特別講演Ⅰ

CONCRETE FOR MARINE STRUCTURES

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1. INTRODUCTION

Japan has a proud maritime history. Being an island, conquering the sea has truly been a necessary accomplishment. Norway is not an island, but a country with a very long coastline. Conquering the sea has also been essential for Norway; for food, transport and communication, within the country and internationally.

45 years ago, hydrocarbons were discovered under the seabed outside Norway, on the Norwegian Continental Shelf. The Norwegian Continental Shelf is part of the North Sea, the Atlantic Ocean, having tough and harsh environment. Brave clients, contractors and engineers saw the potential of concrete structures for the development of the offshore oil and gas industry. Pioneering was the French company Doris, and Norwegian companies followed suit. By now, the Norwegian offshore concrete industry has built more than 3 million m^3 of concrete structures for the oil and gas industry, in Norway and abroad.

The Norwegian deep fiords have been instrumental in the construction of these structures. The topside, the factory, is built simultaneously with the concrete sub structure. When complete the two are mated inshore, before towage out the deep fiords, to the offshore site and subsequent installation. In this manner of inshore prefabrication, the installation period at the offshore location is greatly and therefore delays and safety risks are minimalized.

Concrete may also be used for other applications than the oil and gas industry. Concrete ships and barges, for example, have been built for a century, particularly in war times, when the limited supply of steel was preferred used for other purposes. Traditionally, these ships were heavier than steel ships, and therefore were frequently grounded after the war for reasons of operating expenditure. With modern methods of design and modern concrete technology, these structures may now be commercially competitive also in operation.

Other marine usage may also benefit from the concrete material. Modern requirements in city development, renewable energy production, sustainable growth of industry, and climatic hazards are a few of many drivers in this development.

This presentation will show examples of the use of concrete in the marine environment, as an inspiration, hopefully, to extend the use of a very suitable material.

2. THE BEAUTY OF THE SEA, AND SOME CHALLENGES

The sea has some very helpful properties that often are taken for granted. One of them is the ability to travel on top of it. Figure 1 shows a ship used by Norwegians to cross the Atlantic Ocean more than thousand years ago.

Another beauty is the buoyancy. Figure 2 shows the offshore platform Troll A being towed out of a Norwegian fiord. The platform was on its way to installation in 303 m water depth. Due to foundation reasons, the bottom part of the structure, 16600 m^2, has 36 m deep skirts to penetrate and enclose the very soft clay. The structures draft limitation of 227 m requires it to be elevated as shown, with a 22000 t deck 150 m above sea level. The structure displaced 1,000,000 t, being the second largest object ever moved by man. The largest, platform Gullfaks C, also designed by Dr.techn.Olav Olsen, displaced 1,500,000 t. For comparison, Figure 2 also shows lifting of a prefabricated structure weighing 250 t. “Lifting” Gullfaks C with this type of crane would require 6000 of them, an impossible task.

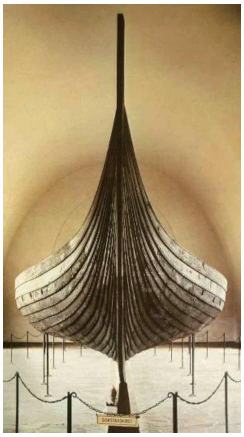

Figure 1 The Gokstad Viking ship

Figure 2 The Troll A Platform being towed out of a Norwegian fiord, displacing 1,000,000 t, and lifting 250 t on shore

Fédération international du béton/International Federation for Structural Concrete (fib) has a Task Group 1.2: Concrete structures in marine environments. In this Task Group, a number of benefits are recognized:

1. Food
2. Infrastructure
3. Energy
4. Environment
5. Dwellings and urban development
6. Nearshore industrial development
7. Offshore industrial development
8. Storage
9. Vessels
10. Recreation
11. Catastrophes
12. Military actions
13. Other

A recently published book “Large Floating Structures”, Reference 1, may give ideas for further applications. Under preparation is “Encyclopedia of Marine & Offshore Engineering” by John Wiley & Sons.

Of course, there are also some challenges. The waves, for example may be 30 m in the North Sea (100-year wave). The chlorides in the seawater may represent a challenge to durability if not properly cared for; Figure 3 illustrates the typical marine environment. Properly designed and built, the life of these structures will exceed 200 years, Reference 2. Yet another challenge is the arctic. Fortunately, the robustness of properly designed and built concrete structures is very valuable in the arctic; an important example is resistance to sheet ice (Figure 4) and icebergs.

Figure 3 The environment of the North Sea

Figure 4 Concrete platform in ice, Sakhalin II (Reference 3)

3. CONCRETE STRUCTURES FOR THE OIL AND GAS INDUSTRY

For obvious reasons the immense size of the offshore concrete platforms is not easily realized. With an artist’s help Figure 5 illustrates the size of the Troll A platform, previously mentioned, compared to known structures. The smallest one is the City Hall of Oslo, Norway. Figure 6 shows singer and songwriter Katie Melua giving a concert in the bottom of the Troll A platform, 303 m under the sea level. Seen in the background of the photograph are the gas risers, instrumental in giving Norway the large wealth over the past decades.

Figure 5 Troll A and other structures

Figure 6 Katie Melua giving a concert in the bottom of Troll A, 303 m below sea level.

The hydrostatic loading 303 m under the sea level is about 1000 times the load on ordinary floors, so obviously the structure and the structural design need attention.

Most of the concrete platforms are designed and built by Norwegians, but not all.

Figure 7 shows the Norwegian built platforms, built by Kvaerner and designed by Norwegian engineers.

There are 50 offshore concrete platforms in the world; a list of these exists in Reference 4. As this publication is not quite up to date, the Sakhalin I platform is the 50’eth, and the Hebron is yet to be installed. ExxonMobil operates both of these. Sakhalin I is located east of Sakhalin, which is north of Japan in ice-infested waters. The Hebron will be installed on Grand Banks east of Canada and is designed to resist icebergs.

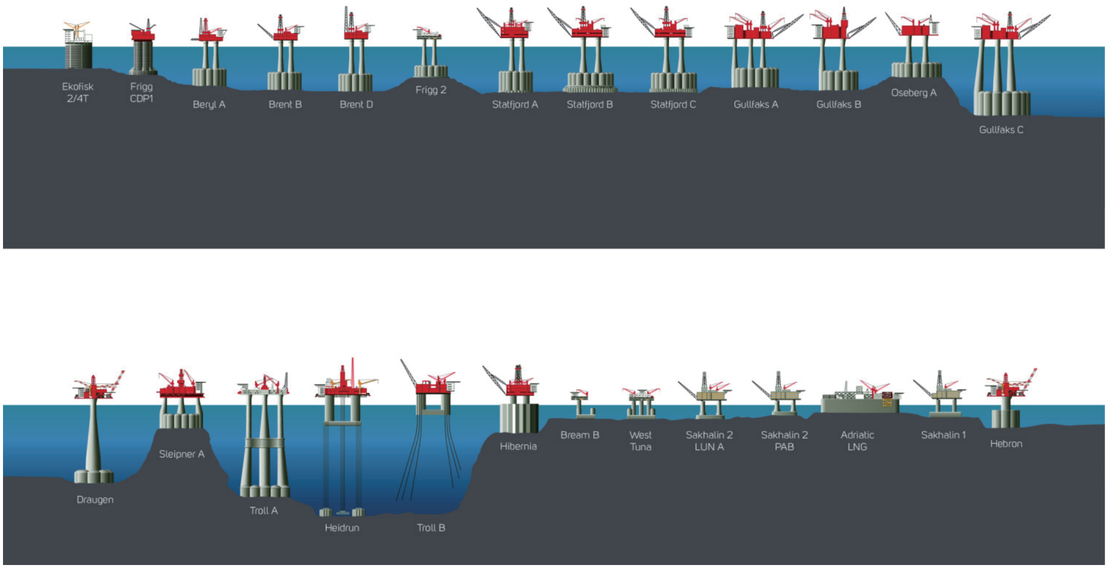

Figure 7 Offshore concrete platforms designed and built by the Norwegians

Reference 5 is a rather comprehensive paper on design and construction of offshore concrete platforms; Reference 1 with one chapter on the Norwegian experience may also be of interest.

4. CONCRETE STRUCTURES FOR OTHER MARINE APPLICATIONS

The competence gained from the offshore concrete platforms for the oil and gas industry is very useful for other applications.

In Norway, it is politically decided to build a ferry-free highway along the west coast from Kristiansand to Trondheim, some 1100 km, crossing eight major fiords. The Norwegian Road Administration is very clear on their wish to hire companies with extensive offshore experience. One result of this is a concept for submerged floating tunnel crossing the Sognefiord, 3.7 km wide and 1.3 km deep, Figure 8 and References 6, 7 and 8.

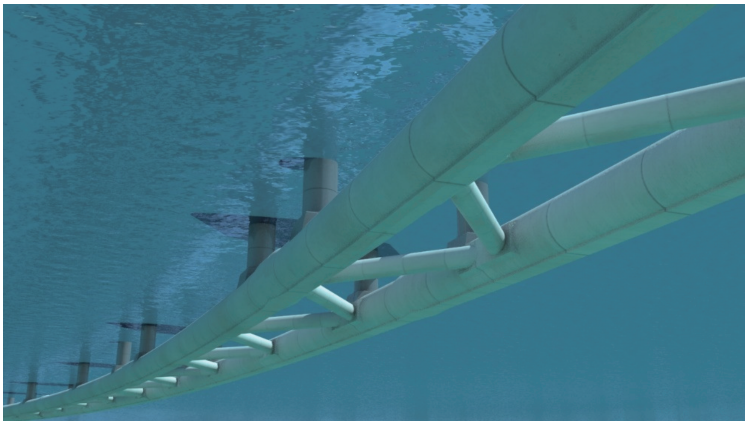

Figure 8 Submerged Floating Tunnel, Sognefiord

A way of crossing long straits is shown in Figure 9 (Reference 9). By putting shafts on the subsea tunnel, as invented by Allan Sharp of UK, length limitations are avoided. The shafts are identical to the Draugen offshore concrete platform, shown lower left in Figure 7. Potential locations of such long tunnels are Bohai Strait and mainland China-Taiwan, both in China, Japan-Korea, Korea-China, and even the Bearing Strait.

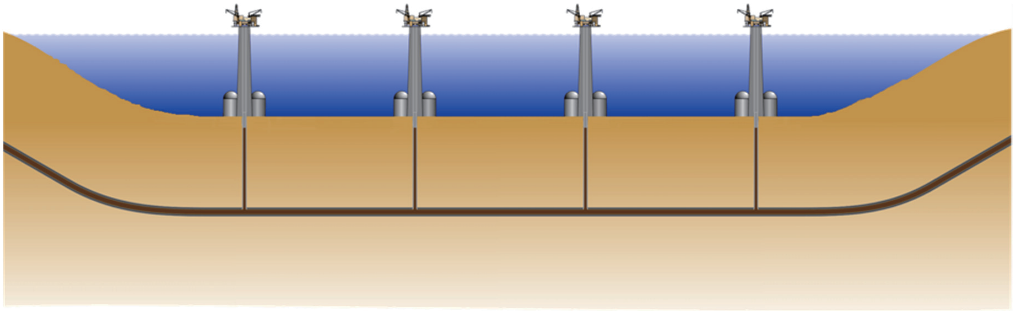

Figure 9 Ultralong subsea tunnels

Yet another application of the offshore experience is offshore wind energy. Again taking advantage of the protected environment inside fiords, helpful when installing delicate machinery; Figure 10 and Reference 10.

Figure 10 Offshore Wind energy – Gravity based, inshore installation, and the floating OO.Star

Here the gravity based wind turbines are very similar to the offshore gravity based platforms. Likewise, the floating wind turbine is very similar to floating platforms.

Fish farming is an important industry in Norway, and the Norwegian fish export benefits consumers around the world. Fish farming in closed concrete containers is considered an alternative to avoid problems of fish escaping and fish illness, as well as to collect the environmentally harmful waste products from the fish farms. Figure 11 shows examples of offshore containers, Figure 12 shows example of coastline farming. The building phase of the single bucket is set to this fall.

Figure 11 Proposed concepts for offshore fish farming

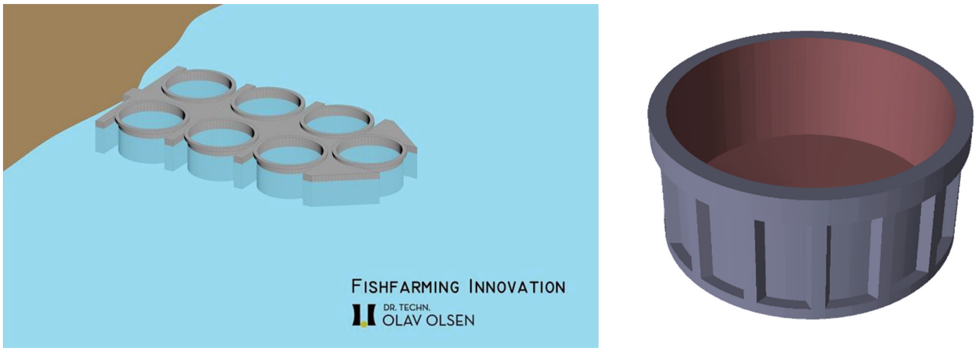

Figure 12 Proposed concepts for near shore fish farming

Figure 13 illustrates a proposal for a floating quay at Longyearbyen, Svalbard. Svalbard does not have the materials nor infrastructure to construct such a structure, so the proposal is to build in mainland Norway and tow it to place in Longyearbyen. The idea is to provide berthing space for cruise ships, later to be extended to include housing of various activities, Reference 11.

Figure 13 Proposed floating quay, Longyearbyen, Svalbard

In more densely populated areas, floating structures may be used for recreational purposes, as shown in Figure 14, showing a sea swimming facility. Note that by using the sea for recreational purpose, the usage of land onshore, for dwellings, may be increased. The sea swimming facility is located in Oslo, the fastest growing capital in Europe. It was built in three parts in a ship dock 70 km south of Oslo, assembled and towed in place.

Figure 14 Sea swimming facility, Oslo

For city development it is also possible to build floating apartments. Architect Tom Wike of ØKAW Architects has sketched a proposal shown in Figure 15. Tom Wike is a member of fib TG1.2 previously mention, and his sketches are part of the work done there.

Figure 15 City development

5. THE DESIGN OF SHELL STRUCTURES

As all other types of structures, marine structures need to be designed. Compared to land based constructions, extra parameters have to be considered.

Firstly, very often the structural engineer is also the architect. This is an important aspect for the conceptual phases in particular. Usually, the structural engineer is equipped with already prepared overall plans for the structure.

Secondly, the disciplines of hydrostatics and hydrodynamics need to be included in the design process.

Thirdly, the structure is typically a containment type of structure, very often a shell structure, to be able to provide buoyancy. Shell structures are efficient structures for distributed loads such as hydrostatic pressure, and therefore light, but they require special skills to design.

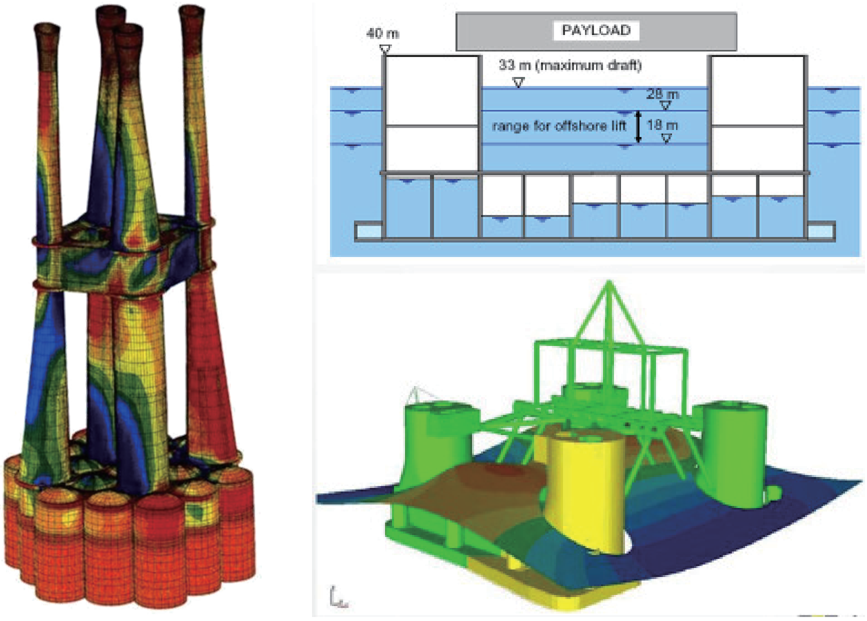

Figure 16 Loads and FE model

As illustrated in Figure 16 there are a lot of loads and loadcases, and both construction phases and the operation phase needs to be included. Waves come from all directions, and ballasting may have hundreds of different phases. In addition to all this; the general shell element has ten stress resultants, Figure 17. This calls for efficient programs that handle the logistics as well as perform sectional design/code checking.

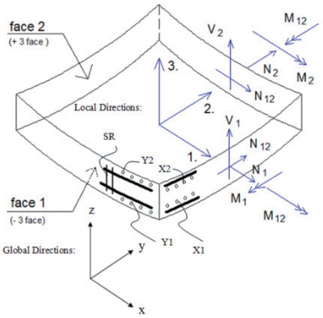

Figure 17 The reinforced shell element

There are codes for marine concrete structures, for example the Norwegian, Reference 12.

Dr.techn.Olav Olsen has developed and worked with the necessary programming tools for marine structures for more than 30 years. The name of the program is ShellDesign.

Recent development in the programming is the ability to predict non-linear response. The need for this is evident, reinforced concrete behaves non-linearly, and it is inconsistent to analyze linear elastically, arrive at a set of stress resultants, and then code-check for non-linear response of the cross-sections. The resulting stiffness differ from the ones assumed in the linear elastic FE analysis.

Instead, we feed the stiffness of the cross-sectional analysis back to the stiffness matrix of the linear FE analysis, and iterate until convergence, Reference 13. The results of such an approach are often very different from the results of the linear elastic analysis. Moreover, the linear elastic analysis is not always on the conservative side. Therefore, the program is considered a tool for safer and more economical design. This is always important, maybe extra important for heavily loaded marine structures of unusual dimensions that need to float.

Another recent development, not yet quite complete, is the implementation of the modified compression field theory of Prof. M.P.Collins et al (references 14, 15, and 16). This assures a rational design also of structural elements of unusual shape, size, and loading.

6. THE FUTURE

Some of the sketches shown in this paper belong to the future. Looking at the 13 elements of fib TG1.2 in section 2 above, where element 13 is “Other”, indicates that the potential use of marine concrete structures is large. In fact, with ever changing design specifications, the imagination is the only limiting factor.

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