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FPSO Design and Conversion: A Designer's Approach

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Abstract

As designer of FPSO vessels ample experience has been gained with both the design of new build FPSOs and the conversion of existing trading tankers into an FPSO. This experience covers FPSO hull design, topsides and topsides support design and the combined application of ship and offshore rules, regulations and standards during the design process.

Items discussed in the paper will address the use of direct calculations versus traditional ship rules, and more generally the differences between naval architectural and offshore-orientated approach. A comparison will be made between new build and conversion projects. Integration of topsides and hull design is required, while maintaining sufficient flexibility to accommodate design changes. Moreover the FPSO hull influence on topsides design will be further examined. Attention should be paid to adherence to common shipyard practice.

Two examples of FPSO hull design will be presented. One is a new build vessel, and the other a conversion. Both projects are comparable with regard to geographical location and mooring system. For both vessels, aspects of hull design and relation between hull and topsides design will be addressed. Typical aspects of hull design to be discussed are cargo and ballast arrangement, extreme bending moments and fatigue design. The impact of the module support arrangement on the hull design and piping design is evaluated.

The general information presented in the paper, and supported by the cited examples, will provide guidance to the industry on how to merge shipbuilding practice and offshore standards.

Introduction

FPSO design has shown a fast evolution in recent years. The concept is more and more frequently used for deepwater solutions and in addition new design concepts are being considered. This is especially the case for the development of oilfields offshore Brazil and West Africa. The field developments of benign environments at West Africa have introduced a new generation of FPSO designs. These are designed as barge-like hulls. The introduction of these new designs in combination with topsides weight in excess of 25,000 tonnes leaves the designer with new challenges.

Parallel to these new developments and due to industry need, FPSO design procedures are being reconsidered by all parties involved, e.g. operators, designers and classification societies. The background for these developments lies in the need for establishing more consistent design guidance. On previous FPSO design projects, the way offshore and shipbuilding principles were combined depended mainly on parties involved and could differ between projects.

FPSO concepts have frequently been based on converted tankers. Shipbuilding standards could be directly applied and the hull design could be covered with existing ship Rules. However, specific operational tanker design criteria are no longer applicable to FPSOs as the hull now becomes a floater with storage capacity rather than a sailing tanker. Therefore it is justified to raise the question whether a new build FPSO is to be considered as an offshore structure or that traditional maritime principles are still applicable.

The key issue of this paper is which design approach is most appropriate; up to what extent ample experience gained on trading tankers is applicable and where offshore standards shall be considered in the design.

The evaluation of an appropriate design approach is started by a review of typical differences between the offshore and shipbuilding industries. This is presented in chapter:

- Shipbuilding and Offshore Approach

Specific differences and similarities between trading tankers and FPSOs are examined through reference to a conversion and a new build project with similar environmental conditions, **table 1**. The relation of hull design with mooring and topsides designs is investigated. This is presented in the following chapters:

- Hull Design Aspects
- Topsides Interface

To facilitate designers to plan future FPSO design tasks, several relevant design issues are discussed in detail, such as:

- FPSO Design Process
- Materials
- Design Loads
- Deformation Effects
- Stress Criteria
- Buckling Criteria
- Fatigue Criteria

Shipbuilding and Offshore Approach

An FPSO, being a permanent offshore installation based on a tanker-like vessel, carries design aspects in it from two design cultures, i.e. shipbuilding and offshore.

The owners traditionally design offshore units under their own management. Normally they utilize engineering consultants for preparing the basic design. The building yard is then approached to make bids on this basic design. As a contrast to this, ships are normally designed by competing yards on a set of performance requirements from the owner. The owner then selects from the competing designs. This difference has important consequences for the way the designers approach their task:

- Offshore designers take the owners requirements, and try to make a reliable design; of course they keep an eye on fabricating cost, but this is only one of their design criteria.
- Ship designers try to make a design that fulfils (most of) the owner’s requirements at minimum fabricating cost, so that they can present a competitive offer to the owner.

The difference in approach has many consequences, which are not always seen by all parties involved.

- In structural design offshore designers pay attention to structural continuity. In contrast ship designers focus on the efficiency of the building process given the yard's facilities. Structural continuity may well be sacrificed for this.
- The structural design office of a shipyard is used to design in a straightforward manner based on rule calculations. Their experience with direct calculations is limited. This may lead to a situation where the yard does not realize the structural implications of building an offshore structure, in which direct load introduction may play an important role.
- In the shipyard there is sometimes a clear division between the disciplines. Large openings in structural webs may be created for pipe or cable runs, without double checking whether this does not comprise structural strength.
- New building yards, especially in the Far East, produce annually a significant number of ships. This may be in excess of 40 ships per year. The FPSO will be just one of them, and is often assembled in the building dock simultaneously with two or more other ships. The FPSO hull is assembled from a large number of “blocks” which are pre-outfitted and painted up to an advanced stage. The assembly period in the building dock is normally only 8 to 12 weeks, which is very short. In order to achieve such a tight schedule, extensive and detailed planning is inevitable and critical to the overall yard performance. Since the capacity of the yard's workshops and block storage area is matched to keep up with the dock capacity, design changes are very difficult to incorporate once steel cutting has started. Late design changes may impact the delivery time of many vessels and can therefore be unacceptable to the yard, even when the owner is willing to pay for the change.
- Profits in shipbuilding are very marginal, offshore contractors ordering an FPSO from a shipyard benefit directly from this. However, one of the consequences is that the shipyards are in a tight position, and are extremely keen on reducing cost. One of the difficult to accept aspects for western engineers is that at some yards give-and-take is virtually impossible. The yards are eager to take but refuse to give.

The differences above are mainly characteristic to new building yards and up to a lesser extend to conversion/repair yards. In general conversion/repair yards are more familiar with the offshore approach. Here also the ability to implement late design changes is better, although they will result in change orders and corresponding claims.

Hull Design Aspects

In this part a selection is made of some typical hull design aspects. Links are made to traditional shipbuilding practice and their incorporation in FPSO design. The following aspects are discussed:

- Main particulars
- General arrangement and tank layout
- Still water loads
- Minimum freeboard
- Weight control

Main Particulars. The main dimensions of an FPSO were traditionally related to trading tankers, for which ample design experience has been gained. Trading tankers, and especially those early built, have relative high L/B and L/D ratios. Hull proportions for new build FPSOs tend to follow values that are lower than for trading tankers. This is illustrated in **table 2**:

L/B = 5.1
B/D = 1.9
L/D = 9.2

Items such as speed requirements, course stability and restricted sailing routes, are no longer applicable. Deviating from traditional hull proportions for FPSOs leaves the designer more flexibility in optimizing the vessel's main particulars for shipyard practice in order to reduce cost.

Consideration shall be given to the extreme hull dimensions to ensure that they still match the shipyard capacity available. Large shipyard docks (600 by 120 m) are dedicated to mass production of standard type of vessels. Smaller dock capacities (380 by 70 m) are sometimes available for one-off designs, which might be beneficial since the FPSO is then built separated from the mainstream production line, which leaves higher construction flexibility.

It should be realized that deviating too much in hull proportions from empirical experience gained in traditional shipbuilding might lead to unforeseen effects in the design process and excessive environmental loading on the hull.

Table 3 gives the main particulars of two examples. The difference in block coefficient is evident. The C_B=0.86 for the converted tanker is in strong contrast to C_B=0.96 for the new build, although the storage capacity is similar, 1.7 and 2.2 mbbls for conversion and new build respectively.

General Arrangement and Tank Layout. For any floating device trim and stability is one of the starting points of the design. This is directly related to the general layout of the FPSO and hull arrangement. Typical items to be considered are topsides weight distribution, riser hang-off points and storage / ballast tank arrangement.

To obtain an even mass distribution, riser, flare boom, accommodation block and topsides must be arranged carefully. This avoids the need for permanent or increased ballast capacity to control heel and trim. The most critical loading conditions are "loaded at full draft" and "ballast at minimum draft". In the fully loaded condition all crude tanks are filled. In this condition heel and trim can not be corrected by variable filling of crude or ballast tanks. The ballast condition may become governing due to a relative high vertical center of gravity of the FPSO. The top of the stability curve may not reach its maximum at a heel angle smaller than 25°. Sufficient ballast capacity shall prevent this.

Trim and stability set boundaries for the topsides designer on the maximum allowable weight and C.O.G. location. It may be difficult for the topsides designer to cope with these restrictions, since the weight distribution of topsides modules is directly related to the process layout.

Depending on turret or spread moored option; the layout of topsides modules will affect the design. Therefore the approach where the most hazardous systems, i.e. gas compression and the more "safer" systems, i.e. power generation and utilities, are fitted shall be considered.

For spread moored FPSOs riser hang-off points are attached at the side of the vessel. The arrangement of the risers along the vessel not only depends on the field and topsides layouts and sea state; stability and heel of the vessel shall be considered as well. For the new build project, moored in 1200 m water depth, 63 risers are mainly arranged at the portside of the vessel. The individual maximum riser load is 220 tonnes, while the total hang-off weight amounts to 1,700 tonnes. Due to the asymmetric distribution, a permanent heel of 3° is to be corrected. The converted tanker example, moored in 450 m water depth, only has 12 risers arranged at starboard with an individual maximum load of 80 tonnes. The heel angle to be corrected is negligible.

Arranging all risers on one side and the boat landing on the other side does away the need for a complicated riser protection structure. To realize this arrangement process layout and vessel stability must both be taken into account. Operational aspects shall also be considered, since it restricts the flexibility for a supply vessel to approach the FPSO.

When an oil tanker is used as an FPSO, it is not required to comply with the provisions of regulation MARPOL 13 to 13G, unless specified in whole or in part by the coastal state. This mainly affects the adoption of special ballast arrangements and double hull requirements. In general new built FPSOs are provided with a single bottom if they are not self-propelled. Double sides are usually fitted to provide some protection against collision.

Requirements for minimum draft also determine the ballast capacity. MARPOL provides guidelines for a minimum draft. Although not directly mandatory, it is recommended from a designer's perspective to comply with this requirement to provide some reserve against slamming. Setting a minimum draft also provides a certain margin against excessive roll motion of the vessel.

A typical tank arrangement of a converted single hull tanker consists of two side ballast tanks in the cargo tank area and generally provides sufficient ballast capacity for FPSO operation. For a new build FPSO it is beneficial to arrange ballast tanks such that initial and operational costs are minimized. A possibility is to design the side tanks as void spaces, and dedicate one large central tank in the cargo block to be used as ballast tank or kept void in loaded condition. Separate trim and heeling tanks are arranged in fore and aft ship. Such an optimum ballast system can only be achieved if riser loads and process modules are evenly distributed.

Still Water Loads. Designing an FPSO with a box-shaped hull result in significant still water loads, which are beyond traditional tanker experience. The cause of this effect is addressed below. A comparison is made with a converted tanker.

The new build example in **table 3** is designed with a blunt and prismatic hull shape. This results in a constant distribution of buoyancy along the length up to and inclusive of the ends of the vessel. This is illustrated in **figure 3**. The converted tanker has a more gradual distribution and less excess buoyancy near the ends, illustrated in **figure 4**. The new build example has a significant topsides weight installed on the main deck, 28,000 tonnes in contrast to 5,000 tonnes for the converted tanker. The latter one has a considerable smaller production capacity, and weight is relatively concentrated around midship.

High topsides loads combined with excess of buoyancy near the ends of the vessel, results in pronounced sagging. The converted tanker, with less topsides weight and a more gradual buoyancy distribution, shows an even contribution of hogging and sagging bending moments.

Sagging bending moments for turret moored FPSOs are less critical. Some buoyancy in the fore ship is sacrificed, and added to this are vertical mooring loads. This avoids initial sagging of the vessel.

Minimum Freeboard. The compliance with minimum freeboard regulations for an FPSO under operation is not mandatory, unless required by the flag-state. During towing or transit the load line convention shall be complied with if the vessel is manned. The International Convention on Load Lines (ICLL) finds its background in traditional maritime tradition and is empirically determined: minimum freeboard guarantees a certain amount of reserve buoyancy, and thus safety.

A difficulty in applying the ICLL to a barge-type hull lies in the correct interpretation of length definition. Selecting the minimum length according to ICLL, 96 % of maximum waterline length at 85 % of vessel depth, eventually results in a higher freeboard than if the maximum length is considered. This is surprising, since normally a larger ship length would result in a greater freeboard. This effect is demonstrated in **table 4**.

In order to avoid confusion about the correct interpretation of length for FPSOs, it is recommended to use identical definitions of length for both Classification Society Rules and load line convention. Therefore it is recommended to use 97% of the overall length of the vessel, as in line with ship rules.

Weight Control. The topsides module designer is responsible for the control of topsides weights and corresponding C.O.G. The hull designer shall review the impact of the various loads such as topsides weight and riser loads on the overall design of the FPSO.

The topsides weight report shall therefore be considered as input for the marine document “Loading Conditions, Stability and Longitudinal Strength Report”. In this report the feasibility of the overall design of the FPSO is validated. It is updated at regular intervals during the design, engineering and construction phase. The calculations shall be based on the reported weight, which is the actual weight with a margin. Relevant loading conditions prescribed by Class and other Authority requirements are validated in combination with the operational requirements. For the overall integrity of the FPSO on site, the following loads shall be considered:

- Topsides weight and C.O.G. (both dry and wet).
- Hull lightweight and C.O.G.
- Cargo crude oil, including content of off-spec and slop tanks.
- Other liquids (Methanol, Marine Diesel Oil).
- Subsea Umbilical Risers and Flow lines (SURF).
- Future Topsides weight variation.
- Future riser or SURF tie-in variations, as well as tie-in of possible future anchor legs.

In order to account for future weight increase in the design stage, it is common practice to spread future topsides weights proportionally over the individual modules while maintaining a constant C.O.G., if no detailed information is available.

In practice it is difficult to work with individual C.O.G. and weight envelopes for each weight group or item separately. It is therefore recommend controlling the overall FPSO weight and C.O.G. rather that of single weight groups.

Topsides Interface

A ship structure is relatively flexible. Topsides modules must therefore be supported such that they are compliant with the hull girder. Also the topsides designer has to set his dimensions and support arrangement in line with the ship structure.

The key issue in interface design is how design requirements for hull and topsides are merged. The hull strong points are to be set early in the design process to facilitate topsides designer. Often these dimensions have to be defined when hull design has not yet been completed. Review of current shipyard practice and evaluation of existing FPSOs results in the following design guidelines for web frame spacings:

– Suez-Max Size	(< 1.5 mbbls storage capacity) S_{Webframe} = 4,800 mm
– VLCC size	(> 1.5 mbbls storage capacity) S_{Webframe} = 5,000 mm

Design Requirements. The most important design requirement to consider is hull deformation due to external or internal loading. These deformation effects will be further discussed in a separate chapter of this paper.

The support arrangement shall provide sufficient flexibility to isolate hull deflections, in addition the topsides module is limited in length to mitigate hull deformations effects. This support flexibility is a necessity to avoid excessive stresses in the support structure itself, and eventually in the process equipment. Process pressure vessels and piping are not design for excessive deformations.

Two examples are discussed here, for a converted tanker and a new build FPSO respectively.

The topsides modules for the converted tanker are supported at the main decks in line with the transverse webs, by means of a multiple column support, as illustrated in **figure 8** and **10**. This principle proved to be a cost effective option and is frequently applied for conversions. The web frames usually have a thickness of 12 – 15 mm and are not designed for large concentrated loads. The module load is therefore spread over a large number of supports, resulting in a favorable load introduction in the existing web frames. Due to limited load carrying capacity of the existing webs, the weigth of each topsides module is limited to a maximum of approx. 500 tonnes. Hull flexibility is only isolated in longitudinal direction. Vertical hull bending curvature is fully transmitted to the module, which restricts the module length to a maximum of approx. 25 m. This affects the modularization of topsides modules and prohibits the use of large preassembled units (PAU) for converted units.

As new build of FPSO hulls allow the incorporation of strong points in the hull structure, the topsides module supports for the new build FPSO are based on support stools. The vertical legs of the modules are either fixed or have a flexible connection. The stools are arranged such that they fit at the intersection of longitudinal girders or bulkheads and transverse webs.

The advantage of support stools is the high load carrying capacity. Especially for new buildings, where the ship structure may be adjusted to the loads, large topsides weights can up to 3,500 tonnes be supported. Elastomeric pads incorporated in the supports allow larger topsides module lengths than tubular columns, which have to provide flexibility by bending. The average module deck length may increases to 35 m. This implies a more favorable modularization, and the use of large PAUs.

Structural design. The tubular stanchions of the multiple column arrangement are connected via transverse gusset plates to the main deck. The stanchions are sniped at a distance of 75 mm from main deck. The gusset plate thickness is 15 mm. This combination provides an optimum between strength and flexibility. Generally the support is made of mild steel, since stiffness is the dominant design parameter.

When support stools are used, local overturning moments must be dealt with. These result in local stresses. To obtain a sufficient fatigue performance of the structure, full or partial penetration welds are required. Shipyards are not familiar with these types of welds, the majority of shipyard welds are fillet-types automatically welded in the plate shop. The use of other weld types shall be planned for early in the structural design process to avoid rework after block assembly.

Interface Drawing. In offshore it is common practice to dimension from center to center plate. Shipyards are used to dimension from moulded plate sides. This may result in a misalignment of half plate thickness if not correctly interpreted. Also the effect of deck camber shall be carefully considered.

Topsides designers favor an axis convention with origin at main deck, in contrast to hull designers. Hull designers are used to an origin at base line of the vessel and a right handed axis convention with x-axis pointing along the length of the vessel and the z-axis directs upward.

To plan for the topsides / hull interface in the design process, it is recommended to use interface drawings. These drawings show the main hull structural arrangement plate thickness, dimensions and axis convention. The interface in both coordinate systems is than firmly linked. An example is illustrated in **figure 2**.

FPSO Hull Design Process

Reviewing the differences and similarities between offshore and shipbuilding one should adopt a design process, which is based on maritime tradition supplemented with specific offshore needs. Hereby use is made of the ample experience gained on trading tankers with respect to design process and construction. This implies that the designer shall have thorough understanding of specific needs of both disciplines.

Design Process. Normally the hull design process is an iterative process. This is known to the marine industry as the “design-spiral”. Each separate design phase is passed through several times until the design converges. A simplified representation of the design process is shown in **figure 1**.

The hull designer starts optimization of hull dimensions and tank arrangement using comparable tanker designs. Based on storage capacity and estimated topsides weight, initial deck space is provided to the topsides designer. The topsides designer in turn verifies the required deck space for the module layout and provides a first estimate of module weight and C.O.G. This is followed by an update of stability and motion behavior. Hull dimensions are reconsidered if necessary.

The interface between hull deformation effects and topsides support loads is a crucial item in the design process. Topsides interface loads can only be determined if data on ship motion and hull deformation is available. Some assumptions are to be made early in the process.

Rule based loads from Classification Societies provide a sound basis for the initial structural design of the hull. These loads are based on experience with sailing vessels; caution should be exercised as these principles may fail for FPSO design. For site specific loads direct calculations shall be adopted. A comprehensive overview of Rule approach and direct calculated loads is presented in (Ref. 5).

The mooring / topsides interface shall be considered early in the design process, consultation of the installation engineer is suggested. Installation procedures may have specific needs and have to be addressed early in the design, which may impact the design. When a single installation winch will be used for tie-in of spread mooring lines and risers, the need for several sheave foundations is evident. The interface between topsides supports and mooring installation equipment may result in congested deck areas, as illustrated in **figure 10.** An example of a spread mooring integration in the hull structure is shown in **figure 9**.

Materials

Material grades for ship and offshore structure applications are specified in a different manner. Material grades for ship structures are specified based on their application. Offshore materials are selected based on their function and criticality in the design.

Selection Procedure. For ship structures the selection procedure is primarily based on the location of the material with respect to the maximum global loads. Five material classes are defined where “I” is the lowest grade requirement and “V” is the highest. This definition assist in quickly preparing the material requirements based on the main scantlings.

The selection for offshore structure material is based on the following gradation of their function or criticality:

- Primary structures
- Secondary structure
- Special structures

Based on plate thickness and specified design temperature, the appropriate steel grade is determined.

Material selection for an FPSO can be based on a “fit-for-purpose” approach. First the hull material is specified in accordance with the appropriate ship rules. Material for special integration structures, mooring and topsides supports is subsequently based on offshore standards. In this way over-specifying due to adopting offshore standards to normal ship structures, is avoided. On owner’s special request higher material qualities may be specified to achieve improved fracture toughness.

Design Practice. In the design process it is recommended to have some reserve on material qualities used. For areas in the ship structure where future upgrades are likely, such as additional support arrangements, enhanced material qualities shall be considered. Specifying Z-quality plating for large deck areas can help to remain flexible with foundation locations during the design stage.

When designing topsides support structures, the material availability shall be accounted for in the design process, especially for conversion projects. Not all yards have the required higher strength materials in stock, and often the delivery time from steel mills is too long for fast track projects. Generally rolled profiles of 235 N/mm² do have a wide availability.

Higher strength materials are frequently encountered in the existing ship structure. In the late 1970’s tanker steel structures began to be more thoroughly optimized with an increased extent of high strength steels (yield strength 355 N/mm²), these hulls now form the basis of conversion projects. Fatigue problems became more apparent since then, so that a yield strength of 315 N/mm² has now become standard shipbuilding practice New build FPSOs are frequently designed using a similar extent of high strength steel (yield strength 315 N/mm²) as trading tankers.

Design loads

Load categories relevant to FPSO design are discussed and categorized according to discipline:

- Hull Loads
- Topsides Loads

Hull Loads

Typical hull loads to be discussed: water bending moments, shear forces, equivalent ship speed, motion behavior and explosion loads.

Still water loads. Classification societies provide guidance values for still water loads, which are used early in the design process and are not prerequisite. The guidance values for the bending moments are based on experience gained on trading tankers.

The design and actual still water bending moments and shear forces for the cited examples are illustrated in **table 5**. The conversion falls well within the Rule approximations. In contrast for the new build the actual magnitudes exceed the Rule values by up to 95%.

In terms of shear forces both the conversion and new build FPSO show a deviation from the Rule values. This is due to tank filling and ballast procedures with alternate tanks full and empty.

It is obvious that Rule based still water bending moments deviate significantly from the actual values for new build

FPSOs, and the use of Rule guidance values in the design shall be carefully considered.

The designer should also consider cargo tank loading configurations where a tank is cleaned and gas freed for inspection and / or repair. This could give rise to asymmetric loading conditions.

Shear Forces Correction. Since the FPSO will experience significant shear forces during operation, special consideration is to be given to the shear strength of the FPSO hull structure. At sea the excessive still water shear forces are simply summed with wave induced shear forces, which is different from trading tankers where extreme shear occurs mainly during loading in harbor. A shear force correction at transverse bulkhead locations of the FPSO must be applied, as for traditional tanker design.

By applying simple beam theory (traditional rule approach) to the hull girder structural design, the shear force Q is the integral of net-vertical load f (x) from the end of the vessel to the considered section. This assumes that the vertical load is directly applied to the longitudinal bulkheads and side shell. However, some fraction of the load is transmitted to the transverse bulkheads through longitudinal elements in the bottom, such as longitudinal stiffeners and girders. The transverse bulkheads in turn will transmit the load to the side shell. This gives rise to a discontinuity in the shear force curve at the location of transverse bulkheads. This discontinuity may either give rise to an increase or decrease of the shear force distribution depending on the internal structural configuration. The more longitudinal structure there exists the higher the transfer of loads to the transverse bulkheads.

Equivalent Ship Speed. Forward speed for a stationary moored FPSO is a curious item, apart from transit from yard to site. However, it is of importance for local structural design calculations to define an equivalent ship speed. The traditional Rule formulae are based on ships sailing at a specified speed with associated empirical correction terms.

Several governing design load parameters are based on the ship speed, such as:

- Design acceleration parameter, a_o
- Internal and external design pressures
- Bottom impact pressures

In order to design an FPSO structure using rule formulae as for normal tanker structures, a ship speed is selected in the range of normal tanker sailing speeds. The classification societies nowadays specify in their Rules speeds between 8 and 15 knots. The equivalent ship speed can be directly entered in formulae for local strength calculations.

The design acceleration parameter, a_o, is based on North Atlantic conditions. For permanent service in other areas, the parameter shall be specially considered. Direct calculation may be required.

Environmental Loads. Typically Rule vertical bending moments for traditional tankers are based on the North Atlantic environment with a 20-year return (10^{-8} probability). The moments correspond to significant wave heights in the range of 16.5m to 18.3m for vessel lengths above 200 m (Ref. 1). This appears to be representative for the extreme waves in the North Atlantic.

The 20-year return period extreme wave heights for benign environments are typically far less, say 8 to 9m. The corresponding site-specific vertical bending moment may be less than the Rule value, and Class may allow a reduction in hull girder section modulus (maximum 25%) provided that the vessel is restricted to a specific or field for its operation.

Economic criteria may drive a project to accept such reduced scantlings. However, a reduction in hull girder section modulus will require the transit condition to be additionally assessed and may also limit the flexibility for relocation or taking the FPSO in for repairs in the future. With tight design and construction spirals, it also introduces additional risk that the main scantlings may need to be adjusted to take into account other influences (explosion loads, topsides weights, etc.).

Frequently weather routing is considered for transit condition to limit the accelerations. Transit is often the governing design condition, especially for blunt shaped FPSOs destined for a field with benign sea conditions, as illustrated in **table 6**. However, accidental conditions shall still be considered. For instance on one occasion an FPSO was lost by the tugs and ended-up in beams seas, while en-route from the yard to South America. The maximum-recorded roll angle was 30°.

Explosion Loads. The ultimate strength capacity of the FPSO main deck structure underneath the topsides modules should be checked for explosion loads. Explosions may occur due to ignition of a gas contamination between the ship's main deck and topsides module lower deck. The most vulnerable hull members to explosion loads are main deck stiffeners.

Explosion loads are considered as an accidental event, which allows the full yield strength of the material to be utilized. Dynamic amplification effects must be accounted for. To cope with this event during the initial design phase, the deck stiffeners are considered as individual single spring-mass systems. The natural frequency for a deck stiffener, is calculated using the following formula, whereby the C-factor represents the appropriate boundary condition:

$$f_n = C\sqrt{\frac{EI}{ml^4}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Normally explosion pressures are in the range of 0.2 – 0.5 bar, which corresponds to a major frequency of f=5 Hz. The lowest natural period of a FB 500*30 stiffener with deck plating is generally above 30 Hz. This means that dynamic amplifications may be ignored.

FPSO deck structures are usually designed for a tank over pressure of approximately 0.25 bar. In addition the stiffened plating arrangement for the FPSO deck has to withstand the hull girder loads, including buckling. Therefore a deck design based on Rule formulae will normally satisfy the explosion loads. However, plastic hinges may develop at the fixed supports and at midspan.

Topsides Interface Loads. Topsides loads are relevant for designing the support structure and integration in the hull. The following design conditions shall be considered:

- Installation / lift (dry weight)
- Transit (dry weight)
- Operation (wet weight)
- Ice Loads

The difference between dry and wet weight is the presence of liquids in pressure vessels and piping equipment, this can make up to 20% of the module weight. Usually wet weight is only considered during operation on site. Experience has shown that incidentally also during installation and transit process equipment may be (partially) filled. Due to time constraints not all equipment may be emptied after testing. The designer shall allow for this by building in sufficient structural reserve.

Ice loads shall be considered for FPSOs moored in Arctic conditions. The impact of ice loads on the module design, and interface loads are significant (Ref. 4). The following load categories are distinguished:

- Spray icing
- Glaze and Rime

For a 1,000 tonnes module the additional amount of ice load may be as large as 200 tonnes. The impact of glaze and rime on a flare tower is even more severe; the extra ice load may even exceed the structure's dead weight. It will also lead to an increased wind projected area of the structure's chords and braces. In general glaze and rime are more governing for the module design than spray icing.

Typical values of topsides interface loads are presented below:

- Support stool philosophy (3,000 tonnes module)

$F_{Longitudinal}$	1,800	[kN]
$F_{Transverse}$	4,500	[kN]
$F_{Vertical}$	15,000	[kN]

- Truss support philosophy (500 tonnes module)

$F_{Vertical}$	2200	[kN]

Deformation Effects

The effects of ship deflection are best explained by considering a ship in a sea-going condition encountering a single regular wave with a length equal to the ship length. This induces a vertical bending moment. The encountered wave may have its crest either amidships or at the ship's ends. Considering the ship hull girder as a beam, the following conditions are distinguished:

- Hogging condition
  The hull deformed shaped is convex. The hull girder is supported amidships at a wave crest with a corresponding wave through at the ship's ends.
- Sagging condition
  The hull-deformed shape is concave. The hull girder is supported at the ship's ends by two wave crests with a corresponding wave through amidships.

Deformation Categories. Deformation effects are generally subdivided into categories to their order of magnitude, which corresponds to their impact on the design:

1st Order effects:

- Vertical hull deflection
- Longitudinal deck elongation

2nd Order effects:

- Deformation local support structure
- Thermal effects
- Tank loading deflection

Global effects stem from the global deformation of the hull and are applicable irrelevant of the support or integration arrangement of topsides modules.

For topsides modules supported on transverse web frames, local support deformations shall be considered. The bending stiffness of the supporting structure can be idealized using equivalent spring constants at the position of the module supports.

For FPSOs operating in mild environments with relatively high over day temperatures in combination with aggressive sun shining, thermal effects can become significant. Global bending moments result from a temperature difference between deck and bottom of the hull. Topsides modules, covering the FPSO main deck normally function as isolation. When the number of modules is limited, or for an FSO, heating effects may become relevant. For tropical conditions thermal expansion is a semi permanent condition. Thermal effects in harsh environment are less relevant and are frequently ignored.

Transverse vertical tank loading deformations can become relevant depending on the FPSO tank arrangement. Alternate or irregular tank filling of two or more adjacent crude compartments results in deflection of the transverse web frames. For topsides modules whose footprint falls entirely within one tank compartment, transverse deformations are less relevant.

Engineering Approach. Global effects are best fitted in a simple engineering approach. Idealizing the longitudinal hull structure as a beam, classical beam deflection theory may be applied. Vertical deflections are calculated using the following formula:

$$\delta_Z = \frac{\sigma . l^2}{8.E.c} \text{ ………………………………………..…...(2)}$$

Longitudinal deck elongation is calculated using the following formula:

$$\delta_X = \frac{\sigma}{E}.l \text{ …………………………………………………(3)}$$

Herein is “l” the length of the module and “c” the height of the main deck above the neutral axis of the hull girder.

Deformation effects shall be considered for the ultimate response of the hull structure, and can be based on the allowable bending stress. Hogging and sagging effects are assumed to contribute equally to hull deflection. Deck elongation typically equals about 1 mm per meter. An example for a typical unit is presented in **table 7**.

Installation. Not only during the operational life of the FPSO deformation affects the design, but also during installation of the topsides modules at the yard deformations are relevant and divided in the following categories:

- Static deformation of hull girder, floating at outfitting quay.
- Deformation of topsides module, lifted in a 4-point-lift arrangement.

Conversion and new build yards generally can not influence the hull deformation condition during outfitting at the quayside, simply because the ballast systems might not be assembled yet. Usually the FPSO is in empty condition at an even keel draught and is in a light hogging condition.

Initial hull deflections are to be considered for pipe-stress calculations. They are of importance for anchor loads and low-cycle fatigue behavior.

The static hogging condition shall be considered in combination with deflections of the topsides modules during lifting. A topsides module in a four-point lift might deflect in opposite direction to the hull, **figure 7**. This affects the installation procedure as is demonstrated in an example for a multiple column design.

During installation, multiple columns are installed on deck more or less in a perfect plane. As the modules arrived they were landed on the columns. This resulted in each module resting only on the central columns. The practical approach to this phenomenon was to keep some load on the hook and flame cut columns that were hitting the module until all load was of the hook and none of the columns showed a gap with the module. Installation of a module on a column support is illustrated in **figure 8**.

Stress Criteria

The stress acceptance criteria for ship and offshore rules differ on to some extend. For local integration structures such as mooring integration and topsides module supports, different stress criteria are used as for the hull. The criteria result in different material specification and design cases. In contrast to offshore criteria, ship stress criteria include empirical correction factors. Traditionally the marine practice has been to use the working stress design (WSD) method whereas offshore may use either the WSD method or the load resistance factor design (LRFD) method (Ref.2).

Criteria. It is common practice, for both offshore and ship structures, to define the permissible stress criteria based on a material factor f_l, **table 8**. The material factor, f_l, is a function of the material yield strength relative to normal strength steels. The material factor provides some contribution to the general safety of hull structures against fatigue failure when using high strength materials. It reflects one of the differences in ship design and offshore approach. The following design stress value are defined:

- Ship Rules: $\sigma_{Design} = 235\ f_l$
- Offshore rules: $\sigma_{Design} = 240\ f_l$

Criteria for direct calculations for ship structures are based on the function of the concerned member. For each member, such as secondary plate stiffeners and main girders, criteria are defined. No distinction is made between operational and survival condition of the vessel. In general ship structures are designed only for the ultimate response considering the following stress categories:

- Global hull girder stress
- Local bending stress

Criteria for offshore structures are based on basic usage factors. These factors are irrespective of the members concerned, and only relate to the loading condition considered. The main load categories are:

- Functional loads
- Environmental loads
- Accidental load

Buckling Criteria

In the offshore industry checks for buckling strength have long been an integral part of the structural design, driven by the recognition that buckling is one of the major factors affecting ultimate strength. In the shipbuilding industry extensive buckling checking has only started to become common in recent years, and then only with regard to longitudinal strength.

Codes and Standards. When buckling of plate field and stiffeners is considered, CN 30.1 "Buckling strength" has long been de facto standard in European offshore engineering. The main reason for this is that it is the only procedure that provides adequate coverage of plate fields and stiffeners under combined load states. Application of CN 30.1 is a relatively straightforward task that can easily be implemented in automated procedures that include stress results from finite element models. A shortcoming of CN 30.1 is the handling of ultimate buckling strength, which can lead to the design of very heavy structures. This is especially the case when large stresses act perpendicular to the stiffener direction.

On the contrary the situation in shipbuilding requirements can be confusing. Part of the longitudinal strength calculations is nowadays a buckling check of stiffeners following IACS guidelines. However, this takes only takes into account the longitudinal stress component. Sometimes also additional checks on stiffeners are prescribed by class societies.

For checking plate fields in ships each classification society has its own rules, resulting in a vast array of different formulations, notably in the buckling curves used (i.e. the correction for initial deformation and plastic limit) and the combination of various stress components. The buckling checks are always based on the reduced yield stress as discussed before, which is somewhat remarkable since the absence of buckling checking is one of the reasons for reducing the yield strength in conventional ship rules.

Engineering Approach. None of the traditional shipbuilding buckling requirements covers the introduction of local loads. This is especially problematic since the buckling requirements often distinguish between the area in the ship where a typical plate field is located (shell, decks or bulkheads) or between the various stress components (global or local). In the first case treatment of the local loads is unclear, since the correlation with the overall loads such a global bending, is not self-evident. When the various stress components are separated the problems stem from another source: finite element models are frequently used for the analysis, in which case it is normally difficult to differentiate between global and local stress components.

When the interface between topsides and ship is addressed, the incompatibility between offshore rules and ship rules becomes difficult to handle.

Fatigue Criteria

An FPSO hull is normally similar in configuration to that of a tanker i.e. longitudinally stiffened plate within cargo and ballast tanks. Although this may be the case there are some operational differences between a tanker and an FPSO that impact upon the fatigue design. Some of the key aspects are:

- Tankers operate at defined drafts; fully loaded and ballast whereas an FPSO operates at constantly changing drafts.
- The draft variation between fully loaded and ballast drafts for some new building FPSO designs may be large (>10m).
- FPSO's either weathervane (turret moored) or are directionally orientated (spread moored) into the environmental conditions.
- FPSOs are often designed with more comprehensive corrosion protection systems compared to most tanker structures.
- FPSOs have specific structures that are not present on a normal tanker (risers, moorings, flare towers, cranes, topsides, etc.).
- A benign environment has a much-reduced influence on fatigue compared to a worldwide environment.
- Tanker hulls are always designed for worldwide trade whereas FPSO hulls may be project specific.

Stringent requirements on fatigue factors are defined for vessels not following regular dry dock / sheltered water inspection such as FPSOs. These exceeds the normal minimum FS = 1.0 for tanker structures. The values are given in **table 10**.

In addition to the differences between an FPSO and a tanker, mentioned above, there are also differences between the offshore and maritime fatigue analysis process. Traditional maritime practice has been to use simplified fatigue assessment techniques due to design time constraints and rely on regular surveys. Only recently the use of more comprehensive analysis is becoming more frequent.

Both industries commonly use the S-N fatigue approach under the assumption of linear cumulative damage; Palmgrens-Miner rule. However, establishing and using the stress for fatigue analysis may be quite different and this is reflected in the S-N curves.

Fatigue Assessment. The tanker approach, as described in CN30.7, is to use four basic S-N curves and modify the nominal stress with an appropriate stress concentration factor (SCF):

- Curve I is equivalent to a C-curve in air or with cathodic protection.
- Curve II is equivalent to a D-curve in air or with cathodic protection.
- Curve III is equivalent to a C-curve in a corrosive environment.
- Curve IV is equivalent to a D-curve in a corrosive environment.

The SCF may be taken from recognised tabular values or may be established through the use of detailed FE models. This approach assumes that the nominal stress can determined and this is not always the case for complex structural connections. This can be particularly important for details where the SCF may vary due to the type of loading. A bracket connection to an asymmetric side longitudinal is a classic example. Here the global loads (e.g. horizontal bending) will result in one SCF and lateral pressure (internal and / or external) will result in another. In this case the correct SCF is to be applied to the corresponding load.

With the simplified approach the phase relationships between the different loads (local and global) may be established through parametric equations. A long term distribution is established through a parametrically established Weibull two-parameter distribution. Rigorous approaches more correctly account for the phase relationship by post-processing with the hydrodynamic analysis results and calculating a Weibull two-parameter distribution at a 10^{-4} probability of exceedence.

Simplified methods are useful as they can be performed rapidly and are, therefore, beneficial as a screening tool. Class societies have simplified tools available to the industry for the assessment of structural fatigue damage.

There are limitations with simplified approaches, of which the designer should be aware (Ref. 3). Generally the simplified approaches consider:

- Empirical loads (parametric equations)
- Nominated stress concentration factors (SCFs)
- Simple beam bending theory
- Assumed load phase relationships
- Ignores shear lag
- Effective flange approximations

There are claims that analysis software for hull fatigue is calibrated against experience. However, there is limited FPSO experience available and tankers have the ability to avoid bad weather and thus avoid being ‘exposed’ to the environment assumed in the analysis assumptions.

It is important to note that SCF’s have only been established for certain details. The designer should not limit their fatigue calculations to these detail types as there is the potential for fatigue damage at a number of alternative locations, e.g. shear lugs, transverse frame gussets, hopper knuckles, etc.

As stated above the SCF approach implies that the nominal stress can be established. However, it is often difficult to accurately establish the nominal stress for such details, particularly with the more frequent use of FE models for structural analysis.

In contrast the offshore industry approach has been to use different S-N curves based on the connection types, see **figure 5** and **6**. Each of these curves has the SCF accounted for in the actual S-N curve so the analyst needs only to establish the nominal stress. For example the F3 curve may be considered as D curve with an SCF of 1.6 or an E curve a D curve with an SCF of 1.13.

The use and level of FE models for structural analysis has an impact on the fatigue analysis approach. It is well understood that stresses are more accurately established through FE analysis as it can include all necessary effects, such as: shear lag, effective flange, relative deflection, double bottom stresses, etc. Generally the FE mesh for normal structural analysis is not sufficient to establish the geometric stress concentration at the considered detail.

In offshore fatigue checks, simplified methods based on extreme dynamic loads can be applied. As an example the fatigue assessment of the column connections (flexible gusset plates) for topsides supports is discussed. The designer shall consider the following cases:

- Maximum roll accelerations combined with maximum heave and wave bending deformations.
- Maximum pitch acceleration combined with maximum heave and wave bending moment deformations.

The accumulative fatigue damage, η, for a 50% head and 50% beam seas assumed life is determined using the following formula:

$$\eta = 0.5\left(\frac{\sigma_{head}}{\sigma_{allwable}}\right)^3 + 0.5\left(\frac{\sigma_{beam}}{\sigma_{allowable}}\right)^3 \tag{4}$$

The allowable stress amplitude for a 20-year return period, σ_{20}, can be derived from:

$$\sigma_{20} < \frac{18.42^{\frac{1}{h}}}{2}[10^{-8}\frac{a}{\Gamma(\frac{m}{h}+1)}] \tag{5}$$

The allowable stress amplitude for a 100-year return period, σ_{100}, is scaled as follow:

$$\sigma_{100} = \frac{\sigma_{20}}{0.92^{\frac{1}{h}}} \tag{6}$$

Design Experience. Ample fatigue life is obtained for new build FPSOs for benign environment if scantlings are based on minimum Rule requirements. A comparison has been made between fatigue performances for Worldwide, North Atlantic and West African conditions using the CN 30.7 assessment procedure. The following assumptions were made:

- Full unidirectional wave heading
- Wave loads included, mooring and topsides loads ignored
- S-N curve II

Results are presented in **table 9**. From the table it is evident that generally fatigue requirements are relatively easily met for benign environments.

Conclusion

In this paper the differences between shipbuilding and offshore approaches have been discussed.

Several relevant design issues have been treated in detail. Special consideration should be given to the following items when adopting tanker based experience:

- Equivalent forward speed
- Still water loads
- Load line convention
- Material selection
- Stress and buckling criteria
- Fatigue criteria

Rule formulae from Classification Societies for calculating the local strength are based on actual ship speed input. Since FPSOs are stationary moored, an equivalent ship speed should be defined to allow the use of traditional marine experience. The design equivalent ship speed varies between 8 – 15 knots, depending on the Classification Society concerned.

Tanker Rule guidance values on still water loads underestimate design criteria for an FPSO. Similarly freeboard requirements for a boxed-shaped FPSO are under predicted by traditional tanker Rules, if the maximum hull length is input as load line length in the formulae. To establish uniform design guidance it is recommended to use the Rule length, 97% of maximum length, as the load line length.

Interpretation of stress, buckling and fatigue criteria, based on ship and offshore standards, have been discussed. Special attention needs to be paid to these interpretations during the design especially for the of S-N curves. These are defined differently for ship and offshore structures. The S-N curves for offshore structures already include SCFs for the detail concerned, while for ship structures the SCF has to be separately determined.

It is essential to define topsides/hull interface, i.e. module support layout in the early design stage. The use of an interface drawing is recommended.

In more general it can be stated that knowledge of ship design and offshore structures design need to be combined to achieve an efficient design for an FPSO vessel.

Nomenclature

C_B = Block Coefficient
L = Hull Length, L, m
B = Breadth of Hull, L, m
D = Depth of Hull, L, m
C_W = Wave coefficient
C = Factor boundary constraints deck stiffener
$f_{n.}$ = Natural frequency of stiffener, t^{-1}, Hz
E = Modulus of Elasticity, m/Lt^2, N/mm²
I = Moment of Inertia, L^4, mm^4
m = Mass of item
S = Web frame spacing, span of stiffener, L, m
δ_Z = Vertical deflection of hull structure, L, mm
δ_X = Longitudinal elongation of hull, L, mm
c = Height of deck above hull neutral axis, L, m
σ = Global hull bending stress, m/Lt^2, N/mm²
l = Length of topsides module, L, m
f_1 = Material factor
η = Accumulative fatigue damage
h = Weibull scale parameter
a = Constant relating to mean S-N curve
m = Inverse slope of S-N curve
σ_{20} = Allowable stress amplitude for 20-year return period, m/Lt^2, N/mm²
σ_{100} = Allowable stress amplitude for 100-year return period, m/Lt^2, N/mm²
M_{SW} = Still water bending moment, mL^2/t^2, Nm
Q_{SW} = Still water shear force, mL/t^2, N

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Tables

Table 1 - Field Examples

Item	Unit	Conversion	New Build
$T_{P\ 100\ year}$	s	16.8	14.9 - 18.8
$H_{S\ 100\ year}$	m	4.2	4.5
$T_{P\ 1\ year}$	s	15.5	10.3 - 17.6
$H_{S\ 1\ year}$	m	3.4	2.3
Water depth	m	450	1200

Table 2 - Hull Proportions Examples

Vessel		L/B Ratio	B/D Ratio	L/D Ratio
FPSO	Actual New Build (N. Sea)	5.0	1.9	9.5
	Actual New Build (N. Sea)	5.4	1.7	8.9
	Actual New Build (Far East)	5.3	1.8	9.5
	Actual New Build (W. Africa)	5.2	1.9	9.7
	Proposed New Build (W. Africa)	4.5	2.0	8.8
	Conversion (S. America)*	6.2	1.8	11.3
	Conversion (W. Africa) *	7.3	1.6	11.5
Trading Tankers	70 – 100,000 DWT	5.6	3.0	16.7
	150 – 250,000 DWT	5.9	2.8	15.8
	250 – 350,000 DWT	5.5	1.9	10.7
	350 – 450,000 DWT	5.6	2.0	11.2

*= Tankers built in early and late 1970s respectively.

Table 3 – Main Dimensions Examples

Main Particulars			
Item	Units	Conversion	New Build
$L_{O.A.}$	m	334.94	285.00
$L_{Moulded}$	m	318.97	276.45
$B_{Moulded}$	m	43.74	63.00
$D_{Moulded}$	m	27.74	32.30
T_{Summer}	m	21.40	24.10
Storage Capacity	bbls	1,700,000	2,200,000
Production Capacity	bbls	100,000	200,000
Topsides weight	tonnes	5,000	28,000
$\text{Displacement}_{Summer}$	tonnes	264,284	417,000
Hull Proportions			
$C_{B\text{-}Summer}$	-	0.86	0.96
L/B	-	7.29	4.52
B/T	-	2.04	2.61
L/D	-	11.50	8.56
B/D	-	1.58	1.95

Table 4 - Minimum Freeboard

Item	Symbol	Unit	Length [m]	
			285 (100%)	273.6 (96%)
Tabular Freeboard	SF_{Tab}	mm	3,198	3,146
Block Coefficient	C_{BF}	-	0.94	0.98
Block Coefficient correction	-	mm	611	705
Depth correction	-	mm	3325	3515
Sheer Correction	-	mm	984	949
Regulated freeboard	SF_{Reg}	mm	8,118	8,315

Table 5 - Still Water Loads

Item	Conversion FPSO			New Build FPSO		
	Rule	Actual	%	Rule	Actual	%
$M_{SW\text{-}Hogging}$ [kNm]	5,123,200	5,072,000	- 1	5,538,000	1,962,000	- 82
$M_{SW\text{-}Sagging}$ [kNm]	4,740,000	4,050,000	- 17	5,530,000	10,800,000	+ 95
Q_{SW} [kN]	80,550	142,250	+ 77	100,160	196,200	+ 95

Note:
– Rule values are considered as reference.

Table 6 - New Build FPSO Accelerations

Item	Transit			Site: 100 year swell			Site: 1 year swell		
[m/s²]	a_x	a_y	a_z	a_x	a_y	a_z	a_x	a_y	a_z
Flare	2.2	12.8	14.8	0.7	0.9	10.8	0.5	0.6	10.5
Module	1.4	9.3	16.2	0.5	0.7	10.2	0.4	0.5	10.1

Note:
– Values include static gravity component of roll and pitch motion.
– Position of flare C.O.G. 78 m above base line of vessel.
– Position of topsides module C.O.G. is 57 m above base line of vessel.

Table 7 – Hull Deformation Effects for Topsides Module

Hull Structure		Bending Stress σ [N/mm²]	Elongation δ_L [mm]	Deflection δ_Z [mm]
Material	σ_{yield} [N/mm²]			
Mild steel	235	175	25.5	8.7
HT – 32	315	224	32.6	11.1
HT – 36	355	234	34.1	11.6

Note:
– Length of module is 35 m.
– Depth of hull is 30 m, position of neutral axis “c” is 15 m.
– Modulus of elasticity is 206,000 N/mm².

Table 8 - Material Designation

Designation	Strength Group	Offshore Rules		Ship Rules	
		σ_{Yield} [N/mm²]	f_1 [-]	σ_{Yield} [N/mm²]	f_1 [-]
NV – NS	Normal (NS)	240	1.00	235	1.00
NV-32	High Strength (HS)	315	1.31	315	1.28
NV-36		355	1.48	355	1.34

Table 9 - Fatigue Damage Ratios

Draught	North Atlantic	Worldwide
Ballast Condition	18.8	7.5
Fully Loaded Condition	22.0	8.0

Notes:
– Damage Ratio is defined as West Africa / North Atlantic or West Africa / Worldwide.
– Minimum damage ratio for specific location not to be less than FS = 3.0 according table 10.

Table 10 - Design Fatigue Factors

Classification of structural component based on damage consequences	Access for inspection and repair		
	No access or in the splash zone	Accessible	
		Below splash zone	Above splash zone
Substantial consequences	10	3	2
Without substantial consequences	3	2	1

Note:
– According to DNV RP OS-C102 Fatigue Strength Analysis of Offshore Steel Structures.

Figures

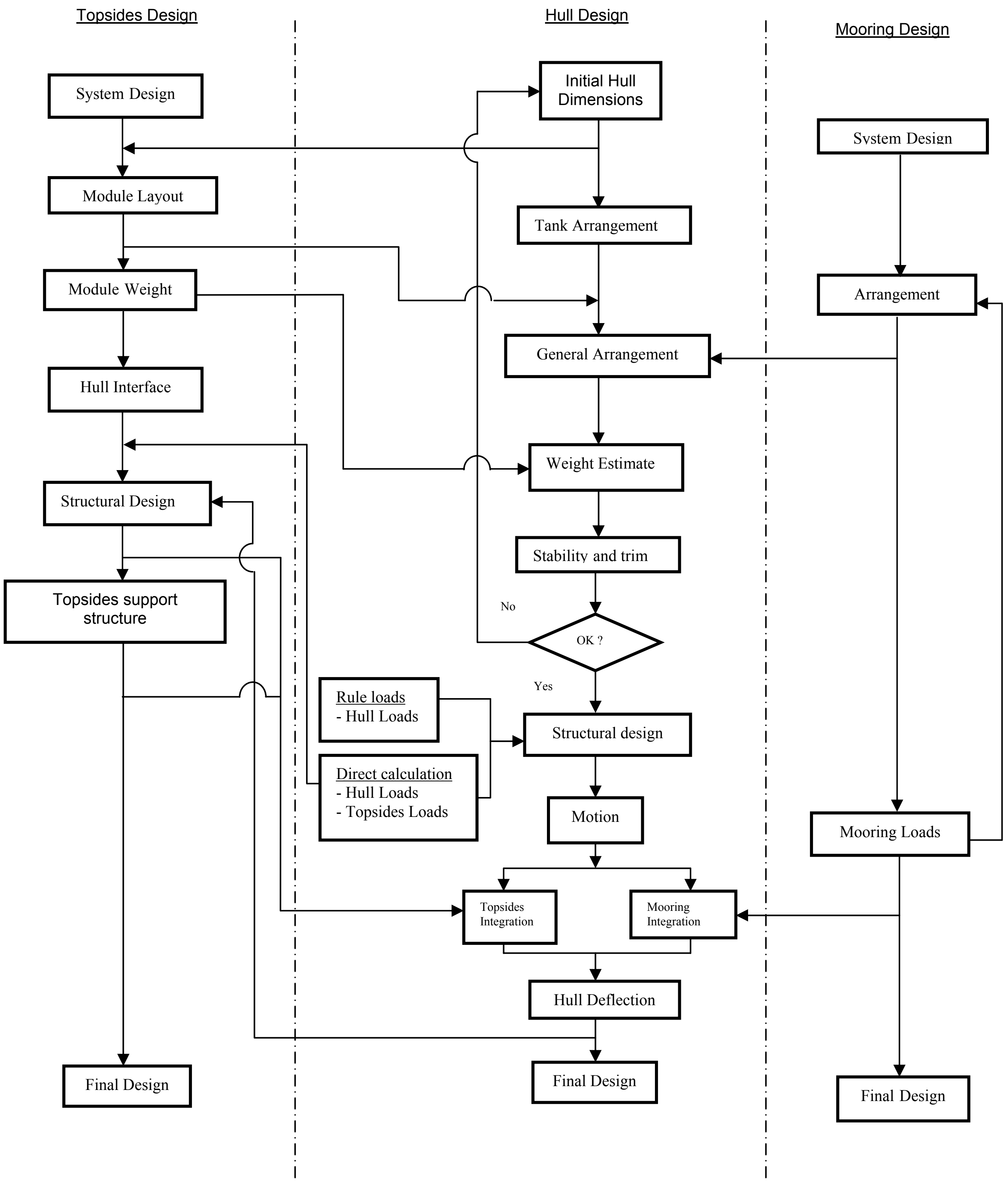

Figure 1 - Example FPSO Simplified Hull Design Procedure

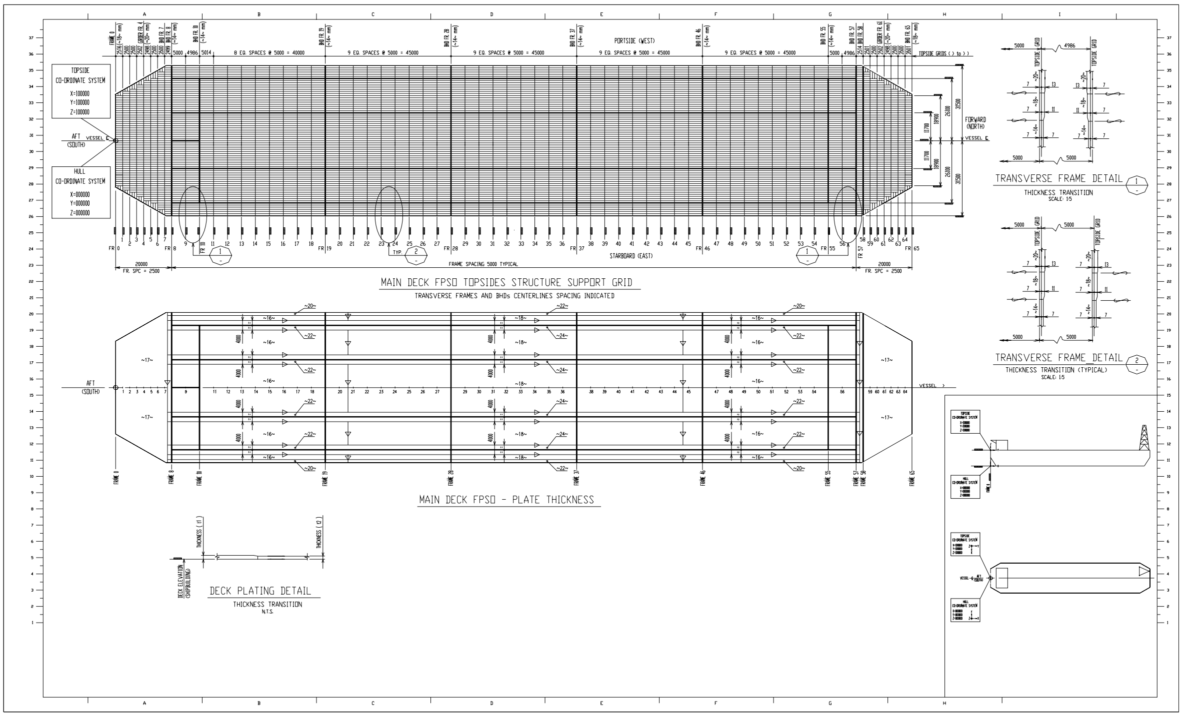

Figure 2^{A} - Example of a Deck Interface Plan

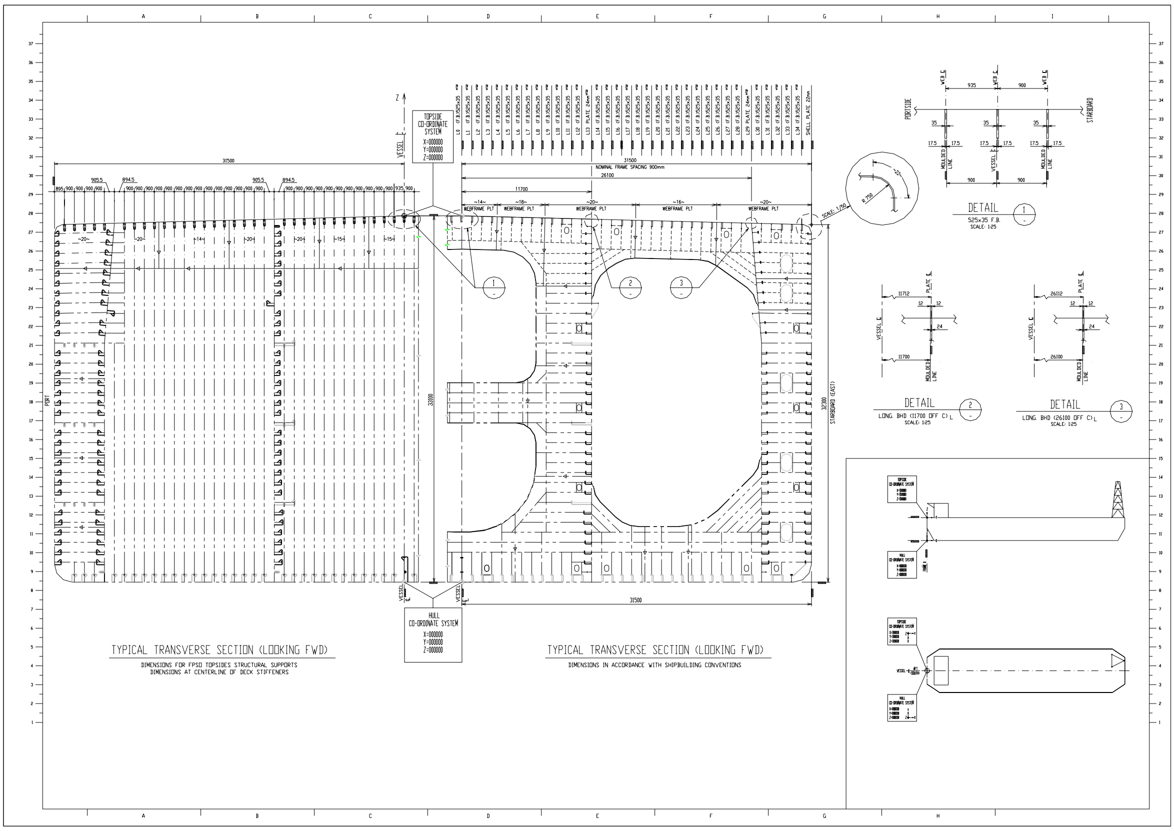

Figure 2^{B} - Example of a Cross Section Interface Plan

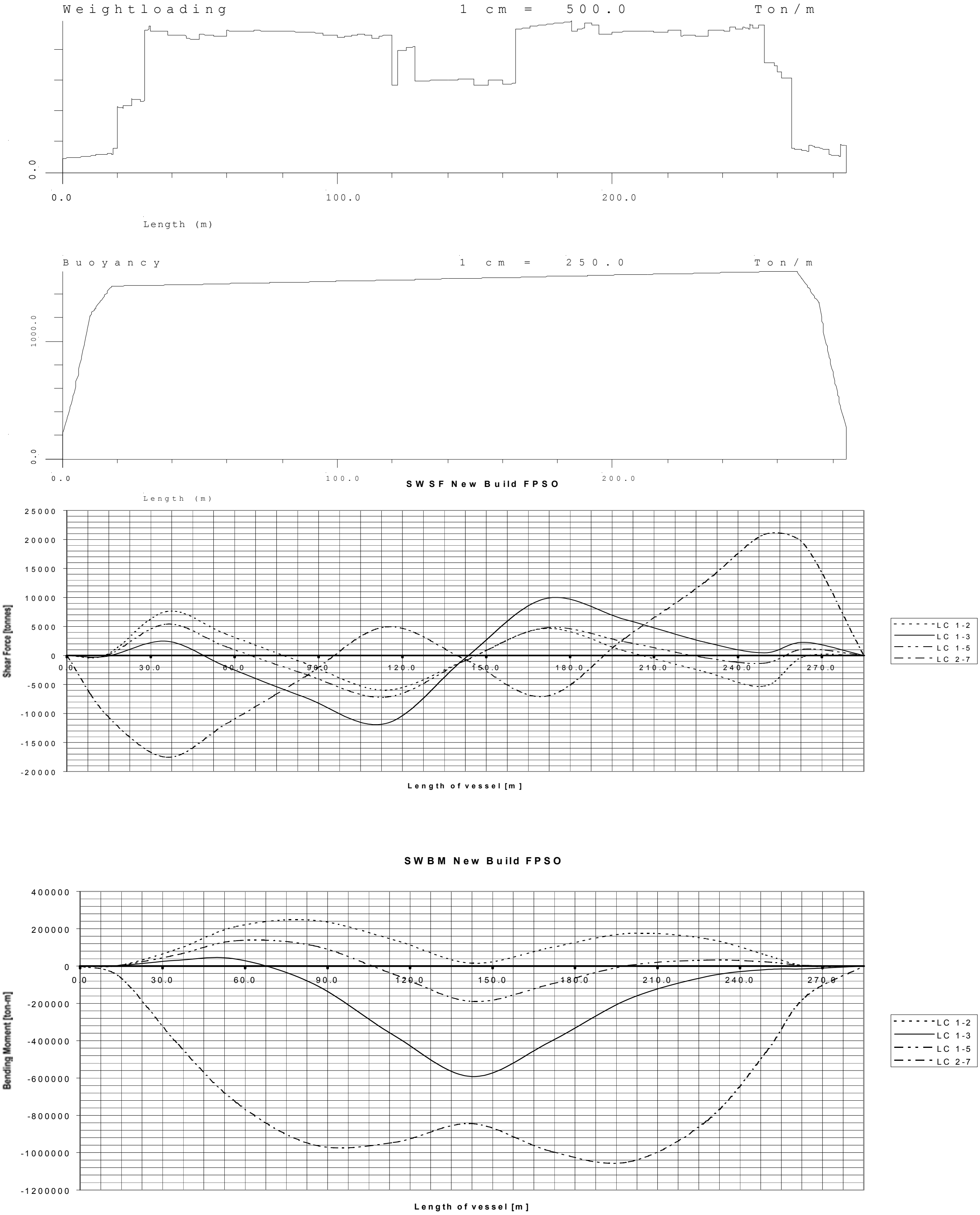

Figure 3 - Still Water Loading New Build FPSO

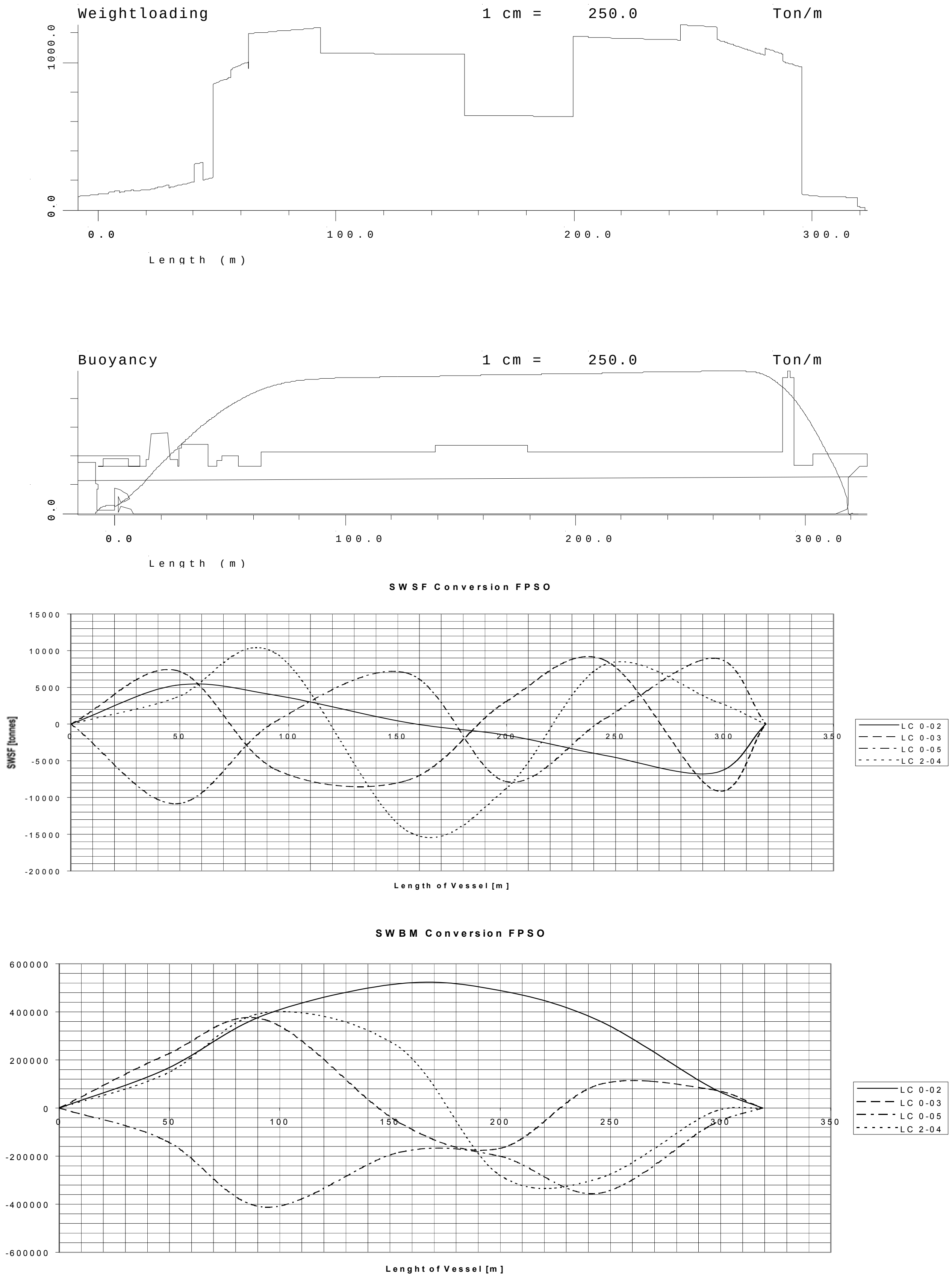

Figure 4 - Still Water Loading Converted FPSO

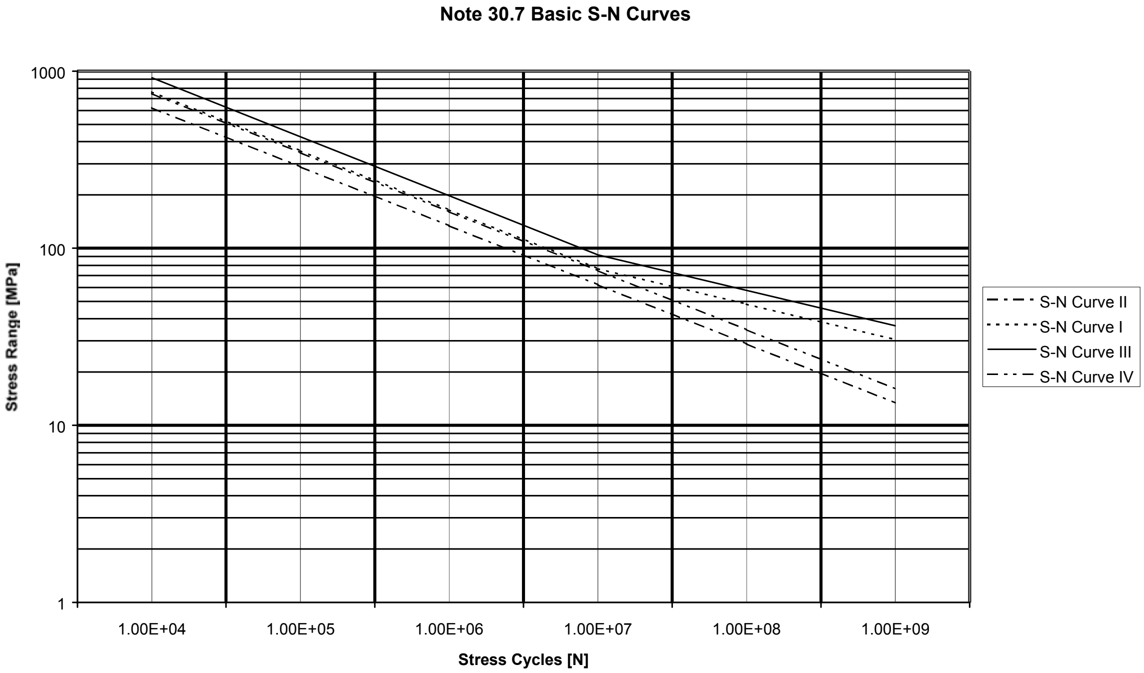

Figure 5 - S-N Curves Ship Structures

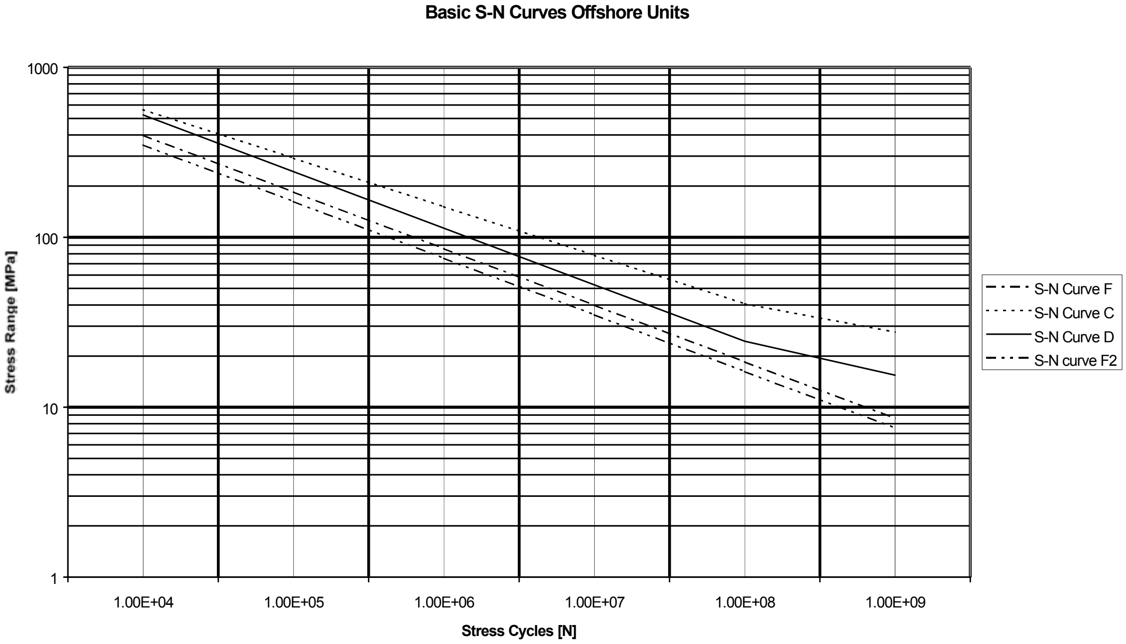

Figure 6 - S-N Curves Offshore Structure

Figure 7 - Deflection Topsides Module in 4-point-lift

Figure 8 - Module Installation on Column Support

Figure 9 - Integration Spread Moored System

Figure 10 - Congested Deck Area for Spread Mooring FPSO