LESSONS LEARNT FROM 12 YEARS OPERATIONS OF A HUGE FLOATING PRODUCTION UNIT MADE OF PRE-STRESSED HIGH PERFORMANCE CONCRETE
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Abstract
The last years have seen an impressive increase of Floating Production Storage and Offloading (FPSO) units deployed all over the world both in number and in variety of designs. But all of them in steel.

This paper presents the lessons learned from the huge floating production unit made of pre-stressed high performance concrete in operation for TOTAL E&P Congo. They touch all aspects of the life of the unit, design, construction and maintenance on site. The paper will also present the main key issues for the floating concrete structures and some guidelines on how to avoid them, resting on some of the available existing codes.

The unit is in production since 12 years on the N’KOSSA oil field in 170 m water depth. Main characteristics: L 220 m, B 46 m, D 16 m, displacement 107,000 t including 73,000 t for the hull and 34,000 t for the topsides. This concrete unit used for construction 27,000 m³ concrete, 2,350 t pre-stressed steel and 5,000 t passive steel.

This paper focuses on the following aspects specific to this floating production unit:
- Structural modeling techniques taking into account the non-linear characteristics of concrete and incorporating a description of passive and active steel.
- Ageing processes of the concrete units and the general typology of the defects encountered.
- Development of a tailor-made inspection program.

Pre-stress concrete has many virtues and the fabrication process gets more and more industrialized, with better knowledge of the parameters and how controlling them. This makes it a potential material candidate that can allow new-builds outside traditional shipyards, providing new opportunities.

However the paper is not intended to make a recommendation between steel and concrete because this entails many other considerations that are not only technical; the paper remains on the technical ground and shares valuable knowledge on the behavior of floating concrete units on the long term prospective of a field life time and on the integrity management techniques developed to minimize the risk of production shutdown and optimize maintenance and repair costs.

Introduction
It will now be twelve years since the concrete FPU (Floating Production Unit) NKP was installed offshore Congo. During that time it has undergone one technical stop for process maintenance as scheduled in the design, else has been on uninterrupted service.

The unit was built in south of France in 1994-95 and installed one year later in the N’KOSSA oil field in 170 m water depth and some 60 km offshore the Congo Coast. To the authors knowledge it is the biggest floating production concrete unit ever built and in service. Its main dimensions are 220 m long, 46 m wide and 16 m deep. This concrete barge used in its construction 27,000 m³ of concrete, 2,350 t of pre-stressed steel and 5,000 t of passive steel, references [3], [4]. Its displacement (weight of the equivalent volume of water occupied by the submerged body of the vessel) is 107,000 t. Two thirds account for the hull and the remaining 34,000 t are the topsides weight.

The production facilities and living quarters for 160 people are fitted on the 10,000 m² deck area which, for construction purposes, is subdivided into six modules: accommodation and central control, utilities, electric power generation, gas compression for re-injection, crude oil, and gas.
Design production is 120,000 b/d of oil sent to the shore terminal and 1,300 metric tons/day of Liquefied Petroleum Gas sent to an 80,000 cu.m LPG FSO. The unit is hold in place, 70 meters away of the NKF2 platform, in a spread moored configuration by means of 12 mooring lines. Figure 1 shows the unit in place with the fixed platform vaguely seen behind.

Figure 1: FPU NKP

Asset Integrity Management

In order to constantly analyze and monitor the condition of the units, a tailor-made methodology has been developed and implemented since 2004 for the Integrity Management of Total Floating Units currently in operation.

The aim of Floating Units Integrity Management is to ensure management and continuous follow up of Floating Units from the safety, environmental, operational, maintenance and quality management viewpoints. It includes recommendations on inspection, maintenance and repairs. This calls for:

1. Structural and anchoring modeling and analysis (1st assessment and subsequent annual re-assessments).
2. Qualitative RBI implementation (Risk Based Inspection).
3. Yearly reviews of the IRM plan (Inspection, Repair and Maintenance).
4. Data management and storage (including reports).
5. Assistance for Emergency Response.
6. Gives the framework for exceptional analysis.

A detailed description of the Floating Units Integrity Management program is given in references [1] and [2]. The program is divided into four complementary, interacting modules as shown on Fig. 2:

1. Structural non linear Finite Element Analysis (FEM) model and dynamic mooring model. (ABAQUS, HYDROSTAR and ARIANE Models).
2. IRM (Inspection Repair Maintenance): inspection plan and schedule incorporating class requirements (renewal of certificates, repairs…), and incorporating RBI (Risk Based Inspection).
3. Database (plans, results of models, inspection reports, class status, etc.), with information shared in a network system.
4. ERS (Emergency Response Service).
In alignment with the integrity management program the unit has been placed within a Classification scope. This holds an important part as the surveys and maintenance actions required by the Classification Society are introduced and accounted for within the system. As they are known in advance they can be arranged to minimize impact on production. The French classification society also reviews the work carried out by the Third Party Assistance company who contributes to the content and deployment of the program. Falling within the Class scope of work are the mooring, hull and marine systems, accommodation quarters and helideck structures and topsides connection to deck. In some cases risers and subsea equipment are also included.

**Pre-Stressed Concrete FPU presentation**

The unit is divided in 26 lateral capacities (B and T capacities) and 13 central capacities (C capacities). The lateral capacities can be used as “ballast tanks” but only the 4 tanks in the corners are used on site to maintain trim and pitch. The central capacities are void spaces.

Running through the central void spaces as a spine is the “Technical gallery” that connects the aft and fore pump rooms (see dark grey color in figure 3) and provides access to the internal capacities.

The “nose” that can be seen on the fore end is a concrete cantilever that supports the flare tower as far away as it can be from the accommodation quarters.
The shell is not a full watertight continuous skin. It is pierced in several locations in order to suck in water for different purposes; process plant cooling, ballast, fire extinction means, fresh water production…. The most important of all comes in through space T9 with a pipe (metallic outside and concrete inside) that penetrates the side shell and runs through two capacities before reaching the “piscine”, an enclosed basin within C10. Three pumps (two in service, one spare) then move the water from the “piscine” to the process plant for cooling purposes.

As it can be seen from figure 3 the hull self supporting structure is made of longitudinal and transversal walls (called bulkheads) that also provide the internal subdivision. They are made of reinforced concrete through which longitudinal, vertical and transversal tendons (pre-stress cables) extend providing compression in the shell plane directions. Depending on the location their thickness varies from 40 to 80cm.

Figure 4 illustrates the most common way naval architects represent the main structure of a vessel, through the midship section, which is a transversal cut done halfway along the length of the unit. On it the transverse main dimensions are given.

**Figure 4: Midship section**

**Concrete pre-stressing**

Concrete structure prestressing consists in applying a compressive load in order to provide global enhanced properties. The main aim is to maintain the concrete always on compression under the design forecasted external loads.

This pre-stress can be applied either internally through the concrete walls or externally. On NKP it’s the former that was applied by using tendons made of several ultra-high.tensile steel strands going through metallic ducts set within the concrete section. The path of these ducts is carefully defined at the design stage having to solve practical constraints (access holes, equipment foundations…) while maintaining the required compressive load.

In order to protect the steel tendons and provide a solid concrete section the ducts are filled with injection grout. Quality control procedures are set in place to minimize the risk of having water or air gaps trapped within. Figure 5 shows the horizontal tendons stretching throughout the deck concrete slabs above one capacity to illustrate the grillage density set in place. Each yellow line is a horizontal pre-stress cable within the deck thickness. Highlighted in red are shown the position of the main members; bulkheads and shell. Figure 6 illustrates the transversal cables through one section.

**Figure 5: Deck pre-stress grillage**
In particular the longitudinal tendons were arranged from design in order to provide an overall bending moment in opposition to the hogging (deck in tension) still water bending moment of normal operation. The distribution of the longitudinal cables across a typical section results in a pre-stressing tension barycenter above the section neutral axis. This is illustrated in figure 7.

The pre-stress is set in place by a pulling jack capable of tensioning cables up to 200m long. Figures 8 and 9 present the pulling jack and a bundle of pre-stressed tendons. On construction the pulling force is calculated to counteract the friction losses, plus the anticipated loss of tension that will come with time from the concrete shrinkage and creep, the steel relaxation and the cable anchorage penetration into the concrete.

Once the winch removed the cable distribution of tension will depend on its length and on its path. Figure 10 shows the theoretical variation along a side shell vertical cable that runs from the deck to centerline along the side shell (cables C2 or C3 of figure 6), with active anchorage at both ends (the cables were pulled from both ends before clamping them onto the concrete).

As said before, the metallic ducts through which the cables are extended are filled with grout, poured before releasing the pulling jack. This grout (a sort of concrete) will help retain the cables by bondage even if it severed at one point. In such case instead of having a sudden release of the cables tension it will redistribute with a local loss at the point of rupture.
Figure 10: Tension distribution along pre-stress cable

So pre-stressing is done in order to ensure that concrete has a background compression in all directions high enough to keep it in that state even under the maximum operational external loads. In order to ensure appropriate loads distribution and shear capacity the known passive reinforcement steel is embedded in the concrete. They are those bars typically seen protruding from concrete beams in any building site on any city. They are also shown in figure 11, which is a photo taken during construction of the NKP barge.

The design of this concrete structure was done according national standards Ref. [7], [8], [9]. Considering the environmental context such procedures enabled to define the operational, ultimate and accident limits.

Materials

Reinforced concrete has three particular properties worth of mention. First, its thermal expansion coefficient is very close to that of steel. This avoids internal stresses from expansion or contraction differences. Secondly, concrete naturally changes state from a flowing material to a solid as the chemical reactions within it take place. When it is poured care is taken to ensure that it occupies all the space between reinforcing steel. As it hardens concrete conforms and bonds to the steel bars, that are usually roughened to increase bonding surface. This bondage avoids relative deflection between concrete and steel and allows considering reinforced concrete as a material on its own as long as it works within the elastic behaviour zone.

Third, the alkaline chemical environment provided by calcium carbonate (lime) causes a passivating film to form on the surface of the steel, thus protecting it from corroding.

A high performance concrete was used for construction due to its qualities such as flowing capacity for pouring; resistance and low porosity once dried out. Low porosity in particular is essential to reduce phenomena like carbonatation and chloride ingress.

As could be expected the steel used for the pre-stressing cables is not the standard marine steel. It has a very high yield limit although very sensitive to corrosion, particularly once loaded.
Materials used:
- High Performance Concrete BHP 70:
  - Minimum compressive yield stress: 70MPa
  - Additive: Silica Powder
  - Initial resistivity 55 KOhms/m
  - Permeability < 10-12 m/s
- Passive steel: HA Fe E 500 / Mild Steel 235
- Pre-stressing steel:
  - Tensile strength 1860 MPa
  - Yield limit: 1653 MPa
  - Young Modulus: 190000 MPa
  - Protected by steel shaft filled with cement mixtures.

**Finite Element Model Analysis**

A numerical model was built aiming at assessing actual and future conditions. ABAQUS was chosen in order to evaluate the particular behavior of reinforced pre-stressed concrete, mainly due to its non-linear analysis capacity. The dynamic loads (motions and sea pressures) were assessed using HydroSTAR (a 3D diffraction-radiation analysis software) and taking into account the latest site metocean data. An interface between HydroSTAR and ABAQUS has been developed in order to transfer the hydrodynamic loads directly to the structural model.

The model was built with the following particularities:

- Reinforced concrete was considered as a homogeneous material with yield capacity values according to tests performed at construction time and using 3D 20-node solid elements (see Fig.12). Young Modulus was taken from standard literature, see references [8], [9].

**Figure 12: FE Model cross section with elements shrunk for better view.**

- Pre-stress cables were explicitly modeled, as illustrated in figure 6 showing the cables branching on a transversal section and in figures 13 and 14 where the whole model longitudinal and transverse tendons are presented. The modeled cables tension accounted for the variation of the pre-stressing load along each cable due to friction and losses due to anchorage penetration. The comparison between the theoretical cable tension and the one obtained in the model was seen in figure 10.

**Figure 13: FE model longitudinal cables**  **Figure 14: FE model transversal cables**

- Concrete creep and shrinkage properties were considered bias coefficients directly applied on the tendons loads, see references [8], [9], [10].
• Topside loads were introduced as concentrated masses placed at each topside module Center of Gravity (CoG) and connected to its supporting stools at deck through rigid connections as shown in figure 16. The flare tower cantilever support was assessed individually and illustrated in figure 15.

![Figure 16: Complete FE model with topside masses and flare.](image)

**Operational experience**
The present section is fed from the experience feedback of the last years during the set in place of the integrity management system. Several different surveys and numerical analyses were carried out in order to define the foundation for the future unit inspection and maintenance plan.

**Inspection and Maintenance plan**
Based on drawings review, survey reports and FE results an inspection campaign has been set up. It includes not only the Class requirements but also additional tasks in order to maximize the unit efficiency. The main objectives are:

- Identify any defect and the deterioration process:
  - Chemical attack.
  - Corrosion.
  - Crack.
  - Coating deterioration.
  - Accidents.
- Define the severity of damage.
- Provide recommendations for repair.
- Provide an image of the condition of the unit to be compared in future campaigns.

**Means of survey**
Depending on location and inspection time different means of survey will need to be used. They can be classed as follows:

- **GVI:** Global Visual Inspection or Overall survey. Intended to report on the overall condition of the hull structure and determine the extent of additional close-up surveys. It should be able to detect meaningful cracks, spills, concrete surface spalling, rust coloring from passive steel corrosion emanating from cracks, material loss, coating deterioration and corrosion of steel structures.
- **CVI:** Close Visual Inspection or Close-up survey. When carrying out a CVI the details of structural components are within the close visual inspection range of the Surveyor, i.e. normally within reach of hand. Prior cleaning of the inspection area may be required.
- **NDT:** Non-Destructive Testing. Is a close inspection by electrical, electrochemical or other methods to detect hidden damage. The inspection method requires direct access to the inspected area. Prior cleaning of the inspection item is normally required. For steel elements such methods include MPI (Magnetic Particle Inspection), ultrasonic images and penetrating dyes. For reinforced concrete such methods include the Sclerometer, sonic measures, potential mapping and radiography.
- **Sample taking:** In some cases the NDT for concrete only provide information of the surface (less than 20mm) and if doubts exist of the actual level of chlorures penetration or carbonatation depth samples may need to be taken. Adequate filling of the space left behind is necessary and procedures and materials to be used have been defined. If the samples are good enough strength tests can be undertaken for confirmation of concrete young modulus and mechanical behaviour.
- **IWS:** In-Water Survey: Survey carried out underwater by divers and/or Remotely Operated Vehicle (ROV). It usually implies prior marine growth cleaning.
**Inspection Program**

Finally the inspection program was defined by division of the asset into different zones as shown on figure 17.

- **Submerged Zone**: everything below the water surface at the service draft.
- **Splash Zone**: area submitted to intermittent wetting due to waves.
- **Atmospheric Zone**: comprises structure and equipment on and above the upper deck.
- **Internal Zone**: includes all structure, spaces and reservoirs beneath the upper deck.

Each zone is then divided in sub-areas, each of which envelopes structure and/or equipment with similar inspection scopes.

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**Figure 17: Zones sub-division**

The following two figures 18, 19 are an extract of the inspection schedule and defined tasks for the internal compartments of NKP. Although empty capacities need appropriate ventilation before man-entry and the outer spaces need prior ventilation of the central ones. This means that surveys are carried all along the year as the different capacities are opened, ventilated, inspected and closed.

**Figure 18**

One of the requirements of the Asset Integrity Management is to know at any time the status of the scheduled inspection campaigns. It is necessary in order for the Integrity Manager to follow the condition of the unit. If a programmed survey has not been carried out he will be informed and make sure it is done.

In figure 20 is illustrated an extract of the web-based inspection calendar for NKP. Colour levels indicate the survey status; done, to be done or overdue.

**Figure 19**

<table>
<thead>
<tr>
<th>Area</th>
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<th>Inspection Type</th>
<th>Access</th>
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<th>4.5</th>
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<td></td>
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</table>

**Figure 20**

- GVT: General Valve Testing
- GUS: General Unit Safety
- MDT: Modular Device Testing
- MD: Modular Device

**Description of Task**
- GVI of internal structure and gauges
- Electric potential measurements from the 3 control points: all pump rooms, including of technical gallery and fire pump room.
- Measurements to be carried out according to "Protection Cathodique – Système de contrôle" (E.E. 11-06-0660)
- GVI of Communication pipes, pressure and drainage arrangement.
- GVI from the closest gauge of Reservoirs and their supports. Anodes shall be replaced.
- Electrical machinery and equipment. GVI according to P3A; C3B; Sec 1 of IEC Rules
- Fire protection detection and extension. GVI according to P4A; C3B; Sec 1 of IEC Rules

**Areas of Particular Interest**
- Auscultation areas of turbines
- Concrete construction joints
- Cross connections of longitudinal and transversal boltheads
Unconsciously reinforced concrete is understood as a durable, hard material and structures made with it are automatically assumed to be built to last. And that is exactly the impression one has when entering the capacities of the NKP. In its majority the walls are smooth and unscathed and making abstraction one would think himself on the basement of a building and not on a floating structure above 170m of water 60 miles from the coast.

The doubts arise with the first cracks and for those not used to work with pre-stressed concrete structures some look menacing. It is then that it has to be recalled that concrete is a continuous chemical reaction and natural cracking is expected (endogenous cracking) during cement hydration. Concrete solidifies and hardens after mixing with water and placement due to a chemical process known as hydration. The water reacts with the cement, which bonds the other components together, eventually creating a stone-like material. During construction as the concrete is poured in different phases, shrinkage from water consumption exists at different levels at adjacent pouring blocks. Cracks may then appear from restrained shrinkage in any of the pourings. Such fissures are usually extremely thin and will end up sealing themselves up if appropriate resin injection is done between pourings, but will still be visible. That’s why simply reporting cracks (except those clearly indicating a significant loss of prestress) is not enough to indicate a problem is occurring. Crack progression with time needs to be recorded. In order to evaluate the risks the FE model is used to try to find an explanation to the defect.

The different surveys mentioned above were defined in order to detect typical concrete degradation process namely:

- Effect of sea water on cements (sulfate, chloride),
- Lime leaching-carbonation,
- Alkali aggregate reaction,
- Reduction in cement content and strength,
- Increase of permeability (permitting Chloride Ingress),
- Fatigue.

As expected from the use of high quality concrete, only a number of the above defects were found on board and are presented on pictures below. Figures 21 & 22 show external hull photos, whereas figures 23 & 24 are pictures taken from the inside:
1: The corner of the hull had been protected by fiber reinforced layer against abrasion from over hanging object like chains, ropes, etc.
2: All steel pipe penetrations are protected by coating
3: The concrete hull was left unpainted and doesn’t present any major defect
4: Metallic inserts or passive bars with lack of concrete cover present local and superficial corrosion
5: Marine growth as usual on offshore unit
6: Metallic insert protectd by coating

7: Manhole for construction phase creates local corrosion

8: Anchors of prestress cables
9: Capacity ullage gauge
Concrete damage from steel corrosion

As seen in the pictures one of the most common detectable defects is steel corrosion. Reinforcing steel (passive steel and pre-stressed cables) in concrete is protected from corrosion due to the formation of a passive oxide film on the surface of the steel. The process of hydration of cement in freshly placed concrete develops a high alkalinity, which in the presence of oxygen stabilizes the film on the surface of embedded steel, ensuring continued protection as long as the alkalinity is retained.

However even without mechanical degradation (impacts, abrasion...), there are two major situations in which corrosion of reinforcing steel can occur; carbonation and chloride ingress. Either way the removal of the passive film leads to the galvanic corrosion process. When this occurs the produced rust takes up a lot more space than the originating steel, straining the surrounding concrete. Since concrete is relatively weak in tension, cracks develop, exposing the steel to even more chlorides, oxygen and moisture – and the corrosion process accelerates.

1. Carbonatation: Carbonation is a process in which carbon dioxide (CO2) from the atmosphere diffuses through the porous concrete and neutralizes the alkalinity of concrete. The carbonation process will reduce the alkakine pH to approximately 8 or 9 in which the passive film is no longer stable. With adequate supply of oxygen and moisture, corrosion will start. The penetration of concrete structures by carbonation is a slow process, the rate of which is determined by the porosity and permeability of the concrete. Carbonatation not only can induce embedded steel corrosion but it also alters the concrete properties.

2. Chloride ingress: Chloride ions can enter into the concrete from de-icing salts or from seawater in marine environments. If chlorides are present in sufficient quantity, they disrupt the passive film and subject the reinforcing steel to corrosion. The levels of chloride required to initiate corrosion are extremely low. Macro cell corrosion can develop from differences in chloride ion concentration in different parts of the concrete structure. Such variations of chloride ion concentration are found whenever concrete deteriorates.

Chlorides penetration and carbonation levels were measured at different locations on NKP. In all locations the values showed high quality concrete with weak depths of both phenomena. As Figure 25 presents, the chloride depth on the outer shell after 7 years on site is limited to the first 10mm.

However, there are places were the steel elements had a too thin concrete layer and steel has been reached as seen on the pictures 21 & 22. As it is a superficial defect (no more than 20mm in shells that are 500mm thick) the repairs are relatively easy to carry out with appropriate scaffolding were necessary.

Figure 24: inner surface of outer shell

Figure 25: Chlorides penetration after 7 years on site at outer shell
In addition, the following corrosion protective systems were set in place at building stage:

- **Structure cathodic protection**: Cathodic protection is a technique to control the corrosion of (reinforcing) steel by making the steel the cathode of an electrochemical cell. CP is defined as the reduction or elimination of corrosion by making the metal a cathode by connecting it to a sacrificial or galvanic anode, or via an impressed direct current. Cathodic areas in an electrochemical cell do not corrode. If all the anode sites are forced to function as current-receiving cathodes, then the entire metallic structure would be a cathode and corrosion would be eliminated. Electrical Continuity of all passive steels and other structural metallic parts is necessary for obvious reasons.

183 anodes (the anodes on internal shell are located in the four capacities used as water ballast tank at the corners of the unit) provide a steel-reference electrode potential around -850 mV as recommended in reference [7] and are intended to protect the reinforcing steel.

- **Exposed steel structures painted**: High quality coating will eventually fail with time as shown of pictures 21 & 22. It is then necessary to clean exposed steel and repaint in order to avoid loss of steel and concrete damage.

One way to check if corrosion of embedded steel is occurring is by means of potential mapping. If corrosion exists the current flow in the concrete is accompanied by an electrical field which can be measured at the concrete surface, resulting in equipotential lines that allow the location of the most corroding zones at the most negative values. This is the basis of potential mapping, the principal electrochemical technique applied to the routine inspection of reinforced concrete structures. The use of the technique is described in Ref.[12]. On NKP all measured potentials correspond to a very low probability of corrosion (less than 10%).

Apart of visual examination of anodes oxidation the working order of the cathodic protection can be carried out by measuring the steel potentials in concrete versus reference cells. On NKP anodes showed consumptions of around 10% and potential measurements between -950 and -1100mV that correspond well to literature to the Aluminum anodes used.

**Concrete cracking.**
Concrete cracks due to tensile stress induced by shrinkage or stresses occurring during setting or use.
As mentioned earlier shrinkage cracks can occur when concrete members undergo restrained volumetric changes (shrinkage) as a result of its water consumption either from autogenous shrinkage or thermal effects (concrete dries faster than normal). Plastic-shrinkage cracks are immediately apparent, visible within 0 to 2 days of placement, while drying-shrinkage cracks develop over time.
Although high-performance concrete can accept a minor degree of tension it is insignificant compared to its capacity to resist compressive loads. Therefore it is usually considered as having no capacity for tensile stress and if a member is under tension loads it is the steel reinforcements that are assumed solicited.
On NKP nearly all the significant cracks detected have been declared as plastic-shrinkage. Exceptions are found on the fore end where, due to flare heating, superficial drying-shrinkage cracks have developed. On the flare tower cantilever support surface signs indicate the structure probably got close to operational limit during towing phase.

**FE Model comparison with real life**
The FE assessment has verified that the design construction keeps the overall structure in compression. However the structural analysis has highlighted some localized areas where lack of compression can be found. These localized areas coincide with the findings of the inspection showing superficial defects, mostly due to practical difficulty of concrete reinforcement in these areas. Examples are degradation of deck edges and flare tower support ends, the latter having pre-stress cables ending on them. All of those are easy to repair and don’t need a high-tech qualification to bring back to as-built situation. Flare tower cantilever surface cracks were explained by the FE model showing that the design was optimized for the site conditions. Particular surveys have been defined for this member as a result of the numerical calculations.
Figures 26 and 27 show the areas with localized lack of compression.

Figures 27, 27: Highlighted areas with lack of compression. Fore end and whole model.

Main conclusions

So far it has been concluded that an efficient cathodic protection was set in place and is actively protecting reinforcement steel.

The choice of high quality of concrete is proving adequate protection agains carbonation and chloride penetration as well as satisfying ageing.

After 10 years concrete hull maintenance and repairs basically consisted on restoring concrete surface cover lost from abrasion and impacts.

Design enhances capacity inspectability. Spaces are open without intermediate members blocking the view (in opposition to webframes and secondary stiffening on steel vessels). GVI is easily done with a number of fixed illumination sources although additional means of access for CVI of the upper parts are necessary.

The main background danger will always be steel corrosion.

A better comprehension of structure aging process could have been obtained if samples had been prepared during construction and left on board (in order to have same ambient conditions) for posterior strength and mechanic properties tests. Similarly pre-stressed samples for fatigue capacity re-assessment should have been performed prior construction and not just base design values on literature. Although concrete preparation is now a well-known science it is also true that there are never two alike as their final properties depend on the used local water and aggregates.

Construction quality control is a must to ensure durability. Once properly set up with competent personnel the building site can be placed nearly anywhere without need for an empty drydock slot.

The definition of the Floating Units Integrity Management program for NKP has allowed changing from a passive and corrective action frame into a proactive scheme. Main non-accidental degradation process and most exposed locations have been identified enabling to set in place an inspection program particular to NKP. It has also made apparent that the sooner such a system is set in place the better. If it can be kept in mind during design it would help on the definition of means of access and identify critical members that cannot be repaired/replaced on site and allocate appropriate safety margins, not only to external loads but also corrosion allowance.

The creation of a finite element model representing as close as possible the as-built and site conditions has helped understand survey outcome. It also means that in case of accident it could be used to evaluate the condition of the unit and help make the right decisions.

References

8. French National Pre-stressed Concrete Standard BPEL 91.