REPORT FOR

PETROLEUMSTILSYNET
PETROLEUM SAFETY AUTHORITY NORWAY

Ageing of Offshore Concrete Structures

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Ocean Structures Ltd
Myreside Steading
Auchenblae
Laurencekirk
AB30 1TX
Scotland, UK

T: +44 (0)1561 320550
F: +44 (0)8707 066079
enquiries@oceanstructures.com
http://www.oceanstructures.com

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1 Introduction

In total 27 fixed concrete platforms have been built for the North Sea of which 15 were for the Norwegian sector, 10 for the UK sector and 1 each in the Danish and Dutch sectors. Of these platforms, 1 was destroyed during the final stages of construction (Sleipner A) and 4 associated with the Frigg field have been decommissioned. In addition there have been 2 platforms removed from the German Baltic Sea. There are also various templates and floating concrete structures in the North Sea. A listing of the oil industry's offshore platforms is contained at the back of this report.

The first concrete structure to be installed in the Norwegian sector was the Ekofisk tank in 1973; the first to be installed on the UKCS was Beryl Alpha in 1975. Both of these are now over 30 years old. Life extension should therefore already be in place or under consideration for many of the structures to ensure they have capacity to continue operations and to act as bases for nearby subsea completions. Ageing is therefore a consideration for the continued long term integrity of these structures.

2 Ageing and deterioration – affected areas

There are several forms of deterioration of offshore concrete structures, see Sections 4 to 12. These forms of deterioration can affect different parts of the structure. Table 1 shows the correlation between the main parts of a concrete offshore structure and the primary degradation mechanisms applicable to these areas.

Table 1 - Causes of damage to concrete structures

	Part of structure						
Deterioration mechanism	**Legs / Towers / shafts – general**	**Splash zone**	**Topsides**	**Steel concrete transition**	**Shaft / base junction**	**Storage cells**	**Foundations**
Chemical deterioration	✓	✓			✓	✓	
Corrosion of steel reinforcement	✓	✓			✓	✓	
Corrosion of prestressing tendons	✓	✓			✓	✓	
Fatigue			✓	✓	✓		
Ship impact	✓	✓					
Dropped objects						✓	
Bacterial degradation	✓	✓			✓	✓	
Thermal effects					✓	✓	
Loss of pressure control					✓	✓	
Loss of air gap			✓	✓			
Scour & Settlement							✓

Sections 4 to 12 describe the mechanisms in more detail.

Analyses have shown however that significant damage is required before significant loss of structural strength occurs to the legs of an offshore structure [1].

3 Concrete deterioration – chemical processes

Concrete is naturally alkaline, due to the presence of several hydroxides derived from the reactions between the mix water and the Portland cement particles. This alkaline environment is important in providing protection against corrosion of the reinforcing steel. Loss of this alkalinity can occur through several processes, including chloride ingress, sulphate attack etc, which are discussed below.

Seawater contains a number of chemical ions which can participate in chemical reactions and which could lead to long term degradation of the concrete. These include sodium, potassium and magnesium, as well as sulphate ions. However offshore concrete is generally very high quality with features including:

- low water/cement ratio;
- thick covers to the outer layer of reinforcement (typically 70 mm in the splash zone, 45 mm underwater);
- limited permeability to seawater; and
- post tensioned to limit cracking.

Concrete exposed to seawater can develop thin protective layers on its surface, which are mainly aragonite (calcium carbonate), and brucite (magnesium hydroxide). These layers protect the surface, modifying the permeability of the concrete and hence reducing the permeation of chlorides to the steel reinforcement. Tests in the “Concrete in the Oceans” programme [2] showed no significant chemical attack on concrete from deep water after 8 years exposure (the length of the test programme).

In some non-offshore concrete structures there has been evidence of alkali-aggregate reaction where the alkali nature of the cementitious material has lead to a reaction with the aggregate used in the concrete mix. This has led to localised damage to the concrete and loss of integrity. Only certain aggregates lead to this type of damage and the crushed granite that was used for many offshore concrete structures has generally not been a problem. It is not known whether the aggregate used in any of the offshore concrete structures is vulnerable to this type of damage.

Carbonation is a slow reaction between the CO_2 in the air and hydroxyl ions in the concrete to produce carbonic acid. This acid reduces the alkalinity of the cover concrete, allowing further carbonation to take place at greater depth. Eventually this leads to the embedded steel losing the protection of the alkaline environment and the possibility of corrosion. However evidence from tests on bridge decks and other structures shows that with large depths of cover of high quality concrete this is unlikely to be a problem in the air zone of the concrete towers.

Sulphate attack is a reaction between the sulphates in seawater and calcium hydroxide in the hardened cement paste. The reaction products can be expansive, leading to cracking and crazing. This is a well recognised problem for marine structures and is usually designed out by, for example, including some pulverised fuel ash in the mix. However this did not occur with the early installations. Visual examination of the legs should detect any sulphate attack problems.

4 Corrosion of steel reinforcement

The continuing integrity of the steel reinforcement in a concrete structure is an essential requirement. Steel embedded in concrete should normally be protected from corrosion for long periods, provided there is a good depth of high quality cover over the steel. However concrete is a permeable material and hence chlorides in seawater will, in the longer term, penetrate to the steel reinforcement. Activation of the reinforcement can occur when sufficient chlorides reach the steel surface and if sufficient oxygen is available this will usually lead to corrosion. This is the case for the splash and air zones, where, in the course of time, corrosion will progress leading to expansive products causing spalling of the concrete cover. This type of corrosion is very typical of many marine structures and also on bridges subject to de-icing salts. Underwater the limited availability of oxygen limits the degree of corrosion and, as shown by laboratory work [2, 3], the corrosion products are non-expansive and do not usually lead to spalling of the cover. This can be a limitation, however, in respect of detecting the corrosion using visual inspection. The splash zone is particularly vulnerable with a plentiful supply of both oxygen and seawater. In this location corrosion will lead to spalling and continuing damage unless repaired.

Cracking is a process which allows ingress of seawater to the embedded steel. Typically the design basis requires control of cracking following the construction phase, with a limit of 0.1 mm for the splash and atmospheric zones and 0.3 mm for the submerged zone [4]. Cracking of the cover can occur during operation, when tensile stresses are present, due to a number of factors including, fatigue stresses, loss of localised reinforcement, external damage or the presence of expansive corrosion products from corrosion of the reinforcement. This can be followed by spalling where localised sections of the concrete are lost, leading to enhanced water ingress. Evidence of significant cracking from inspections indicates the potential for degradation of the structure.

Intense localised corrosion has been observed in underwater concrete test sections [2, 5] where:

- there has been a local breakdown of passivity (from for example cracking);
- there is low concrete resistivity (e.g. from immersion in seawater); and
- there is an efficient cathode (which may be in the splash zone where there is sufficient oxygen to support the high local corrosion rate).

Electrical conductivity through the steel reinforcing network can act as a link between anode and cathode. Similar localised intense corrosion of the reinforcement has been seen in bridge decks which have become saturated with chlorides from de-icing salts.

In most offshore concrete structures the reinforcement is connected to the cathodic protection system, despite attempts at the construction stage to isolate the reinforcement. This can happen particularly with unintended electrical connectivity to flowlines and pipelines as well as other external attachments. This has led to a higher than planned drain on the sacrificial anodes, and in some cases these have had to be replaced. The cathodic protection has the advantage that it protects the reinforcement to some extent, minimising the level of corrosion where seawater has permeated to the steel. Maintenance of the CP system is therefore a basic requirement to minimise the corrosion reaction.

In the 1980's design criteria for CP systems recommended or required a minimum protection current of 1 mA/m^2 for the reinforcing steel [6], Current requirements are noted in ISO 19903 [7] but do not included guidance on the value of protection current ISO 19902 [8] suggests CEN [9, 10] and NACE [11] documents The latest DNV rules [12] similarly do not give explicit requirements.

The CP system has minimal protection for the splash zone which is the most venerable to corrosion.

"Crack blocking" has been observed [2] as a result of seawater being pumped in and out of cracks due to cyclic stresses. The seawater reacted with the concrete to form both aragonite and brucite which tend to build up at the mouth of the cracks and hence limit the ingress of seawater; this blocking can have beneficial effects.

5 Corrosion of prestressing tendons

High strength prestressing tendons are required to maintain the structural integrity of the concrete structure. These tendons are placed in ducts which are usually grouted following tensioning. The degree to which grouting was effective, given the long ducts and in some case their horizontal orientation, has led to concerns that seawater can penetrate into the ducts and cause corrosion of the very high strength tendons. A review of the durability of prestressing components [13] concluded that the first tranche of concrete offshore structures (pre-1978) was more vulnerable to corrosion of the prestressing tendons, as later platforms benefited from improved grouting materials and procedures. It was also considered that there would need to be significant loss of prestress (~40%) in a leg before it would fail under typical design wave loading. These failures would also need to be in the same section area to be a danger. In land based structures failures have tended to occur near anchorages or construction joints. In reference [1] it was concluded, in terms of prestressing, that "Corrosion is possible but because of the dispersed arrangement of prestressing and the staggering of anchorages away from critical sections we would expect any failures to be distributed around the structure".

6 Fatigue

Where cyclic stresses exist in the structure, fatigue of the steel reinforcement can occur, leading eventually to localised loss of reinforcement and potential cracking of the concrete cover. This can be exacerbated by the presence of seawater which will accelerate the process. Cracking can lead to further damage to the steel reinforcement due to corrosion.

Fatigue of attached steelwork can also occur. This includes pipe and riser clamps. The transition between the concrete leg and topside deck is a difficult design problem, often involving complicated welding, which can be subject to fatigue.

Fatigue of the concrete can also occur, particularly if the concrete suffers stress reversal. This is more likely for a decommissioned structure where both the loss of compressive preload and loss of portal frame action has resulted from removal of the deck structure.

It should be noted that the manifestation of concrete fatigue looks very similar to concrete overstress and hence can be misdiagnosed.

7 Accidental Damage – Ship Impact

Vessel collisions with the towers of a concrete structure have occurred including those more serious events shown in Table 2. These can lead to cracking and localised damage to the concrete section. Concrete columns are fairly resistant to minor collisions but more energetic ones can cause significant damage. Table 3 lists a significant repair which was needed as a result of ship collisions, requiring removal of the damaged concrete and replacing it with new concrete, combined with resin injection.

Although accidental impact is not an ageing effect the accumulation of damage from several impacts can be.

Vessel collision can cause localised damage to the area of towers close to the waterline. Several minor collisions can lead to enhanced damage which can lead to leakage, which would usually be found from inspection of the inner walls of the towers before being significant. It should be noted that condensation can also be fount in the internal walls of shaft which should not be confused with seepage through the walls.

The consequences of accidental damage on the legs can be leakage leading to loss of pressure control (see section 12) and consequent overstress of the cell / legs connections or direct loss of strength in the area of the damage.

8 Accidental Damage – Dropped Objects

Although accidental impact is not an ageing effect the accumulation of damage from several impacts can be.

Dropped objects are also causes of damage to concrete structures, particularly to the roofs of the storage cells. Dropped objects can be classified into two types, dense and slender. An example of a dense object is a pump unit (weighing many tonnes) whilst a slender object could be a drill collar. Both can cause significant damage, which in some cases may not be visible externally. This damage may result in perforation or scabbing (loss of concrete on the inner face of the roof). The latter mode has been shown from research and testing [14] to be a typical outcome from a dropped object, which could eventually lead to liquid leakage. One means of limiting damage from dropped objects was to provide a fender layer on the cell roofs, preferably of lightweight concrete. It is not known how many installations had fender layers or what their current condition is (it is known that Beryl A had a lightweight concrete covering which has suffered some impact damage). Table 3 includes a repair requirement for damage to a cell roof, where a 300 mm deep hole was formed externally, requiring repair using aggregate and resin.

Minor impacts can lead to spalling of the inner section of the roofs which is very difficult to find by inspection. Repeated impacts could lead to more serious damage accumulating.

9 Concrete Deterioration - Bacterial

Bacterial activity (e.g. sulphate reducing bacteria (SRB)) in concrete structures containing water and oil can lead to the production of acids, which attack the concrete. Laboratory tests have shown significant loss of material when sufficiently acidic conditions exist [15].

This type of environment can occur in the concrete storage tanks, which are present in several concrete offshore structures, due to the oil-water mixtures from the operation of displacing the stored oil with seawater. SRBs are known to grow rapidly under certain acidic conditions, which can cause loss of material reducing wall thickness. The rate of loss is dependant on the pH value. Unfortunately the storage tanks are almost impossible to inspect due to very limited access and hence the level of damage from SRBs is difficult to assess. One mitigating factor is the thick coating that is expected to exist on the inner walls of the tanks due to the presence of waxes in the oil.

Drill cuttings can accumulate around the lower sections of a concrete platform or on cell roofs. These piles consist of cuttings and oil and / or water based muds. Up to the early 1980’s muds were based on diesel oil, replaced in 1984 by low toxicity oil. The presence of oil and water can encourage the development of bacteria, which are likely to be anaerobic, favouring the growth of SRBs and possible deterioration of the concrete material.

Cleaning of the area by water blasting is a possible mitigation measure.

10 Temperature effects

The storage of hot oil in the concrete tanks at the base of many concrete installations leads to thermal stresses that can lead on to cracking of the concrete. Concrete is vulnerable to significant temperature differences, which arise from the hot oil on one side of the wall and cold seawater on the other. Tests have shown that temperature differences of up to 45 ºC can be sustained with the correct design details [2]. However if the coolers fail (the oil is cooled before storage) or unusual conditions occur oil with temperatures up to 90 ºC can be diverted into the storage cells, with potential cracking of the walls. Over a long period of operation these effects could accumulate.

The increased stresses from thermal effects can lead to cracking of the concrete and overstress of steelwork in and around the walls and roofs of the storage cells, including the critical junction with the legs.

11 Loss of air Gap

A suitable air gap is a design requirement, typically the requirement was for the underside of the deck to be 1,5 m above the maximum wave crest in the 100-year return period storm when most for the North Sea concrete platforms were designed. Current requirements are typically for deck clearance of the 1 x 10^{-4} wave crest.

12 Ballast system /pipework

In many of the concrete platforms the stresses in the base cells and the adjacent parts of the leg are influenced by the internal pressure in the cells. The pressure is controlled by the water level in a ballast water header tank within one of the legs. In platforms with active oil storage systems water is continually pumped out of the ballast tank to the sea (when oil is flowing to storage) or allowed to flow from sea to the ballast water system (when oil is being exported). The normal underpressure of the cells in relation to the adjacent sea water is around 3 – 4 bar. Any failure of the ballast water or oil storage pipework can lead to a loss of the control of ballast water system, and hence to a loss of the pressure regime within the cells, leading directly to possible overstress of the structure. The pipework and also the valves on the ballast water pipework on several platforms have corroded and malfunctioned and the ballast water header tanks have also corroded and needed recoating.

Failure of the ballast water system can lead to loss of underpressure which leads to increased stresses in the storage cells and the junctions of the cells with the legs.

The triangular void between storage cells is usually open to the sea and therefore subject to the full hydrostatic head. Some problems have occurred with this location in the past which have lead to leakage into the cells.

13 Foundation degradation

Concrete gravity structures have a very large base area, and the gap between this and the seabed is usually grouted. Deterioration of this grouting or movement of the seabed (including erosion of the seabed under the concrete) can lead to loss of foundation capacity and the potential for the installation to slide, tilt or overturn, depending on the environmental conditions. Sliding could lead to damage to risers and conductors.

Subsidence can cause significant damage to foundations. Evidence that subsidence is occurring requires further investigation.

14 Damage to Offshore Concrete Structures

Limited data is available on recent damages to offshore concrete structures. The last survey was published in 1994 and listed 14 incidents as shown in Table 2 [16].

Table 2 shows that corrosion to steel components and construction faults were the most frequent causes of damage. Accidental damage (dropped objects and vessel collisions) also occurred with a significant frequency over the period.

Other known causes of damage include vessel impact on the Brent C installation with a 2 500 tonne supply boat, requiring repair and impact from a 0,5 tonne crane black on the cell roof of Beryl A platform, which damaged only the concrete protective layer. In 1981 on another concrete platform an oil storage cell was penetrated by a section of steel pipe which fell as a result of a lifting tackle failure. This led to loss of draw-down pressure and loss of production.

Table 2 - Causes of damage to concrete structures

Causes of damage	Number of incidents
Steel components	
- corrosion	3
- fatigue	1
- operations	1
Construction fault	3
Dropped objects	
- installation	0
- operations	2
Vessel impact	1
Design fault	1
Other	2
Total	**14**

Repairs to offshore concrete structures as a result of damage cannot be easily categorised into different structural systems, due to the number of individual solutions. Table 3 shows typical repairs to concrete structures, all with the aim of restoring the original structure [16].

Table 3 - Typical repair systems for offshore concrete structures

Cause of damage	Consequence of damage	Repair solution
Vessel impact	Water seeping through cracked wall	Resin and caulking used to seal damaged area externally; a 200 mm section of wall was removed internally and recast. A coffer dam was placed against the outer wall and the outer 200 mm of wall then removed and recast. Resin injection points were cast into the new concrete to ensure a good bond between the old and new material

Cause of damage	Consequence of damage	Repair solution
Faulty construction joint	Leak manifested several years after construction. Repaired 10 years after construction.	Initial repair attempts using resin injection were unsuccessful. Optic fibre examination showed voids within 1200 mm wall. Voids were injected with cementitious grout, with epoxy grout being used for the final contact with the old concrete.
Leaky grouted prestressing duct (depth of 90m)	Water leakage	Stopped by injecting resin from the dry end
Dropped object	Damage to a 500 mm thick cell roof slab at a depth of 80 m. Deep hole (300 mm in depth) was formed in the concrete, with water flowing through slab,	Repair made by prepacking aggregate within the hole, covering the hole with a steel plate and injecting grout to restore the original concrete profile
Cracks in external shear walls	Water ingress.	Resin was injected into cracks. In some cases the crack was jacked apart before the resin was placed so that on removal of the jack the resin was compressed into the crack void. Ballast was added to the structure to prevent the cracks reopening under wave loading.
Scour hole at pipeline entry point	Hole extending 4 m beneath the structure	Void was grouted and subsequently protected by rock dumping.

15 Performance Measures for Ageing

Several measures of performance related to ageing are proposed to provide useful information. These include:

- History of inspection and repairs
- History of accidental damage (including unusual operating conditions affecting oil storage)
- Recent inspection data (including condition of repairs)
- CP levels from inspection and change over time
- Condition of CP system and anode usage (current and previous)
- Structural analyses on loss of prestressing, drawdown
- Original design codes used and comparison of these with up-to-*/-date codes

16 Conclusions

This report has identified how ageing and deterioration can affect different parts of an offshore concrete structure. Concrete deterioration processes have been reviewed, together with ageing processes that can effect the reinforcing steel and prestressing tendons. The effects of accidental damage (ship collision and dropped objects) have also been discussed. A list of existing offshore concrete structures is also presented. Several performance measures relating to ageing are also proposed.

17 References:

[1] HSE, “Review of Major Hazards to Concrete Platforms”, Ove Arup and Partners, HSE report, 1996

[2] Department of Energy, “Concrete in the Oceans Programme – Coordinating report for the Whole Programme”, Offshore Technology report OTH 87 248, HMSO, 1989 HMSO

[3] Department of Energy, “Fundamental Mechanisms of Corrosion of Steel Reinforcement of concrete immersed in seawater: result from phase II”, Offshore Technology report OTH 87 238, HMSO, 1987

[4] HSE, “Concrete”, Offshore Technology report OTO 01 046, HSE Information Center, 2000

[5] Department of Energy, “Detection of Corrosion in Submerged Reinforced Concrete”, Offshore Technology Report OTH 87 239, HMSO, 1987

[6] DNV, “Rules for the Design Construction and Inspection of Offshore Structures”, 1981 (Superseded)

[7] ISO 19903, "Petroleum and natural gas industries — Fixed concrete offshore structures"

[8] ISO 19902, "Petroleum and natural gas industries — Fixed steel offshore structures"

[9] CEN EN 12473:2000, "General Principles of Cathodic Protection in Sea Water"

[10] CEN EN 12495:2000, "Cathodic Protection for Fixed Steel Offshore Structures"

[11] NACE Standard RP0176-2003, "Corrosion control of fixed offshore steel structures associated with petroleum production", National Association of Corrosion Engineers, 2003

[12] DNV-OS-C502, "Offshore Concrete Structures", April 2007

[13] HSE, “The Durability of Prestressing Components in Offshore Concrete Structures”, Offshore Technology report OTO 97 053, HSE Information Service, 1997

[14] Department of Energy, The Assessment of Impact Damage caused by Dropped objects on Concrete Offshore Structures”, Offshore Technology report OTH 87 240, HMSO, 1987

[15] Department of Energy, “Concrete Offshore in the Nineties – COIN”, Offshore Technology report OTH 90 320, HMSO, 1990

[16] Marine Technology Directorate, “Review of Repairs to Offshore Structures and Pipelines”, Publication 94/102, Marine Technology Directorate, 1994

Annex A Listing of NE Atlantic area offshore concrete installations

Year of installation or start-up	Field/Unit	Location	Type	Design by
1973	Ekofisk	Norway	Platform	DORIS - Tank
1975	Beryl A	UK	Platform	Condeep - NC/Olav Olsen
1975	Brent B	UK	Platform	Condeep - NC/Olav Olsen
1975	Frigg CDP1	UK	Decommissioned platform	DORIS
1976	Brent D	UK	Platform	Condeep - NC/Olav Olsen
1976	Frigg TP1	UK	Decommissioned platform	Sea Tank
1976	Frigg MCP-01	Norway	Decommissioned platform	DORIS - Jarlan Wall
1977	Dunlin A	UK	Platform	ANDOC
1977	Frigg TCP2	Norway	Decommissioned platform	Condeep - NC/Olav Olsen
1977	Statfjord A	Norway	Platform	Condeep - NC/Olav Olsen
1978	Cormorant A	UK	Platform	Sea Tank
1978	Ninian Central	UK	Platform	DORIS Jarlan Wall
1978	Brent C	UK	Platform	Sea Tank
1981	Statfjord B	Norway	Platform	Condeep - NC/Olav Olsen
1982	Maureen ALC	UK	Decommissioned loading system	Concrete base articulated. Loading column
1983	Schwedeneck A	Germany	Removed small platform	DORIS/IMS– Baltic Sea
1983	Schwedeneck *	Germany	Removed small platform	DORIS/IMS– Baltic Sea
1984	Statfjord C	Norway	Platform	NC/Olav Olsen
1986	Gullfaks A	Norway	Platform	Condeep - NC/Olav Olsen
1987	Gullfaks B	Norway	Platform	Condeep - NC/Olav Olsen
1988	Oseberg A	Norway	Platform	Condeep - NC/Olav Olsen
1989	Gullfaks C	Norway	Platform	Condeep - NC/Olav Olsen
1989	N. Ravenspurn	UK	Platform	Arup

Year of installation or start-up	Field/Unit	Location	Type	Design by
1989	Ekofisk P.B	Norway	Platform	DORIS - Protection Ring
1992	Snorre	Norway	Template	NC/Olav Olsen - Concrete Foundation Templates
1993	NAM F3-FB	Netherlands	Platform	Hollandske Bet.
1993	Sleipner A	Norway	Destroyed platform	Condeep - NC/Olav Olsen
1993	Draugen	Norway	Platform	Condeep - NC/Olav Olsen
1994	Heidrun	Norway	Platform	Condeep - NC/Olav Olsen
1995	Troll A	Norway	Platform	Condeep - NC/Olav Olsen
1995	Heidrun TLP	Norway	TLP	NC/Olav Olsen TLP
1995	Troll B	Norway	Semi	DORIS Semisub
1996	Harding	UK	Storage base	Taylor Wood Eng.
1999	South Arne	Denmark	Platform	Taylor Woodrow