Detailed Design and Construction of the Hull of an FPSO (Floating, Production, Storage, and Off-loading Unit)

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ABSTRACT
This study presents the ways and means of detailed design and construction of an FPSO installed in the AKPO field, offshore Nigeria with a close attention on the offshore market in deepwater developments.

First, we explain the overall process of the on-going AKPO FPSO from detailed design to construction and lessons learned from AKPO FPSO, contributing to successful design and construction of future FPSO’s. The design and construction of an FPSO (Floating, Production, Storage, and Off-loading unit) is divided into two parts: one for the hull system and the other for the topside system. The FEED (Front End Engineering Design) and specification on the FPSO commenced with the DBR (Design Basis Report). This resulted from a feasibility study on the exploration of the specific field in order to meet the market requirements for stabilized oil. We performed a detailed design of the hull system of AKPO FPSO based on the FEED and coordinated the overall FPSO designs of the hull and the topside systems, which were performed by other contractors. After finishing the detailed design of the FPSO, we performed the construction and integration of the hull and the topside.

Second, we describe some problems and their solutions of the detailed design and construction of the AKPO FPSO. Through this study, readers will be able to learn the detailed design and construction of the FPSO.

KEY WORDS: FPSO (Floating, Production, Storage, and Off-loading unit); Design; Construction; FEED (Front End Engineering Design); DBR (Design Basis Report)

INTRODUCTION

Introduction to FPSO

FPSO, which stands for Floating, Production, Storage, and Off-loading unit, is a floating vessel that is able to produce crude oil and gas. It is made up of two parts: the topside and the hull. The topside, like chemical plants, produces and off-loads crude oil and gas, and the hull, like a big tank, stores the produced oil. The FPSO produces and processes crude oil and gas on the topside, and stores the stabilized oil in cargo tanks of the hull. The FPSO also off-loads the stabilized oil and gas to a shuttle tanker through the oil export/metering pump (Mather, 2000). However, the FPSO alone can not produce oil and gas in the oil field. It requires many offshore production systems such as the SPS (Sub-sea Production Systems), UFR (Umbilicals, Flow lines, and Risers), mooring lines, a shuttle tanker, an off-loading buoy, etc., as shown in Fig. 1. Thus, the design and construction of an FPSO includes many other offshore production systems (Shimamura, 2002; Infield, 2005a, Infield, 2005b; International Maritime Associates Inc., 2005).

Fig. 1. Offshore production systems

Fig. 2 shows a typical layout of an FPSO. The FPSO is subdivided into two parts: topside and hull. An FPSO has many sub-systems such as the flare tower, living quarters, lay down area, mooring fairleads and a helicopter deck.
Introduction to the Nigeria Field Development Project

The AKPO field is located in the offshore area called OPL 246 off Nigeria, as shown in Fig. 3. This oil field, which was discovered in March 2000, is located 200km from Port Harcourt. The water depth, where this oil field is located, is 1,275~1,470m. The AKPO field development project refers to the project which produces oil and gas in this field. The AKPO field development project consists of several major oil companies, namely NNPC (Nigerian National Petroleum Company), Sapetro (South Atlantic Petroleum, Nigerian Company), Petrobras (Brasilian Oil Company), and Tupni (Nigerian subsidiary of Total). The share of each company for this project is 50%, 10%, 16%, and 24%, respectively.

Fig. 3. Layout of the Nigeria field

From the perspective of field development, this project is largely made up of the FPSO, SPS, UFR, OLT (Offshore Loading Terminal), as shown in Fig. 1. The FPSO of this project is made by the consortium members. HHI (Hyundai Heavy Industry Co., Ltd.) is charged with the hull, Technip Co., Ltd. with the topside, Cameron with the SPS, and Saibos with the UFR. The design and construction of the FPSO was done by HHI, HSHI (Hyundai Samho Heavy Industry Co., Ltd.), and Technip. The detailed design of the topside was done by Technip. The detailed design of the hull and the construction of the topside was done by HHI, and the construction of the hull was carried out by HSHI. The methods used to produce the detailed design and construction of the hull of the FPSO is studied to help future design and construction of the hull of FPSOs.

ELEMENTS OF THE FIELD DEVELOPMENT PROJECT

The field development project is made up of FPSO, SPS, UFR, and OLT, as shown in Fig. 4. More details about each element are presented here.

Fig. 4. Elements of the Nigeria field development project

FPSO

FPSO of this project consists of mooring, riser structure, accommodation, process (oil, gas, and water) facilities, gas and water injection facilities, flaring facilities, oil storage facilities, export facilities (pumping and metering), gas export facilities, and control systems, as shown in Fig. 4. The overall functions and specific characteristics of each component are as follows.

- Total production capacity (total fluids): 200,000barrel/day
- Stabilized oil (Fig. 4(a)): maximum 185,000barrel/day
- Produced gas (Fig. 4(b)): 530Mscfd (Million standard cubic feet per day)
- Injected gas (Fig. 4(c)): 215Mscfd at 400bar
- Export gas (Fig. 4(d)): 320Mscfd at 193bar
- Fuel gas: 25Mscfd
- Injected water (Fig. 4(e)): 420,000bwpd (barrel water per day) at 200bar
- Produced water: 150,000bwpd
- Crude storage (Fig. 4(b)): 2,000,000barrel (BBLS)
- Spread mooring (Fig. 4(f)): 4 × 3 lines
SPS (Sub-sea Production Systems)

SPS are the sub-sea systems that were drilled by the fixed platform or the drill ship and from which oil and gas were extracted, as shown in Fig. 4(g). SPS also called wellheads or X-mas trees. In this project, SPS consist of 48 wells, as shown below.
- 24 oil producer wells
- 3 gas injection wells
- 21 water injection wells

UFR (Umbilicals, Flow lines, and Risers)

UFR are the specific facilities that transfer the produced crude oil from SPS to the topside of FPSO which is equipped with process systems, as shown in Fig. 4(h) (International Maritime Associates Inc., 2005). In this project, components of UFR are as follows.
- 4 production flow loops and risers (Fig. 4(b)): production lines for the crude oil from oil producer wells
- 1 gas injection line and risers (Fig. 4(c)): gas injection line for compensating for the pressure of oil producer wells after producing the crude oil.
- 4 water injection lines and risers (Fig. 4(e)): water injection lines for compensating for the pressure of oil producer wells after producing the crude oil.
- 4 production umbilicals (Fig. 4(i)): specific lines for installing cables to supply electric power for SPS.
- 4 injection umbilicals (Fig. 4(i)): specific lines for installing cables to supply electric power for gas and water injection facilities.
- 1 export gas pipe line (Fig. 4(d)): specific line for transferring gas to Amenam AMP2 Platform (Fig. 4(j)). In general, the crude oil of oil producer wells is separated into oil, gas, and water through the high and lower pressure separators. That is, after the stabilized oil is stored in cargo tanks of the hull of the FPSO (Fig. 4(k)), the stabilized oil is off-loaded to a shuttle tanker (Fig. 4(l)) through the oil export/metering pump and the dehydrated gas is used for gas injection wells and main turbine generator through the dehydration and export compressor. Then, the remaining gas is transferred to Amenam AMP2 Platform.

OHLT (Offshore Loading Terminal)

OHLT is the specific facility which transfers the stabilized oil in cargo tanks of the hull to the shuttle tanker through the export and metering pump in the topside, flow lines, and off-loading buoy, as shown in Fig. 4(m) (International Maritime Associates Inc., 2005).

DETAILED DESIGN PROCEDURE AND MAIN ACTIVITIES OF THE HULL OF AN FPSO

Procedure for the FPSO Field Development

In order to develop the field, an exploration and feasibility study must first be performed. Then, based on the result of the study, FEED of FPSO is commenced if the economic value of the field development is positive, taking the circumstances of offshore market into account. In case of the Nigeria field development, FEED was performed by Doris Engineering Co., Ltd. in a 10~12 month periods. After FEED, the detailed design of the topside of FPSO was performed by Technip and the detailed design of the hull was performed by HHI in a 12~14 month periods. Then, the construction and installation of the topside was performed by HHI and the construction of the hull was performed by HSHI. Fig. 5 shows the overall procedure of the FPSO field development of this study (Barltrop, 1998a; Barltrop, 1998b).

Detailed Design Procedure of the P&ID of FPSO and Main Activities

Fig. 6 shows the detailed design procedure of the hull of FPSO and the main activities of the detailed design. As shown in Fig. 6, the core of the detailed design is preparing the P&ID (Pipe & Instrument Diagram) for each system or facility of the hull. More details about preparing P&ID at this stage are as follows.

IFR (Issued For Review) P&ID

Based on the initial data of FEED, the design of the hull was performed. At this time, IFR P&ID was prepared for submission to our client. Main activities are as follows.

* Specification incorporation

Specifications on client’s requirements are largely divided into the project specification and the company specification. These were incorporated in the P&ID after a technical review. Moreover, among the client’s requirements, if specific requirements are not acceptable in the technical or commercial view, clarification works has been performed using the specifications deviation.

* FEED clarification

Among FEED data, clarification has been submitted to the client on items whose scope of work or technical points are uncertain, and related design works has been performed with the items reviewed by the client.

* Incorporation of lessons learned from previous projects
Potential risk elements have been removed in advance because lessons learned from previous projects have already been incorporated at the early stage of this project.

**IFA (Issued For Approval) P&ID**

In going from IFR P&ID to IFA P&ID, the most important activity is the design of various systems in the hull. In detail, the interface data between the topside and the hull of FPSO must first be incorporated, and the utility balance which was fixed at FEED stage must be verified at the detailed design stage. After that, the design of the systems, including hydraulic calculations, has been performed based on the updated utility balance. During this procedure, preparing equipment and instrument datasheets and overall line size calculation are very important activities in achieving a balance of all systems of the hull.

**IFC (Issued For Construction) P&ID**

In the process of constructing IFC P&ID from IFA P&ID, the P&ID should include actual construction information. At this stage, the most important activity is the incorporation of safety factors and client/class comments. Line and equipment lists which are very important items at the construction stage should be updated based on IFC P&ID. The design should be performed considering safety factors such as the fire zone and hazardous area. The HAZOP (Hazard and Operability Analysis) study, which is very important for safety in offshore design, has been performed two times in this project in order to remove potential risks during the site operation of FPSO. Moreover, client/class comments on consideration items of the safety, operation, and maintenance of each system have been incorporated in IFC P&ID through technical review. The interface data of each vendor and related rules/codes have also been incorporated in IFC P&ID.

**As-Built P&ID**

In preparing the As-Built P&ID, the main activity is the incorporation of modeling changes or construction changes. Moreover, safety work and items on operation and maintenance are also important. In detail, preparing system descriptions, safety charts, shutdown philosophy, an emergency shutdown diagram, alarm, a set point table, and the O&M (Operating and Maintenance) manual should be included at this stage.

**Detailed Design Procedure of the Hull Structure & Appurtenance Supports of the FPSO and Main Activities**

Hull scantlings are in general based on the two design aspects, load (demand) and strength (capability). All probable loads during the life of the hull are considered for the basic scantling and strength analysis. These loads are applicable in strength formulae and calculation methods where a satisfactory strength level is represented by allowable stresses. Fig. 7 shows the detailed design procedure of the hull structure & Appurtenance supports of the FPSO and main activities of the detailed design.

As shown in Fig. 7, the procedures for the design of the hull & appurtenance supports can be divided into four parts mainly as follows:

**Pre-design step of Hull Basic Drawings and Analysis**

The pre-design steps are the same as P&ID procedure which was mentioned above.

- Specification incorporation
- FEED clarification
- Incorporation of lessons learned from previous project

**Hull Scantling & Strength Analysis**

In the basic design process from IFR to IFC, the priority tasks are longitudinal scantling and strength analysis of the main hull. The computer calculation programs can be used with various input data and usage factors in order to optimize the longitudinal scantling. Before and after this procedure, UFR and topside engineering coordinators should communicate frequently with one another and share their engineering ideas, including the interface data and loads, in order to achieve a successful design without delay.

The basic design procedures for the hull scantling & strength analysis are as follows;

* Hull Key Plan Drawing and Calculation
  - Midship section (cargo hold structure) drawing and calculation
  - Construction profile drawing and calculation
  - Shell expansion drawing and calculation
  - Key section of aft end structure drawing and calculation
  - Key section of fore end structure drawing and calculation
  - Hull deflection calculation
  - Weight calculation

* Appurtenance Key Drawing
  - Mooring protection structure
  - Hull side caisson & support
  - Riser & umbilical support
  - Topside module support
  - Flare tower foundations
  - Mooring equipment foundations
  - Riser & umbilical installation aids supports
  - Pipe rack support structure
  - Loading/offloading support
  - Export lines supports
  - Crane pedestals & foundations
  - Crew boat berthing structure
  - Towing bracket support
* Strength Analysis for Hull and Appurtenance Supports

(a) Main Hull
- Design brief for strength analysis
- 3D Mid-hold analysis
- 3D Aft-hold analysis
- 3D Fore-hold analysis
- Detail finite element assessment (Longitudinals, Stringers, Web frames)

(b) Appurtenance
- Design brief for strength analysis
- Topside module support (See Figs. 8-9)
- Riser and umbilical installation aids supports (See Fig. 10)
- Hull side caisson and support
- Crane pedestals and foundations
- Crew boat berthing structure
- Towing bracket support
- Flare tower foundations
- Mooring equipment foundations
- Underwater fairleader, deck and side sheave, stopper, winch
- Riser & umbilical support
- Pipe rack support structure
- Loading/offloading support
- Export lines supports
- Living quarter and helicopter deck support
- Life boats davit and support
- Miscellaneous hull appurtenance (See Fig. 11)

Fig. 8. Arrangement of topside module supports

Fig. 9. FEM model for topside module supports

Fig. 10. Concept and FEM model for riser & umbilical installation aids supports

Fig. 11. Concept and FEM model for sea water lift pump caisson for towing and onsite

Fatigue Assessment for Hull & Appurtenance Supports

Fatigue damage was calculated at a range of assumed crack planes to account for worst situations of complex stress. At critical locations, shell elements of size of 2xw x 2xw, where xw is length of the weld toe, were used in structural details to determine the hot spot stresses for fatigue assessment.

The wave induced loads and motions in regular waves were determined by using a hydrodynamic program based on linear potential flow theory.

The non-linear, non-harmonic process at the mean water-line was modeled so that the additional pressure due to the presence of the wave
crest above the mean water-line was included. The effect of wave
trough was also included, such that if the combination of hydrostatic
and dynamic pressure at a point was negative, then the total pressure at
that point was set to zero.

* Fatigue Analysis of the Longitudinal Hull
  - Phase 1 (Hold FE model analysis)
  - Phase 2 (Hydrodynamic and hold FE model analysis)
  - Refined (Longitudinal & bracket toe and heel)
  - Refined (etc.)

* Fatigue Analysis of the Transverse Hull
  - Phase 2 (Hydrodynamic & Hold FE model analysis)
  - Hold FE modeling
  - Screening (The pre-step for the fatigue analysis to determine the area
    which experienced the highest stress from the same type of load
    component): Stringer connection, Web connection, Hopper corner, etc.
    - Refined (Transverse)
    - Refined (Shear lug and cutout)
    - Refined (etc.)

* Fatigue Analysis of Appurtenance & Helicopter Deck Support
  - Phase 3 (Full ship model analysis)
  - Hydrodynamic analysis
  - Screening: Crane pedestal foundation connection, Riser & umbilical
    support aft & fwd end, etc.
    - Refined (Topside support, pipe rack support, flare tower foundation)
    - Refined (Riser and umbilical support, hull side caisson and support,
      mooring equipment foundations, etc.)

Most positions tried in previous lessons were reinforced by thicker
plates and soft shapes in prior. However, several positions of the
welding around the toes could not meet the allowable stress level. Thus,
the welding beads were modified into soft type and counter grindings
were provided onto the plates which were recommended by IIW
(International Institute of Welding). Some critical positions (See Fig.
12) were replaced with thicker plates even though above efforts.

Fig. 12. Bracket toe of a crane pedestal

Impact Analysis including Design Brief

* Collision
  - Bow
  - Side
  - Stern
  - Riser protector

- Mooring off-take protector
- Caisson / supply vessel berthing area

* Fire
  - Riser support
  - Topside module support

* Explosion
  - Deck / living quarter
  - Topside module support

* Drop Object
  - Lay down module / deck
  - Living quarter

Structural Category Plan

The category definitions should be clarified in accordance with the
latest BV rules (NR497, dated May 2006) and hull general
specification. There are three kinds of categories as follows.

- Special category
- First category
- Second category

The special category and hot spot stress areas should receive Complete
Joint Penetration (CJP) welds according to AWS (American Welding
Society) Requirement and CJP welds should be applied for the fatigue
concerned areas and high tension areas also but it is not mandatory for
the first category and high stress concentration areas.

Detailed Structure Drawings

Detailed structure drawing can be developed based on the hull key plan
and key drawing of appurtenances. These drawings have been separated
according to the characteristic of the structures and updated with
outfitting system. The convenience utilization of the yard’s facilities
and safe working of fabrication & maintenance was considered with
reference to the category plan, arrangement of outfitting on the hull
deck, machinery arrangement for the machinery space, block division,
detailed assembly procedure, etc.

* Detailed Hull Structure Drawings
  - Aft end construction
  - Transverse bulkhead
  - Hull deck plan
  - Longitudinal bulkhead
  - Framing in hold
  - Fore end construction

* Appurtenance Detailed Structure Drawing
  - Riser and umbilical support, installation aids supports
  - Topside module support
  - Hull side caisson and support
  - Flare tower foundations
  - Mooring equipment foundations and turndown sheave
  - Pipe rack support structure
  - Oil loading/offloading support
  - Crane pedestals and foundations
  - Crew boat berthing structure
  - Living quarter and helicopter deck support

Block Production Drawings
Block production drawings can be developed based on the hull structure drawings and separated according to the drawing of the block division plan. The convenience utilization of the yard’s facilities and safe working of cutting, assembly, transforming, pre-erection, and erection was considered with reference to detailed assembly procedures.

* Block division
* Detailed assembly procedures (See Fig. 13)

![Fig. 13. Detailed block assembly procedures](image)

* Block fabrication drawings
* Welding map
* Non destructive test plan

PRODUCTION PROCEDURE AND MAIN ACTIVITIES OF THE HULL OF AN FPSO

Procedure of the Hull Construction of an FPSO

The construction procedures for the hull of an FPSO consist of the procurement stage, the dry dock stage, and the on-shore stage, as shown in Fig. 14. In the procurement stage, raw materials such as steel are ordered in advance, taking into account such factors as lead time (approximately 60~180 days). Then, the steel is cut after arrival in the yard. In the dry dock stage, completed blocks are loaded after turn-over tasks and block inspection is performed after welding tasks before launching. In the on-shore stage, the tasks such as piping, instrument and equipment work, cabling, fire work, and insulation/unit cabin installation of living quarters (L/Q) are performed after finishing launching. Also, it is necessary for shore power to be supplied at the proper time by pre-commissioning in order to prepare commissioning.

Main Activities of the Hull Construction of an FPSO

Activities of the Procurement Stage

After finishing the basic and detailed design of the hull of the FPSO, the first steel order is made 6 months before W/C (Work Commence or steel cutting) considering the lead time of the steel procurement. The first steel order includes bottom blocks, longitudinal bulkhead blocks, plates of transverse bulkhead blocks, and built-up materials which can be worked on in advance. After that, the second steel order is made 4 months before W/C for making side shell blocks and L/Q blocks. Finally, the third steel order is made 2 months before W/C for making appurtenance blocks which will be performed later.

Activities of the Dry Dock Stage

In the dry dock stage, main activities are the erection of blocks of the hull including L/Q, the installation of appurtenances, and the loading of pipe racks. More details about this are as follows.

* Activities Related to the Hull Blocks
Activities related to the hull blocks are the tasks for steel cutting, assembly, panel unit, pre-outfitting, pre-painting, pre-erection, and erection.

* Activities Related to the L/Q Blocks
Activities related to the L/Q blocks are the tasks for living quarters, lay down module, helideck, and so on.

* Activities Related to the Hull Appurtenances
Activities related to the hull appurtenances are the tasks for the topside support structure, riser protector structure, mooring line and fairlead, riser support structure, UFR, pump caisson, crane pedestal and foundation, crew boat berthing structure, and so on.

* Activities Related to the Pipe Racks
Activities related to the pipe racks are the tasks for the steel cutting, assembly, pre-painting, and erection.

Activities of the On-shore Stage

In the on-shore stage, main duties such as cabling of the hull including L/Q, fire work, insulation/unit cabin installations, pipe spool installation, etc. are performed after launching. In addition, interface work between instruments are also performed. Moreover, connection work between the topside and the hull is performed after topsides installation. If the overall procedure is not a problem, the hull of the FPSO will be delivered after performing pre-commissioning and commissioning. At this stage, the interface work between the topside
and the hull on-shore are very important for smoothly hooking up SPS which is installed in the field after sail away. Fig. 15 shows the launching of the hull of the FPSO which was built by HSHI.

LESSONS LEARNED

Lessons learned through the detailed design and construction of the hull of an FPSO can be summarized as follows:

In verification work on the initial FEED, incorrect or hazardous engineering data have not been sufficiently verified. Thus, extreme problems in the overall design of various systems of the hull have been raised due to the weight increase of topsides. In order to solve these problems, the overall design on the hull has been verified, changed, and compared with FEED. Also, many M/H’s (Man-Hours) were required in this project. Based on this valuable experience, sufficient verification works on initial FEED data is very important.

If critical safety study such as HAZOP is performed at the early stage of preparing the P&ID, it is possible for the P&ID to be fixed as soon as possible. Thus, the safety study should be executed at the IFA P&ID stage in order to reduce cost and schedule delays of the overall project.

In an FPSO, the interface engineering between the topside and the hull is very important. However, it was very difficult for this project to proceed because of the insufficiently organized project team. Therefore, organizing a good project team on interface coordination is very important. In case of unforeseen events on the hull during the detailed engineering of the topside, it is very important for the coordination teams of the topside and the hull to communicate smoothly.

The vendor selection should be made quickly. The design schematics might change totally depending on the vendor specification. However, in the FPSO, there were many design changes due to the uncertainty or delay of the vendor selection. Therefore, quick selection of the vendor for the interface design is most important.

In an FPSO, CJP and PJP welds of the highest quality should be carried out and checked by NDT to investigate any rack of welds, harmful undercuts and notches. Thus, welders should be educated and properly prepared. The shortage of man power will seriously affect the construction schedule.

In case of comments which impact the construction, it is necessary for the client and the contractor to collaborate and solve those comments.

During the launching of the FPSO after attaching appurtenances on the side shell, it is best to keep in mind that damages to the side shell and appurtenances should be avoided in case of dock out after floating. Especially, if the wind speed is above 7m/s, the launching should be stopped and postponed. Also, the weight control is very important because various systems of the topside are installed after installing appurtenances on the hull.

After launching the hull of the FPSO, a problem is generated due to minor movements of the hull while bolting work is being performed at the steel fender. In order to solve this problem, the bracket type of the hull has been changed from the recess pocket type to the pivot type bracket.

In erecting L/Q blocks, which is one of the main events, a crane with a safety working load above 3,000ton should be arranged because the weight of L/Q blocks is over 2,000ton.

When unit cabins are installed after installing the L/Q blocks, the telecom cable frequency test should be performed in advance so as to prevent re-work because of insufficient compatibility on frequency.

At the procurements stage, it is very important for raw materials to be ordered well in advance in order to avoid work delay.

CONCLUSIONS

Based on our valuable experience of the detailed design and construction of the hull of an FPSO, this study presents the following results. First, the scheme of the FPSO field development has been examined. Second, detailed design procedures and activities of the hull of an FPSO have been examined. Third, construction procedures and activities of the hull have been examined. Finally, critical points on interface work between systems and disciplines in the hull construction have been examined. The above contents will be used as guide-lines in order to reduce M/H and cost impacts on the design and construction of the hull of future FPSOs.

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