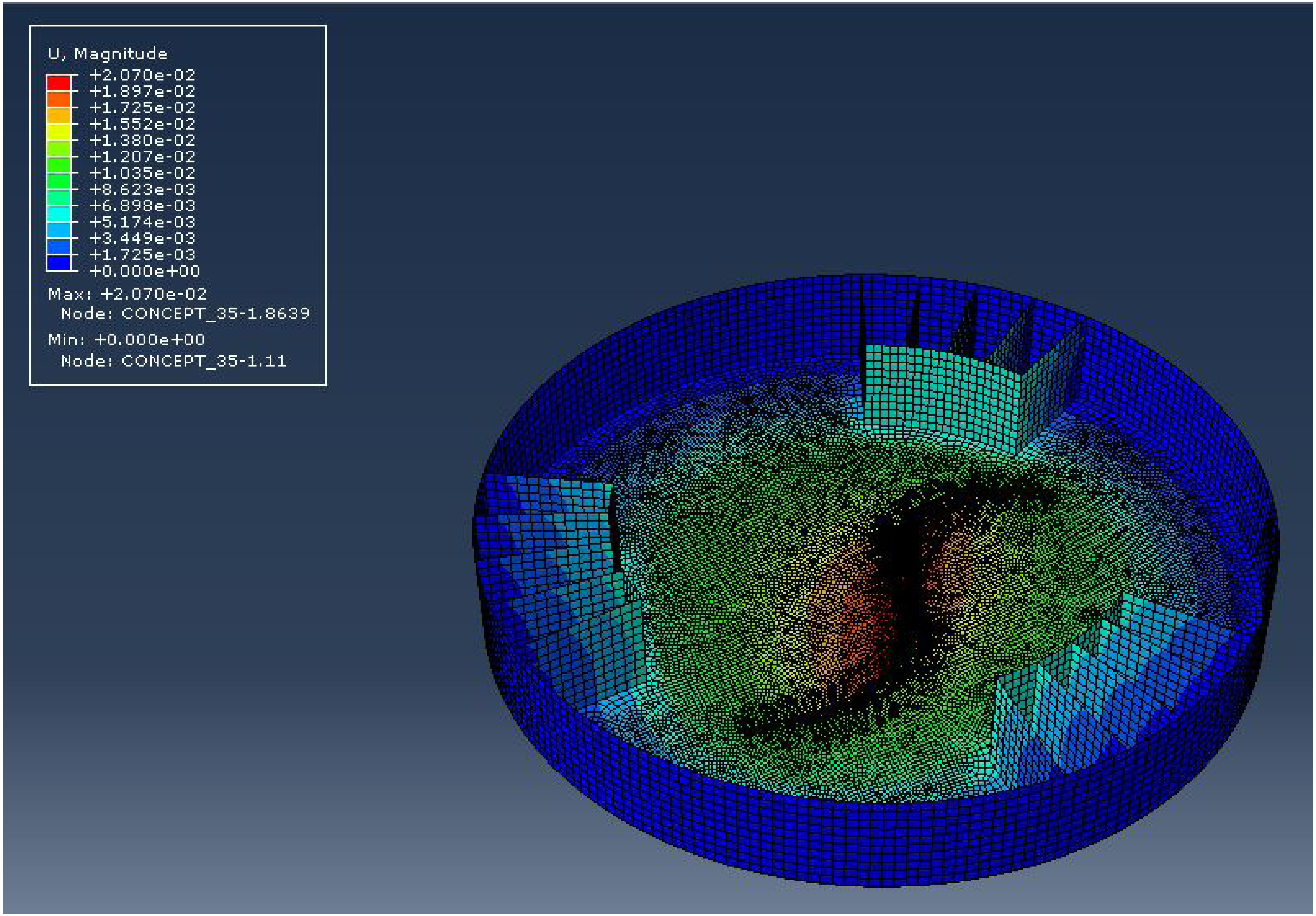

Figure 46: Showing the resulting deflection of the main deck with three sections when including the bench, 20 [mm].

Appendix H. Cracks in deck

Euro code 2 (EC 2) puts regulations on cracks with respect to the structures durability and shape. The structure should either be completely free from cracks in the service state or have a characteristic crack width less than an acceptable value, according to standards [20].

Table 4: Maximum allowed crack width, *wk* [mm] for different exposure classes [25].

Life length / Exposure class	L100	L50	L20
XC1	0.45	-	-
XC2	0.40	0.45	-
XC3, XC4	0.30	0.40	-
XS1, XS2 XD1, XD2	0.20	**0.30**	0.40
XS3, XD3	0.15	0.20	0.30

Exposure grade XS2 (marine environment) and assuming L50 gives a maximum allowed crack width of 0.30 [mm], according to table 3.

The crack width is calculated, according to EC 2 as:

$$w_k = s_{r,max} \nu \frac{\sigma_s}{E_s} \quad \text{[mm]} \qquad [24]$$

v is a constant that takes the impact of the concrete in between the cracks into considiration, however this constant can be set to 1 for an estimated value [24]. E_s is the young's modulus of the reinforcement and σ_s is the stress in the reinforcement, which is estimated by the Navier's formula with inputs from the FE analysis (see Appendix H.1 Computation of stress in rebars). $s_{r,max}$ is here the characteristic distance between the cracks and is calculated as:

$$s_{r,max} = k_3 c + k_1 k_2 k_4 \frac{\Phi}{\rho_{p,ef}}$$

k_1, k_2, k_3 and k_4 are all standardized koeficients and c, Φ and $\rho_{p,ef}$ are thickness of covering concrete layer, diameter of the reinforcement and the effective reinforcement content respectively. k_1, k_2, k_3, k_4, c and $\rho_{p,ef}$ are all found in literature [20] while Φ are decided empirically (see Appendix H.1 Computation of effective stress in rebars)

H.1 Computation of stress in rebars

Naviers formula was used in order to compute the effective stress in the rebars.

$$\sigma = \frac{N}{A} + \frac{M}{I} z$$

The moment and normal force was extracted directly from the FE analysis in ABAQUS (cf. figures 46 and 47). Where the maximum moment was approximately 1.8 [MNm] and the normal force was approximately 1.0 [MN].

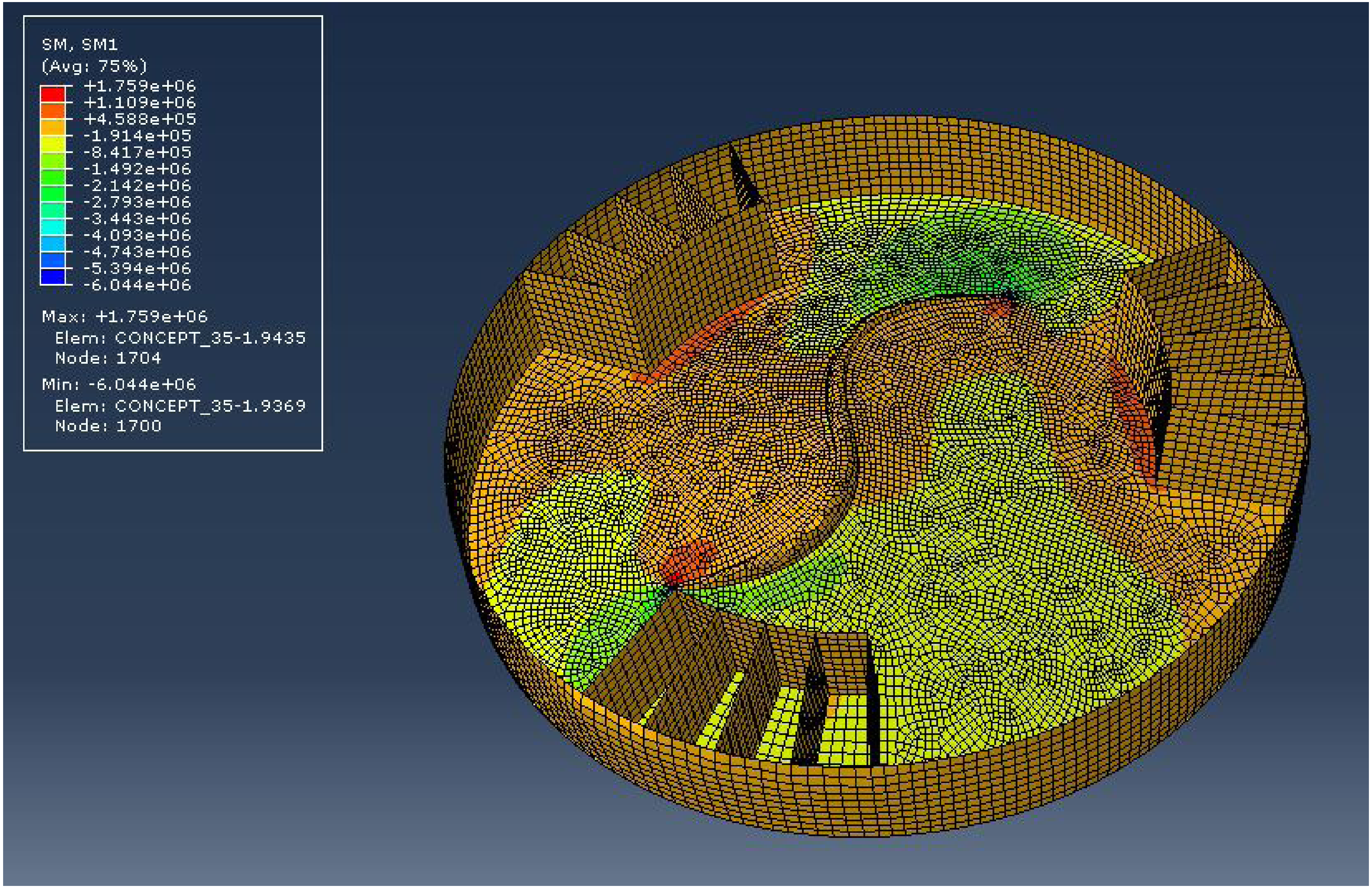

Figure 47: Resulting maximum bending moment, 1.8 [MNm].

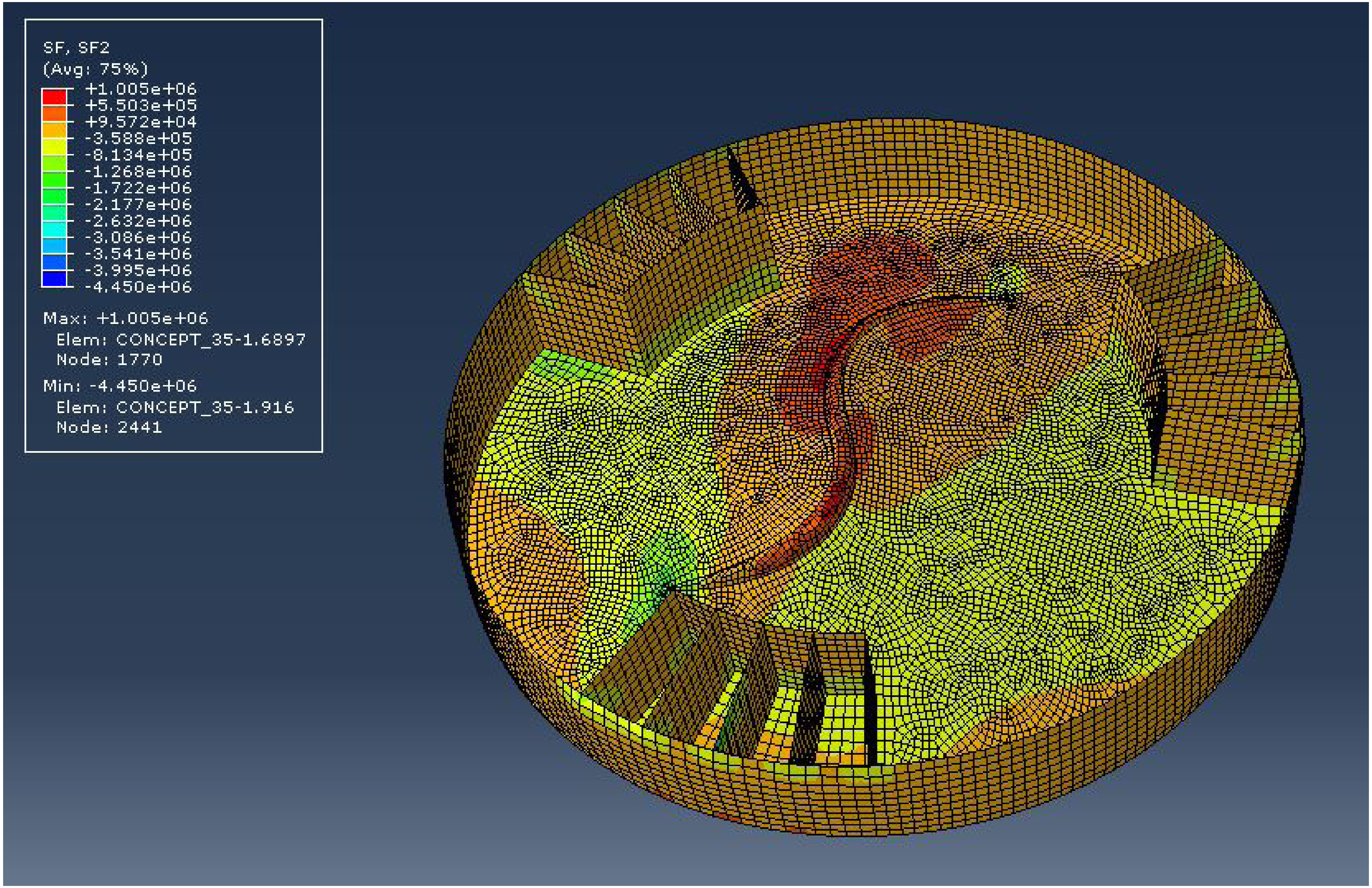

Figure 48: Resulting normal force, 1.0 [MPa].

The effective area and the displacement vector *x* was calculated with the theory of single layered reinforcement [20].

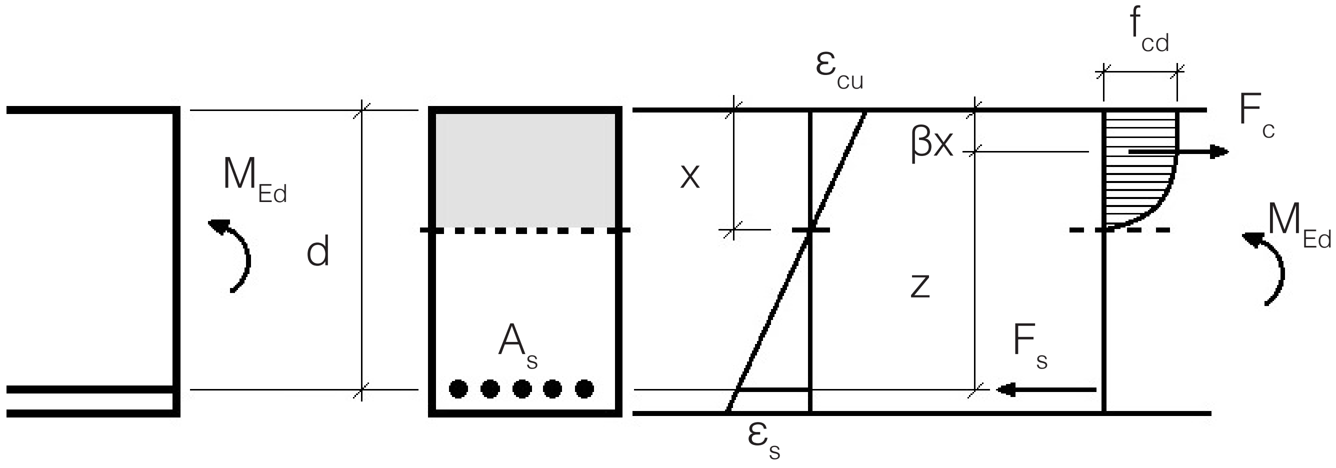

Figure 49: Principal sketch of bending of a concrete beam section with a single layer reinforcement [20].

$$f_{cd} \cdot b \cdot 0.8x = \sigma_s \cdot A_s$$

$$M_{Rd} = f_{cd} \cdot b \cdot 0.8x(d - 0.4x)$$

Combining these two equations gives an expression for the displacement vector *x*:

$$x = \left(d - \frac{M_{Rd}}{\sigma_s A_s}\right)\left(\frac{1}{0.4}\right)$$

It should be noted that the σ_s in this expression is not the effective stress of the rebars but rather the tensile stress of the rebars, thus 300 [MPa]. The diameter of the rebars and the number of rebars per meter, and hence the effective area, was changed in order to obtain an acceptable value of the displacement vector and in turn an acceptable crack width.

A diameter of 20 [mm] and 15 rebars per meter resulted in an effective area of approximately 4700 [mm^2] and a displacement vector of approximately 0.7 [m].

The effective area was computed to approximately 4700 [mm^2]

$$A_s = 15 \cdot \frac{\pi 20^2}{4} \approx 4700 \quad [\text{mm}^2]$$

which resulted in an displacement vector x of approximately 0.7 [m]

$$x = \left(1.55 - \frac{1.8 \cdot 10^6}{300 \cdot 10^6 \cdot 4.7 \cdot 10^{-3}}\right)\left(\frac{1}{0.4}\right) \approx 0.71 \quad [\text{m}].$$

The resulting effective stress was calculated to approximately 100 [MPa]

$$\sigma_s = \frac{1 \cdot 10^6}{4.7 \cdot 10^{-3}} + \frac{1.8 \cdot 10^6}{1.62 \cdot 10^6} 0.71 \approx 216 \quad [\text{MPa}].$$

Lastly the characteristic distance between the cracks $s_{r,max}$ and the crack width w_k was calculated to approximately 185 [mm] and 0.20 [mm] respectively.

$$s_{r,max} = 3.4 \cdot 30 + 0.8 \cdot 0.5 \cdot 0.425 \frac{20}{0.041} \approx 184.9 \quad [\text{mm}]$$

$$w_k = 184.9 \cdot 1 \cdot \frac{216}{200 \cdot 10^9} \approx 0.20 \quad [\text{mm}]$$

The resulting crack width is acceptable according to table 4 that say that the maximum allowed crack width for a structure in marine environment is 0.30 [mm].

Appendix I. Mooring

The loads that acts on a floating structure are mainly caused by winds, currents and waves. The wave load is divided into two parts, one component with the same period as the wave motion and the other component is a second order function dependent on the short term mean value of the motion of the water. However, the second component is often considered constant together with the wind and current loads and it is these constant loads that puts the requirements on the mooring system.

The requirements on the mooring system is that it should hold the structure within a required amplitude, depending on what situation the structure is used in, and that the resulting stresses in the cables should not exceed 1/3 of the ultimate tensile stress in the service state [33].

There are a couple of ways to compute the stresses in the mooring system. However, the equilibrium position must always be decided, by computing the movements of the free structure (not moored) caused by the first component of the wave load and the constant loads. This is a complex dynamic problem dependent on several parameters e.g. wave heights, mean wave period, etc. [29,33]. Due to its complexity it didn't fit in this thesis.

A mooring system depicted in figures 49 and 50 is preferable since it absorbs movements and forces smoothly and since it provides great damping thanks to that the part of the cable on the bottom absorbs energy when it gets lifted up and put back down.

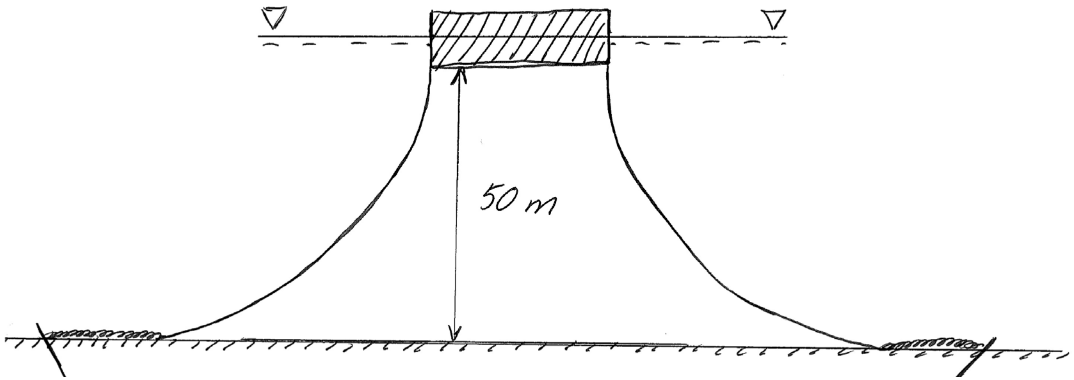

Figure 50: Preferable mooring system

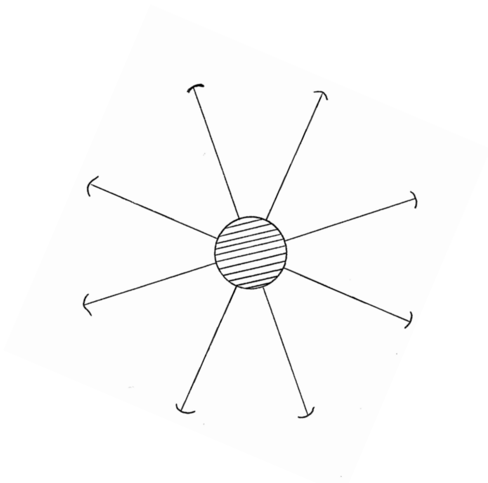

Figure 51: Possible cable pattern.

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