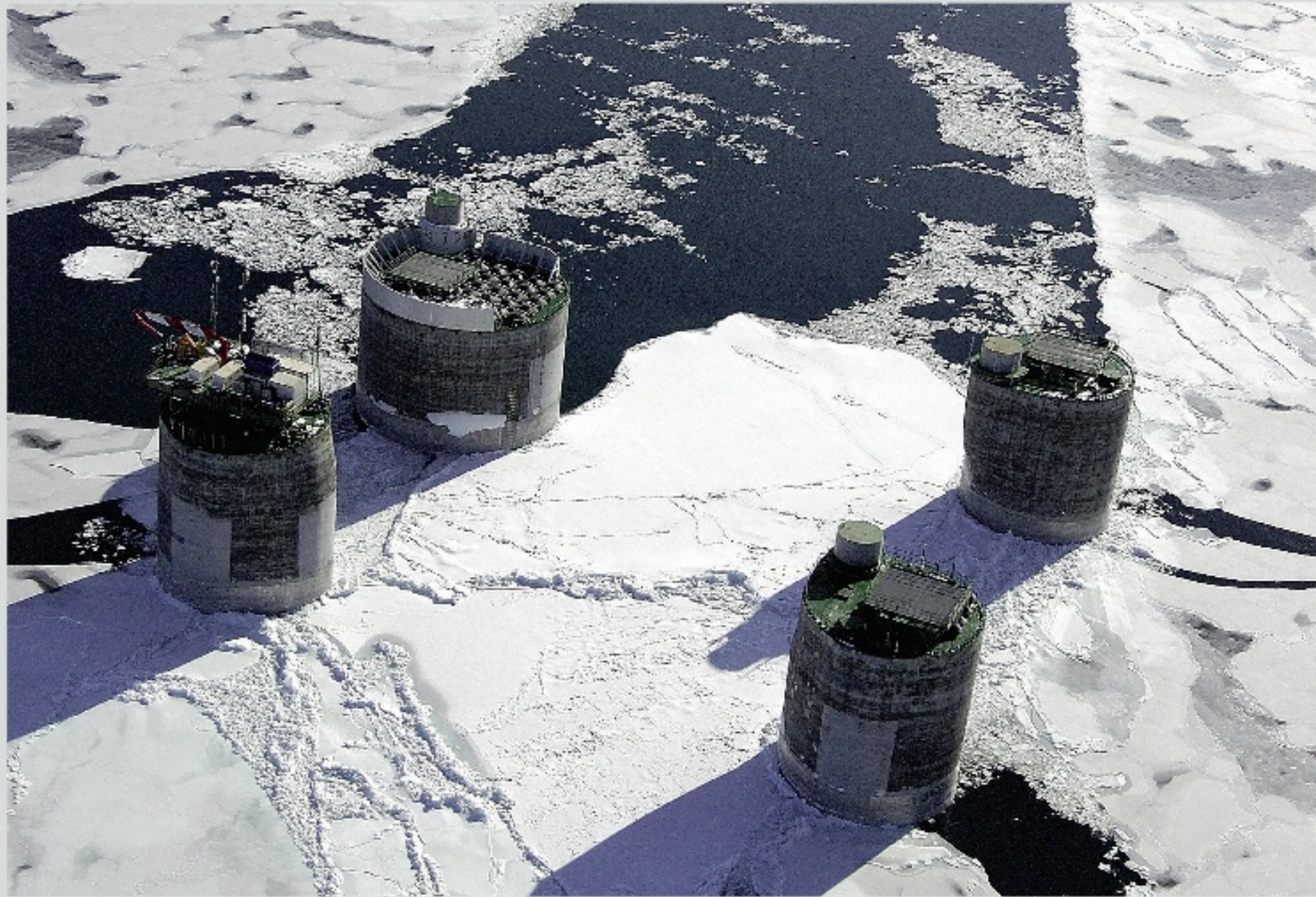




Concrete structures for oil and gas fields in hostile marine environments

Concrete structures for oil and gas fields in hostile marine environments

State-of-Art Report prepared by

Task Group 1.5

October 2009

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* Ben C. Gerwick Jr. was a world authority on offshore concrete structures and inspired the Task Group in the early stages of the work. Sadly he passed away in December 2006, but his profound contributions to the field of marine concrete structures are much appreciated.

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Cover image: Sakhalin-2 project: The concrete gravity base structure for Piltun-Astokhskiye-B (PA-B) platform in the harsh environment of the Sea of Okhotsk (photo courtesy of SEIC Ltd.)

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Contents

1	Summary	1
2	The history and performance of offshore concrete structures	2
3	Project planning and execution	5
4	Design	6
4.1	General	6
4.2	Loads	7
4.3	Design procedures	8
5	Construction	9
5.1	Construction phases	9
5.2	Yard/dock specifics	10
5.3	Construction methods	10
5.4	Marine operations	12
6	Materials	12
6.1	Concrete	12
6.2	Reinforcement and prestressing	13
6.3	Outfitting	14
7	Durability	19
7.1	Corrosion of reinforcement	19
7.2	Freeze-thaw resistance of concrete	19
8	Environmental issues	20
8.1	Environmental impact	20
8.2	Decommissioning/recycling	21
9	Concrete in the Arctic	21
9.1	Oil and gas reserves	21
9.2	The Arctic	21
9.3	Interaction with ice	22
9.4	Interaction with icebergs	23
9.5	Client perceptions	24
10	Other applications	25
11	Codes and standards	26
12	Bibliography	27

Preface

Since the 1970s a considerable number of large prestressed concrete structures have been delivered to the petroleum industry for offshore production of oil and gas in harsh and demanding environments. After some years with little development activity, there is a renewed interest in robust structures for the Arctic environment, for Liquefied Natural Gas (LNG) terminals and for special floating barges and vessels. Currently, concrete solutions are being considered for projects north and east of Russia, north of Norway and offshore Newfoundland, among others.

Concrete is also in increasing demand in built up coastal areas for a variety of purposes such as harbour works, tunnels and bridges, cargo terminals, parking garages and sea front housing developments where durability and robustness are essential.

In 2006 *fib* (fédération internationale du béton/International Federation for Structural Concrete) established a Task Group with a mandate to gather the experience and know-how pertinent to the development, design and execution of offshore concrete structures, and to elaborate on the applicability of concrete structures for the Arctic environments. The findings of the task group are presented in this present State-of-Art Report.

The report is based on experience gained from the design, execution and performance of a number of offshore concrete structures around the world and in particular in the North Sea. Ongoing inspections have shown excellent durability and structural performance, even in structures that have exceeded their design lives, in conditions often characterized by extreme wave loads, freezing conditions, hurricane force winds and seismic actions. This forms the “background” for discussing the applicability of concrete structures for the Arctic regions.

Although to a large extent dedicated to oil- and gas- related structures, the report will also be of relevance to other marine applications where the same design principles, material selection criteria and construction methods apply.

This State-of-Art report is not in itself a code, nor is it a textbook. Rather, extensive reference is made to proven and readily available design codes and construction guides, as well as relevant papers and proceedings and other *fib* publications.

Twenty-three engineers, carefully selected from one or several of the 49 major offshore concrete projects around the world, have participated in *fib* Task Group 1.5.

The Task Group wishes to thank the oil companies, contractors, consultants and academics who contributed material and pictures.

Tor Ole Olsen
Convener, *fib* Task Group 1.5

1 Summary

Concrete offshore structures have been successfully delivered to the international oil and gas industry for more than 35 years. Some 50 major concrete platforms of different shapes and sizes, supporting large production and storage facilities, are currently operating in hostile marine environments world wide and have excellent service records.

The vast majority of the current offshore concrete structures are Gravity Base Structures (GBS) founded on the sea floor, and characterized by their ability to resist extreme loads and, once installed, their robustness to accommodate design changes to the topsides and production equipment. Most have a tower and caisson 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 floaters and includes catenary or tension leg anchored floating hulls or large barges capable of carrying considerable payloads and accommodate storage of LNG or other products without the need for dry-docking over the life of the field. A third category is 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.

Concrete offshore structures differ from the more common steel jackets and floating hulls customarily 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 various 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 and are further expanded upon in the subsequent chapters of this report. Figures about costs on previous projects are not included as they are considered to be not so relevant for future new concepts for hostile environment.

Merits associated with concrete GBS:

- The concrete substructure can be robustly designed to resist extreme loading conditions such as large 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 topsides 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. 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 can 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 environmental protection 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 favourably to those associated with a steel substructure.
- A concrete GBS may be installed over a predrilled template for early production start.
- The ability to mate and carry a complete integrated deck structure gives scope for parallel construction and time savings on the project schedule.

The Arctic challenge is characterised 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 design redundancies, robustness, durability and low maintenance are well suited to this challenge.

2 The history and performance of offshore concrete structures

Concrete platforms for the offshore production of oil and gas are delivered in many shapes and sizes and can be adapted to a variety of water depths, environmental conditions and production requirements. The most common form is that of the GBS, which sits on the sea floor, is stable under its own weight, has a capacity to support large and heavy topsides and can store oil in its large caisson. A GBS generally consists of a shell or plate caisson structure and a number of straight or tapered shafts supporting the topsides and housing drilling and production equipment. Little or no site preparation is required and skirts incorporated in the base and penetrating the sea floor will ensure foundation stability. The GBS concept thus allows 3-fold use of the caisson; buoyancy, storage and foundation structure. This GBS structure may be even more valuable in the Arctic.

Floating concrete hulls for semi-submersible or tension leg platforms have also been delivered to the oil and gas industry, together with concrete barges, concrete islands, LNG terminals and other structures.

A list of the 49 major existing offshore concrete structures for oil and gas production is given in Table 2-1.

fib, through its then predecessor FIP, realised the potential for prestressed concrete in the offshore industry in the early 1970's. In 1973 FIP published the first edition of what was to become a most important document in this field; "FIP Recommendations for the design and construction of concrete sea structures". Another FIP report "Durability of Concrete Structures in the North Sea" was published in 1996 and demonstrated the very satisfactory performance of structures subjected to more than 20 years of exposure to hostile marine conditions.

Also Det Norske Veritas (DNV) made an early effort to design rules for offshore concrete structures. Since these first publications, a number of similar and supporting documents have been developed and now provide detailed guidelines and mandatory requirements for design and construction of marine concrete structures. The most recent of these is the international standard ISO 19903:2006 "Petroleum and natural gas industries – Fixed offshore concrete structures", which has also been adopted as European standard EN ISO 19903 and further implemented as a national standard in all the 30 European countries cooperating in the European organization for standardisation, CEN. Other similar codes include the Norwegian Code NS 3473, now widely used for offshore projects worldwide, the American Code ACI 357 and the Canadian Standard S474.

Nr	Year Install.	Original Operator	Field/ Unit	Platform Type	Water Depth	Concrete vol. m ³	Location
1	1973	Phillips	Ekofisk	Caisson, Jarlan Wall	71 m	80 000	North Sea (N)
2	1974	Atlantic Richfield	Ardjuna Field	LPG Barge	43 m	9 200	Indonesia
3	1975	Mobil	Beryl A	GBS 3 shafts	118 m	52 000	North Sea (UK)
4	1975	Shell	Brent B	GBS 3 shafts	140 m	64 000	North Sea (UK)
5	1975	Elf	Frigg CDP1	GBS 1 shaft, Jarlan Wall	104 m	60 000	North Sea (UK)
6	1976	Shell	Brent D	GBS 3 shafts	140 m	68 000	North Sea (UK)
7	1976	Elf	Frigg TP1	GBS 2 shafts	104 m	49 000	North Sea (UK)
8	1976	Elf	Frigg MCP-01	GBS 1 shaft, Jarlan Wall	94 m	60 000	North Sea (N)
9	1977	Shell	Dunlin A	GBS 4 shafts	153 m	90 000	North Sea (UK)
10	1977	Elf	Frigg TCP2	GBS 3 shafts	104 m	50 000	North Sea (N)
11	1977	Mobil	Statfjord A	GBS 3 shafts	145 m	87 000	North Sea (N)
12	1977	Petrobras	Ubarana-Pub 3	GBS caisson	15 m	15 000	Brazil
13	1978	Petrobras	Ubarana-Pub 2	GBS caisson	15 m	15 000	Brazil
14	1978	Petrobras	Ubarana-Pag 2	GBS caisson	15 m	15 000	Brazil
15	1978	Shell	Cormorant A	GBS 4 shafts	149 m	120 000	North Sea (UK)
16	1978	Chevron	Ninian Central	GBS 1 shaft, Jarlan Wall	136 m	140 000	North Sea (UK)
17	1978	Shell	Brent C	GBS 4 shafts	141 m	105 000	North Sea (UK)
18	1981	Mobil	Statfjord B	GBS 4 shafts	145 m	140 000	North Sea (N)
19	1981	Dome Petroleum	Tarsuit	Concrete Island, LWA	16 m	8 800	Beaufort Sea
20	1982	Phillips	Maureen ALC	Concrete base artic. LC	92 m	3 500	North Sea (UK)
21	1983	Texaco	Schwedeneck A*	GBS Monotower	25 m	3 620	North Sea (D)
22	1983	Texaco	Schwedeneck B*	GBS Monotower	16 m	3 060	North Sea (D)
23	1984	Mobil	Statfjord C	GBS 4 shafts	145 m	130 000	North Sea (N)
24	1984	Global Marin	Beaufort Sea **	GBS caisson, Arctic	16 m	14 300	Sakhalin (R)
25	1986	Statoil	Gullfaks A	GBS 4 shafts	135 m	125 000	North Sea (N)
26	1987	Statoil	Gullfaks B	GBS 3 shafts	141 m	101 000	North Sea (N)
27	1988	Norsk Hydro	Oseberg A	GBS 4 shafts	109 m	116 000	North Sea (N)
28	1989	Statoil	Gullfaks C	GBS 4 shafts, Skirt Piles	216 m	244 000	North Sea (N)
29	1989	Hamilton Bros	N. Ravenspurn	GBS 3 shafts	42 m	9 800	North Sea (UK)
30	1989	Phillips	Ekofisk P.B	Protection Ring	75 m	105 000	North Sea (N)
31	1996	Elf Congo	N'Kossa	Concrete Barge	170 m	26 500	Congo
32	1993	NAM	F3-FB	GBS 3 shafts	43 m	23 300	North Sea (NL)
33	1992	Saga	Snorre CFT	Suction anchors, 3 cells	310 m	7 800	North Sea (N)
34	1993	Statoil	Sleipner A	GBS 4 shafts	82 m	77 000	North Sea (N)
35	1993	Shell	Draugen	GBS Monotower	251 m	85 000	North Sea (N)
36	1994	Conoco	Heidrun Found.	Suction anchor, 19 cells	350 m	28 000	North Sea (N)
37	1996	BP	Harding	GBS Foundation/ Storage	109 m	37 000	North Sea (UK)
38	1995	Shell	Troll A	GBS 4 shafts, Skirt Piles	303 m	245 000	North Sea (N)
39	1995	Conoco	Heidrun TLP	Concrete TLP, LWA	350 m	63 000	North Sea (N)
40	1995	Norsk Hydro	Troll B	Semisub	325 m	43 000	North Sea (N)
41	1996	Esso	West Tuna	GBS 3 shafts	61 m	29 000	Australia
42	1996	Esso	Bream B	GBS 1 shaft	61 m	14 000	Australia
43	1996	Ampolex	Wandoo	GBS 4 shafts	54 m	28 000	Australia
44	1997	Mobil	Hibernia	GBS 4 shafts, Ice Wall	80 m	165 000	Canada
45	1999	Amerada Hess	South Arne	GBS	60 m	35 000	North Sea (DK)
46	2000	Shell	Malampaya	GBS 4 shafts	43 m	34 000	Philippines
47	2005	SEIC	Sakhalin LUN-A	GBS 4 shafts, Arctic	48 m	35 500	Sakhalin (R)
48	2005	SEIC	Sakhalin PA-B	GBS 4 shafts, Arctic	30 m	28 000	Sakhalin (R)
49	2008	ExxonMobil	Adriatic LNG	LNG terminal	29 m	95 000	Adriatic Sea (I)

Notes:

* The unit has been removed and demolished by the end of its life

** Relocated from Beaufort Sea to Sakhalin.

Table 2-1: Existing Offshore Concrete Structures for Oil and Gas Production.

In hostile environments and remote areas with limited infrastructure the concrete concept provides a competitive solution to an oil and gas industry predominantly served by steel jackets, floating hulls and sub-sea installations. Construction at a benign inshore location ensures cost efficient and timely delivery of a nearly complete and commissioned structure to its final destination in deeper water and more exposed conditions.

For small fields with moderate water depths and in more benign climatic conditions, or where oil storage is not required, the concrete concept may not always be the best option. Decommissioning and removal may become a major cost issue. This, however, must be weighed up against the significantly longer life time of concrete structures as compared to steel, and the fact that the GBS concept offers considerable adaptability to changing functions

and requirements during operation. Once installed, topsides design and weight can often be significantly modified. Topside weight increases of 10% and up to as much as 50% have been accomplished, so has a change in production from oil to gas. The ability of the concrete solution to accept significant future modifications and weight increases, adds value in the form of creating valuable “real estate” at remote offshore locations.

The analysis and detailed design of a concrete GBS in hostile waters are considerable tasks requiring relevant experience and adequate control procedures; however, this is the case for all major projects executed in these environments. Floating concrete structures can have superior floating characteristics compared to steel hulls. The increased weight, displacement and draft are beneficial for hull motions, although anchor forces may increase due to the generally larger hull displacement.

Where desired, oil storage in the caisson compartments can be achieved by replacing ballast water already present. Oil can be in direct contact with the concrete wall, no membranes are required. Dry storage, where the oil is stored below an inert gas blanket, may be required for lighter oils and condensates. The design and operation must account for the action of Sulphate Reducing Bacteria (SRB) or Sulphur Oxidising Bacteria (SOB) on oil or oily residues in storage, which can generate noxious gas.

All structures are made of heavily reinforced high strength/high performance (HS/HP) concrete subjected to extensive quality control. Concrete must be high strength to achieve the desired performance and durability, compatible with slender elements, minimum weight and minimum draught when afloat. Such concretes can now be reliably produced at most locations through carefully selected materials and adequate mix proportions.

Concrete structures require little or no maintenance during their service life and the Life-cycle Costs are very favourable compared to steel structures. The steel reinforcement is well protected from corrosion by HS/HP Concrete and adequate cover compliant with the Code requirements for the relevant exposure conditions and prescribed design life. Cathodic protection systems have been installed to protect embedded or attached steel components, not the reinforcement, although current drain to the reinforcement must be accounted for.

Standard test methods are available to verify all relevant concrete properties. In contrast to general civil constructions, offshore projects are generally organised more like a permanent industry with considerable focus on efficient production facilities, experienced staff and modern quality assurance principles.

In-service inspections of existing concrete platforms have revealed excellent performance characteristics and the need for little or no maintenance of the concrete hull. Examinations of drilled out cores from several North Sea platforms after 20 years of service have revealed that the chloride content near the steel is generally small and below the critical threshold value for the initiation of rebar corrosion.

The design and construction of concrete structures to operate in hostile areas such as the Arctic and sub-Arctic has successfully been accomplished in the past with the most recent examples being Hibernia (1997) on Canada's east coast and the Piltun (2005) and Lunskeye (2005) platforms in the Russian Sakhalin region.

The versatility of the concrete concepts is illustrated on the collage of realised concepts in the mid-section of this bulletin. This shows a number of existing structures ranging from very large caisson GBSs with tall and slender towers to floaters and LNG barges.

3 Project planning and execution

Offshore concrete projects embrace a number of technical disciplines and involve a long chain of suppliers and manufacturers. Each project is a prototype with unique features and challenges and is delivered into an industry which is well known for its focus on quality and safety. The complexity and schedule demands of the projects often favour delivery on an EPC or EPCI basis (one contract embracing engineering, procurement and construction and installation), but separate contracts for engineering and for construction are sometimes chosen to ensure a wider choice of bidders and utilization of the available expertise and capacity. Bids are often invited on the basis of an engineering study, or FEED, so that detailed design and construction are conducted in parallel in order to meet the scheduled start of production. Coordination and management of the interfaces between different activities and different disciplines have a major impact on the efficiency and progress of the work.

The time required to construct and deliver a structure will depend on a number of factors, including the size and complexity of the project, the available resources and the targeted installation date at the field. The early North Sea platforms were generally ready for deck mating and tow-out two years after start of construction and in accordance with the original project schedule. The smaller Sakhalin platforms took 18 months to complete in a parallel construction programme in a purpose built dry dock in Russia, and the giant Troll A platform took three years to build and one more year for mechanical completion, deck mating and tow-out.

A concrete project will lead to a major transfer of construction technology to the area where it is built and can provide significant potential for regional development and improvement in the capabilities of local companies. Based on previous experience from Norway, Newfoundland and Southeast Asia, the value of local content will typically be in the range of 50 to 90 % of the total cost. Concrete substructure tends to increase the local content also in topside and mechanical outfitting.

The availability of suitable dry docks may be a concern in some regions. Some of the docks utilized in previous projects are still in existence; others have been redeployed for other commercial purposes. Dry docks are commonly 10 to 15 m deep, some even 20 m, and closed by simple bund walls or re-floatable caissons.

Durable marine concrete structures require a quality level well above that associated with general land based construction. The specification requirements for materials and workmanship laid down in mandatory national and international codes need to be verified by rigorous test programmes and site trials to ensure the transfer of relevant technology and experience. Rigorous quality assurance programmes are implemented to ensure that the specification requirements are planned, achieved and documented. A quality control system is set in place for all major operations and site activities during the construction phase. Verification of work procedures, methods, materials, production data and test results is an essential part of the quality assurance programme.

It is essential to perform constructability reviews of the design before construction commences in order to achieve an efficient construction process on site. Through this process complex drawings are translated into working documents suitable for the operators at the work face and this task requires particularly experienced engineers and supervisors.

The labour force for the project is normally recruited from the local area and supplemented with selected skilled labourers. Working methods are similar to those adopted in general civil construction, but the safety and quality performance of the work generally has a higher priority on offshore structures. An extensive training and induction program should be established to prepare the labourers and the supervisors for the task and to secure a proper transfer of technology. Local supervisors can be employed to directly supervise the local workforce under the control of the client or main contractor supervision.

A third-party independent agency is generally employed to verify that all activities are executed, monitored and documented in accordance with the specification requirements and the statutory legal provisions.

4 Design

4.1 General

The objective of design is to develop concepts which meet or exceed the client's expectations and address authorities' requirements in a robust and optimal way. Design also involves documentation for construction and the development of working drawings for the construction crews.

The analysis and detailed design of a concrete structure in hostile waters are considerable tasks requiring relevant experience, but the overall design procedure, the design requirements and the quality control schemes are quite similar to those used in the design of more conventional concrete offshore structures.

Concrete shell and plate structures generally exhibit great inherent robustness. Structural analysis and design based on linear theory allows for some redistribution of internal forces, providing inherent adequate ductility and resulting in a greater margin of safety against collapse than the combined design load and material factors would imply.

A marine concrete structure is subject to severe loads during all phases of its life. Typical phases are:

- construction in a dry dock;
- construction afloat at an inshore location (if required);
- deck mating before tow;
- tow to field;
- installation at offshore location;
- alternatively deck mating after installation (if required);
- operation;
- decommissioning;
- removal.

Some temporary phases (particularly the float-out of a shallow base and the submergence prior to inshore deck mating) have a significant influence on the design.

The main steps in design are to identify the loads, to calculate the internal load effects in the structure when subjected to the different governing combinations of these loads, and finally to select element sizes which fulfil all design criteria (code checks). Since offshore platform construction began in the 1970s, an extensive development of all these steps has taken place in parallel with the development of computer technology.

Today, generally accepted methods and procedures, based on internationally accepted rules and regulations and supported by reliable and efficient computer tools, are available for design. These now permit a more consistent and high level of safety to be achieved, together with an optimal use of materials.

Durability must be a prime consideration in the design process where simplicity in shapes and details, generosity in dimensions and robustness in terms of constructability are key elements in securing quality. The interface between design and construction must be properly managed, and detailed planning and work preparation for the different phases of construction should not be underestimated.

4.2 Loads

The typical categories of loads experienced by marine concrete structures are:

- dead weight;
- live loads;
- differential pressures from water and stored oil;
- temperature;
- environmental loads;
- accidental loads.

The differential hydrostatic pressures may be very considerable. For instance, for the Troll A platform, differential pressures of 3 MPa (300 m water head) act at the base of the caisson. By forming the structural elements as cylindrical and spherical shells, the pressure difference is carried in a safe and economical way by membrane compression. For more moderate pressure differences, plate structures behave very well through a combination of membrane and bending action. All existing major offshore concrete platforms are shell/plate structures.

Thermal loads are of special importance in connection with tightness and durability. Comprehensive development work has taken place over the years regarding design for temperature effects. By treating temperature effects as imposed deformations (which is the reality), much more accurate design results and reasonable amounts of reinforcement are nowadays obtained, compared to the early concrete platforms, and tightness and durability criteria are satisfied in a much better way.

Recognized theories for waves, current and wind loads exist today. Computer calculations are frequently supplemented by basin model tests for more complex analytical tasks such as air gap demonstration. Many platforms have been designed for 100 year wave heights of 30 m or more. Design for such loads is ordinary technology today, and the existing platforms have been able to resist such loads perfectly.

Seismic loads often govern parts of offshore structures in more active seismic regions. Generally, concrete structures and their foundations have been shown to be adequate and robust (meaning that there are inherent structural redundancies in the design) with regard to seismic activity when properly designed and detailed. One could argue that, due to the monolithic nature of the GBS, under extreme earthquake events, seabed sliding of a few tens of centimetres would not jeopardise their integrity and can allow seismic energy to be dissipated in rare events.

In addition to the ordinary action effects, accidental loads such as explosions, ship impacts, dropped objects etc. may have even more serious consequences than for onshore facilities. Because of the robustness of the actual concrete structures, they have been able to withstand such loads well. For example a ship impact from a supply boat could cause substantial local damage to a shaft, whilst maintaining its overall load carrying capabilities and functions until repairs can be effected.

In Arctic/cold areas, loads from ice are a great challenge for offshore structures. The ice loads may be generated by icebergs, ridges (ref. the Hibernia platform) or by sheet ice (ref. the Sakhalin II platforms). The ice has been estimated to generate very high local pressures (corresponding to hundreds of metres of water head; 6 MPa for Hibernia) and large global loads, sometimes considerably larger than the loads caused by waves and earthquake. Concrete offshore structures have generally demonstrated that they resist ice loads well and have some superior qualities compared to other types of structures.

Ice is a very complicated material and the understanding of ice behaviour and its resulting pressures and loads have been subject to many years of research. The loads used some 20

years ago are now regarded as far too conservative and more economic designs are now being proposed.

In addition to the ordinary load effects caused by the ice, abrasion of the concrete surface is a vital issue with regard to the long term performance of concrete in an Arctic environment.

4.3 Design procedures

The structural analyses and design of offshore concrete structures comprise several disciplines. Structural concrete and geotechnical engineering are the main focus of this report; the other disciplines are encountered on all types of offshore projects so the report only addresses them where differences arise due to their combination with concrete.

Like all other complicated structures, the design of offshore concrete platforms utilizes Finite Element Method (FEM) computer programs. Although originally developed in the 1960s, a variety of commercial programs are now available which are much more accurate and efficient than for the early platforms. Except for some local designs, linear models are still widely used.

The analysis and design of complex marine structures involve a large amount of data manipulation. A large number of load conditions must be accounted for, the geometry can be complex, and a large number of design checks based on rather sophisticated rules and regulations have to be carried out. To make assessment more straightforward, post-processing tools have been continuously developed by engineering companies.

For offshore structures, demonstration of adequate tightness and durability are important serviceability considerations. Two measures introduced in the design of the first concrete platforms have proven to be very effective: Compression was ensured in the main parts of the structures either through the use of post-tensioning tendons or by adopting a drawdown system where the liquid (water and/or crude oil) pressure inside the structure was lower than the outside water pressure. Further criteria, which were much stricter than was commonplace for onshore structures at the time, were introduced in relation to acceptable stresses/crack widths, concrete quality, cover of the reinforcement and for the prestressing tendons.

Regarding fatigue, the actual concrete plate/shell structures are robust, i.e. the design and detailing is less influenced by fatigue than for typical steel structures. This is demonstrated by the fact that the design life of several platforms has been extended considerably without any need for strengthening. The fatigue design checks are based on generally accepted methods and codes and can influence the amount of reinforcement needed, but fatigue rarely affects the choice of concrete dimensions.

Different foundation principles have been applied for existing offshore concrete structures, all without the need for piles. The most common principle has been to install the structure with concrete or steel skirts incorporated in the base during dry dock construction and made to penetrate the sea floor by adding ballast water to the storage compartments. In some cases the voids in the skirt compartments between the concrete base and the sea floor are filled with cement based grout. The skirts transfer the loads down to sufficiently competent soil layers, and also act as scour protection. The grout ensures an even distribution of the loads on the sea-bed.

The under-base grouting represents one of several uncertainties which need to be considered when refloating.

The skirts range from very short (0.5 – 1 m deep) steel or concrete skirts to 40 m deep concrete skirts (skirt piles). For many platforms the skirt penetration load has been increased during installation by lowering the water pressure in the skirt compartments below ambient (suction). In addition, individual adjustment of the suction in the various compartments has proven to be a very efficient means of adjusting the inclination of the platforms.

Offshore structures are subject to cyclic loading from waves, ice or earthquakes. Pore pressure build-up and dissipation together with cyclic degradation of soil capacity are evaluated in connection with the foundation design. In some cases, soil drain systems have been applied to mitigate these effects.

The geotechnical design also includes the simulation of the interaction between soil and structure. This simulation commonly includes soil and structure deformation effects on pipelines, conductors and risers.

Experience from the installation and operation of existing platforms has shown that the principles used for foundation design are robust and reliable. Similar to the structural analyses and design methodology, the geotechnical design methods and tools have experienced an extensive development over time.

3D modelling is now common practice for all geometry drawings. This offers many benefits since the risk of working with inconsistent information is much reduced. Data from the model can be made available on site facilitating the placing of formwork etc. By including embedded items, post-tensioning reinforcement, etc., in the 3D model, clash checks are performed. Refined models of complicated areas including ordinary and post-tensioning reinforcement are also prepared to simulate the construction process and assist with constructability assessment. Offshore structures typically include heavily reinforced areas and involve demanding slip-forming or jump-forming operations for which proper planning and preparation are vital.

5 Construction

5.1 Construction phases

Construction commences in a dry dock and then, if required, and depending on its size and displacement, the structure is moved to a deep water site for completion. Whilst moored at the deep water site the platform is gradually ballasted to the desired draft and freeboard by pumping seawater into the storage compartments.

Construction afloat requires a considerable floating rig of batching plants, workshops, offices and storage facilities and a fleet of supply vessels and ferries. It is therefore common practice to take maximum advantage of dry dock construction and float-out on an air cushion in the skirt compartments.

The large foot print of the caisson and the height of the shafts render the project very crane intensive and the simultaneous execution of many activities, some at great height, makes work planning and safety top priority issues.

A high degree of completion can be achieved at inshore locations prior to tow-out. Where water depths permit, heavy topsides, fully assembled and pre-commissioned and weighing up to 50 000 tonnes, can be mated on to the concrete substructure by in shore float over in deep and sheltered water, eliminating costly offshore operations including hook-up and commissioning. Topsides can also be installed using land-based cranes at quayside (e.g. West Tuna and Bream B). In shallower water the concrete hull may be floated out at a suitable draft and installed on location before the deck is installed by float over or by lifting of modules. Decks weighing up to 28 000 tonnes have been installed in this way.

The different stages of construction are illustrated in Figure 5-1, for the case of an inshore float over and mating.

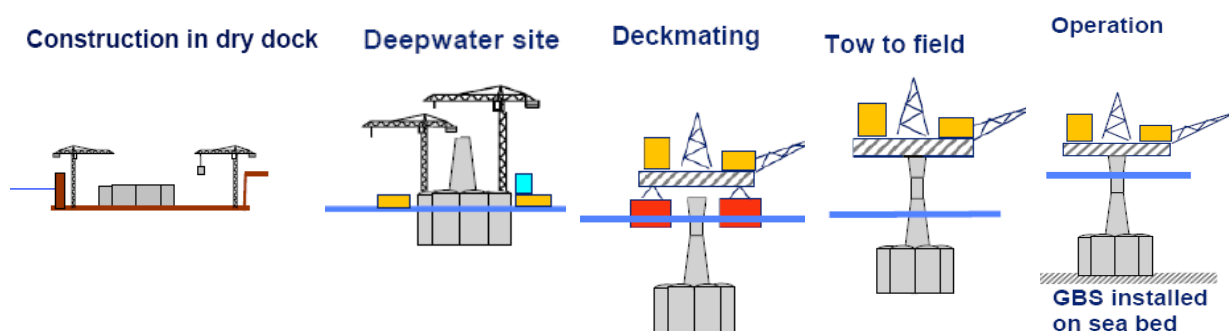


Figure 5-1: The construction and installation phase.

Inshore mating of nearly complete and fully integrated decks eliminates the need for large crane vessels, often with limited availability, and saves precious time through parallel construction of topsides and substructure. Offshore float-over may provide similar benefits. Close integration of concrete work with topsides outfitting in terms of detailing, logistics and yard facilities has proven challenging and may erode some of the competitive advantage concrete hulls can demonstrate over steel.

The completed platform can be towed to the field, or held under tow, in relatively harsh weather conditions and this contributes to significant cost and production schedule savings as compared to comparable steel structures. Installation is generally achieved in a matter of days so it can take place during a forecast weather window. Little or no preparation of the sea floor is required.

5.1 Yard/dock specifics

Dry docks are commonly 10 to 15 m deep, some even 20 m, and closed by simple sheet piled walls or floatable gates and have in the past been developed on green field coastal sites by either controlled excavation with dewatering or blasting and levelling. In order to establish a new dry dock, experience from recent projects has shown that some six to eight months may be required for site development. Application for permission can be a lengthy process and needs to be taken into consideration when a new dry dock is contemplated. A floating barge can act as an alternative to a dry dock for smaller concrete structures. The structures can then be lifted off or floated off by ballasting down the construction barge when complete. Alternatively, medium sized concrete portions of caissons may be prefabricated in a ship dock and assembled afloat by using prestressing tendons.

Once the dry dock is established, dewatering systems, batch plants, rebar shops, prefabrication yards, workshops and stores, office facilities, etc., are mobilized and installed on site, as would be the case for any major civil engineering project. Large integrated offshore projects are particularly crane intensive and a sufficient number of tower cranes and mobile cranes need to be available.

For the Adriatic LNG project the very large concrete caisson (180x90x40 m) was built in a 20 m deep dry dock near Gibraltar and fully fitted out with production and storage facilities before tow-out, thus eliminating more costly production afloat at an inshore location.

5.3 Construction methods

The construction of concrete offshore structures has been based on conventional and proven methods developed by the construction industry over time and then further developed

to suit the particular features and requirements of the offshore projects. The transfer of this particular offshore-related construction experience to new locations, cultures and environments has proven to be an important aspect for the successful delivery of new projects.

The prevailing construction method for vertical surfaces has been slip-forming, whereby caisson walls and shafts are produced in a continuous lifting process at a speed of several metres per day, thus eliminating horizontal construction joints and the need for tie bars through the walls. Reinforcement, embedded items and subsequent layers of concrete are installed near the top of the moving forms where access is easy for the operators and for inspection. Slip-forming is labour intensive over short periods but offers significant savings on the time schedule. Slip-forming requires special skills and is commonly performed by a specialized subcontractor. Uninterrupted supplies of all the component materials are essential and the setting time of the fresh concrete must be compatible with the targeted lifting rate of the formwork assembly. Slip-forming of complex shapes can be performed within strict geometrical tolerances.

More conventional proprietary climbing formwork systems or jump-forming, whereby the structure is subdivided into smaller sections, can be viable alternatives to slip-forming. Formwork assembly and placing of reinforcement, ducts and inserts is completed over the full height of the chosen section before concreting is completed from the bottom up, often by means of tremie pipes to ensure complete filling of the form. After striking the forms, the construction joints, including protruding reinforcing steel and ducts, are cleaned of any loose material and laitance before the forms are reassembled for the neighbouring section. This method is less labour intensive and less dependent on specialized subcontractors, but takes longer to perform.

In marine structures watertight construction joints are essential and require special attention. Removal of laitance and porous concrete by water jetting or other means is done as soon as the concrete has set and hardened sufficiently. The subsequent adjoining layer of fresh concrete must be thoroughly consolidated in order to get a dense concrete at the joint. In addition, for vertical joints and horizontal joints on the top of block outs, pre-installed grout or epoxy injection tubes can be beneficially deployed. It is recommended that any injection or grouting of construction joints, embedment, sleeves, etc., is thoroughly tested in order to ensure that the selected materials, method and equipment work as planned.

Concreting during cold weather is standard practice in all countries that cross the Arctic Circle. Temperature control of the work environment is required before placing concrete, which usually includes insulation to capture the heat of hydration and heating of the working area and the construction joints. By taking appropriate measures, concreting has been carried out on the Hibernia and Sakhalin II projects at temperatures below -10°C for prolonged periods. Some particularly frost-sensitive operations such as grouting of cable ducts are best scheduled for milder weather.

Offshore concrete structures typically have a very high average density of reinforcement and prestressing. Embedded mechanical systems, steel sleeves and temporary openings through the walls add to the congestion and clashes are inevitable, requiring some cutting of bars and modifying of details at the work face. Any such modifications shall be subject to approval by the designer. For highly congested areas, mock up tests on site prove invaluable to achieve efficiency in the full scale site operations.

Mechanical outfitting is installed in parallel with the ongoing civil work of the concrete structure. Outfitting should be function tested and commissioned as far as practicable before leaving the dry dock, to minimise the possibility of problems arising in later phases of installation or operation.

Some typical construction aspects are shown on the collage in the mid-section of the report, including dry dock construction, construction afloat, deck mating and tow-out as well as slip-form construction, dense reinforcement and prestressing and mechanical outfitting.

5.4 Marine operations

Offshore concrete structures are large floating vessels during construction, tow-out and installation at the field and marine engineering is an important aspect of every project. Floating stability and weight control need to be considered at all stages and are major issues together with the design of temporary anchorages, towing gear and installation procedures at the offshore location, where strict tolerances apply to the positioning of vessel in relation to preinstalled wells and templates. The standard installation procedure is based on tugs only (no guiding piles are needed). Many platforms have been installed on site within a fraction of a metre tolerance and even less where installed over a predrilled template (with the help of guiding systems).

Weather conditions in the Arctic put extra constraints on the marine operation, not only the ice, but also the potential lack of light, low temperature, accessibility, etc.

Installation windows can become major hold points in the master schedule where specialist equipment is being hired. Missing the window may cause significant delays to the start of production. In contrast GBS structures only require a fleet of tugs so there is more flexibility in the float-out and installation schedule compared to structures needing heavy lift vessels.

Water ballasting is an ongoing operation to maintain the desired draft and freeboard during construction afloat, when under tow and to ensure controlled submergence and penetration of the skirts at the field. By increasing the draft during tow by ballasting this can increase the robustness of the towing operations in case of bad weather.

The scale of the marine operations can be illustrated by the tow-out and installation of the very large Troll A platform in 1995. The platform was towed 174 nautical miles to the field at a draft of 227 m and the tow was performed by means of 10 tugs at an average speed of 1.5 knots. On location, the penetration of the skirt piles through the soft soils and to a final depth of 35.7 m beneath the sea floor was achieved in 5 days.

The heaviest platform, Gullfaks C, had a displacement during tow of 1.5 million tonnes and constitutes the heaviest object ever moved by man.

6 Materials

6.1 Concrete

Concrete must be of high strength and consist of sound and proven components. A well designed concrete mix combined with details that facilitate placing and compaction, proper curing and adequate cover to the steel will ensure adequate durability. The term “high performance concrete” is commonly used in this context and embraces high strength, suitable workability and stability as well as proven and adequate durability.

High performance concrete in offshore structures requires the use of:

- high strength/low heat cement;
- pozzolanic additives such as fly ash, slag or silica fume;
- high-quality aggregates of suitable size, strength, grading and mineral composition;
- chemical admixtures such as superplasticizers, set retarders and air entraining agents;
- low water/binder ratios and high workability.

Durable high-strength/high performance (HS/HP) concrete can now be produced at most locations through rigorous material selection (sometimes transported some distance from proven sources) and adequate mix proportions. Standard test methods are available in national and international codes to identify suitable materials, define the relevant engineering properties and monitor the achieved quality during construction. A mix design development program is required to optimize the concrete mix designs and to verify their compatibility with the chosen plant, construction procedures and the prevailing climate. The chosen concrete mixes must be sufficiently robust to tolerate the changing conditions and priorities normally associated with complex construction site and large projects embracing many activities and trades.

Light weight aggregate concrete (LWAC) is suitable for marine structures and can give significant weight reductions whilst maintaining high strength and durability. Low densities reduce the draft and can improve floating stability during the marine phases.

Modern HS/HP concretes have excellent cryogenic properties and are well suited for the construction of LNG storage facilities. Most concrete properties (compressive and tensile strength, E-modulus, permeability, creep, thermal expansion and conductivity) improve as the temperature approaches cryogenic values, the extent of improvement depending primarily on the moisture content of the concrete. In the event of an LNG leakage, and subsequent fire, concrete slabs and walls can provide short term fire protection of adjacent mechanical plant and equipment.

Concrete is normally considered to be an excellent fire proofing material. Shallow surface spalling may occur in concrete exposed to a severe hydrocarbon fire and can be mitigated by including polypropylene fibres.

6.2 Reinforcement and prestressing

Due to the severe loading conditions, high densities of reinforcement are encountered on most offshore structures. Densities of 300 – 400 kg/m³ are not uncommon and may rise to 700 – 800 kg/m³ (even up to 1 000 kg/m³ for Arctic structures) locally in special cases. Large diameter bars are therefore often used and special efforts are required in the work planning and preparation of working drawings. Small diameter aggregates are generally used in order to improve concrete placing into the forms and to improve compaction.

In general hot-rolled ribbed bars of weldable quality and high ductility (yield stress 500 MPa or more) shall be used.

Special reinforcement couplers of documented properties and performance may be needed at construction joints and temporary openings, as well as in reinforcement congested areas for replacing conventional overlapping length bar splices. T-headed bars (standard reinforcement bars with a small square or rectangular plate friction welded on to the ends) have been used instead of conventional shear reinforcement on several offshore projects to reduce the congestion of small diameter stirrups and facilitate the placing of concrete. T-heads may also be used to anchor larger bars.

Offshore concrete structures are generally heavily prestressed in order to achieve the necessary load-bearing capacity and minimize the extent of tensile cracking. Proper installation of the prestressing system is vital to the performance and durability of the structure and should be performed by specialised subcontractors and subjected to rigorous quality control through all stages of placing ducts, threading, tensioning and anchoring of tendons, grouting of the ducts and sealing of the anchorages. All these interdependent activities must be performed according to a coherent time schedule and agreed procedures.

A number of technical reports and guidelines have been developed by *fib*, ACI and others for this purpose.

Due to the density and complexity of the reinforcement and the prestressing system, a full scale mock up test on small sections is sometimes performed on site to train the working crews and identify problem areas.

6.3 Outfitting

The mechanical outfitting of an offshore concrete structure consists of two categories:

- temporary systems required for safe construction, tow-out and installation,
- permanent systems required to tie in the platform to the reservoirs and the service systems for the topsides.

Most of the temporary systems will be closed down, and sometimes grout injected, or removed, during the service life of the platform. The permanent systems consist of conductors, risers, J-tubes, and pipelines for fire- and sea water systems, disposal lines, liquid storage and instrumentation. Most of the equipment and pumps are installed in a utility shaft in the GBS. Glass Fibre Reinforced Plastic (GRP), 6 Mo steel or titanium is sometimes used in permanent systems that are not replaceable and essential for the platform operation and removal after 30 or 40 years at sea. Elsewhere, high density polyethylene or carbon steel is commonly used.

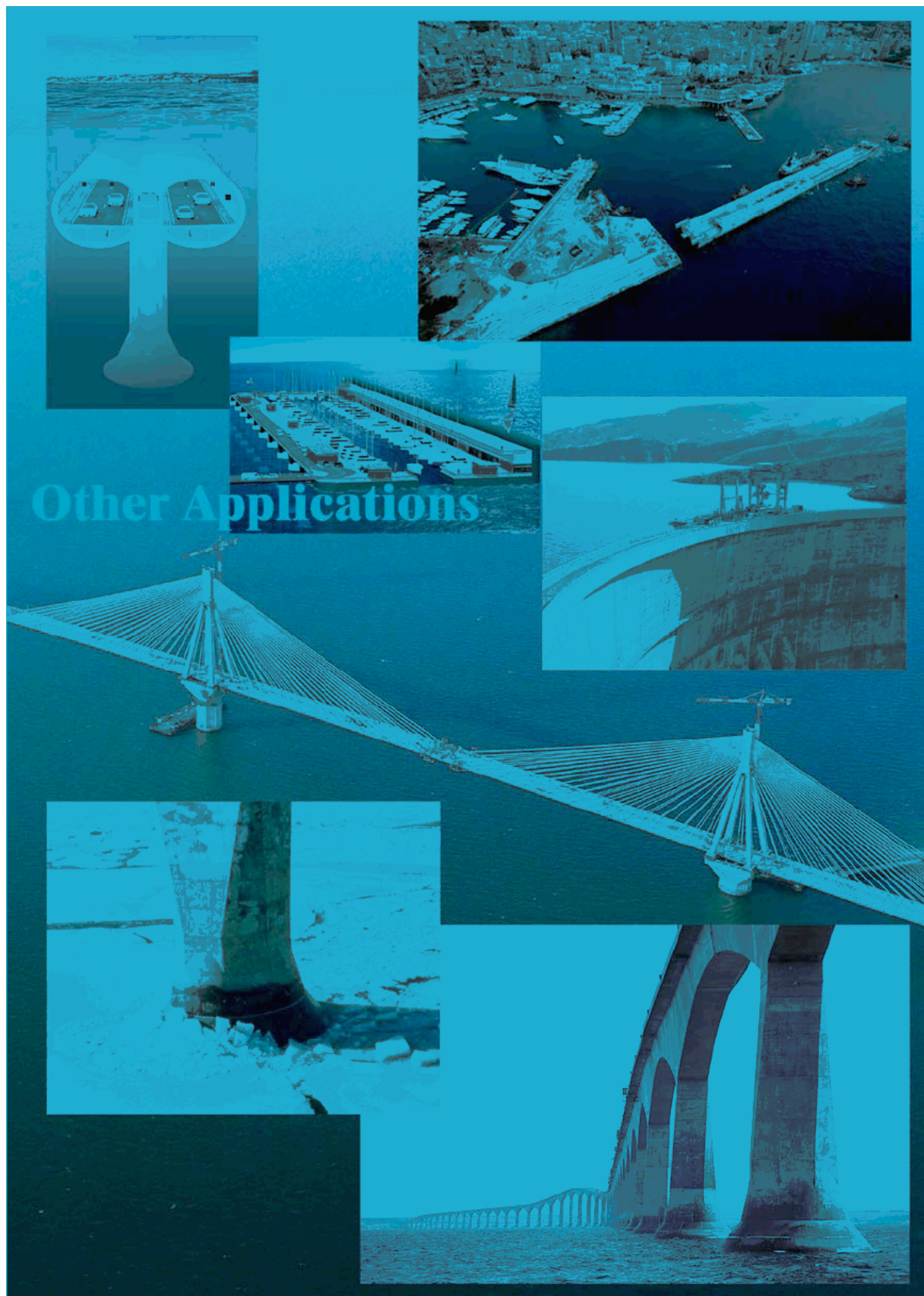
The steel structures in the utility shaft and pipe work and systems elsewhere in the GBS is attached to the concrete by embedment plates accurately positioned and installed during the civil construction work. Penetrations through walls are often adopted for sleeves connected to the pipe systems and temporary openings are installed for access and for subsequent installation of mechanical plant and equipment. Strict geometry control is required for these activities in the interface area between different systems and disciplines. The design life for the outfitting should be the same as for the GBS, except for items such as rotating equipment which may require periodic replacement.

Typically the steel equipment is equipped with cathodic protection, by attaching sacrificial anodes to the steel components.









7 Durability

7.1 Corrosion of reinforcement

Concrete in seawater has adequate durability, provided attention is paid to some basic rules of mix design and construction. The essential requirements are the use of HS/HP Concrete with low permeability, together with adequate and uniform concrete cover to the reinforcement, preventing sufficient oxygen and seawater carrying chlorides from penetrating to the steel and initiating corrosion during the service life of the structure. The use of mineral additions such as fly ash, blastfurnace slag and silica fume has been found to significantly improve the durability of marine concrete due to improved resistance to the ingress of chlorides and reduced risk of thermal cracking. The required minimum cover to the principal reinforcement for different exposure conditions is specified in several codes. The early FIP recommendations of minimum 50 mm cover in the submerged zone and 65 mm in the splash zone has proven to be adequate for the North Sea platforms after more than 30 years. The more recent Norwegian Code NS 3473 stipulates a minimum cover of 60 mm in the submerged zone and 70 mm in the splash zone for 100 years service life.

Offshore concrete structures are normally subject to regular inspection schemes. The most important concern is the ingress of chlorides that might destroy the passivity of the steel provided by the concrete cover. A recent survey of some 180 cores drilled from a number of North Sea structures, gave a sound basis for extrapolation of the remaining initiation period until the possible onset of corrosion and confirmed the relevance of the code requirements.

Some of the early North Sea platforms received a coating of epoxy in the splash zone of the concrete shafts. The coating was applied to the young concrete during slip-forming. Similar coatings have been applied from time to time on other projects to compensate for inadequate concrete cover in local areas. This epoxy coating on some of the early platforms is still intact, and in-field inspection has demonstrated that it also effectively blocks chloride penetration to the concrete.

The overall conclusion of the North Sea coring programme and recent life expectancy studies is that the specifications for marine structures, as presented in modern codes, are sufficiently strict concerning concrete composition and cover to the reinforcement to ensure a design service life of more than 100 years.

For future structures, there is, however, still potential to focus on the workmanship to avoid local imperfections and on inspection to detect and repair these before tow-out. If the concrete is cracked due to shrinkage, creep, thermal gradients and other unfavourable stresses, a more rapid penetration of chlorides to the steel may take place. The design codes stipulate crack width limitations for the Serviceability Limit State (SLS) depending on the actual environmental zone under consideration. The most stringent crack width limitations apply to the splash zone and the atmospheric zone. These zones are more or less continuously subjected to wetting and drying and there is enough oxygen to sustain the corrosion process.

A more relaxed crack width limit applies to the permanently submerged zone. In this zone cracks that permit water ingress tend to close themselves with time by additional hydration of the cementitious materials and deposition of filling materials.

7.2 Freeze-thaw resistance of concrete

The question of durability in freeze-thaw conditions was addressed in the early FIP recommendations adopted for the North Sea platforms, stipulating a workable concrete mix with a high cement content and a low water-cement ratio in order to achieve proper placing and compaction, and in particular the use of agents to entrain controlled amounts of air.

Attention must be paid to the appropriate pore size distribution of the entrained air and the spacing between pores in the hardened concrete. The microscopic bubbles will permit any water trapped in the concrete to expand in the voids on freezing and thus prevent degradation of the concrete. For frost damage to occur, the actual degree of water saturation in the concrete has to be higher than a minimum critical value.

A number of test procedures exist for evaluating the freeze-thaw resistance of concrete. The majority are based on subjecting test specimens to freezing and thawing cycles and measuring weight loss or some other property change. Having verified the inherent freeze-thaw resistance of the chosen concrete mix design, site control of freeze-thaw durability is best performed by monitoring the concrete mix proportions and ensuring an adequate air void content of desired bubble size, spacing and stability.

8 Environmental issues

8.1 Environmental impact

The life-time environmental impact resulting from a concrete structure compared to its alternatives is often questioned. The dominant emission from concrete production is CO₂. Others are SO₂, NO_x and dust emissions, the latter being almost eliminated when applying modern production technology.

90% of the total CO₂ emission arises from cement clinker production. Dependent on the energy source, about 60% of this again originates from the de-carbonation of limestone, and 40% from energy consumption.

In Table 8-1 some typical numbers for estimated equivalent CO₂ impact of some building materials are listed.

Material	kg CO ₂ equivalent / tonne material
Concrete	122
Wood	40
Steel (from scrap material)	710
Steel	3 215
Cement	656

Table 8-1: CO₂-equivalent for some building materials.

Comparing some steel jackets to concrete structures for water depths in the range 70 - 150 m, in the North Sea, concrete can be demonstrated to provide a favourable solution regarding CO₂ emission, looking at the production figures for the steel and concrete material only. It is the steel reinforcement that is the main contributor in case of the concrete structures.

The effects of all transportation and fabrication activities, the potential for utilizing local resources and the necessary life-cycle maintenance programme will have a favourable bearing on the concrete option.

8.2 Decommissioning/recycling

Concrete GBSs can be re-floated and removed upon decommissioning. Techniques exist for residual oil stripping or stabilisation within the concrete hull. The submerged concrete hull will survive for a very long time in a marine environment and will not cause adverse pollution. Complete removal is costly and gives rise to significant emissions, so it may not be considered the best practicable environmental or safest option. Nonetheless, the UK government now insists that operators provide a financial guarantee that covers the future cost of complete GBS removal.

A successful removal requires good planning and a high degree of offshore control. Comprehensive preparations and consequence analyses, accounting for inaccuracies and tolerances, will contribute to assuring a safe operation with respect to personnel, environment and costs. This is especially important when managing challenging phases such as the moment the platform separates from the seabed.

After the platform has been brought safely to shore, possibly with the full topsides still supported, avoiding offshore topsides decommissioning, it can either be refurbished and brought to new sites for installation, or dismantled into sections. This is likely to be done while the platform is still floating. The sections are subsequently brought to shore either for reuse in, for example, coastal defence systems, or for demolition and recycling. Cells that have stored oil must undergo thorough cleaning before dismantling. Durability properties of the concrete have proven to be excellent resulting in limited depth of oil penetration.

Recycling of concrete generally means down-grading of material. Most recycled concrete materials are currently used for land fill and to some extent in the road building industry. They are seldom used for manufacturing new structural concrete. This is mainly due to problems in declaring the properties of the materials and the lack of sufficient amounts holding uniform quality. Offshore concrete will meet both these requirements which suggests that it should have a wider range of application as recycled material.

9 Concrete in the Arctic

9.1 Oil and gas reserves

Until alternatives to oil and gas become available to meet bulk power and fuel demands, the world's oil and gas reserves will remain a vital part of the global economy.

There are now fewer new oil fields being discovered in mature oil and gas provinces, driving exploration into more hostile environments, in particular to the ice-infested areas of the Arctic and sub-Arctic. How far can we stretch the inherent benefits of robust concrete structures to facilitate the extraction of oil and gas in these more hostile areas?

The increasing demand and cost for energy are prompting a renaissance in the development of these regions. It may also be argued that the assumed reduction in ice thickness and coverage in Arctic regions is likely to increase the rate of development of these regions.

9.2 The Arctic

Some of the harshest environments on the planet are located in the Arctic and Antarctic regions. The Arctic includes the Arctic Ocean (which overlies the North Pole) and parts of Canada, Greenland, Russia, Alaska, Iceland, Norway, Finland and Sweden. This region is generally defined as that area above the Arctic Circle. The Arctic Circle is located at 66° 30'N

latitude, and as a guide defines the southernmost part of the Arctic. The climate within the Circle is very cold and some of the area is always covered in ice. Sub-Arctic regions generally extend south as far as latitude 50° N although areas further south including the east coast of Canada, the Sakhalin areas of the Okhotsk Sea as well as the Baltic and Caspian Sea are also significantly impacted by seasonal ice.

The design and construction of concrete structures to operate in these areas has successfully been accomplished in the past and include Concrete Island Drilling Systems (CIDS) in the Alaskan Beaufort Sea, Hibernia on Canada's east coast and the Piltun and Lunskeye platforms in the Russian Sakhalin region. The design of these structures has been accomplished taking into account the severe environments experienced in these areas, using design experience gained over the past 30 years in the North Sea, Baltic Sea and Beaufort Sea.

Offshore structures are often exposed to severe environmental loading resulting from huge waves, hurricanes, current and tidal effects, seismic action and high concentrations of chlorides. In cold climates the effect of low temperatures on construction materials, equipment and operations are additional challenges. Freezing spray from waves, freezing rain, etc., can cause ice formation on exposed surfaces. Sea ice or glacial ice as in icebergs, are however the most challenging exposure.

There are wide variations of temperatures in Arctic and sub-Arctic areas. In the marine Arctic environment air temperatures can range from 20 °C in the summer to -40 °C and lower in the winter. These low temperatures can cause severe thermal gradients through the concrete and affect the design. Repeated thermal cycles and freeze-thaw are also a concern and must be considered.

9.3 Interaction with ice

In the lower regions of the Arctic and in the sub-Arctic, sheets of sea ice form and melt annually with each winter and summer season. Annual ice formation or "first-year" sea ice is generally weaker than multiyear sea ice that does not melt seasonally but grows thicker year after year in the higher Arctic regions. First-year ice begins to form as temperatures drop in September and October and begins to disperse between May and June, depending on the latitude.

The contact pressure during ice-structure interaction has been the matter of much discussion. It decreases with increasing contact area (structure width times ice thickness), but other factors like ice velocity and ice properties are important. Nonetheless it is important that the structure be designed for a contact pressure that not only gives the maximum global effect, but also local effects (punching) on concrete plates and shells.

As ice breaks towards the structure, the global ice load varies in magnitude over quite small time intervals. The amplitude and frequency is dependent on ice drift, ice properties and structural parameters. The load may be low frequency with a saw-tooth pattern, where the load drops to zero between the peaks. For higher ice velocities the dynamic load will be higher frequency, where the amplitude is only a small percentage of the maximum load. With certain conditions, a frequency lock-in effect can occur, where the load interacts with the structure and dynamic response can be expected. Thus a dynamic analysis of the ice-structure interaction should be conducted during the design of the structure in order to capture any coupling between load and response.

Ice ridges are formed due to shear or compression forces in the ice cover. As the ice sheet breaks up, a ridge is created with a sail, a consolidated layer and a keel. The sail and keel consists of ice blocks frozen more or less together, while the consolidated layer is a solid part of the ridge where the water between the blocks is frozen. The consolidated layer is formed

quickly after the creation of the ridge and increases in thickness throughout the winter as energy is conducted through the ridge into the cold air. If the ridge survives one or more summers, it is called multi-year and has more in common with an iceberg, than a first-year ice ridge. The forces an ice ridge exert on a structure are governed by geometry (especially keel depth, keel extent and thickness of consolidated layer), age (first or multi-year). Ice ridges are in most cases the governing ice feature if icebergs are not present.

Ad-freeze is the phenomena where ice features will freeze and bond to a structure. The bond between the ice feature and the structure can be quite strong and might be a concern if the ice sheet suddenly starts to move. It is predicted that a high degree of contact can give very high global ice forces. Ad-freeze generally occurs in sheltered areas (e.g. bays, harbours) where the ice can freeze to the structure, while this is not an issue for most offshore applications.

When a structure is subjected to sea ice, the drifting ice will abrade the material at the water line. This occurs on both steel and concrete structures. Thus special steel alloys are used for this application on e.g. icebreakers. Concrete structures have been used in the Arctic for many years. Good examples are the concrete island drilling system (CIDS) built in Japan and towed across the Pacific for service in the Alaskan Beaufort Sea and the Prince Edward Island (PEI) Bridge. On the PEI bridge steel ice shields were installed on the first bridge piers to protect the concrete, whereas on later piers the ice shield was cast in High Strength Concrete (1500 km of ice pass the bridge piers every year). On the Sakhalin II development, steel ice shields were used to cover the shafts in the waterline to mitigate the uncertainty regarding the extent of ice abrasion. Further work is necessary, however, to decide on the most appropriate design and dimensions for the ice shields, if needed. There have also been examples where concrete structures have not functioned properly, like in the Baltic Sea where lighthouses have been badly abraded. Research work is ongoing to document the abrasion resistance of high-quality concrete and to understand the processes better.

9.4 Interaction with icebergs

A number of structures have been designed for, and employed in, areas frequented by icebergs. Icebergs are large pieces of freshwater ice that have broken off from glaciers and have an interior temperature of the mean air temperature of the area where the iceberg comes from. The glaciers that produce most of the world's icebergs are found in Franz Josef Land, Greenland, Alaska and Antarctica. More or less all the icebergs in the Barents Sea come from the glaciers on Franz Josef's Land. Glaciers in western Greenland produce large amounts of icebergs that follow ocean currents and travel south along the east coast of Canada in large numbers to the Grand Banks.

Icebergs can range in size from a growler the size of an average car to a very large iceberg over 75 m high, over 200 m long and weighing several million tonnes, not counting the ice islands that break off the ice shelves in Antarctica.

Despite their size, the icebergs on the Grand Banks can move an average of seventeen kilometres a day.

There are two basic types of icebergs. Tabular type icebergs have steep sides and a flat top and float with the surface of the glacier upwards. Non-tabular icebergs have a wide variety of shapes and are generally smaller than the tabular icebergs. In addition to these types, the size of the iceberg is classified from less than 5 m to over 200 m in length.

The Grand Banks developments have spurred significant research on the determination of iceberg loads on offshore structures. The research includes better estimates of iceberg populations, better modelling of iceberg mass, length, velocity as a function of sea state, and the mechanisms of interaction between icebergs and structures. Work on ice mechanics has

also resulted in better understanding of the ice failure processes during an impact with a structure. It has been found that most ice impact forces are concentrated in small localized areas, termed “high-pressure zones”. These govern the design of smaller areas of the external shell of a structure. There is a significant scale effect in ice failure resulting in global average pressure decreasing with an increase in contact area. This is mainly associated with fractures in the ice resulting in large pieces breaking off, thereby reducing average contact pressure.

9.5 Client perceptions

The work of *fib* Task Group 1.5 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 due to 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 within a weather window that is selected at short notice. 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.

Some of the perceived challenges with concrete structures in the Arctic included:

- Construction sites may be difficult to establish adjacent to the Arctic fields.
- Deep draft towing channels may be a problem and steel hulls typically have smaller draft.
- Removal may be difficult and costly.
- Each structure is a one-off prototype, which means that proposals and budgets cannot be readily benchmarked.
- Concrete structures are, perhaps wrongly, perceived as costly.
- A limited field of experienced EPC contractors could limit the number of competitive EPC bids. On the other hand a concrete option could deliver additional benefits when the steel fabrication market is overheated.

Some priorities for further studies for the Arctic were also identified in the survey:

- better understanding of ice loads and ice abrasion;
- better understanding of foundations on permafrost;
- concrete mix design with respect to freeze-thaw durability and ice abrasion;
- improved construction procedures for Arctic conditions;
- identification of suitable dock sites and towing routes;
- efficient hull/topsides mating and integration;
- evaluation of all relevant Health, Environment and Safety (HES) factors for Arctic conditions.

10 Other applications

Although most of the existing oil and gas concrete platforms and terminals are Gravity Base Structures, concrete floating platforms of different types have also been successfully developed, such as large barges (N’Kossa), semi-submersible platforms (Troll B) and tension leg platforms (Heidrun TLP).

Concrete marine structures have also been successfully developed for other applications than oil and gas platforms, sometimes in extremely harsh conditions, taking advantage of the experience gained in high performance concrete and in construction techniques implemented in the offshore oil and gas industry.

Such developments include:

- coastal protection and harbour extensions;
- light houses;
- large bridge foundations;
- underwater parking facilities;
- water-front city developments;
- immersed tunnels;
- marine renewable energy structures.

The large cable stayed Rion-Antirion bridge in Greece and the Prince Edward Island Confederation bridge in Canada represent two major projects over the last decades in the domain of large bridge foundations, which demonstrate the good performance of concrete subject to waves, winds and currents, high seismic activity and heavy marine traffic (resistance to large boat impact). These bridge foundations have been built using offshore techniques of fabrication in dry and wet docks, and subsequent tow and installation on site.

Prince Edward Island Confederation bridge is the longest bridge in the world, spanning over ice covered waters. The bridge pier foundations are subject to ice actions five months per year and include a 52° conical ice shield which actually lifts the ice flow up so that it breaks in bending. Some piers are fitted with carbon steel skin armour to prevent ice abrasion, while the latest built piers are made of ultra high strength concrete instead.

For the Rion-Antirion bridge the four tall pylons carrying deck sections spanning 560 m are founded on large diameter (90 m) concrete caissons produced in a 15 m deep dry dock and installed on the sea bed in the Gulf of Corinth in water depths up to 65 m.

The 352 m long Monaco harbour floating jetty, which serves as a breakwater as well as housing a parking garage and a cruiser terminal, was built in a 15 m deep dry dock near Gibraltar and towed to Monaco and installed in a completed condition, demonstrating how offshore technology can be utilized in other projects. Reinforced concrete is known for its excellent behaviour in fatigue, which is of prime interest for offshore structures and particularly floating units. Durability is another advantage of concrete that allows a design life of 100 years (as was the case for the Monaco jetty) or more, to be specified in the knowledge that little maintenance will be required if proper design and workmanship are employed.

Current developments in the Oslo Harbour include a 30 000 m² underwater parking garage built in sections in a dry dock and floated into position on top of pre-installed columns, all with a postulated design life of 300 years.

Also in harsh and near Arctic conditions there are many examples of demanding onshore structures such as bridges, industrial plants and large concrete dams that have performed very well when the concrete mix is properly designed and cold weather concreting is performed in accordance with sound procedures.

11 Codes and standards

The International Organisation for Standardization, ISO, has through its Technical Committee, TC67, Subcommittee SC7 *Structures*, developed a series of standards for the design of offshore structures. This suite of standards comprises both object/material related standards (e.g. fixed steel structures, fixed concrete structures, etc.) and material/object independent standards (e.g. metocean design, geotechnical design, marine operations etc.). All these are coordinated to give a consistent design by complying with the umbrella standard ISO 19900, *General requirements for offshore structures*, giving all principles on which the design shall be based. This standard corresponds to what Europeans know as EN 1990, *Basis of design*, or others would know as ISO 2394, *General principles on reliability for structures* which most design standards refer back to, more or less explicitly.

ISO 19903, *Fixed offshore concrete structures*, covers all phases, operations and systems normally involved in the execution of an offshore concrete project, including:

- general requirements;
- actions and action effects;
- structural analysis;
- concrete works;
- foundation design;
- mechanical systems;
- marine operations;
- corrosion control;
- topsides interface;
- inspection and condition monitoring;
- assessment of existing structures.

Standards are a well recognized instrument in the construction industry. Standards allow the implementation of documented and generally accepted technology applicable to most of the elements of a construction project, and would include design standards, execution standards, material/product standards and testing standards.

The standards normally cover most of the relevant conditions in an appropriate manner. For structures placed in a harsh Arctic environment it will, however, be prudent to scrutinize and evaluate the standards that are considered for use. Concrete is a robust construction material, well suited for use in a harsh environment, and standards that are intended for use in such conditions will normally cover the relevant aspects appropriately.

The prime issues would be: materials with adequate ductility, material with low permeability and good frost resistance, and a construction technique adapted to the cold climate. The structural behaviour of concrete and ductile reinforcement under service temperatures down to below -50°C are in general the same as for the normal service temperatures in the range from -20°C to + 50°C.

ISO 19903, *Fixed offshore concrete structures*, will be an important document for future offshore projects with respect to all its services as well as the design, execution and selection of materials for the concrete structure. For the materials and execution part, ISO 19903 is based on the European standard EN 206-1 and the parallel international standard ISO 22965-1 and ISO 22965-2 for specification of the concrete material. For the execution of concrete structures, prEN 13670 and ISO/DIS 22966, are currently in the process of being ratified.

ISO 19906 is currently being developed and at the time of publication of this bulletin is at the stage of Draft International Standard. The document will become the future ISO standard on offshore structures in Arctic and cold environments.

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