STRUCTURAL INTEGRITY MANAGEMENT FOR A LARGE PRE-STRESSED CONCRETE FLOATING PRODUCTION UNIT

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ABSTRACT

Offshore Floating Production Units, usually deployed under long-term plan, handle the field production so they cannot be easily removed for dry-docking and repair. 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 our Floating Units currently in operation.

The paper gives a description of this methodology, and then focuses on how the methodology was deployed for the large pre-stressed concrete Floating Production Unit (FPU) located offshore Congo on N’KOSSA field. This FPU is the largest existing pre-stressed concrete Floating Production Unit, built with high performance concrete, installed offshore since 1996 in 170 m water depth. She has now accumulated 10 years of production.

A significant part of the methodology is based on a full Finite Element Model (FEM) with non-linear analysis capacity for the concrete structure, incorporating a description of passive and active steel.

There is often an anchored perception that a concrete unit is something not requiring attention once installed. This paper shows otherwise, underlining the complexity of modeling the highly non-linear characteristics of pre-stressed high performance concrete and degradation modes.

AIM OF THE INTEGRITY PROGRAM

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. And gives the framework for exceptional analysis.

PANORAMA OF FLOATING UNITS BY THE INTEGRITY MANAGEMENT PROGRAM

First priority for implementation of the program has been given to the most important assets, i.e. those being operated by our Company and having the function of storage, and/or production, and/or offloading - in short F(P)(S)U.

These Floating Units can be ship-shaped or box-shaped or any other shape such as TLPs, SPARs, SEMIs, etc. They can be in steel or concrete and can handle various types of hydrocarbon products (oil, condensates, gas, LPG, LNG...).

The Floating Units Integrity Management program also applies to the anchoring systems and to the offloading buoys, either coastal (associated with onshore storage) or offshore (associated with offshore field development).

The Fig. 1 is a world map showing the location of the present Floating Units concerned in priority by the Floating Units Integrity Management program (due to lack of space the Figure is not showing all the loading buoys).

CLASSIFICATION OF THE UNITS AND EQUIPMENT FALLING UNDER THE SCOPE OF THE PROGRAM

Classifications of the units

The Company E&P referential stipulates that the Floating Units shall be classed. This concerns namely:
- All the F(P)(S)Us.
- All the permanent anchoring systems of these units.
- All the transfer systems (side-by-side, tandem) and all the loading facilities SPMs and other types (Single Point Moorings like offloading buoys...), either coastal or associated with offshore installations.
The equipment falling under the scope

The equipment falling under the scope of the class is logically the same as those falling under the scope of Floating Units Integrity Management program.

However the requirements of the program go beyond the class requirements as they encompass the full life of the Floating Unit, the risks, the constraints dictated by the absence of dry-docking and the cost of in situ repairs and the implementation of an emergency response.

The topsides (process), risers and submerged transfer lines connected to the Floating Units are covered separately by other integrity management programs. However they are taken into account in the models as they interact with the Floating Unit structure and with the mooring.

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**The Specificity of the Floating Units concerned**

One of the principal challenges encountered was to define and develop a program applicable to units as different as converted tankers (FSO, FPSO), new-build constructions (FSO, FPU), a concrete unit (FPU), a refrigerated LPG storage unit (FGSO), and a TLP, all in varied environments and in an extensive range of water depths and anchoring patterns.

It was soon realised that these different units have a number of specific points in common, justifying the development of a specific system of integrity monitoring:

- They are all compartmented (cargo tanks, seawater ballasts, cofferdams) and governed by strict regulations like the ones on intact stability and stability after flooding of compartments. They have specific circuits for cargo, ballast, treatment, tank washing and inerting, etc.
- A number of international regulations derived from rules specific to oil tankers apply, or are applied voluntarily: prevention of pollution, safety of life at sea, security for vessels coming to load on the units, flagging in some occasions, etc. On the whole, the rules of the classification societies apply at least at the design stage.

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**Fig. 1: Location of the Floating Units concerned by the Integrity Management program**

**THE FLOATING UNITS INTEGRITY MANAGEMENT PROGRAM**

The goals of our Floating Units Integrity Management program

Because of the major role the Floating Units play in field production schemes, what we expect of the Integrity Management Program is to obtain information:
- On their condition at all times so that we can keep their class certificates valid on the 5 years terms and maintains their integrity over their design life span.
- Enabling us to predict any aggravation in deterioration to the structure and its mooring system over the long term, and thereby to minimize the risk of failures that require either production shutdown or significant reductions in their operational storage capacity, for example.
- Permitting a fast reaction whenever problems or emergency situations arise (a graduated appropriate response).
- That is grouped and shared across a network (sites, affiliates, head office experts and specialized Third Party Assistance companies providing models and expertise).

Tecnitas, a subsidiary of Bureau Veritas, was selected for the NKP large pre-stressed Floating Production Unit in Congo as the Third Party Assistance company, contributing to the content and deployment of the program and to monitoring of the unit in order to guarantee the neutrality of the analyses and studies and likewise the choices recommended.

In addition, Bureau Veritas has review the work carried out by Tecnitas and provided experts for the classification of this particular unit.

The Fig. 2 gives an overview of the Integrity Management.

Fig. 2: Overview of the Integrity Management

Description of the program
A detailed description of the Floating Units Integrity Management program is given in references [1] and [2]. Below is a summary of the main elements.

The program is divided into four complementary, interacting modules as shown on Fig. 3:
- Structural non linear Finite Element Analysis (FEM) model and dynamic mooring model (ABAQUS and HYDROSTARand ARIANE Models).
- IRM (Inspection Repair Maintenance): inspection plan and schedule incorporating class requirements (renewal of certificates, repairs…), and incorporating RBI (Risk Based Inspection).
- Database (plans, results of models, inspection reports, class status, etc.), with information shared in a network system.
- ERS (Emergency Response Service).

Fig. 3: The four main tasks in the program
Communication and collaboration of asset information is identified as a key factor when considering a successful asset integrity management solution. By opting for a solution that is connected with a database and where information is communicated through a network system, one opens up the possibility of sharing and communicating the information to a number of interested parties.

As shown in Fig. 4 there may be a number of stakeholders that may have an interest in accessing the asset integrity management database, either to view stored data or to contribute to the population of data.
- The Subsidiary in charge of the integrity of the assets.
- The Head Office experts (structure and mooring, hydrodynamics, marine, inspection & maintenance, RBI).
- Third selected Third Party Assistance companies providing tools and services.

### DATA MANAGEMENT ON THE WEB-BASED SYSTEM (VeriSTAR AIMS / DNV FLCM)

- Secured web application
- Controlled access using passwords
- Users:
  - Subsidiary / Offshore Site
  - Head Office Experts
  - Third Party Assistance company
- Floating Unit Integrity Management:
  - Database
  - Inspection plan
  - List of maintenance operations
  - List of comments
- Class activity follow-up
  - Upcoming inspections
  - Certificates
  - Class reports

![Fig. 4: Data Base and networking system](image)

The program is run as follows:

**Deployment and first assessment**
- For the Floating Units already in service, besides deployment of the four main tasks listed above, a “first assessment” is made, comprising:
  a) A complete analysis (history, trend analysis, structure and mooring models at “as-is” status, design verification, and residual fatigue calculations) and
  b) A baseline inspection.
- For units under construction, an “as-buil” structural model, an “as installed mooring model and all the corresponding documentation are established and an inspection plan is drawn up before delivery.

**Yearly re-assessments**
- Each year, the database is updated (with inspection reports, thickness measurements, etc.) as are the structural and mooring models that are run. Trend analyses and fatigue studies are undertaken, incorporating the real history of the Floating Unit (load cases, met-ocean data, etc.). The effects and consequences of deteriorations in the structure and mooring are evaluated, and structural details are studied. The inspection plan is updated to factor in the new status of the unit.

Exceptional studies may be commissioned, e.g. longevity studies for older Floating Units.
- The first assessment is presented during a mission to the affiliate. The yearly reassessments are reviewed jointly at meetings including the affiliate, the head office experts and the specialised Third Party Assistance company. The classification society and the contractor (for units on lease) may also be invited to take part.

This periodic process represents the so-called integrity management circle for the Floating Unit and is shown in Fig. 5.
IMPLEMENTATION OF THE PROGRAM TO THE LARGE PRE-STRESSED CONCRETE FLOATING PRODUCTION UNIT NKP

The FPU was built in Marseille (France) in 1994-95 and installed in 1996 in the N’KOSSA oil field in 170 m water depth and some 60 km offshore the Congo Coast. See Fig. 6.

This is the first floating concrete FPU ever installed. Its main characteristics are: 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, water depth 170 m. This concrete barge used in its construction 27,000 m3 concrete, 2,350 t prestressed steel and 5,000 t passive steel, references [3], [4].

Fig. 6: N’KOSSA concrete FPU

All production facilities and living quarters for 160 people are placed along the 10,000 m² deck surface 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 by means of 12 mooring lines.

UNIT PRESENTATION AND LOCAL ENVIRONMENT

Design

See Fig. 7 and photos: Compartment arrangement.

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.

Ten central void spaces are crossed by the “Technical gallery” which connects the aft and fore pump rooms (see dark grey color).

A particular space inside the capacity C10, known as “Piscine” (swimming pool in French), is used as a basin to collect the water pumped from a depth of 50m. The water is sucked in with a pipe (metallic outside and concrete inside) that penetrates the side shell and runs through two capacities before reaching the “piscine”. Three pumps (two in service, one spare) then move the water from the “piscine” to the process plant for cooling purposes.

Fig. 7 and photos: Compartment arrangement of the N’KOSSA concrete FPU
The Midship section is given on Fig. 8.

![Fig. 8: Midship Section of the N*Kossa concrete FPU](image)

The external “shell” is a 50cm thick wall of reinforced concrete through which longitudinal and transversal tendons (pre-stress cables) extend providing compression in the shell plane directions.

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 barycentre above the section neutral axis (Fig.9). The structural analysis has verified that such design construction keeps the overall structure in compression.

![Fig. 9: Pre-stress cables tensions barycenter and section neutral axis](image)

**Concrete structure pre-stressing concept**

Concrete structure pre-stressing consists in applying a compressive load in order to provide global enhanced properties. The main aim is to maintain the concrete always under 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.

The pre-stress is set in place by a pulling jack capable of tensioning cables up to 200m long and calculated to counteract the friction losses, the concrete shrinkage and creep, the steel tendons relaxation with time and the cable anchorage penetration into the concrete. Fig.10

In order to protect the steel tendons and provide a solid concrete section the ducts are filled with injection grout, closely verifying that no water and air gaps are trapped within.

![Fig. 10: Pre-stress Anchorage and tensioning phase](image)

**Materials**

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, both described in the corrosion protection section.

Pre-stressing the structure in the three directions provides an assurance for water tightness and avoiding tension anywhere within the concrete section below.

Concrete is a continuous chemical reaction and natural cracking is expected (endogenous cracking) during cement hydration. 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.

- **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.

**Environment and Mooring System**

The conditions offshore Congo can be talked as mild although consideration has to be taken for squalls. The wave spectrum
used for calculations is a JONSWAP with a spectral peak parameter $\gamma$ of 2.

The unit is spread moored with 12 mooring lines in wave’s predominant direction (nearly south-north orientation) and for the first time suction anchor piles in soft clay were used, now a prevalent anchoring technique for deepwater sites, reference [5].

**ASSET INTEGRITY**

**Inspection Program for the concrete hull**

A preliminary inspection program was drafted after several meetings between experts of different disciplines. The intended aim is to provide a real picture of the unit with constant improvement, i.e. survey results will allow to tune future inspections.

The inspection plan was build considering the following key aspects:
- Design Review selecting potential problem-prone areas.
- Survey Reports on site during construction.
- Degradation process of material and pre-stressing concept.
- Environment including both the surrounding conditions and the industrial aim of the unit.
- The results of FEM analysis.

As the result, the inspection program was divided into several zones as shown on Fig. 11:
- 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.

**Design Review**

For each zone, items requiring inspection were highlighted and details on the inspection scope (extend and level of inspection) were written down. Examples of areas requiring particular attention are:
- Bilge keels and bottom penetrations.
- Topside stools and connection to deck.
- Flare tower support.
- Ballast tanks and "piscine".
- Concrete cover of pre-stress cables heads at the splash zone

**Degradation process of material and pre-stressing concept**

Cracking of concrete is nearly unavoidable being the main causes:
- Due to material properties: Cement hydration shrinkage during hardening process and creep under continuous load.
- Due to external loads: Structure deformation leading to localized tension.
- Due to degradation mechanisms: Carbonation, corrosion of embedded steel,… etc.

That’s why simply reporting cracks (except those clearly indicating a loss of prestress) is not enough to indicate a problem is occurring. Crack progression with time is needed to be recorded in order to evaluate the reasons and risks emanating from the defect.

The main deterioration process are 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..

Some of these degradation processes not only have an impact on concrete but also on the steel reinforcement embedded within.

Pre-stress concrete could be considered as a different material to simply reinforced concrete, with different behavior and global properties. Any signs of pre-stress loss (cracks coming from it are self-explanatory generally) must be dealt with promptly and a structure assessment through FEM is necessary.

In this context, mechanical facts can change the capacity of pre-stressed concrete section like:
- Impacts boarding, fall of equipment, etc.)
- Abrasion (off landing, ropes, supplier etc.).
- Abrasion (industrial liquids),
- Accidents.
- Collisions.
- Corrosion of steel structures.
- Inefficient cathodic protection.

The asset Integrity Management imposes to have a strategy of inspection and maintenance of the concrete. Corrosion protection is a central element of this step.
Corrosion Protection

Reinforcing steel (passive steel and pre-stressed cables) in concrete normally does not corrode because of the formation of a passive oxide film on the surface of the steel due to an initial corrosion reaction. 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. Normally, concrete exhibits a pH above 12 because of the presence of calcium hydroxide, potassium hydroxide and sodium hydroxide. The mentioned film isolates the steel from the environment and avoids corrosion as long as the film is intact.

However, there are two major situations in which corrosion of reinforcing steel can occur:
1. Carbonation.
2. Chloride contamination.

1. 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 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. Carbonation not only can induce embedded steel corrosion but it also alters the concrete properties. It is rarely a problem on structures that are built with good quality concrete with adequate depth of cover over the reinforcing steel as it is the case for the NKP concrete FPU.

2. The role of the chloride ion (present in natural salt) in inducing reinforcement corrosion is well documented. 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. The removal of the passive film from reinforcing steel leads to the galvanic corrosion process. 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.

When corrosion of the embedded steel 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 can develop easily, exposing the steel to even more chlorides, oxygen and moisture – and the corrosion process accelerates.

Additional protective systems set in place
- Side shell and internal structure cathodic protection: 183 anodes (the anodes on internal shell are located in the four capacities used as water ballast tank at the corners of the unit). See illustrations on Fig. 12 and 13. These anodes provide a steel-reference electrode potential around -850 mV as recommended in reference [6] and are intended to protect the reinforcing steel.
- Electrical Continuity of all passive steels and other structural metallic parts that may become in contact with sea water.
- Control system, reference anodes and telltales set in place.
- Exposed steel structures painted.

Fig. 12: Anode on side shell at construction time

Fig.13: General cross-section with anodes locations

Finite Element Model

Description

A numerical model was built aiming at assessing actual and future conditions (see Fig. 14 to 22). 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.16). Young Modulus was taken from standard literature, see references [7], [8].
- Pre-stress cables were explicitly modeled, accounting for the variation of the pre-stressing load along each cable due to friction and losses due to anchorage penetration (see further below for details on methodology used and description of prestressing concept given above).
- Concrete creep and shrinkage properties were considered bias coefficients directly applied on the tendons loads, see references [7], [8].
- 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 (see Fig. 17).

Fig. 14: global FEM model

Fig. 15: Capacity subdivision

Fig. 16: Typical Cross section

Fig. 17: Full model representation with topsides and flare tower

Fig. 18: Typical section with reinforced concrete solid elements and transversal cables representation.

Fig. 19: Schematic representation of pre-stress cable segment through a solid concrete element.

Fig. 20: Longitudinal cables view
be read directly on the cable at the FEM. As it can be seen the difference is nearly inexistent.

![Pre-stress variation along a transverse cable](image)

**Fig. 23: Pre-stress variation along a transverse cable**

**Model Validation**

This representation of pre-stress cables required to be validated by running elementary load cases of the design calculations done more than a decade ago and comparing both analyses. At that time pre-stress loads were introduced as nodal forces along the theoretical path of cables.

The comparison showed the validity of the ABAQUS model and provided the following conclusions:
- Effects of the cable offset to the concrete slabs/girder Center of Gravity (CoG) is appropriately assessed through this representation. Fig. 24 shows a simple test on a continuous beam.

![Example of cable eccentricity effect](image)

**Fig. 24: Example of cable eccentricity effect**
- Several different cables with different sections and loads going through the same slab/girder can be independently tracked and the effect of losing any of them quickly analyzed.
- The effect of global and primary structure deformation on the cables stress level can be checked.

Results of the global structural analysis of the concrete FPU

Initial numerical results have been obtained and have 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.

Fig. 25 and 26 show the areas with localized lack of compression. The different colors express the variations between low compression to partial tension (calculations done in hogging, still water condition).

Non-Linear Analysis
For the localized areas were tension can be found, a non-linear analysis should be carried out with the following material particularities:
- Passive steel reinforcements are explicitly modeled.
- Plastic behavior of both concrete and steel.

INSPECTION
A number of surveys campaigns have been carried out fulfilling the tasks described in the inspection program.

Objectives
- 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

GVI: Global Visual Inspection or Overall survey: Survey intended to report on the overall condition of the hull structure and determine the extent of additional close-up surveys. Such an inspection 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: Survey where 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. To be done after a GVI to inspect in detail selected critical elements where minute defects may be starting.

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. If defects have been found or there are suspicions of hidden damage, NDT should be carried out to know the extend and depth of the damage. 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.

IWS: In-Water Survey: Survey carried out underwater by divers and/or Remotely Operated Vehicle (ROV).
In addition to the above means of survey the search for chloride ingress and carbonation degree usually requires probing samples of a certain depth drill out of the concrete surface.

The principal results from the surveys carried out have been:
- The natural ageing of the pre-stressed concrete was found according to design expectations. The unit design life is 30 years.
- Reporting of surface cracks for continuous monitoring.
- Characterization of surface defects and definition of punctual repairs and condition maintenance.
- Prioritizing the maintenance tasks.
- Confirmation of adequate global behavior and condition.

CONCLUSIONS

General conclusions for a concrete Floating Unit
- With appropriate high quality concrete, corrosion control and maintenance, no coating is necessary on concrete on submerged zone.
- The absence of secondary reinforcement connections (typical to a steel structure like longitudinal stiffeners in way of primary structure) reduces the number of areas where stress concentration may occur.
- In a normal working condition the inspection times can be considerably reduced compared to that of a steel homologue. Open spaces are easy to ventilate and to inspect.
- A Finite Element Model (FEM) is unable to precisely simulate the ageing behavior of concrete without an appropriate calibration system set in place since the construction.
- Knowledge of the construction techniques, the deterioration process and their visible signs is required for an adequate inspection.
- The unit durability is largely dependent on the quality of construction and respect for building tolerances.

Main conclusion of the studies and surveys of unit:
- After 10 years in service with minimum maintenance work, the structure remains in a good shape, see Fig. 27.
- Most of the degradation signs seem superficial and correspond of the service and age of the unit.

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REFERENCES