TURUN AMMATTIKORKEAKOULU
ÅBO YRKESHÖGSKOLA

Opinnäytetyö

NAVAL ENGINEERS LOOK ON THE FEC-CONCEPT AND OTHER VLFS-STRUCTURES

Tuomas Wasén

Kone- ja tuotantotekniikka

2011

TURUN AMMATTIKORKEAKOULU	TIIVISTELMÄ

Kone- ja tuotantotekniikka

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Laiva- ja venetekniikan insinöörin katsaus FEC-konseptiin ja muihin suuriin kelluviin rakenteisiin.

Laivatekniikka	Pentti Häkkinen
05/2011	

Tässä opinnäytetyössä tutkittiin Turun ammattikorkeakoulun ja arkkitehti Aaro Söderlundin yhteistyössä kehittämää FEC-konseptia; suurta kelluvaa kaupunkirakennetta, jota suunnitellaan rakennettavaksi Tianjiniin, Kiinaan.

Työn alussa on selvitetty FEC:n taustoja ja toimintaperiaatteita. Tämän jälkeen jaotellaan erilaiset kelluvat rakenteet kategorioihin ja tarkastellaan rakennettuja sekä suunniteltuja referenssejä. Seuraavaksi katsotaan hieman laivanrakennuksesta tuttuja vakavuuslaskuja ja esitetään mahdollinen kelluvuusratkaisu.

Työn lopussa tarkastellaan erilaisia elämänkaaritilanteita ja pohditaan katastrofitilanteiden mahdollisia vaikutuksia FEC:n turvallisuuteen. Viimeisessä kappaleessa käydään läpi lisäselvitystä vaativat kohdat ja pohditaan hieman FEC:n erilaisia mahdollisuuksia ja ongelmakohtia.

Työtä on tehty käyttäen hyväksi löydettyjä tutkimuksia ja artikkeleita, laiva-alalta tuttuja sääntöjä sekä opiskelutovereiden ja Pentti Häkkisen & Aaro Söderlundin tarjoamia näkökulmia aiheeseen.

Hakusanat: Kelluvat rakenteet, VLFS

Säilytyspaikka: Turun ammattikorkeakoulun kirjasto

TURKU UNIVERSITY OF APPLIED SCIENCES ABSTRACT

Mechanical engineering	
Tuomas Wasén	
Naval engineers look on the FEC-concept and other VLFS-structures	
Naval architecture	Pentti Häkkinen
05/2011	

This bachelor's thesis studies the FEC-concept – a large floating city structure, planned to be placed in Tianjin, China - developed by Turku University of Applied Sciences and architect Aaro Söderlund.

At the beginning, we take a look on the FEC and the idea behind it as well as some of the basic principles of it. After this, we divide the floating structures in to categories and take a look at the built and developed references. Next we introduce some basic stability calculations and present a possible solution for the displacement.

At the end we view different lifespan issues and assess the possible effects of a catastrophe situation on the safety of the FEC. Last chapter takes a look on some of the issues that need more research and also gives some insights on the possible problems and possibilities of the FEC.

The thesis was done by using various material gathered along the way, regulations used by the naval industry and also the insights given by fellow students and Pentti Häkkinen & Aaro Söderlund.

Keywords: Floating structures, VLFS

Deposit at:

CONTENTS

APPENDICES

FIGURES

1 Introduction

This bachelor's thesis was done as a part of Turku University of Applied Sciences Floating EcoCity –project. It studies the different technical requirements of a very large floating structure or a Mega-Float as it's commonly referred as.

The main reasons for developing floating cities is simple: due to the population growth land areas are under heavy use and therefore land value has risen dramatically. Especially large coastal cities are put in a tough spot when the need for expansion rises. For a long time the solution has been vertical; building skyscrapers and other tall buildings has been the easiest way. Thanks to technical advancements over the past few decades ocean colonization has become both technically and financially possible.

1.1 Climate change

Climate change has been a major focus of global attention for the past decade. Global warming has caused the sea levels to rise in the 20th century at the average speed of 1,7 ± 0,5 mm y^{-1} (Solomon, S et al. 2007, 409). Reports also show that as we have come closer to the 21st century, the rate at which sea level has risen has increased; estimations based on satellite altimetry suggest that the sea level rise has been as high as 3,1 ± 0,5 mm y^{-1}, but tide gauges show a similar decadal pattern in the sea level diagrams since the 1950s, so it still remains to be seen is it a matter of decadal variability or a change in long term. What also needs to be noted is, that satellite altimetry is a relatively new method of measuring. Before the early 1990s man relied solely on tide gauges, so the results aren't entirely comparable.

Sea level rise varies around the world. In some regions the sea level rise is several times the average rate, where as in other regions the sea levels have dropped. Areas with low coastlines and strong interannual variability in sea levels are under heavy observation. The Netherlands suffer every year from flooding, and the Maldives are in danger to be completely wiped out. If sea levels reach the 0,44 m above 1990s sea levels, as suggested by scientists, land reclamation and building dams just isn’t efficient any more.

1.2 Floating EcoCity

Tianjin is a harbour city of Beijing on the delta of Huang He in China. It is one of the fastest developing industrial regions in the world, with an annual growth of c. 15% in 2009. The area is populated by 12M inhabitants and it is one of the three central areas of development in modern China, along with Hong Kong and Shanghai, thus it provides an excellent test ground for urban architecture and city development. (Söderlund & Kääriä)

The Tianjin area faces many different challenges – both human and natural. Soaring land prices, pollution and ever-growing population are just the newest additions to the list of challenges, which is already filled with various natural problems such as sandstorms, floods, tides and even earthquakes and tsunamis. The water is polluted and acid rains pour down frequently.

Investors are already looking for new solutions. The Floating EcoCity –concept (FEC-concept) is aimed to ease these problems and help Tianjin to continue its growth. By building floating islands, the city would be able to expand in a whole new way. The skills to build something this big are already there within the shipbuilding world. After all, the worlds largest cruise ships aren’t much different to the FEC – basically only the propulsion is missing.

The FEC consists of two basic units, the hexagonal platforms and the EcoFlo Vessels. The latter ones would be newbuilt, but also Malaccamax-size (470*65*20 m) tankers could be used in case of recession. Both, the hexagonal platforms and the EcoFlo Vessels, would have central parks framed by the apartments and covered by a tent, which creates its own mini-biosphere for the FEC.

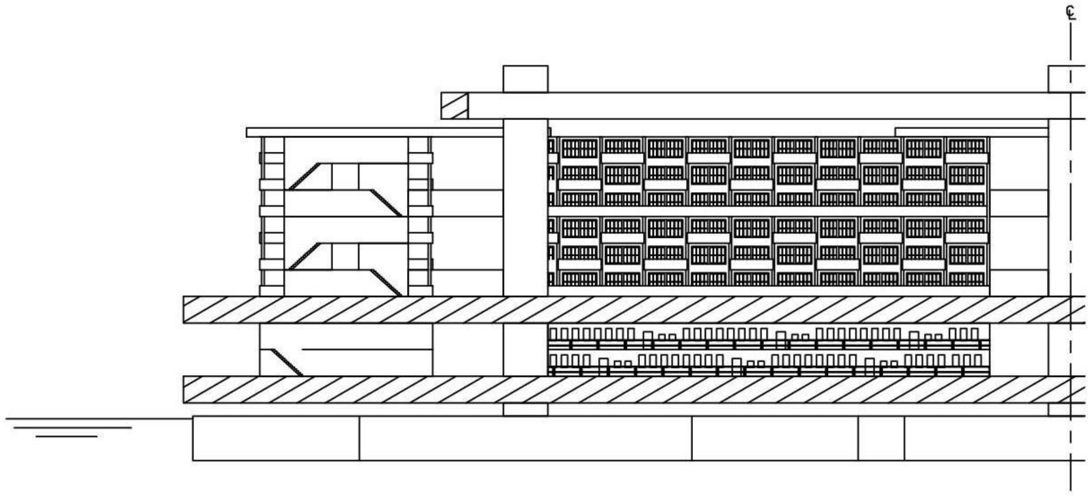

Figure 1 Intersection of the hexagonal platform structure

Figure 1 explains a little about the structure of the FEC, when it is structured of the hexagonal caissons. The whole structure would stand on six separate caissons, which would provide the buoyancy. On top of that, there would be the lower platform with all the storage and maintenance space. And on top of that there would be the upper platform, with the apartments and the central park.

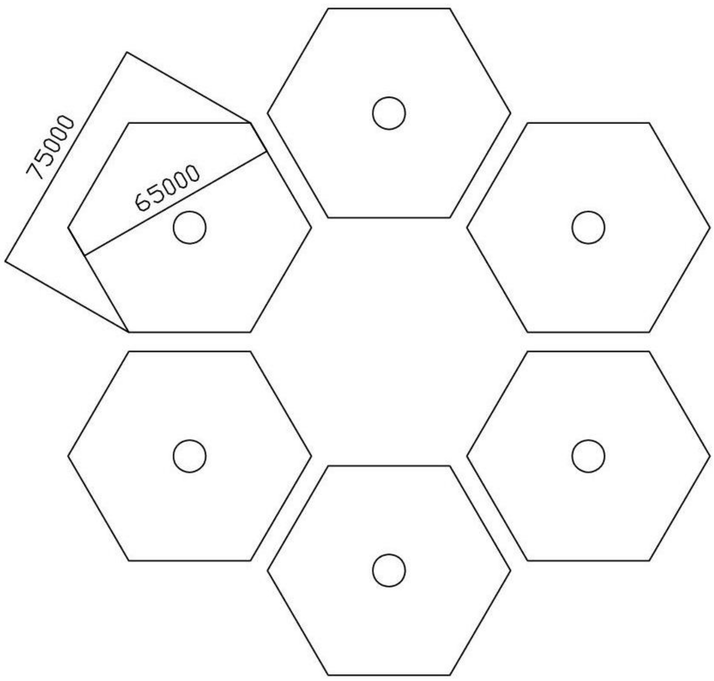

Figure 2 Hexagonal caissons (Söderlund 16.12.2010, personal notification)

Figure 2 shows the positioning of six hexagonal caissons below the lower platform. Hexagonal platforms would be standing on six smaller hexagonal caissons, which would offer unmanned storage space for pumps, batteries and other necessities. Each caisson would have a column on its weight point, which would be in line with the columns that support the biospheric tent. The caissons would be detachable for maintenance situations; the FEC would be designed so that it would still survive if one of the caissons should be removed or damaged. Between the caissons there would be “ButterFlexes” that absorb and collect the energy caused by the waves and the movement of the caissons.

The FEC is also aims to tackle the ecological problems by being CO2-negative, with the central parks greenery purifying the air, water and soil in addition to producing oxygen. The improvement of water quality would be handled by aquatic macrophyte farms, which would locate under the pontoons next to the caissons.

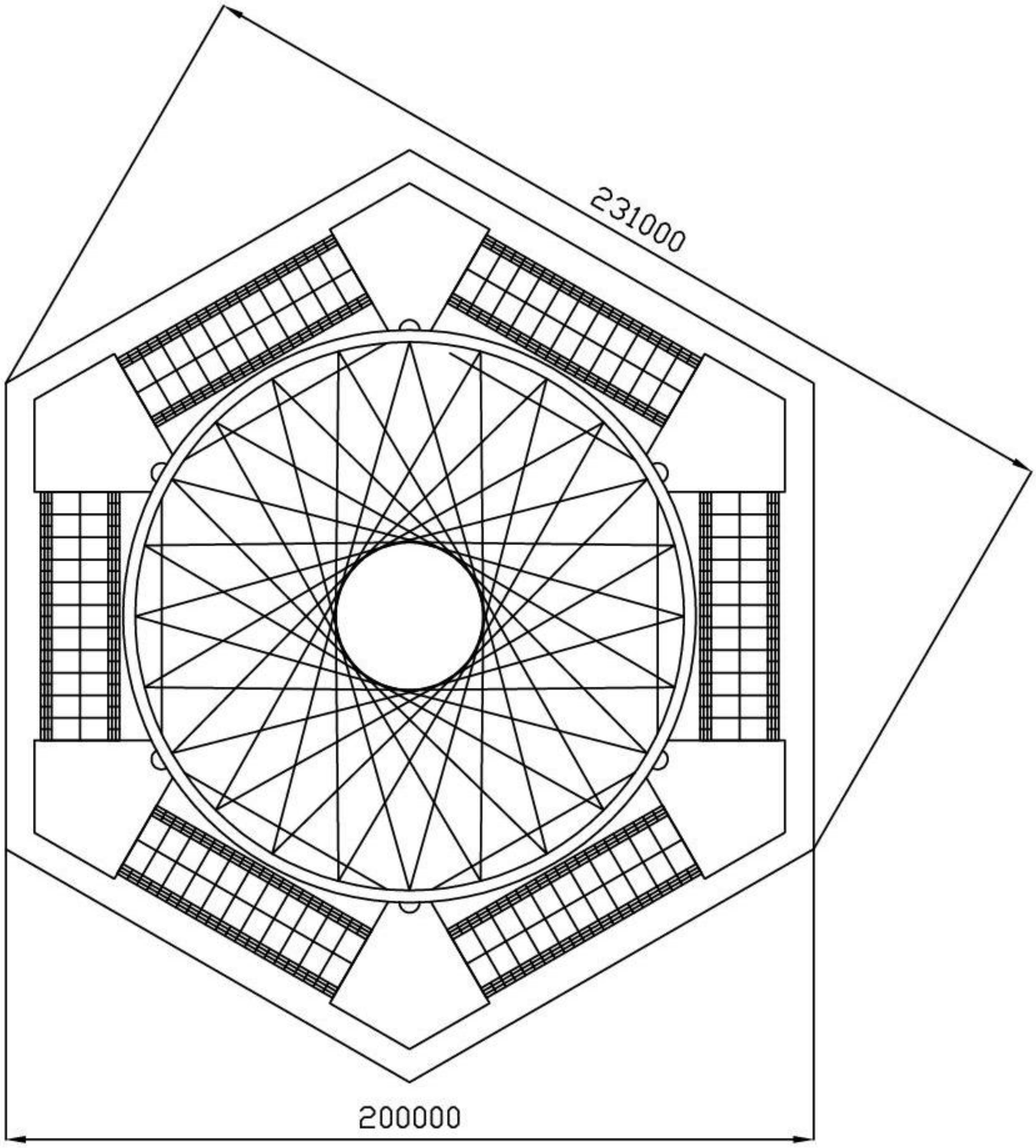

Figure 3 Upper platform with the biospheric tent (Söderlund 16.12.2010, personal notification)

The infrastructure would be built on two different platforms set on top of each other. On the lower platform which would be 1,5 meter above sea level, there would be storage spaces roads, car parks, and service spaces. The free height would allow 2 floors, which should be sufficient for all the needed service space. The upper platform would primarily serve as a space for the central park and the apartments. One platform would hold 6 floors of apartments – 264 of them altogether. The apartments would be pistol-shaped lofts, so that there could be four sets of apartments laid on top of each other, with the corridors on the 2^{nd} and 5^{th} floor.

1.3 Thesis' goals

These thesis aims to take a look on the FEC-concept from a naval engineers perspective and introduce other floating structures with some similarity and/or adaptable features to the FEC-concept. Even though the thesis is based on the FEC-concept, its considerations can be used on similar structures and one of the goals is also to evaluate VLFSs as habitable structures on a more universal level. Some weight evaluations will be made and lifespan issues, such as maintenance and tsunami & collision situations will be brought up.

At the end of the thesis, there will also be a list of critical points that would need to be researched and assessed before the actual building process could begin.

1.4 Scope of the thesis

The FEC-project is a large project, as one would guess, and thus defining the limits for my thesis is inevitable. One hexagon platform alone is supposed to inhabit around 800 people, who expect their basic needs to be covered; basic infrastructure (plumbing, transportation, energy, garbage disposal) nurseries, schools, leisure activities etc. If EcoFlo Vessels are used, large tankers need to be converted into functional units, and that brings up its own problems.

This thesis concentrates on the hull structure and stability of the hexagonal platform, thus leaving out the possibility of using Malaccamax-sized ships as EcoFlo Vessels. Also, no in-depth look will be made on the basic infrastructure such as plumbing, services, energy production and waste management etc.

1.5 Methods

The amount of published material seems to be endless. Going through it will take a lot of time, and probably the same amount will be used just to eliminate the unessential information. The engineering and architectural world seems to be full of ideas about ocean colonization. Most of the information discussed in the thesis is taken from the material provided by Aaro Söderlund, who is the main architect behind the FEC-project.

When calculating masses and stabilities, the absence of structural plans and calculation programs will be a problem. Horizontally the weight distribution would probably be if not right at the centre line, but at least very near it. Vertically the weight distribution depends a lot on the structure and what is actually built on the FEC. Therefore the calculations will only be directional and universal, and only principles will be featured. Since the FEC is only in its basic design phase, certain information such as weight and weight distribution are still missing. A rough estimate on the weight can be used if needed; it is estimated that a large cruise ship weights as much as $0{,}12T/m^3$ (Levander, 2007). However, this is only an estimate and whether or not it is usable on the FEC remains to be seen. This makes it impossible to compute the GM. Also, when the classification society DNV was interviewed (Pösö, 31.1.2011), no definite answer was given about which rules would be applied. So, even if the GM could be calculated, the results could not be compared to anything.

2 Floating structures

Floating structures can be separated in to *eight different categories* according to the use of the structure (E. Watanabe et al. 2004). As time goes by and the use of floating structures becomes more common, these categories will go under observation as some of them are quite vast.

Even though ocean colonization has not yet come to reality, floating structures have been used through history. Around 480 BC, the Persian king Xerxes led his troops across the Hellespont using about 600 boats laid in two rows. *Floating bridges* are commonly used around the world even nowadays. There are three over mile-long floating bridges in Lake Washington. Norway has the Bergsoysund bridge, which is 845 meters long and also the 1246 meter long Nordhordland bridge. Japan built the 410 meter long Yumemai Bridge with the idea, that it could be swung aside if a channel for a very large ship needed.

Floating docks, piers and container terminals are ideal for ships; since both of them float their position is constant with respect to the waterline. They also have the advantage when building in deep waters.

Floating storage facilities and *floating emergency bases* are most commonly used in the Far East, especially in Japan and its coastal cities. The greatest advantage, which these structures have, is that they're completely isolated from earthquakes. Environmentally hazardous materials such as oil can be stored in a very safe way, by using floating storage facilities. People are also protected with a similar method; when an earthquake threatens people are loaded onto the emergency base which is transported and moored away from the shore.

Undeveloped and under-construction coastal areas need basic infrastructure, like energy production and waste disposal. *Floating plants* are an excellent solution for this. They can be towed from location to another, or if needed, installed onto its location. *Floating entertainment facilities* follow the same idea. The term itself is a bit confusing as floating houses can be put in to this category, although the study (E. Watanabe et al. 2004) doesn't mention floating houses at all. Entertainment facilities and houses are very much alike – only the function differs. Both facilities have plumbing, heating and social spaces. The study also proposes, that "VLFSs have been constructed to house entertainment facilities with a scenic 360 degree view of the surrounding water body" which probably adds to their appeal.

Floating airports and mobile offshore bases are ideal comparisons when studying *floating cities*. Both categories consist of VLFSs of the highest structural complexity.

Especially airports, which are long, have to sustain large longitudinal tensions caused by the movement of the water.

2.1 Built references

On the next seven chapters, there are some examples of the built references of floating structures.

2.1.1 Floating bridges

- Bergsoysund Bridge. Norway. Pontoon bridge. 931 meters. Opened in 1992.
- Lacey V. Murrow Bridge. USA. Pontoon bridge. 2020 meters. Opened in 1940. Rebuilt last in 1993. Still a floating structure.
- Evergreen Point Floating Bridge. USA. Pontoon bridge with movable midsections. 2310 meters. Opened in 1963. Planned to be replaced because of capacity problems
- Yumemai Bridge. Japan. Pontoon/Arch Bridge. Opened in 2001.

Figure 4 Yumemai bridge (© All rights reserved by ingis_jpn)

2.1.2 Floating docks, piers and container terminals

- Floating dock in Texas Shipyard. USA. 124m*109m. Built in 1985.
- Floating pier in Ujina Port. Japan. 150m*30m*4m.
- Valdez Floating Dock. USA. 210 meter long dock designed for berthing container ships. Built in 1982.

Figure 5 Floating dock in Sevastopol (© George Chernilevsky)

2.1.3 Floating storage facilities

- Kamigoto oil storage facility. Japan. Capacity of 4,4 million m^3.
- Shirashima oil storage facility. Japan. Capacity of 5,6 million m^3.

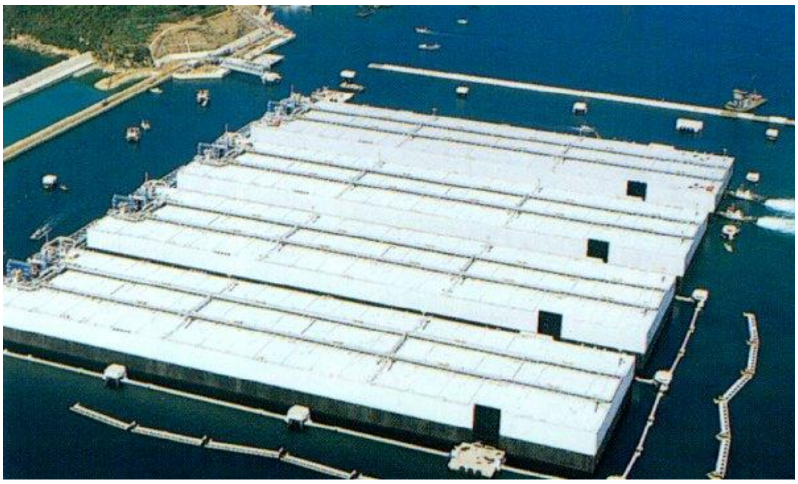

Figure 6 Kamigoto oil storage facility

2.1.4 Floating emergency bases

- Several rescue bases parked in Tokyo Bay, Ise Bay and Osaka Bay. Japan. Used in case of tsunamis and earthquakes.
- Brahmaputra Response Base. India. Used mainly to counteract drowning incidents.

Figure 7 Brahmaputra Response Base (© Ritu Raj Konwar)

2.1.5 Floating plants

- Two-sectioned plant. Brazil. 230m*45m*14,5m. One section pulp plant and the other a power plant. Constructed in 1978.
- Floating power plant. Bangladesh. 60,4m*46,6m*4m. Purchased in 1979 from Japan.
- Akademik Lomonosov. Russia. Floating nuclear plant. 144m*30m*10m. Launched in 2010.

Figure 8 Akademi Lomonosov (© Reuters)

2.1.6 Floating entertainment facilities

- Onomichi Floating Island. Japan. Amucment facility. 130m*40m*5m.
- The Estrayer. Japan. Entertainment facility. 128m*38m.
- Awaji Island Fishing Pier. Japan. 102m*60m*3m.

Figure 9 Floating Jumbo restaurant in the Philippines

2.1.7 Floating airports and mobile offshore bases

- Floating airfield. USA. 1810ft*272ft. Constructed in 1943. Was eventually disbanded after the Charles Lindbergh flight.
- The Mega-Float. Japan. Floating runway. 1000m*60m*3m. Has been dismantled and is no longer in use.

Figure 10 The Mega-Float

2.2 Planned references

Many of the planned VLFS-projects have been born from the fact that our current living conditions are not probably as permanent as one would hope. Earth population has more than doubled since the 1960s and so has the annual energy consumption. Over the last two decades scientists have become increasingly worried over the fact that we are consuming more energy than we can produce and at the same time we're producing more and more pollution than what we – or the earth – can handle. CO_2 emissions cause global warming, which cause sea level rise and thus create problems on already overpopulated coastal areas. The Shimizu Corporation has two extremely interesting projects involving floating structures: Green Float – a botanical city concept - and the Shimizu Mega-City Pyramid – a massive pyramid constructed in the Tokyo Bay.

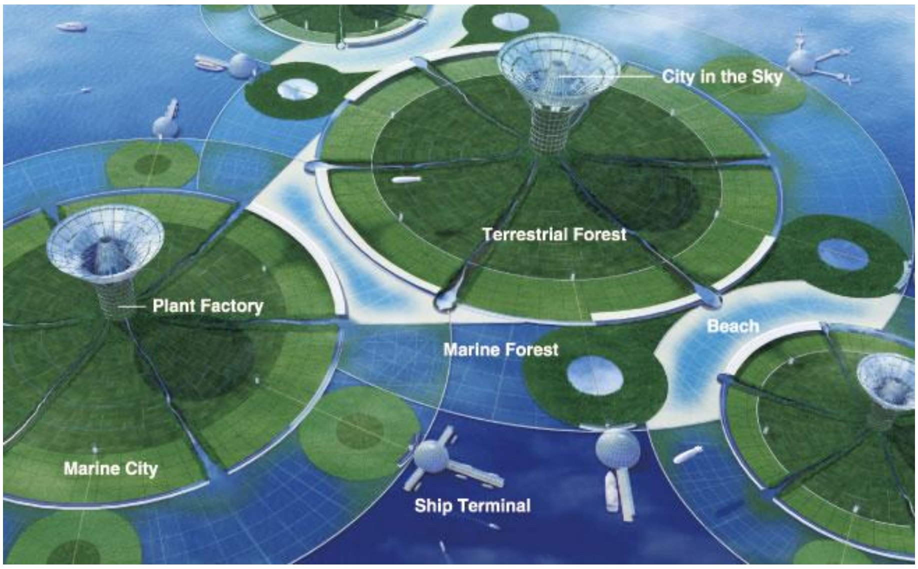

Figure 11 Shimizu Corporations Green Float

The Green Float is aiming to be carbon negative, self-sufficient food wise and waste-free. The islands are supposed to locate in equatorial areas, which would mean ~27°C degrees year-round, minimal typhoon impacts and virtually no affect from tsunamis, due to its enormous size and sufficient water depth. A single island could inhabit as many as 40000 residents.

Figure 12 Shimizu Corporations "Pyramid City in the Air"

The Mega-City Pyramid was introduced on Discovery Channels show Extreme Engineering; a pyramid 14-times the size of the Great Pyramid at Giza, housing 750000 people and reaching a height of 730 meters. As Tokyo is the largest city in the world with over 30 million residents, this structure would bring some relief to the lack of space in the Greater Tokyo Area. In addition to the residential areas, the pyramid would serve as a working place for as many as 800000 people. However, the structure is so massive that it would not be possible to build it with materials and methods of today. Therefore the whole project is just a plan for now. And even though the structure itself is not floating, the innovations behind the project could take the engineering world by storm; new materials and construction methods could prove to be revolutionary.

At the Venice architecture biennale in 2010 the Australian pavilion introduced an underwater city with large pods to inhabit. Keith Dewey, the owner and designer of zigloo.ca has introduced something similar with a seascraper of the depth of 400 meters. Vincent Callibaut has designed Lilypad, a floating ecopolis for climat refugees. It is a a amphibian city for as many as 50000 people and one of the main ideas behind it is, that it would travel around the world following the marine streams. Maldives, whom would be under a huge threat if the sea levels would rise, have taken the initiative and started to plan floating islands, which would ease their difficult situation. The government has already bought land from nearby nations, and just to make sure that Maldivians are safe extra cautions have been taken.

One of the less scifi-like plans is the Poseidon Project made by the Seasteading Institute. By the year 2015, they would build a seastead for at least 50 people. The idea behind all this is to build a technologically safe and stable structure on international waters, and make sure that the seastead is economically self-sufficient and politically autonomical. Ideologically the Poseidon Project has a evident link with the ideologies of the renowned futurist Jaque Fresco.

3 Hull structure

As the FEC is not supposed to move anywhere, there is no need to take look at the hull hydrodynamic features. As one could guess, the hull wouldn’t differ much structurally from a ships hull. Similar bulkheads, girders and stiffeners would probably be used, and most likely even a double hull would be wise to use.

3.1 Classification

Figure 3 shows the basic flow for the design of a VLFS. And as one can see, the process can be divided into three different stages. On the first stage basic design variables as plate thickness, structural depth and size are defined using a method of hydroelastic response analysis. On the second stage structures are tweaked in according to how the VLFS acts in different loading situations. 3D models are used and irregular situations are taken under observation. The third stage is used for safety assessments; how does the VLFS survive in damage or ultimate stress situations.

When the classification society De Norske Veritas was interviewed, no definite answer was given for which set of rules would be used, but the most likely choice would be their offshore rules. (Pösö 2011) And of course, if there are no applicable rules those could be created in a partnership with the chosen classification society.

After all, the classification societies aim as much to monitor the building of marine structures as they develop new regulations.

In the FECs case, critical points will be the caisson joints and their durability, tensions in the hull caused by the height differences during bigger waves, damage situations – especially how much damage the FEC can sustain without sinking – and loading situations. Figure 3 can be used as a checklist for the design or as a reference point to determine the possible problems when designing a VLFS.

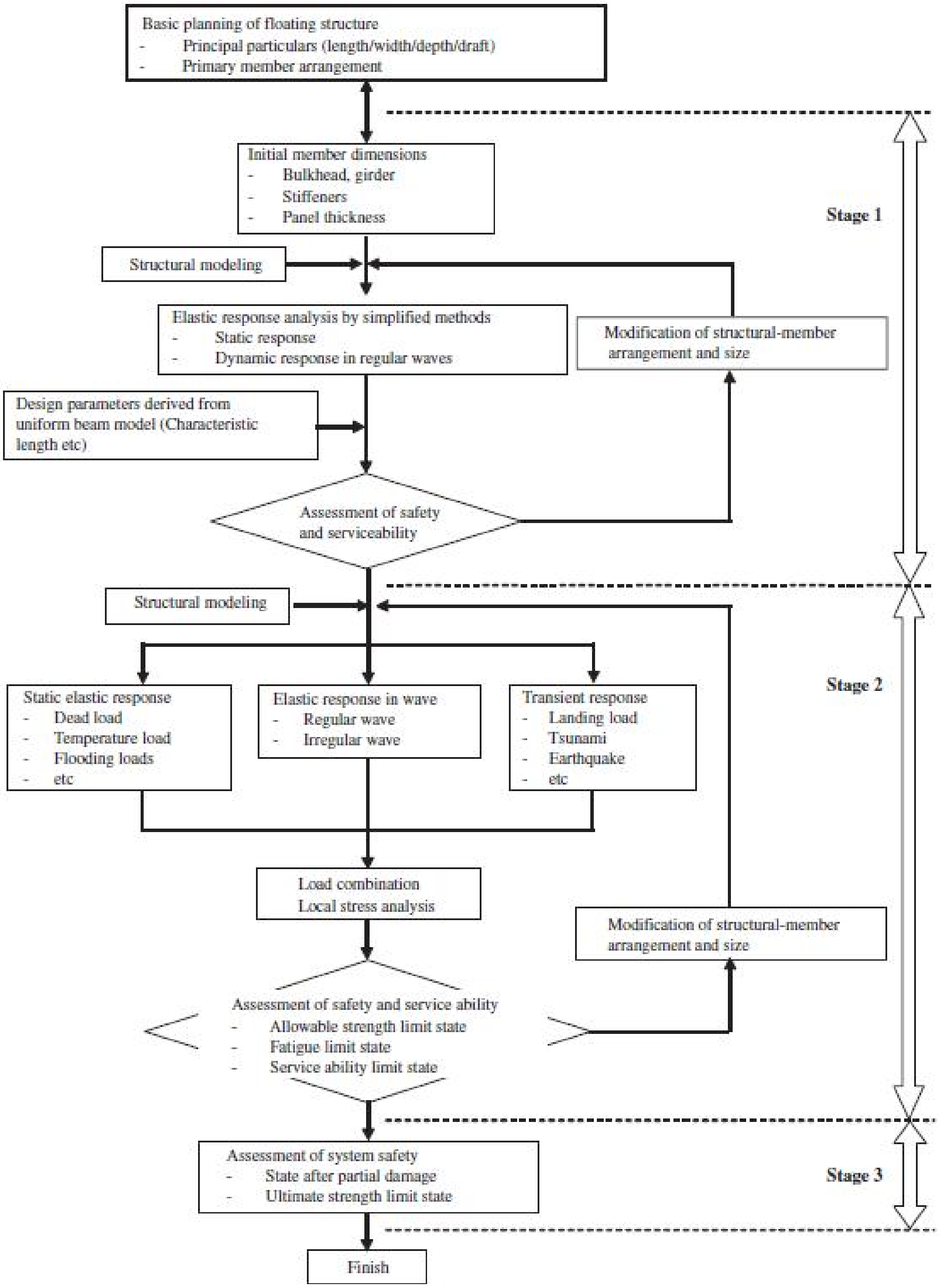

Figure 13 Structural design flow of VLFS (Fujikubo 2004, 204)

3.2 Stability of the FEC

Ships stability is calculated by using two stories; the weight story and the water story, which have to match. The weight story is combined of two distances: KG and GM. KG is the distance between the ships keel point (K) and the centre of gravity (G), and GM is the distance between the centre of gravity (G) and the metacentric height (M) of which the ships holds as a rocking point.

The water story is also a combination of two distances: KB and BM. KB is the distance between the ships keel (K) and the centre of buoyancy (B), and BM is the distance between the centre of buoyancy (B) and the metacentric height (M). When the inclination angle is small (<7°), the distance between the centre of gravity and the metacentric height can be calculated by using the following formula

$$GM = KB + BM - KG$$

When the ship is inclined to an angle (f) by an outer moment (M_{ULK}), the centre of buoyancy shifts (B → B'). This creates a straightening moment (ΔGZ), which in a balanced situation is equal to the outer moment. GZ can be calculated with the simple formula

$$GZ = GM * \sin \varphi$$

Stability regulations are set by classification societies such as DNV, American Bureau of Shipping and Lloyd's. Classification societies are organizations which establish and maintain the regulations for ships and offshore structures. These organizations have their own regulations for stability rules. Applied rules depend on which classification society is used to validate the construction of the FEC.

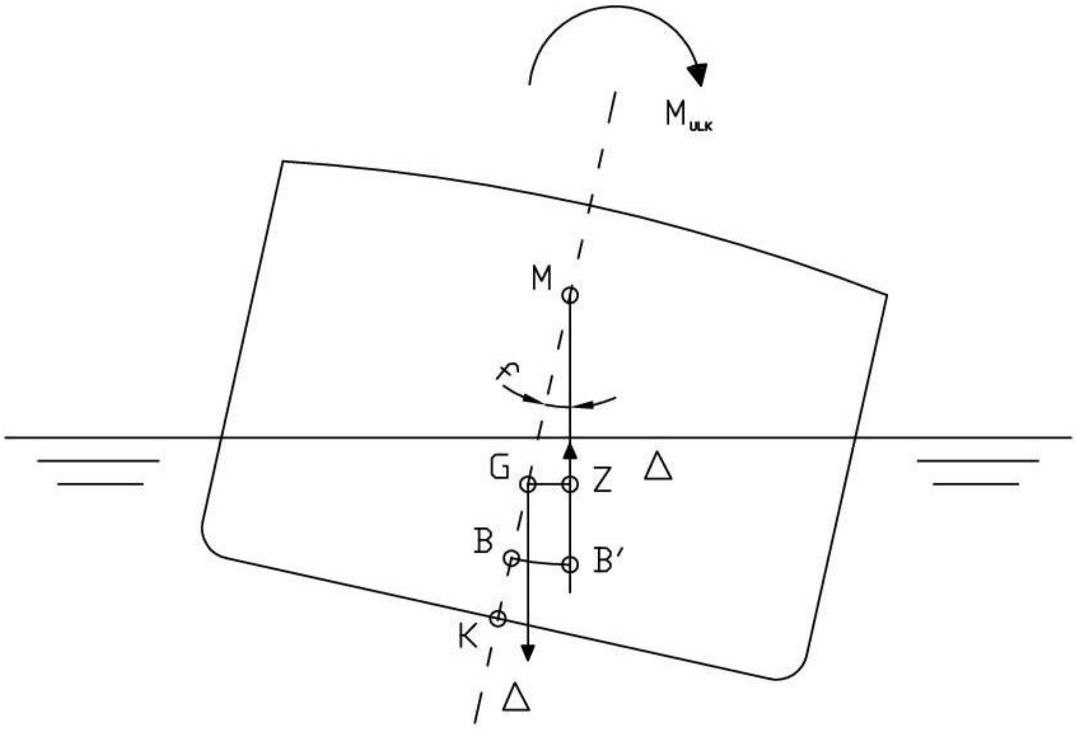

Figure 14 Basic principle of ship stability

This same method can also be applied to the FEC, when computing its stability. What is also favourable is the FECs hexagonal shape, which means that there is no need to compute the longitudinal stability since it is basically horizontally symmetrical.

3.2.1 FEC displacement

As the FEC is supposed to standing on the caissons, which would float the structure, it is important to determine how much the caissons can actually support. The dimension information is still a bit contradicting, but we'll compute an example situation using six hexagonal caissons with a side of 37,5 m and a height of 6 m.

First we need to solve the area of a single caisson

$$A = \frac{3\sqrt{3}}{2} * s^2 = \frac{3\sqrt{3}}{2} * (37{,}5m)^2 \approx 3655m^2$$

Since the caisson would be 6 m in height the overall draught couldn't be more than that - preferably less, of course. With a draught of 5,5 m, a single caisson displaces water as much as

$$\nabla = A * d = 3650m^2 * 5{,}5m \approx 20095m^3$$

As seawater weights 1,025 t/m^3, six caissons would be able to bear the weight of

$$\Delta = 6 * \nabla * \rho = 6 * 20095m^3 * 1{,}025\ {}^{t}\!/_{m^3} \approx 123580t$$

But, since the caissons need to be singly changeable, we need to compute the effect of losing a single caisson. The mass and displacement are only affected by the weight of the removed caisson, so we can use the already computed mass and displacement. By doing this, we will compute the new draught with a larger mass than the FEC has and we'll achieve some safety with the result.

$$d_{NEW} = \frac{6 * d}{5} = \frac{6 * 5{,}5m}{5} = 6{,}6m$$

This exceeds the height of the caisson (6 m), which means, that the original draught needs to be reduced. With the draught of 5 m, we get the following values

$$\nabla \approx 18270m^3$$
$$\Delta \approx 112345t$$
$$d_{NEW} = 6m$$

Even though the d_{NEW} is the same as the caissons height, we need to remember that the FEC has lost the caissons mass and is slightly lighter than with six caissons. What also needs to be remembered is that when one caisson is removed the FEC will incline. The effects of the inclination need to be estimated. More accurate results need to be determined, when the wanted draught and masses are determined.

If the weight would be estimated with the formula (0,12T/m^3) given in chapter 1.5, the weight of the FEC would be

$$200m * 200m * 45m * \frac{0{,}12T}{m^3} = 216000t$$

If the weight would actually be in line with the estimate, the caissons would need to be enlarged. What must be remembered, is that the FEC does not need the same, heavy machinery that a large cruise ship needs. This would of course bring the overall weight down some bit.

3.2.2 Ballast tanks

The use of ballast tanks would be beneficial when an inclination needs to be straightened or when the draught would need adjustment. Such situation could possibly be born when a fleet of cars/trucks move around the FECs lower platform, when one of the caissons is removed or when the structure is damaged and flooded. These situations cause unwanted tensions in the hull, which then could be eased by using ballast tanks.

Placing the ballast tanks inside the caissons would be the most obvious choice; since they are already in the water, the energy used to pump the water would be minimised. When a caisson would be changed, the FEC could be inclined to the opposite direction of the changed caisson by using the pumps correctly.

Of course, when using ballast tanks, there is the problem of free-surface effect. This means, that the GM is reduced when liquid is allowed to move freely inside the structure. The free-surface effect is accounted in the structural design. The use of ballast tanks would require some sort of computer program to calculate the effects and observe the filling process. In a docking situation the needed pumping power and speed is much less than in a collision situation for example, where the use of ballast tanks need s to be quick, efficient and accurate.

4 Lifespan

Just as any other large structure, the FEC should be easily maintainable. As years go by, it needs to stand the test of time and in order to achieve that, possible weaknesses need to be assessed and solutions for these weaknesses engineered. Lifespan for this kind of structure would have to be several decades. During a period of that long the FEC will most probably be challenged in many different ways; tsunamis, earthquakes, corrosion, collisions, fires etc.

4.1 Maintenance

The greatest natural threat for the hull would be corrosion and the polluted water. Corrosion can be controlled by painting/coating the metal, and thus protecting it from seawater. Other methods include the use of anodes or simply by using a more corrosion resistant metal. Of course, cost issues have a huge effect on which method is chosen. HVAC– and interior-maintenance can of course be done on-site, which helps a lot.

4.2 Docking

As pointed out in chapter 1.2, the caissons are removable and changeable. This offers the possibility of leaving the rest of the complex on its place where it’s supposed to be while only removing the parts that need to be maintained or replaced. The removal and installation of a single caisson may prove to be somewhat of a tricky task; waves cause the caissons to move and most probably the removing process would be done from water, which means that there would be two individually moving planes, which makes the task even harder. Easiest way to remove a caisson, would be to submerge it a little then slide it out of its place.

Only a handful of dry docks are able to handle such large structures as the caissons. When choosing a location for the FEC, one should also notice this as transporting the caissons to the end of the earth isn’t rational or even economically smart.

4.2.1 Transporting

Both the caissons and the hexagonal platforms would need to be floated to its site. Since the platforms aren’t meant to float, they would need the assistance of the caissons on that. The width of 231 meters, means that the transportation wouldn’t be easy and would probably be best to use local shipyards to manufacture the structure. Of course the hull could be constructed in parts, which then would be transported on-site and then assembled there. Transporting the caisson should be much easier; with a width of 75 meters the structure would be easier to handle. Tugboats would be an obvious choice for the task.

Apartments could be done modularly, so that they would be easy to install on-site. This would also mean easy transportation, for example on a cargo ship. This means that the apartments would be best to be built fit the TEU-capacity dimensions. The dimensions on Fig.2 would give dimensions of 11,2m*19,5m. The height isn’t given on any of the material, but one would guess that the minimum height would be somewhere above 5 meters. The size could prove a little tricky, but certainly not impossible.

4.2.2 Expansions

With the under 300 apartments, that a single hexagonal platform holds, one doesn’t solve the demand for space in China, for example. For that you need several hexagons set in groups. The hexagons in the group need to be connected with each other, the groups need to be connected with other groups and also some kind of passages with land need to be established. Pontoon bridges are commonly used around the world, and these are an ideal choice for the FEC. As both lay on the water surface, they adapt to the waves and each others movements allowing the complex to “live” a little.

Joints between the hexagons need to endure not only movement in all three directions but also torsion. The use of the same “ButterFlexes” as between the caissons could be a functional solution – the energy caused by the movement would be collected and stored, and later used by the FEC. The passages between land and hexagon groups are an interesting task to handle; the land is stationary where as the hexagons move with the tides and waves. The joints need to endure horizontal movement and torsion.

5 Extraordinary situations

At the third stage of structural design, designers determine how the FEC survives damage situations. How many and which caissons – and to what degree - are allowed to be damaged so that the FECs safety isn't compromised.

5.1 Tsunamis

Tsunamis are usually born from earthquakes, volcanic eruptions or impact events. Basically all mass movement on the water surface or below water has the potential to generate a tsunami. An earthquake is caused by the sudden movement of a tectonic plate. When this happens beneath the sea it causes a vertical movement in the water mass. The potential energy caused by the sudden vertical movement of the water transforms to kinetic energy which is released horizontally. Tsunamis are barely noticeable when in deep water; the waves are at most only a few meters high with the wavelength being tens or maybe hundreds of kilometres. The speed of a tsunami is related to the depth of the water; a tsunami in a 6100 m deep ocean is estimated to travel at the speed of 890 km/h.

Tsunamis act like shallow-water waves, and thus their speed can be calculated using the following formula, where c represents speed, g acceleration due to gravity and H is the depth of water.

$$c = \sqrt{gH}$$

The height of a tsunami can be calculated by using wave heights in deep and shallow water (h_d, h_s) and water depths in deep and shallow water (H_d, H_s).

$$\frac{h_s}{h_d} = \left(\frac{H_d}{H_s} \right)^{0,25}$$

As the tsunami hits the shallow waters it slows down but the energy remains constant. This causes the height of the wave to grow. Tsunamis act like strong fast-moving tides, and not like normal waves which break when reaching the shore – although some times they may break far offshore. As we've seen in the recent years, tsunamis cause immense destruction even with proper cautions made. The tsunami that hit Japan in the March of 2011 was reported to be as much as 38 meters in height and to have reached 10 km inland. It was caused by an M_W 9.0 earthquake. The destruction was devastating and the full effect of it will remain to be seen in the years to come.

The most effective way to avoid tsunami-caused damage is to set the FEC in deep waters. Wave height stays small and at the best case nothing unusual will be noticed. But if the FEC should be built near the shore, breakwaters should be considered. They may help to prevent damages, but as we saw in 2011 not even the biggest of breakwaters can help if the tsunami is big enough. A 63 meter deep and 1960 meter long breakwater failed to prevent the tsunami to hit Japan. Of course, tsunamis of this kind of magnitude happen so very rarely, but worst case scenarios need to be thought out.

Pacific Ocean is filled with tsunami warning equipment. Depending on where the tsunami is born, adequate time to take precautions may be possible. Floating the FECs away from the shore would also be an effective way to prevent destruction. This requires adequate arsenal of tugboats, fast uncoupling mechanisms and reliable warning systems. Possible passages from land to the FEC also need to towed away as they might cause severe damage if they would hit the shore.

Mooring equipment needs to be reliable and safely secured in the seafloor. If a gigantic structure such as the FEC is let loose with the tsunami, not only is the FEC in danger, but also everything on the shore. Fastenings between the FECs should prevent larger collisions between the FECs and even prevent them to crush one another.

5.1.1 Resident safety

The apartments on the FEC are stationed around the central park; six blocks and six floors. Each apartment is pistol-shaped, and that means there are four apartments laid on top of another. The corridors would be located in the 2^{nd} and 5^{th} floor.

If a tsunami hits the FEC, there is a possibility that the apartments are crushed against each other which would mean that the corridor becomes hazardous. Secure fastening of the apartments is essential. Emergency ways should be clearly labelled and fast evacuation is crucial. Maybe even some kinds of tsunami shelters ought to be built; a shelter for 800 people needs space and this would mean a larger size for the FEC.

In case of a fire breaking out, the apartment blocks would need to be divided into firezones. This way the fire itself could be isolated and only some apartments would be lost. The parting could be done both vertically and horizontally; 1^{st}, 2^{nd} and 3^{rd} floor would be isolated from the 4^{th}, 5^{th} and 6^{th} floor, and horizontally the dividing could be done by every 4^{th} apartment, for instance. Extinguishing could be done using the Hi-Fog water mist fire protection system, since it’s proven its functionality in the marine industry.

5.2 Collisions and leakage

Such as any marine structure, the FEC needs to be designed so that it can stand collisions to some degree. Since the FEC would be stationary, the most likely thing to cause a collision would be a ship or another FEC. A strayed ship is probably the more likely, from these two, to cause the damage, since the FEC would only move in a situation where its moorings would break. A fundamental issue is the fact, that how many caissons can the FEC lose and still be afloat. As the FEC is designed to be stable with only five caissons because of the changeable caissons, the loss of one isn’t critical. The loss of two adjacent caissons could already be critical, since buoyancy could be lost on that side and thus the whole structure could become unstable. In theory, it could even be possible to build the FEC so that it could survive with only three caissons left.

It would even be smarter to design the FEC so, that if a collision occurs the force behind it wouldn't destroy the FEC itself, but it would dislodge the moorings and let the FEC move. If the collision would happen with the passages between the mainland and the FEC, it would be better for the passage way to suffer the damage.

6 Conclusions

6.1 Further research

In order to determine the stability of the FEC, one needs to determine the dimensions and masses of the structure. As mass depends a lot on the size and what is mounted on the FEC, the basic dimensions need to be assessed first. After this, structural modelling can be commenced and thus start evaluating the stiffness of the structure. A lot of this can be done using NAPA or a similar computer programme.

Load responses need to be researched; static, elastic and transient responses need to be researched not only individually but also as combined stress factors. Transient loads, such as tsunamis and earthquakes need to be studied further to determine their impact on the location. At this point, if the loads are too strong the use of ballast tanks and what can be achieved by using them comes imminent.

Collisions and tsunamis could cause massive damages, but how to minimize the threats? We have already pointed out that by placing the FEC in deep water helps to avoid the effects of a tsunami, but if the FEC would to be placed near the shore, what could be done to help prevent damages? A breakwater probably, but how big is needed in case of a worst case scenario? And what about, the moorings; we most certainly do not want the FEC to drift ashore or against another FEC, causing severe damages. Could the damages caused by collisions be prevented? Double hull is always a good start, but could some sort of buffers be used? Or what sort of benefits would be achieved if the FEC's could move a bit to avoid bigger collisions?

If the caissons are used as presented, how to make sure that the joints are durable? Of course, the caissons are to be replaceable, but to make sure that they do not bend and break in case of a collision or a tsunami, should one consider several joining points?

The use of “ButterFlexes” can also be questioned. Are they durable? What do they cost? How much do they produce energy? And most importantly, are they cost efficient?

All in all, a complete structural modelling should be done with also a look on the extraordinary situations and their effects on the FEC. With the assistance of a classification society, proper regulations need to be determined and hence stability issues should also be covered.

6.2 Summary

When going through the material the task ahead seemed endless and hopeless. Many of the planned references were sci-fi like dreams about a better world living harmoniously with the surrounding nature. Many of the presentations were about pretty pictures rather than engineering skills.

Floating cities are, if not the present, but the very near future. Building methods and regulations have and will still evolve; classification societies have given a clear signal about the growing demand for such structures and are determined to answer to that call. Especially Japan and China show a definite interest on floating applications. This would ease the pressure on their coastal growing centres such as Tianjin, China. Also, countries like the Netherlands and the Maldives, which would suffer from sea level rise could find a solution by building floating housing.

As I was told, one of the reasons behind creating the FEC-project was to create more opportunities for the suffering marine industry. This is a good point; the skills to construct these kinds of structures are there. Structurally a floating city doesn’t differ much from a cruise ship and in some ways it would be an easier task. It isn’t supposed to move anywhere, there’s a lot less machinery and hydrodynamics aren’t important.

Critical points when designing a floating city are stability, system safety and cost efficiency. The structure should be able to handle rough waves without tipping over. It should also survive the loss of its buoyancy. And since one of the reasons behind building something like this is the rise in land costs, it should be cheaper compared to the traditional city building.

The proposed hull form for the FEC is an ideal choice; it’s basically symmetrical horizontally, which gives it a good, even stability. A large GM would be imminent, since large inclination angles aren’t desirable due to living comfort. Constant monitoring of the structures stability could be wise, and to help the stability ballast tanks should prove to be beneficial.

General arrangements should be well thought of with sufficient service spaces and spaces for machinery and tanks; HVAC-spaces, pump rooms, generator rooms, black and grey water tanks, fire water tanks, sweet water tanks etc. Even floating power plants could be used if lack of space occurs.

Since the structure would be meant to last for decades, maybe even centuries, lifespan issues arise. To help prevent problems quality materials need to be combined with a first-class workmanship. Natural threats need to be assessed, and to be met with proper caution. Modularity is imminent, since it allows easy installations and maintenance. Most of the maintenance work should be able to perform on-site, instead of transporting the whole structure to a far away country.

Tsunamis would be avoided by stationing the structure in deep waters, and if that isn’t possible breakwaters should be built. They could even be built in deep waters to ease the effect of waves. If a tsunami would hit the structure, there’d be two critical issues; mooring durability and resident safety. Moorings should hold the structure in place, so that it wouldn’t to shore or against other structures. No detailed information about tsunamis was found; tsunamis aren’t predictable and so they are hard to study. What was found, was that tsunamis – force-, height- and speed-wise are related to the magnitude of the displacing force and the depths of the water.

Following SOLAS-regulations should prove to be a good choice; the regulations have proven to be functional when safety issues are concerned. Well planned firezone distributions and exit routes, with an evacuation plan could save lives. If leaks were to occur pumping stations would be needed.

7 List of references

Pekka Räisänen (toim.) 2000. Laivatekniikka, modernin laivanrakennuksen käsikirja. Turun ammattikorkeakoulu.

Alexey Andrianov 2005. Hydroelastic analysis of very large floating structures. Delft University of Technology.

Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.). Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

E. Watanabe, C.M. Wang, T. Utsunomiya and T. Moan 2004. Very large floating structures: applications, analysis and design. Centre for Offshore Research and Engineering. National University of Singapore.

Current World Population. Available http://www.worldometers.info/population/

BP Statistical Review of World Energy June 2010. Available http://www.bp.com/ > Reports and publications > Statistical Review of World Energy 2010

H. Suzuki, H. Suzuki, B. Bhattacharya, M. Fujikubo, D. A. Hudson, H. R. Riggs, H. Seto, H. Shin, T. A. Shugar, Y. Yasuzawa and Z. Zong 2006. ISSC committee VI.2: Very Large Floating Structures.

Masahiko Fujikubo 2005. Structural analysis for the design of VLFS. Hiroshima University.

Prof. Stephen A. Nelson 2010. EENS 2040 Natural Disasters. Tulane University. Available http://www.tulane.edu/~sanelson/geol204/tsunami.pdf

Life of a Tsunami, U.S. Geological Survey, 2008. Available http://www.usgs.gov/ > Natural Hazards >Tsunamis > The Basics: Life of a Tsunami

Japan (East Coast of Honshu) Tsunami, March 11 2011. Available http://nctr.pmel.noaa.gov/honshu20110311/

Physics of Tsunamis, West Coast and Alaska Tsunami Warning Center Available http://wcatwc.arh.noaa.gov/ > Tsunamis > Tsunami Science > The Physics of Tsunamis

Repair Dockyard List, ClassNK. Available http://www.classnk.or.jp/ > Information Services > Classification Related > Repair Dockyard List

TRY2025 The Environmental Island -GREEN FLOAT-. Available http://www.shimz.co.jp/english/index.html > Shimizu's Dream > GREEN FLOAT

TRY 2004 The "Pyramid City in the Air" Concept. Available http://www.shimz.co.jp/english/index.html > Shimizu's Dream > TRY 2004

Lilypad, a floating ecopolis for climate refugees. Available http://vincent.callebaut.org/ > Projects > Lilypad, a floating ecopolis for climate refugees.

The Poseidon Project: Building The World's First Independent Seastead by 2015. Available at http://seasteading.org/ > Home > Old Poseidon Page

Aaro Söderlund, Juha Kääriä. Case Floating EcoCity Tianjin China.

Pösö, Antti 31.1.2011. Antti.Poso@students.turkuamk.fi

Kai Levander 7.-8.2.2007. Laivatyypit ja meriliikenne. Laiva-alan luentopäivät, Turku.

Tsunami Facts and information, Australian government, Bureau of meteorology. Available http://www.bom.gov.au/index.shtml > Tsunami warnings >Tsunami facts and information.