Fish Farming in Floating Structures

Tor Ole Olsen

Abstract The world will see an increased use of floating structures for various purposes as well as an increased harvesting of food from the sea. Farming of salmon has become a major contributor to food. Norway has excellent conditions for farming salmon; a long coastline (100,000 km including islands) with nice and fresh water. Norway produces 1.3 million tons of salmon per year (the weight of all Norwegian people is 0.3 million tons). The export value of salmon is the second largest after oil and gas. Starting from a small scale some 50 years ago, entrepreneurial fishermen have developed salmon farming into a huge business. Traditional salmon farming is performed in open nets. The open net solution is inexpensive, and suitable when placed in pure and clean water with ample current that provides for changing the water, which is important for salmons. However, there are challenges for the open net approach. The nets are vulnerable, and a broken net allows farmed salmons to escape, and possibly mingling with the wild salmons. The open net allows feces to fall through, and polluting the sea. Sickness may be spread by toxic water, and sea lice may enter and infest the fish. The obvious remedy to these challenges in "crowded" areas is to farm in closed buckets. One prototype bucket was designed, built and installed on the west coast of Norway, with excellent results. No salmon lice were found in the bucket. The salmon "liked" the closed bucket because one can provide a current that gives the salmon exercise. Salmons farmed in this way are larger and better fit, and thereby achieve a higher selling price. There are many activities around farming that will be described in the paper, and they are linked to the experience of marine concrete structures in general.

Keywords Fish farming · Floating structures · Design of floating structures · Design for fish welfare

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1 Introduction

As a designer of concrete structures you need to know stresses and strains, behavior of the reinforcement, the loads, and many other things. As a conceptual designer of concrete structures, you also need to understand the purpose of the structure. All structures have a purpose. When designing a bridge conceptually, you have a number of handbooks to form your basis for design. Every country has road authorities that produce a number of handbooks. How do you proceed when designing for fish welfare? The fish, obviously, does neither speak nor write handbooks. You need to rely on experience and other disciplines, like biology.

2 Present Technology

Industrialized fish farming started with entrepreneurial fishermen throwing nets out from their seaside properties, and farming fish in them. Fish farming depends on local and national legislations, as well as relations to environmental restraints, local people, unions and costs and economics. I shall refer to fish farming in my country, Norway, that I know the best.

There are 4000 open net cages for fish farming in Norway, the largest 160 m in circumference. This size is tuned to the maximum number of fish allowed in one cage, 200,000. The reason behind this limitation is the consequence of failure of the net and farmed fish mingling with wild fish. Norway produces 1.3 million tons of salmon a year. The weight of all Norwegian people, large and small, is 0.3 million tons! In 2018, Norway exported seafood, not only salmon, for 10 billion Euros, which is more than the export value of wine from France. If every Norwegian should eat all the exported seafood, they would have 7 seafood meals a day, every day of the year. So seafood is important for Norway. But there are challenges!

Norway has a lot of gifts from nature: clean water, proper temperature, long coastline (100,000 km including islands), protected fiords, and long traditions of mastering the sea, which has been so important for the country.

So what are the challenges?

- *Lice* certainly influence the welfare of the salmon. In addition it is costly to handle, and lice is a quick adaptor to new treatments. Many years ago it was believed that the cure was close at hand, but the opposite is the case.
- *Escaping salmon* is, of course a loss, but it is also a danger to the wild salmon, through mixed breeding.
- *Feces*: Fish live in the ocean, and the ocean can take care of feces. The problem is when the feces is concentrated, as it is in many Norwegian fiords.
- *Overfeeding* means that some of the feeding goes straight through the net. Neighboring fish have no limits to intake of food, and becomes deformed.
- *Medicines* where doses do not only go to the needed ones.
- *Illness* speaks for itself, and it becomes a large problem in congested areas.

It is obvious that most of the problems are associated to "crowded" areas. It may sound a bit spoiled to say this, Norway has a land area of 533 times that of Singapore, and approximately the same human population. But many of the fiords are "crowded" by fish farming cages. The result of all this, in Norway, is that production of salmon has not increased since 2012, in spite of the wishes from politicians and others.

3 Cure

The simple cure, in a "crowded" area, is a watertight cage. Obvious it might seem, but there are some hesitations. Mostly because it is a novel way of fish farming, and it is a way of fish farming that reduces the benefits of clean and properly tempered water. And there is a cost issue. However, the benefits against external threats are clear. In floating closed cages, one can collect the water from a depth beyond the lice. The cost of pumping is not so large, as the water level inside the closed cage is almost the same as outside. The water needs to be changed every 60–90 min. One can collect the feces, and dry it and use it for fertilizing, or even fuel. As an example, cement producers are looking for alternatives to fossil fuel, to reduce the environmental impact of cement production.

Another cure is moving the farming offshore, to a less "crowded" area. An open net may be used, but it needs to be protected against ships and propellers. Yet another cure is placing the farming on land. This is, as of now, a more expensive solution, and will not be discussed herein.

4 Marine Concrete Structures

Fortunately, we know how to design and build marine concrete structures. In particular, over the past 50 years, about 50 marine structures have been successfully designed and built for the oil and gas industry. One of the more spectacular ones is the Troll A Platform, operated by Equinor and others. Sitting on the sea bed 303 m below the water surface, in 30 m waves, it has an overturning mudline moment of 100,000 MNm, on soft, yogurt like clay. Parts of the structure is subjected to 303 m water pressure, about 1000 times the load on an ordinary floor. Figure 1 shows the Troll A platform with other structures. The small one is the City Hall of Oslo, Norway. Katie Melua sings in the bottom of the platform.

Figure 2 illustrates a tow out of the Troll A platform, with its 22,000 t deck 150 m above sea level. The Troll A platform displaced 1 million tonnes when towed out. The Gullfaks C platform displaced 1.5 million tonnes as the heaviest object ever moved by man over a distance of some 400 km (see Fig. 3). These are the two beauties of the sea—buoyancy and the ability to transport on it.

Well-designed and well-built concrete structures are robust and sustainable in the marine environment. Core tests of offshore concrete platforms for the oil and gas

Fig. 1 Troll A and other structures, and Katie Melua giving a concert 303 m below sea level

Fig. 2 Tow out of Troll A

Fig. 3 Gullfaks C, its final destination, built in, and transported from Stavanger

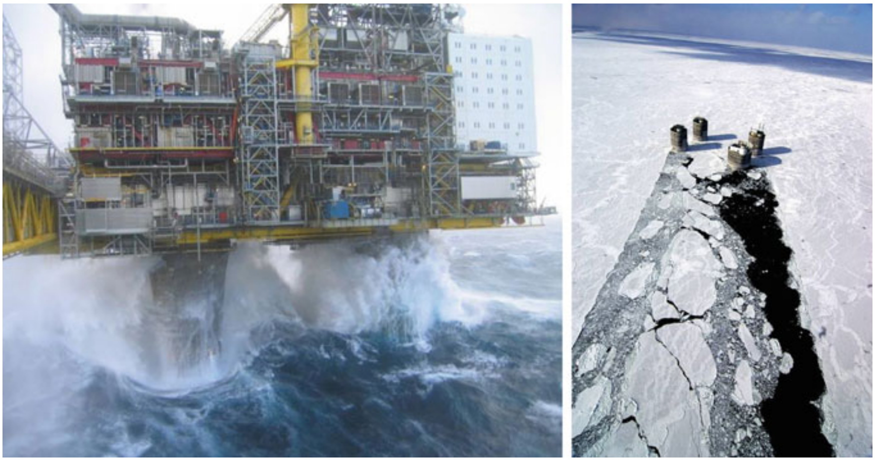


Fig. 4 Challenges at sea

industry located in the harsh North Sea indicate a life of more than 200 years. Figure 4 illustrates some of the challenges at sea.

The experience from the marine structures for the oil and gas industry is vital. But this is not enough. The oil and gas industry has rigorous regimes for safety, QA, and codes and standards for design and construction. That is all fine, but the level of cost is accordingly. Other structures, in particular fish farming structures, are at a different level, and most importantly, the fish farming structures are not heavily loaded. Design has to account for this.

Marine concrete structures is not a novel phenomenon. Concrete ships and barges have been built for more than a century, particularly in war times, when steel was scarce. Lambot built his concrete canoe almost two centuries ago (see Fig. 5). Also in Fig. 5, one can see the concrete Mulberry Harbor built and installed by the British during the Second World War to transport military vehicles from the ships to the Normandy beach.

Fig. 5 Lambots canoe from 1848, and Mulberry Harbor from the Second World War

Fig. 6 Sea bath in Oslo

Fig. 7 Floating apartments, concept, Norway

In Norway, with 100,000 km coastline and few people, floating concrete structures have been built for recreation, Fig. 6 shows a very popular sea bath installed in Oslo.

Also in cities, floating structures provide possibilities for pleasant and creative dwellings, Fig. 7.

Other examples of marine concrete structures are floating wind generators (see Fig. 8), and submerged floating tunnels for strait crossings (see Fig. 9).

References [1, 2] give many more examples of large floating structures.

The international concrete federation fib has recognized the importance of marine concrete structures for the future, and works actively with the issue.

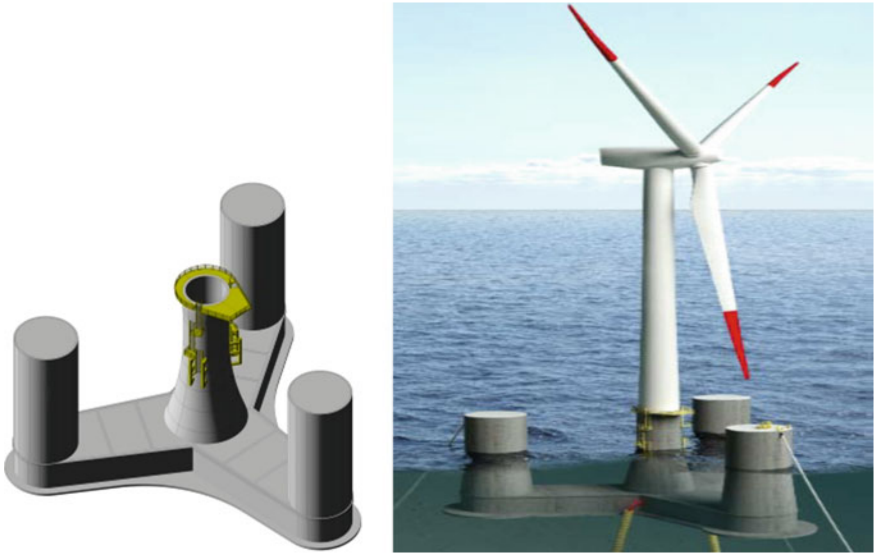


Fig. 8 Floating wind generator

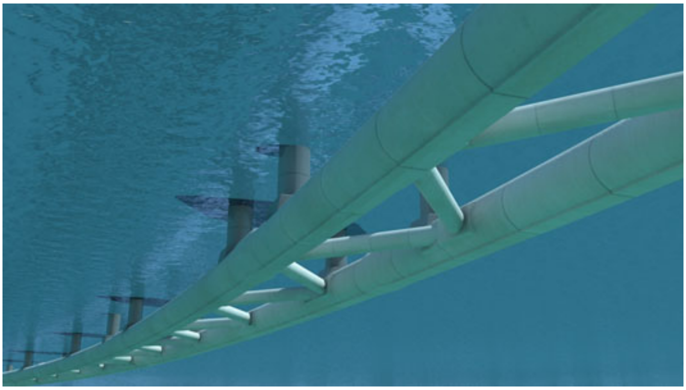


Fig. 9 Submerged floating tunnel

5 Design

When doing conceptual design it is important to understand the purpose of the structure, the loading, and the governing load conditions: in other words "first principles". It is also important to understand the structural response. This is important because it is not possible to evaluate all loading situations. In many respects, this calls for a general oversight of the design.

The conceptual design phase is the time to make the good choices that will influence the success of the structure. The experience from the oil and gas industry is

Fig. 10 Heavily loaded gas platform Troll A and an almost not loaded fish farming bucket

Fig. 11 Shell structure

valuable and useful for a future with different kinds of floating structures. However, the designer of different structures should be aware of the changing circumstances.

In Fig. 10, the left structure Troll A is extremely stressed. When designing it, the gas delivery from the platform was already sold, and the delivery date was set. The fish farming "bucket" to the right (explained in detail in the next section) is practically not stressed at all, and it competes with a net. Design is fascinating!

One of the obvious challenges of design is weight; heavy structures do not float. And heavy structures are often the result of poor design, consequently good design is essential. Shell structures are efficient structures to carry distributed loads, illustrated in Fig. 11, and they are therefore often used.

From a design and cost point of view, there are many loads acting on a floating structure. Waves from all directions, ballasting changing over time, and live loads changing over time (Fig. 12).

Another important element of the marine structure is the method of construction, as illustrated in Fig. 13; a sea crane lifting a small structure from land to sea. Larger structures need other means, such as a dry dock. The principles of constructing large structures are illustrated in Fig. 14. It is very important to integrate construction and design closely. Also important: to float, marine structures are made as slender as

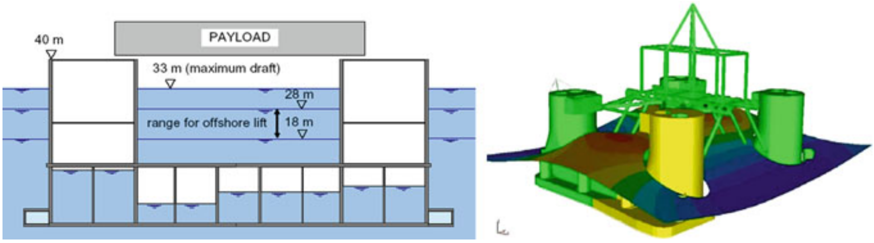
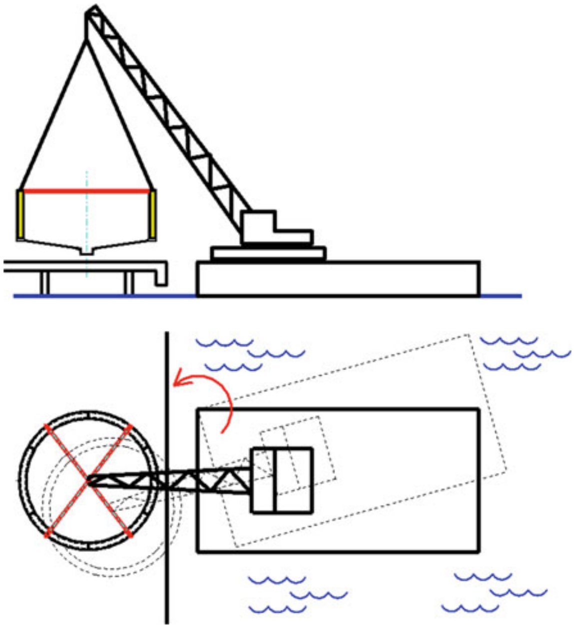


Fig. 12 Loads on a floating structure

Fig. 13 Small sea structure lifted from dock to sea



possible. This means that the content of reinforcement is high, calling for careful design and construction planning. Needless to say the weight control is an important part of the marine structure project.

To handle all the loads and all the code checking, programs that automate design are required.

Whilst design automation to calculate loads and perform code checks is part of everyday life in a design office, the eyes and reviews of an experienced engineering team is still a prerequisite for successful design deliverables.

Both linear and non-linear finite element programs are commercially available. Practical experience when modelling and selecting element types is a critical aspect of the linear and non-linear FE analyses employed for concrete design. Reinforced concrete will demonstrate non-linear behavior and methods such as the Modified Compression Field Method and the Modified Compression Field Theory, devel-

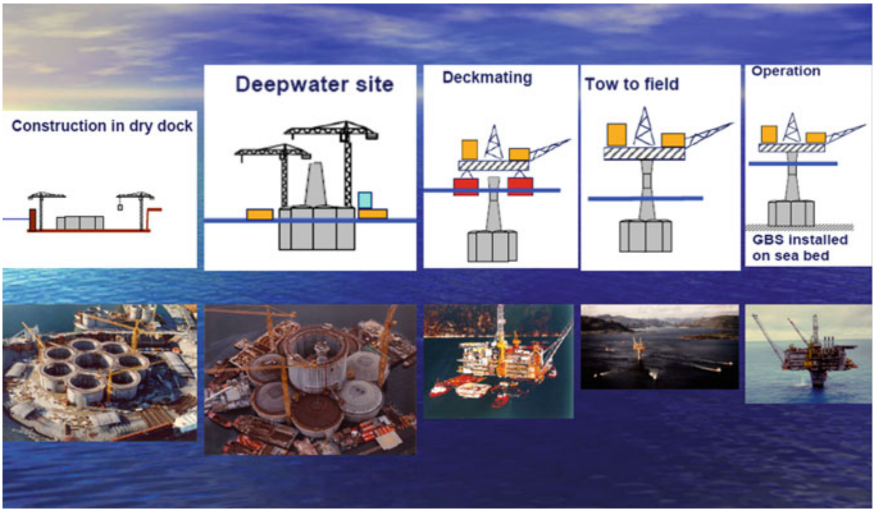


Fig. 14 Principles of constructing large marine concrete structures. The Draugen Platform is the example here. First dry dock, so float out and completion before deck mating. The deck is built in parallel with the concrete structure. Finally tow out, installation and production of, in this case, oil

oped by Professor Collins and his team at University of Toronto, provide a rational approach to estimating shear capacity beyond the standard design codes. This is especially important for shear, as shear is often handled empirically, and marine concrete structures do not resemble laboratory test specimens. In our practice, we have developed software for about 40 years, and are still refining it. We call it ShellDesign.

Traditionally large Finite Element (FE) analyses are based on the principle of linearly material behavior. As we know, reinforced concrete does not behave linearly, Fig. 15 is a simple illustration of this, and shows that the assumption of linearly elastic behavior may be unsafe in some cases and too safe/expensive in other cases.

As a consequence we have developed a nonlinear scheme; first run a linearly elastic FE analysis, then code check sections based on ordinary non-linearly principles. Then we compare stiffness from the point checks with the stiffness's assumed in the FE analysis, and upgrade as required. This is an iterative process, possible even for very large global FE analyses. The scheme is illustrated in Fig. 16. The Modified Compression Field method is incorporated in ShellDesign.

It is thus possible to handle a wide range of analyses of reinforced concrete structures. The linear and effortless transition from simple conventional concrete design, to advanced non-linear, triaxial concrete analyses equips the end user with a highly efficient design tool. The result is lighter and safer structures. This analysis made it possible, for the Sea bath described previously, to reinforce some of the walls with only one layer of reinforcement, saving a lot of weight due to strict requirements to cover of reinforcement for structures in the sea. A detailed description of ShellDesign, with examples, is given in Ref. [3].

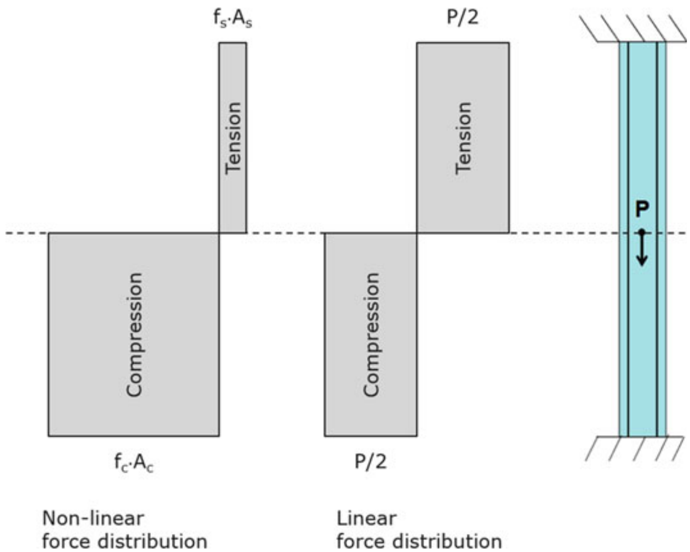


Fig. 15 Illustration of too safe/expensive and unsafe, if assuming concrete behaves linearly elastic

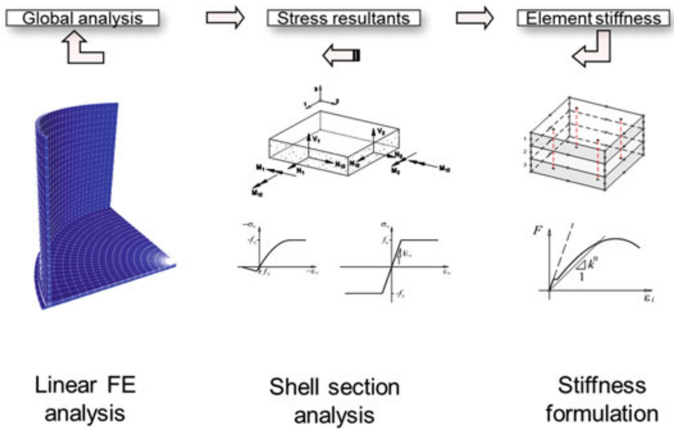


Fig. 16 ShellDesign flowchart

Many institutions have contributed significantly to design rules and design practices: ACI (Committee 357), DNV-GL, ISO, Norwegian Standards and fib.

Fig. 17 The fish farming bucket

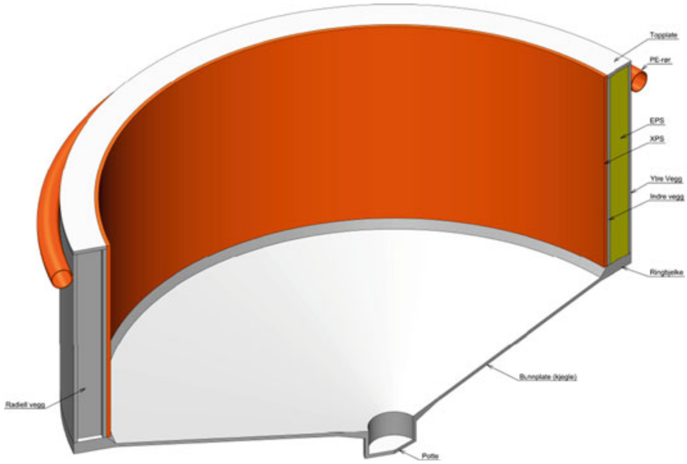


Fig. 18 Principle of fish farming bucket

6 Fishfarming Cages

The problems with fish farming with traditional open nets, in "crowded" areas, are already explained. The obvious solution is to close the cage. The closed fish farming "bucket" of Fig. 10 will be described in detail. In principle it is a simple bucket, made of concrete (see Fig. 17). It can hold 1000 m^3 of water.

It has a slender cone in the bottom, with a pot to collect feces and dead fish. The walls are double with Styrofoam in between, to provide buoyancy, Figs. 18 and 19.

The bottom cone has rebars to carry the weight while lifted, the ring beam has pretension cables to carry the thrust from the cone while floating with less water inside than outside. Otherwise the structure is reinforced with steel fibers (which are handled in ShellDesign as shown in Fig. 20).

The bucket, named Salmon Home #1 and owned by FishFarming Innovation, is the first concrete fish farming bucket built (see Figs. 21 and 22).

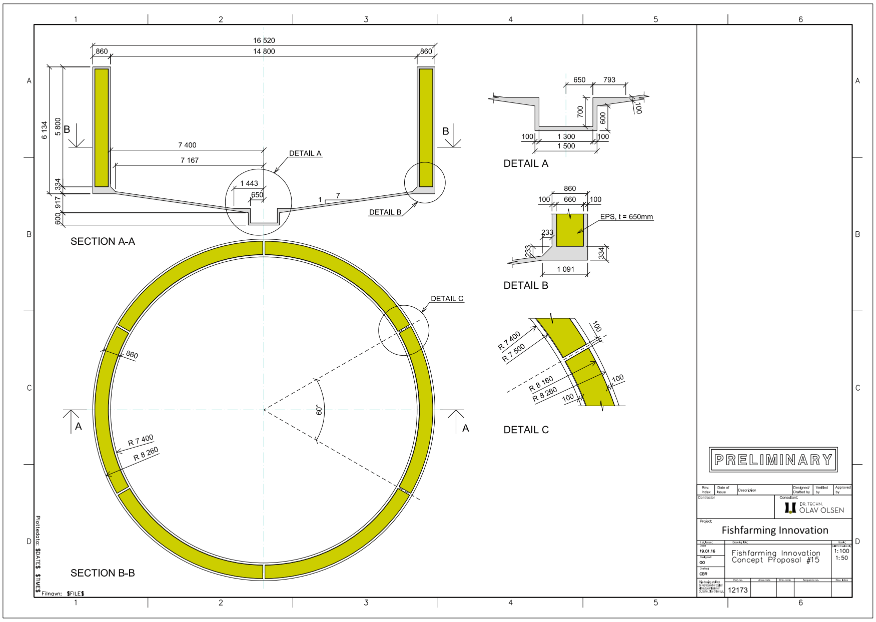


Fig. 19 Drawing of bucket

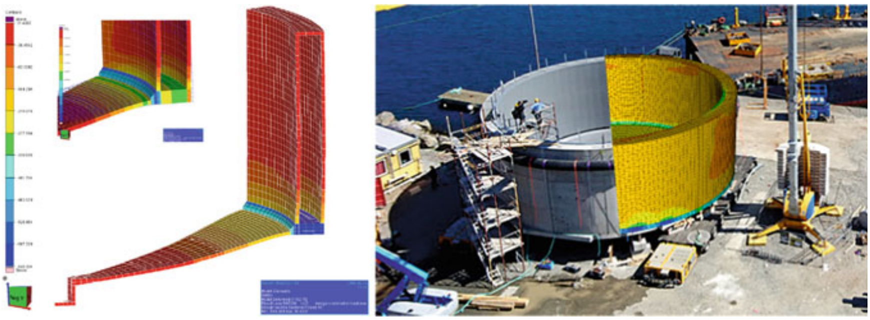


Fig. 20 FE model

The bucket now produces salmon with very good results (Fig. 23). Also working on the bucket is comfortable and safe.

Another proposed closed cage, housing 37,000 m^3 of water, is named Stadion Laks. This too is intended for "crowded" areas, and illustrated in Figs. 24 and 25. This concept is equipped with a lot of facilities, such as feed, feces, handling equipment for the fish, cranes, quarter, pumps, safe landing system for ships, and energy supply.

For "non-crowded" locations, like off shore, open nets are acceptable, if protected against ship impacts. One such concept is the Blue Farm, a tension leg offshore cage for a very large number of salmon (see Figs. 26 and 27).

Fig. 21 Completed bucket ready for lift out

Fig. 22 Lift out

There are some relatively advanced analyses that are required for this type of concept, but because of experience acquired from similar structures, it is manageable (Fig. 28). The hydrodynamic analysis of the net requires special competence.

Cost is a vital parameter. The bucket described above was a prototype, and relatively expensive because many things had to be pioneered and developed. The plan is to build several more, and a standardized construction will give lower costs. Costwise it is difficult for a concrete wall to compete with a net, per m^2 (Fig. 29).

Fig. 23 In successful operation

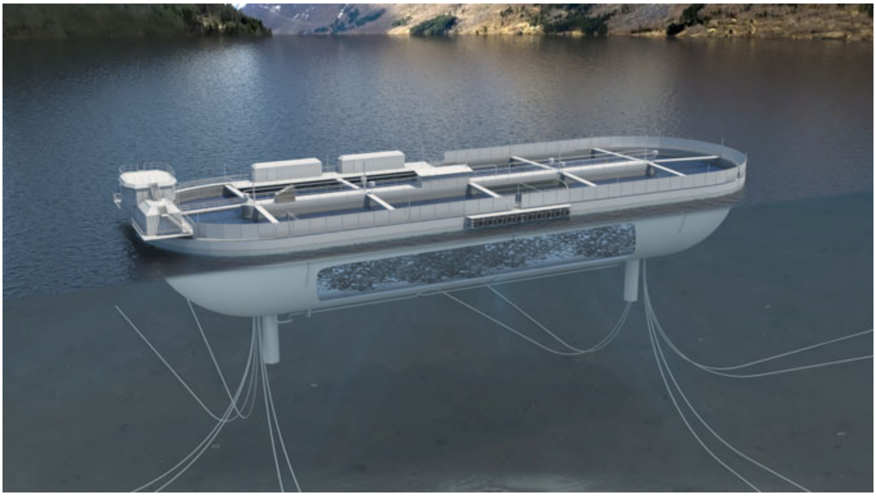


Fig. 24 The Stadion Laks

Fig. 25 Salmon export

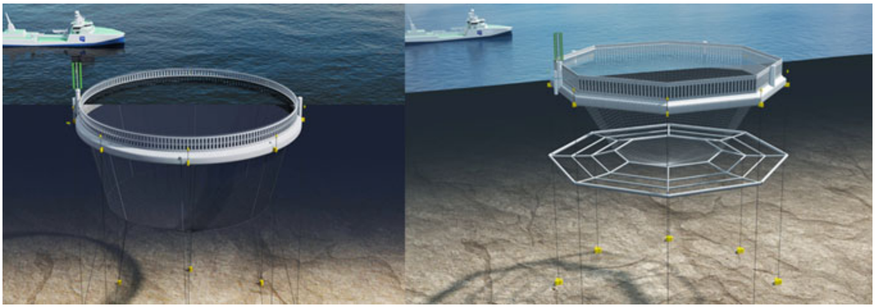


Fig. 26 Blue Farm ocean farm. Initial concept to the left, improved for construction reasons, to the right

A recent Norwegian research report [4] describes fish farming in detail, and concludes estimates of cost of farming, in Norwegian kroner NOK (1 € ~ 10 NOK) as shown in Table 1.

Expected average selling price in 2019 is 62 NOK/kg. Business is good now, it has been for some years. But it is not always good. By looking at the numbers and the assumptions behind them, it is clear that comparisons of cost should include more than what is included in the research report, such as:

- It is allowed (Norway) to have a higher density of fish in closed cages (50–75 kg/m^3) as compared to open nets (25 kg/m^3)
- Closed cages can be more closely "packed", so space is saved
- Open net farming requires location to be left idle for 2–3 months after a production cycklus, for environmental reasons

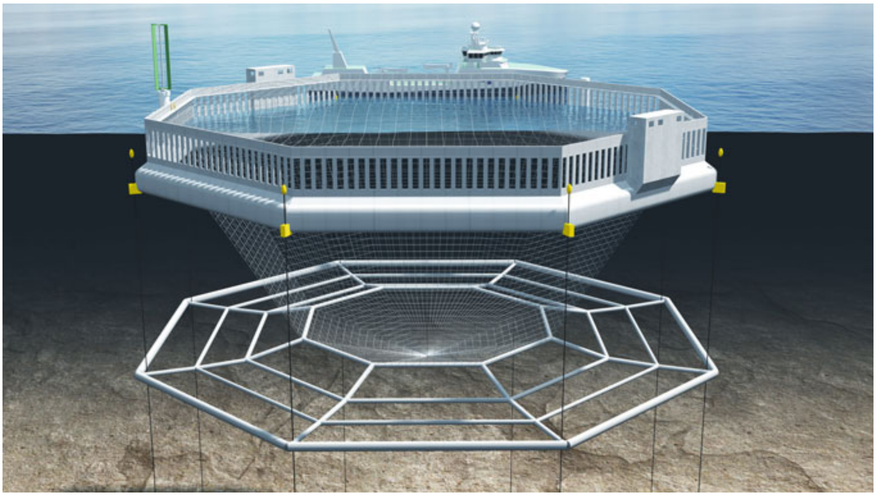


Fig. 27 Blue Farm ocean farm, details

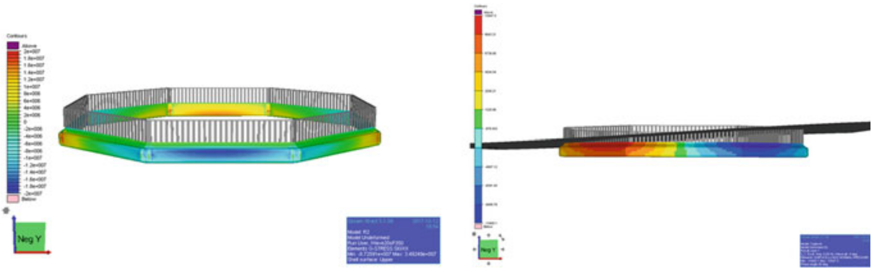


Fig. 28 Hydrodynamic and structural analyses of Blue Farm

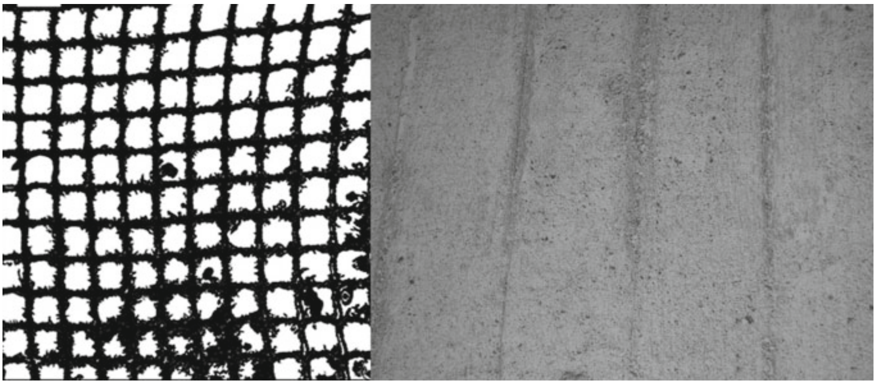


Fig. 29 Net and concrete wall

Table 1 Reported cost of farming salmon, for different production methods

		NOK/kg
Open cages in the sea		30.60
Fish pens on land		43.60
100 g fish on land, then in open cage in the sea	0 delicing treatments	28.00
	5	31.30
	10	33.80
500 g fish on land, then in open cage in the sea	0 delicing treatments	28.90
	3	30.70
1000 g fish on land, then in open cage in the sea	0 delicing treatments	30.80
	2	32.40
Closed cage		37.90

- Closed cages can have on board silo for feed, space for handling the feces, space for oxygen production etc., and will not need an expensive work boat for effective production
- Closed cages allows control of water quality, such as salinity, temperature and oxygen
- In closed cages you can make a current in the water, for better fish welfare
- In closed cages, as mentioned, you avoid sea lice and sickness coming in with the water, can take care of the feces, avoid escaping, and overfeeding the surrounding fish
- A closed concrete cage virtually lasts for ever.

By including these elements, it is believed that fish farming in closed concrete cages is cost efficient also, not only environmentally friendly. The future will see an increased use of concrete in the marine environment; concrete will indeed be a valuable partner. We need to be creative to fully utilize its potential.

References

1. Olsen, T, O., Weider, O., & Myhr, A. (2015). Large marine concrete structures: The Norwegian design experience. In C. M. Wang & B. T. Wang (Eds.), *Large floating structures*. Singapore: Springer (2015).
2. Wang, C. M., Dai, J., Jiang, D., & Olsen, T. O. (2017). Large floating concrete structures. *Concrete in Australia, 43*(2), 29–40.
3. Pettersen, J. S., Bjønnes, S. G., Hausmann, R. E., Fiskum, K., & Nyhus, B. S. (2017). ShellDesign—innovative concrete design. In: *HPC/CIC Conference, Tromsø, Norway*, March 2017.
4. Bjørndal, T., & Tusvik, A. (2018). *Økomisk analyse av alternative produksjonsformer innan oppdrett*. SNF-rapport nr. 07/18, Samfunns-og næringsforskning AS, Bergen, Norway, Oktober 2018, ISSN 1503-2140.