Reinforced concrete is commonly used for marine structures, such as bridges, quays, lighthouses and docks. Frequently these structures are built more or less the same way as ordinary land based structures, although utilizing the presence of water is sometimes taken advantage of, as shown in Fig. 1.

Even ships and barges have been built in concrete, particularly inwartimes when steel is used for other purposes. These ships and barges have behaved well, but shown a bit heavy for efficient economic use.

In the early 1970’s concrete was introduced as a proper construction material for offshore structures for the oil and gas industry. These were structures remote from shore subjected to harsh environments, and they had to be floating from the construction site at shore to the final location. Redundancies are therefore expensive, and the meaning of robustness needs to be clear and understood.

The design and construction of these offshore concrete structures will be described in this paper.

**Keywords:** Offshore concrete structures, gravity based structure, design, harsh environment, oil and gas, arctic.

1. **INTRODUCTION**

Experience with concrete ships since the 1920’s and floating bridges in Washington State since 1955 demonstrates that concrete is a favorable material for hulls of floating structures.

Offshore concrete structures have been installed in the North Sea for more than 35 years. These platforms which must be designed during temporary and towing operations as floating bodies subjected to a considerable hydrostatic pressure difference were all towed to location, some over distances of several hundred kilometers, before the platforms were subsequently ballasted on to the seabed.

The general conclusion drawn from service performance of these offshore concrete structures is that they have proved excellent behavior and require significantly lower expenditure for inspection, maintenance and repair than steel structures. Experience has shown that offshore concrete structures currently in use are virtually maintenance-free. Many platforms have passed their intended design lives, many have got their functional duties enlarged, and many have shown a remarkable strength towards abnormal events.

The increasing importance of local content in the oil and gas development projects is favoring concrete as the building material in countries with limited number of offshore steel yards; every country has a concrete construction industry. Concrete structures can be built in greenfield areas with very little infrastructure. The majority of the workforce does not need special education and can be recruited locally. Hence, choosing concrete may significantly increase the local content of a project.

The two latest offshore concrete projects being realized are the two Sakhalin platforms (built South of Vladivostok, Russia, installed in 2005 east of Sakhalin in Russia) and the Adriatic LNG Terminal (built in Spain and Italy, installed in 2008 outside Venice in Italy). Different structures with different specifications, they will hopefully do an excellent job fulfilling the needs of their owners and the society.

Plans for further oil and gas exploitation in ever increasing harsh environments have accelerated the focus and interest for the efficiency of offshore concrete structures.

2. **HISTORY**

The history of floating concrete sea structures goes back to the 19th century. In 1848 Lambot for the first time used reinforced concrete to build a boat. During World War I, 14 concrete ships were built due to the steel shortage - including the 130 m long U.S.S. Selma.
At that time reinforced concrete had already been used in shipbuilding (small ships) in the Scandinavian countries.

104 World War II concrete ships saw widespread wartime service in battle zones. Twenty-four of these ships were large sea-going vessels and 80 were sea-going barges of large size. The cargo capacities ranged from 3,200 to 140,250 tons. Ref. 16, gives a good description of the early development of the concrete hull.

From 1950 to 1982 approximately 1,130 concrete hulls are registered to have been built. Most of them are small with overall length less than 50 m. Among the bigger ones, two groups of sizes are dominant, - approximately 250 hulls with length ranging from 58 to 67 m, and 40 hulls with a length of 110 m.

In the late 1950’s, a number of prestressed concrete ocean-going barges were constructed in the Philippines (additionally 19 barges from 1964 to 1966), and concrete lighthouses were constructed as caissons in the 1960’s. Concrete lighthouses are installed in the Irish Sea, in Eastern Canada and in the Gulf of Bothnia. Many pontoons, barges and other crafts have been successfully built in the former USSR, Australia, New Zealand and the UK.

A number of notable pontoon bridges have been built of concrete. Ref. 17 gives an overview of the long traditions within this area. The first floating concrete bridge was built across Lake Washington in 1940.

Since the Ekofisk Tank was installed in 1973, designed by Doris in Paris, 48 other major offshore concrete structures have been built. Refs. 1, 2 and 11 provide a list of these structures, an updated and more extensive list will be included in an upcoming fib Bulletin on “Concrete structures for the oil & gas field in hostile marine environments”.

In the North Sea there are 15 concrete platforms installed in the Norwegian sector including the floaters Heidrun TLP and Troll B Semi. There are 12 concrete platforms installed in the UK sector including the storage/foundation tank for Harding. In addition there are concrete platforms installed in the Baltic Sea, Brazil, Indonesia (concrete barge), Gulf of Mexico, Canada, Germany, USA, Holland, Congo and Australia. The most recent concrete platforms have been installed in Denmark (South Arne), the Philippines (Malampaya), Sakhalin and the Adriatic.

In Norway the concrete offshore adventure was started by a constellation of the contractors Selmer and Høy-Ellefsen, building the Ekofisk Tank. These two construction companies had extensive experience building concrete structures on land and at the shore, and wanted to utilize this experience also for offshore petroleum construction.

In 1973 Selmer and Høy-Ellefsen signed a contract with Mobil to construct the Beryl A “Condeep” (Concrete Deepwater Structure). Olav Olsen, the founder of the engineering company Dr.techn.Olav Olsen, was with his expertise on thin shell structures a contributor to Høy-Ellefsen’s invention of the Condeep platform. The picture shown in Fig. 2 shows the first model test of a Condeep to check floating stability.

Fig. 2 Prototype of the Condeep.

Fig. 3 shows the tow of Beryl A in 1975, from its construction in sheltered Norwegian fjords on its way to the harsh environment of the North Sea, Fig. 4. These figures illustrate some of the design criteria for offshore structures, and at the same time they indicate why concrete may be the best choice of construction material.

Fig. 4 shows that it is not possible to build structures offshore. But they must be installed, and may have to be completed with respect to the foundation (piling, grouting) and topside installation. The degree of inshore completion influences the cost and safety of the field development.

Offshore Concrete Structures
The robustness of concrete structures has allowed for tie-in of wells, more topside equipment and subsequently higher production for a large number of these platforms. Also in the future these existing concrete platforms will demonstrate their flexibility when nearby fields are developed with subsea installations and tie-ins, calling for modifications of existing platforms.

Fig. 5 illustrates the Condeeps built by the Norwegian Contractors (Selmer, Høyer-Ellefsen and Furuholmen). Dr.techn. Olav Olsen designed them, some times in collaboration with others.

Probably the most impressive Condeep is the Troll A platform, shown in Fig. 6 and Fig. 7. The platform was complete with its 22,000t topside 150m above the sea level during tow out and installed at 303 m water depth in the North Sea in 1995. Parts of the Troll A structure were subjected to a water pressure of 3.5 MPa during construction.

The construction of offshore concrete structures in Norway came to a halt in the mid 1990’s, but continued other places, lastly in Russia, the Philippines, Spain and Italy.

In 1986 Olav Olsen proposed the use of skirt piling for the Gullfaks C platform. The principle of skirt piling has extended the application of gravity based structures to areas with poor soil conditions, and has since been widely used for GBS structures, jackets (bucket foundations) and suction anchors in soft soil typically found in deepwater fields.
Fig. 6 The Troll A Condeep during tow-out.

Fig. 7 The Troll A Condeep, with other structures.

Fig. 8 Gas pipes, a concrete structure and Katie Melua

3. CONCRETE OFFSHORE STRUCTURES

The typical offshore concrete structure is gravity based (GBS), which means that it sits on the seabed by its own weight. If soft soil, the structure may be equipped with skirt piles. One of the more elegant Condeeps is the Draugen platform (Fig. 9). Shell’s Draugen platform was successfully installed in 1993. Draugen is equipped with 9 m long concrete skirts beneath the base.

The Gravity Base Structures are characterized by their ability to resist extreme loads and, once installed, their robustness to accommodate design changes to the top sides and production equipment. Most have a tower configuration designed to minimize wave force and overturning moments and some are equipped with perforated Jarlan walls to reduce the wave force. Another category consists of semi-submersible floating hulls or large barges capable of carrying considerable payloads and accommodates storage of LNG or other products. A third category would be generally smaller platforms such as concrete islands, mono-towers founded on small caissons and hybrid platforms consisting of a concrete base with a steel truss tower.

Offshore Concrete Structures 4
Concrete offshore structures differ from the more common steel jackets and floating hulls customary delivered by ship yards and fabrication yards. It should be realized that a concrete GBS is a concept rather than a choice of concrete versus steel and that the merits of the different options for field development need to be examined on a broader basis. Some of the merits particularly associated with a concrete GBS are listed below:

— The concrete substructure can be predictably and robustly designed to resist extreme loading conditions such as significant wave and wind loads, high water pressure, seismic actions, impact loading and ice abrasion. A number of international codes now cover all aspects of design and construction.

— The GBS concept offers considerable adaptability to changing functions and requirements during operation. Once installed, topside design and weight can often be significantly modified in response to depletion of the field.

— A high degree of completion of the entire project can be achieved at inshore locations prior to tow-out. Where water depths permit, heavy topsides can be mated on to the concrete substructure by float over at an inshore location, eliminating costly offshore operations and the need for large lifting vessels.

— The completed platform can be towed to the field, or held under tow, in harsh weather conditions. Installation of a concrete GBS is generally achieved in a matter of days and can take place during a forecast weather window.

— Drilling conductors, risers and J-tubes are mainly contained within the concrete shaft and caisson walls, protecting the equipment and catching unforeseen leakage.

— Oil storage capacity may be provided inside the GBS hull where pipeline export is not appropriate or possible (up to 2 mill. bbls.). Storage provision can also enable continued production in the event of temporary disruption to the export system.

— In-service inspections of existing concrete platforms have revealed excellent performance characteristics and the need for little or no maintenance of the concrete.

— Concrete GBSs may be re-floated and removed. Alternatively, they can be decommissioned and stripped of all mechanical plant and equipment and left fully or partly in place as a well marked reef.

— The concrete GBS offers good protection to the environment in terms of control of accidental leakages and resistance to extreme and otherwise detrimental loads. The CO₂ emissions arising from the construction of a concrete GBS structure compare favorably to those associated with a steel hull.

— The majority of existing concrete GBS structures have been delivered on time and within budget.

The caisson provides buoyancy in the construction and towing phases, and a foundation structure in the operation phase. In addition the caisson may also provide storage volume for oil. This multiple usage of the structure may prove very economic, particularly when oil storage is required.

Steel structures may of course also be built to provide buoyancy and storage, but buoyancy at large water depth is demanding and expensive for steel structures. The inshore construction of concrete offshore structures provides good conditions for quality construction. The construction site of Norwegian Contractors at Hinna, near Stavanger in Norway, was a very professional and effective construction. The design and construction of 15 Condeeps accumulated a large amount of expertise.

Typical fabrication cost for offshore concrete structures in the past range from 1,500 – 3,500 USD per m³ concrete, inclusive mechanical equipment and installation.

The arctic challenge is characterized by limited access, extreme conditions, a need to mitigate the unforeseen, frost and ice, a sensitive environment and short weather windows. Concrete structures with their strength
redundancies, robustness, durability and low maintenance are well suited to the challenges of the arctic.

Prestressed reinforced concrete structures have characteristics that are useful for the type of structure evaluated here:

— High stiffness
— Good resistance to environmental loading
— Favorable in ice-infested waters
— Robust with respect to accidental loading such as ship impact, dropped objects or terrorist attacks
— Functional and safety features common to a land based plant
— Enhanced concrete material properties with decreasing temperature
— Excellent fatigue resistance
— Maintenance-free, good durability expected low operation cost
— Need for less skilled work-force for bulk part of the construction, may be built locally
— Good resistance to seismic loading
— Well proven technology for decommissioning

As mentioned most offshore concrete structures sits on the seabed. Nevertheless they have been afloat for the construction and installation phase. Some offshore concrete structures float permanently, calling for anchoring and proper hydrodynamic response also in the harsh winter nights.

The introduction of floating concrete platforms for offshore oil and gas production started back in 1976 with the ARCO barge. The successful construction of the Heidrun TLP (1995), the Troll Oil Semi (1995) and the Nkossa barge (1996) has opened for interesting potentials to the offshore industry as to the suitability and economics of concrete floating structures. Recent studies also conclude that floating concrete structures are well suited for floating LNG plants.

During the 1970’s concrete gained recognition as a well-suited material for construction of offshore platforms for the exploration of oil in the North Sea, as has been already mentioned, most on them GBS’s sitting on the seabed.

Permanently floating offshore concrete vessels related to the petroleum industry are now installed in the Java Sea, in the North Sea and outside the coast of Congo in West Africa, examples follow:

The ARCO barge (Ref. 18): The Ardjuna Sakti is a floating prestressed concrete LPG storage facility with overall dimensions 140.5 × 41.5 × 17.2 m (length × beam × depth). Fully loaded, the vessel displaces 66,000 tons. The ARCO barge was built and completely outfitted in Tacoma (Washington) and towed 16,000 km (10,000 miles) across the Pacific Ocean to the Java Sea in 1976, where it is permanently moored.

Concrete barge ‘C-Boat 500’: The prototype barge, of 37 m length, 9 m beam and 3.1 m depth and of 500 dwt loading capacity was built in Japan in 1982.

Heidrun TLP (Ref. 19): Conoco’s Heidrun platform is the world’s first TLP with a concrete hull and the largest permanently floating concrete structure ever with a concrete volume of 67,000 m³. The topside related weight is 89,000 tons (net 65,000 t topside) and the displacement 285,000 tons. The platform was installed on location in the North Sea in 1995, at a water depth of 345 m.

Troll Oil Semi (Ref. 20): Norsk Hydro’s Troll Oil FPS platform is the world’s first concrete catenary anchored floater. The Troll Oil semi submersible hull has a concrete volume of 46,000 m³ and supports a topside weight of 32,500 tons. The displacement is 190,000 tons. The platform was installed on location in the North Sea in 1995, at a water depth of 335 m.

Nkossa barge (Refs. 21 and 22): Elf Congo’s Nkossa barge is the world’s largest prestressed concrete barge. The floating production vessel of which the dimension is 220 × 46 × 16 m was built in Marseille, France, and towed 4500 nautical miles to the west coast of Congo in West Africa where it was permanently anchored in 170 m water depth in 1996. The total displacement fully loaded is 107,000 tons, and the concrete volume of the barge is 27,000 m³. The hull supports six topside modules with a total weight of 33,000 tons.

4. DESIGN, MATERIALS AND CONSTRUCTION

All structural design require due respect for the use of the structure. For offshore concrete structures the construction method needs special attention, and so do the hydrodynamic loads and the influence of the salt water on the durability.

Considering the phases the structure floats. It is obvious that the deadweight of the platform is of importance. A vessel must carry its own weight plus a payload. For the concrete platform the payload is the topside and equipment, as well as any ballast required for hydrostatic and/or geotechnical stability.

The significance of weight and strength is simply illustrated in Fig. 9 for a “unit” cylindrical structure subjected to hydrostatic pressure, Ref. 3.
The effect of strength and weight of concrete, on concrete volume required for a “unit” vessel, Ref. 3.

The figure also demonstrates the importance and potential benefit of research. The pay-off of this research is tremendous. Jan Moksnes Ref. 4 presents some of the results of Norwegian research on concrete over the period 1980-2000.

Equally important as structural efficiency is the performance of the material over time. It is evident from Fig. 4 that the environmental impact in terms of spray and seawater is extreme. Concerning the issue of deterioration by chloride-induced corrosion, which has been a main focus when designing marine offshore concrete structures, limiting values for concrete composition and cover to the reinforcement have been imposed based on experience with other marine structures like harbor works and bridges.

There are examples of premature failures for concrete structures in coastal areas (e.g. bridge piers and quay structures) - suggesting that the marine environment is demanding and imposes special requirements on materials and workmanship. It is in this context important to distinguish between the onshore and offshore concrete industry. The problems experienced in coastal areas for the onshore concrete industry is caused by, for example Ref. 23: improper cover, misplaced reinforcement, improper handling/placing of concrete or poor quality of concrete (e.g., seawater contaminated aggregates, improper concrete mix proportions).

In Norway, the experiences with coastal bridges have shown that the principal causes of failure are the same as reported above. In general, however, marine structures built by the concrete industry have suffered very limited from degradation - refer for example list of surveys presented in FIP’s state-of-the-art report on inspection, maintenance and repair of concrete sea structures, Ref. 27.

In 1999 a large Norwegian research program, Ref. 5, investigated the durability of concrete structures, covering bridges, industrial structures, quays and offshore platforms. Main emphasis was on chloride penetration and reinforcement corrosion. Six offshore concrete structures were investigated (years in operation at time of inspection):

- Statfjord A (16)
- Gullfaks A (7)
- Gullfaks C (4)
- Oseberg A (8/9)
- Troll B (2)
- Ekofisk Tank (17/22)

The project was primarily aimed at bridges, in particular those in the marine environment. For comparison and correlation the platforms were included.

Inspections and measurements document that the concrete in the offshore platforms is not flawless. But when the intended quality of concrete and cover to reinforcement are achieved, the concrete is very durable and serves its function very well. Based on measurements of chlorides in the cover zone, anticipated life of such concrete is more than 200 years Refs. 5, 6 and 7.

There are virtually no costs associated with the maintenance of offshore concrete structures, Ref. 13. According to Dr. George Hoff (Mobil) the Beryl B steel jacket substructure, installed in May 1983 in the North Sea (weight in air: 12,150 tonnes), has USD 2,300,000 higher annual maintenance cost compared to the Beryl A concrete substructure installed in 1975. The Beryl A concrete GBS is located only 10 km away from Beryl B and is “doing the same job” under the same environmental conditions. This means, again according to Dr. Hoff, that the accumulated saved maintenance cost for the concrete GBS over the field lifetime exceeds the total EPCI cost for the concrete substructure back in 1975. This aspect will become clearer when modern methods of calculating economic return (i.e. LCC) become more common or mandatory.
A comprehensive list of references to information pertaining to the performance of North Sea concrete structures is presented in Ref. 6. No significant sign of material deterioration, corrosion of reinforcement or other material-related deficiencies have been observed. Observed deficiencies are mainly caused by falling objects or ramming ships. Platforms designed for 20 years operation are now passing/have passed their prescribed design life. Inspections and investigations confirm that their life time can be extended.

Various codes give well-established rules for assessing fire resistance. Two hydrocarbon fires inside North Sea concrete platform shafts in the late seventies are reported. The consequence was a surface scaling about 10-20 mm deep over a height of 5-10 m. This marginal impact is attributed to the large heat capacity and low thermal conductivity of concrete. No repair was found necessary - clearly demonstrating the excellent fire resistance of concrete, which is definitely required for offshore structures for the petroleum industry.

Concrete is normally considered to be one of the best fire proofing materials available, a factor of unquestionable importance for an offshore oil or gas platform/storage. There are many instances, both ashore and afloat, of fire providing disastrous to steel structures, but causing no more than local to no damage to concrete structures. As an example constituting the most impressive testimonial that could possible be confirmed that their life time can be extended.

Prestressed concrete was chosen as the hull material for the ARCO barge because of its seaworthiness, competitive cost, fire resistance, durability and speed of construction. After almost twenty years of continuous service, various tests were carried out for the concrete barge. Due to its excellent condition, Ref. 21, ARCO has given its barge an “indefinite” lifespan - a solid proof of the excellent performance of concrete in a marine environment as well as its good fatigue resistance.

The nature of hydrodynamic loads is such that they are greatly reduced as you move down from the watersurface. Therefore a buoyancy structure deeply submerged may be far more efficient than one just below the sea level.

Most countries of the world have a construction industry for concrete structures; few have for large steel structures. This is a competitive edge for offshore concrete structures.

Structural design is performed stepwise with increasing accuracy and increasing extent. Before the structure is built, a comprehensive detail design including reinforcement drawings and bar lists will be performed. Before that, however, typically several design phases have been performed.

The importance of the early design phases is significant. This is when the competitiveness is established, and also the robustness of the structure to meet changes at later stages. Offshore structures are subjected to very severe loadings, and increasingly more so as arctic frontiers are developed. The structures will during stages float. Redundancies are therefore expensive, and the meaning of robustness needs to be clearly understood.

Typically construction contracts are design and build contracts; EPCI contracts (Engineering, Procurement, Construction, Installation). Then the quality of design performed in former phases is important. The conceptual design is very important for the good result. Conceptual design requires a general understanding of the function of the structure, not only an understanding of reinforced concrete.

The description of the offshore structures are more on the general, conceptual level in this paper. This does not imply that the detailed analyses and detail design is not very important. Hydrostatic stability is essential and often governing for the overall layout of the structure. Hydrodynamic response is also important for the design, it will determine if it is possible to place the structure in water as well as predict loads on the structure. Structural design is important for safety, construction and cost, and to the strive to make the structures float.
Rational design procedures are important, as the offshore structures are well outside the laboratory size of test specimen size, hence empirical knowledge will be of limiting experience, rather the opposite, it may be dangerous. As mentioned the offshore structures float, at least for periods of time, and weight redundancies are very expensive. This puts structural design in a squeeze.

To ensure rational design practice extensive collaboration with Prof. Michael P. Collins and University of Toronto has been successful. The combined analytical, computational and experimental expertise of that University has been most useful for a good development.

As an illustration consider the bridge failure described by Prof. Collins in his London Lecture in 2008, Ref. 15. Fig. 13 shows failure of the bridge with member dimension well outside the size of the typical experimental shear beam; a major shear failure caused by inadequate shear provisions and the consequent lack of sufficient number of stirrups. Fig. 14 shows test facilities for real size members, experimental results and comparison of design standards. When coupled with rational theories and analytical means, Michael P. Collins and the U of T have contributed significantly to the quality of structural design.

The conventional sectional design method for shell and plate sections of offshore concrete structures accounts for the non-linear material behavior of reinforced concrete when establishing cross-sectional response. Since the non-linear sectional response is based on the results of the linear-elastic FE analysis, the corresponding state of strain is not consistent with the strains from the linear FE-analyses upon which the design is based and it represents other stiffness properties.

This lack of a consistent formulation of the behaviour of cracked reinforced concrete accounting for both equilibrium and compatibility has resulted in excessive conservatism, but – at least in theory – possibly also to inadequate design.
In our analysis and design tool ShellDesign this inconsistency is eliminated by an iterative analysis and design approach which ensures that the stiffness parameters used in the linear FE-model are consistent with the calculated sectional stiffness at the actual load and reinforcement levels.

In order to fully utilize the non-linear behavior of a concrete structure, a consistent material model which treats all forces, including (in-plane and out-of-plane) shear forces is prerequisite. We plan to solve this by implementing Modified Compression Field Theory (MCFT) in ShellDesign and by doing so we simultaneously address the well-known and important weakness of the simplified methods for design of transverse shear in shell elements.

We believe that ShellDesign will bring state-of-the-art in the design of complex concrete structures a significant step forward and result in a number of benefits such as:

- Increased accuracy, safety and confidence
- Reduced construction costs due to more evenly distributed reinforcement and possibly reduced total reinforcement quantities
- Potential for documenting an increased excess capacity in existing structures (increased loads/redesign)
- More accurate documentation of real residual strength capacity in reassessments of existing structures

5. RULES AND REGULATION

There are several recognized international rules and regulations pertaining to the design and execution of offshore concrete structures. The overall common requirement is that the structure shall be designed, executed, transported and installed in such a way that:

- the reliability level of the installed platform meets the intended reliability level;
- all functional and structural requirements are met.

In the early days of offshore concrete structures, no national or international standards were available for their design and construction. In addition to the early FIP documents already mentioned, also ACI committee 357 “Offshore and marine concrete structures” published in the 1980’s and 1990’s ACI 357R-84 “Guide for the design and construction of fixed offshore concrete structures”. This document is currently being worked on, so is a specific work on offshore concrete structures for the arctic.

Later the International Organization for Standardization (ISO) took the initiative to develop a full package of standards for the subject under the auspices of ISO TC-67 “Materials, equipment and offshore structures for petroleum and natural gas industries”.

Of particular importance to our subject is ISO 19903 on concrete structures. This standard is developed by TC-67/SC7. By June 2007, this document got the needed ISO positive votes and thus became an approved international standard. ISO 19903 covers all aspects as design, construction, installation, assessments of existing structures as well as their removal.

The ISO 19903 “Petroleum and natural gas industries - Offshore structures - Fixed concrete structures”, lists all those areas of design that are particular to offshore concrete structures, and acknowledges that design may be performed according to national standards provided it is supplemented with additional rules for all those areas not properly covered by the national standard. It then in a note states that the Norwegian Standard NS 3473, Ref. 25, is recognized to meet all those requirements relevant for the design of offshore concrete structures.

Another soon emerging standard expected to support ISO 19903 is ISO 22966 “Execution of concrete structures”. This covers all concrete related site activities and will be based, due to the “Vienna Agreement”, on the European CEN EN 13670 supposed to be issued for formal vote in 2008.

This means that after 3 decades of efforts, the world’s stakeholders in the field of offshore concrete structures for oil and gas fields have united in a common tool-box of standards under the ISO umbrella.

In Norway the following main class notation is used for ship-shaped FPSO’s complying with Det Norske Veritas (DNV) class requirements and the Norwegian rules and regulations as issued by the Norwegian Petroleum Directorate; +1A1 Oil Production and Storage Vessel (N).

The analyses and design will then follow the extended calculation procedures for hull structures - additional class notation CSA-2.

The wave loading experienced by a permanently moored shipFPSO is quite different compared to that of a sailing merchant ship (may in general vary some 25 to 35% above that of the response calculated from DNV rules for merchant ships). This calls for a separate hydrodynamic analysis, independently of the fact that concrete FPSO’s/barges are “unusual” and cannot easily be fitted into existing standard steel categories.

The analyses and design of a concrete hull will therefore follow the traditional approach for offshore concrete floaters, as demonstrated and approved in detail engineering of the ARCO barge, Heidrun TLP, Troll Oil Semi and the Nkossa barge:

- the reliability level of the installed platform meets the intended reliability level;
— all functional and structural requirements are met. 
— hydrostatic analyses (drafts, internal/external waterlevels, still water moments and shear forces, afloat stability - intact and damage) 
— hydrodynamic analyses (global responses and hydrodynamic wave pressures) 
— mooring analyses and design 
— structural response analyses (finite element analyses) 
— structural design verification (code checking according to Norwegian standard NS 3473 or DNV concrete design rules harmonized with the rules in NS 3473) 

To date we are not aware of any offshore concrete structure that has been built to other national standards than the Norwegian NS 3473 without the need of extensive supplements. Areas normally not adequately covered for offshore structures are such as; fatigue, tightness, design provisions for shell type members, design for durability and cracking etc. Elf Congo’s Nkossa barge has been designed to Bureau Veritas shipbuilding specifications, using the NS 3473 for the concrete design verification, where it is registered as a “certified” hull. The Canadian Hibernia platform and the Australian West Tuna, Bream B and Wandoow platforms have all been designed according to NS 3473. The detail design of the Sakhalin GBSs, the civil design team headed by Dr.techn.Olav Olav Olsen, is carried out in accordance with the approach set out by Det Norske Veritas Rules for Classification of Fixed Offshore Installations (DNV Rules). The reference standard for concrete design is British Standard BS 8110, but according to what stated above, specific interpretations and additions have been necessary in order to make this standard applicable for offshore structures. For this purpose the Norwegian standard NS 3473 is used as supplement. BS 8110 is most likely used because the initial conceptual phases were performed by a UK consultancy. 

The reference standard to be used should be agreed at an early stage in the project, as the choice of standard might strongly influence the platform geometry and dimensions, while standards not intended for offshore use might be unnecessarily conservative on certain aspects relevant to offshore conditions. 

The reference standard shall incorporate recognized codified constitutive models for the non-linear behavior of concrete shell elements. It shall give the design parameters required for the type of concrete, e.g. normal weight or lightweight concrete, and strength class used. For high strength concretes and lightweight concrete, the effect of reduced ductility shall be considered. This in particular applies to the stress/strain diagram in compression, and the design parameter used for the tensile strength in calculation of bond strength, and transverse shear resistance. 

6. DECOMMISSIONING OF THE OFFSHORE PLATFORMS 

Even though the offshore platforms, steel or concrete, may be fit for many years, international regulations will put constraints on the use of the oceans. Particularly important here is the OSPAR (OSlo PARis) Convention. In July 1998 it was decided that all platforms in the North Sea shall be removed after completing their duties. 

An exemption was made for concrete platforms, because of the believed complexity of the operation. But in an addendum to the Convention, was a statement that there are no plans for future use of concrete platforms. This may be interpreted as a competition obstacle. 

fib initialized work on the subject, in their Task Group 3.2 Recycling of Offshore Concrete Structures. The TG was convened by the author of this paper, and reported as fib Bulletin 18. 

The conclusions of the work were: 
— It is feasible to remove the offshore concrete structures. 
— Removing the entire installation is most likely the safest and most cost efficient way to remove the topside. 

The OSPAR Convention requires that the topside of the concrete platforms must be removed. The work of TG 3.2 is described in Refs. 1, 2 and 8. 

7. LNG TERMINALS 

The future will see an increased use of offshore LNG terminals, even in ice infested waters. The worldwide LNG trade has increased steadily and the trend is expected to continue. Concrete offers a unique combination of advantages over steel. Fig. 15 shows a picture of the Adriatic LNG Terminal being constructed in Spain. When in operation, Fig. 16, it will facilitate safe import of energy far away from inhabited areas. 

Fig. 15 The Adriatic LNG Terminal being built in Spain.
8. THE ARTIC

Some 25% of the world’s undiscovered reserves of oil and gas are believed to be located in the arctic. It seems reasonable therefore to expect Atlantic Canada, North Sea, Barents Sea, Caspian Sea and Sakhalin to be the prime markets for future concrete production facilities.

Some of the challenges associated with the arctic are ice loads and ice abrasion, limited installation windows, limited access for mitigation of unforeseen events, extreme focus on HSE (health, safety and environment), and the consequences of pollution. In more general terms the challenges for future projects in the areas mentioned above are associated with extreme loadings such as earthquake, ice berg impact, ice abrasion, and the safe removal of the entire installation upon completion of the field production.

Concrete is a very well suited material to build rough structures for the arctic. Several structures are built. Fig. 17 shows these platforms when constructed in Nahodka south of Vladivostok, and Fig. 18 shows one of them during installation and Fig. 19 after installation, prior to deck installation.

The Sakhalin II platforms are subjected to sheet ice. Ice is a science of its own, and must be understood to determine the actions the platforms are subjected to. Fig. 20 shows another type of ice, the ice berg. The coast of Newfoundland is subjected to these, and the Hibernia platform, a concrete GBS, is designed to resist them. The platform has been in operation for a decade.
To document and demonstrate the usefulness of concrete structures in harsh environment, fib (fédération internationale du béton) took the initiative to write a state-of-the-art Bulletin on the subject, collecting Task Group expert members from Russia, Canada, US, France, UK and Norway. The work of fib Task Group 1.5 “Concrete structures for the oil & gas fields in hostile marine environments” describes the challenges of the Arctic and the design of concrete structures to function in such a harsh environment. The state-of-the-art report is intended to support the industry in this effort and to facilitate the dialogue with prospective clients.

The work of the fib Task Group 1.5 (Refs. 12 and 14) included a survey of client observations and opinions regarding future deployment of offshore concrete structures in arctic regions. The predominant view was that the concrete option was considered suitable for arctic conditions for its strength and robustness, its ability to shelter risers and conductors inside the concrete hull, its ability to store oil in the caisson and the ability for tow from a more benign location and installation at the field in a short selected weather window. Oil companies are fundamentally steel minded and have little or no in-house concrete experience and some expressed their concerns about relying on a limited, but experienced, field of design consultants and civil contractors.

Positive aspects were mentioned to be:

- The structures can be floated out and installed in a short period of time. No site preparation or pile driving required.
- Risers and conductors can be placed inside the concrete shafts.
- Functions well at low temperatures without use of special steel.
- High content of local materials and labor.
- Robust structure.
- Unskilled labor can be employed provided experienced supervision is available.
- Integration of topsides with the concrete structure will be a winning proposition, where possible.

Aspects to be worked with were mentioned to be:

- The issue of ice abrasion resistance of concrete is not solved.
- Difficulties finding and establishing suitable construction sites.
- Constraints related to construction site/towing route restrictions.
- Many company executives are unfamiliar with concrete and have a negative perception.
- Removal.
- Few EPCI contractors for competitive bids.
- Better understanding of ice loads is needed.
- Concrete structures are perceived as costly.
- Better understanding of foundations on permafrost.
- Concrete mix design with respect to freeze-thaw durability.
- Improved construction procedures for arctic conditions.
- Evaluation of all relevant HSE factors for arctic conditions.

9. RECENT CONCEPTS

In response to the need for deep water production and storage, new concepts have been developed for this purpose. The Semo (Semisubmersible monohull) is illustrated in Fig. 21. The overall design philosophy is indicated in Fig. 22.

Fig. 21 The Semo.

Fig. 22 shows two design approaches leading to the same result, and a very logical result. A lot of work has been performed on the concept. Floating structures are more complex to design; there are a lot of parameters that need to be counted for. Analyses show that the Semo concept is feasible, robust and flexible with regard to most types of offshore developments.
Advanced motion analyses and simulations verify that the concept has superior sea motion characteristics. To further prove the motion characteristics the Semo was tested in the ocean basin at Marintek Trondheim. The results from these tests were as expected very positive and we consider aspects around 2nd order motions as solved.

**Fig. 22** The design philosophy behind the MPU Semo.

A very simple FSO (Fig. 23) has been developed lately, as a result of the need for oil storage offshore. The concept bears similarities to the Semo, but has different design specifications.

These concepts have sparked enthusiasm among medium sized ship/offshore yards which do not have their own dry-dock facilities available. They see the concepts as a possibility to enter the “FSO/FPSO market” which so far has been dominated entirely by ship shaped solutions.

**Fig. 23** Simple FSO.

Local content will be more important in the future, and concrete creates interesting opportunities with regard to local fabrication and assembly. For many countries it is important to build new industry and to further develop the economy. The fabrication of a concrete structure can give significant amount of work locally, which could give a political advantage compared to solutions built in other countries.

10. OUTLOOK

The offshore concrete platforms are a niche product in a market dominated by steel structures. Concrete platforms will only be considered when several of the characteristics attached to the concrete concept apply. These would almost certainly include a severe environment (large wave loads, large water depth, and tough climate), the need for intermediate storage due to lack of crude export infrastructure, robustness with respect to environmental challenges and extreme loads and an appreciation of the importance of high local content.

There are also great lakes covering hydrocarbons, sometimes far away from the ship building industry, and concrete is well suited for transport.

It seems reasonable to expect arctic development in Atlantic Canada, North Sea, Barents Sea, Caspian Sea and Sakhalin, markets for future concrete production facilities. The market for concrete LNG storage facilities is wider and floating and fixed LNG liquefaction plants can be foreseen in areas such as Barents Sea, Kara Sea, Sakhalin, NW Australia, W Africa, Brazil and Venezuela and LNG receiving terminals in GOM, Mediterranean and SE Asia.

The real challenge for the concrete industry, however, is to develop concrete concepts that will be competitive in the above situations and markets, to demonstrate that they can be designed, built and delivered efficiently and safely, and that they will meet the expectations and requirements of the operators and the public authorities. The future may benefit from the experience from the oil and gas projects, to achieve robust and safe structures for other application of concrete in the marine environment.

The example below (Fig. 24) shows a concept for a submerged floating tunnel, hiding the highway, arriving directly into the basement of a beautiful town, Refs. 9 and 10.

**Fig. 25** shows a proposal for a gravity based offshore windmill, benefiting from the same aspects as the gravity based offshore concrete structure for the oil and gas industry. For the windmills, the importance of quick installation is even more profound, as so many shall be installed.
The pictures in Fig. 26 illustrate the MPU Heavy Lifter, designed to remove offshore steel jacket platforms. Unfortunately, the owner went broke and the project was aborted. Before that, however, the structure was designed and concrete fabrication almost completed. Of particular interest is the development of a very usable LWA concrete, with an average unit weight of 1.57 (excl. reinforcement). The material and the structure is described in detail in refs. 29 and 30.

REFERENCES


