Abstract
This paper discusses the structural interface on FPSOs between the hull structure and the topsides modules. It identifies the most common topsides foundation concepts applied on FPSOs, and discusses the consequences of each configuration for the layout of the unit, the design of the hull structure and the topsides. The information needed by the hull designer and the topside designer is identified. Moreover, the differences between shipbuilding and offshore construction design practices are discussed, and it is identified where and how these fall short for FPSO purposes. Topics that are addressed are overall safety, operational aspects, such as tank entry and mechanical handling, and the design specifications for the hull and the topsides modules. In order to control the schedule and costs of FPSO projects, fabrication of the hull and topsides should be allowed without impractical or unduly strict specifications imposed on the shipyard or the topsides fabricator. At the same time the traditional design specifications for hull and topsides design may fall short to cover the functional needs for FPSO service.

Introduction
To date, FPSOs have been in operation for several decades. Initially this development concept was selected for marginal fields in remote and environmentally benign locations. With the further advancement of sub-sea completions, flexible risers and turret mooring systems, the FPSO made its way in the nineties to harsher environments and larger development schemes that were previously uneconomical. Comparatively little investment had to be made in production- and export facilities, whereas the investment still had a residual value after depletion of the field as it could be re-deployed elsewhere. Furthermore, contractors emerged that were offering lease schemes, lowering the up front investments even further. With the shift of new discoveries towards ever deeper water, the FPSO is becoming more and more the default development platform for deep water for the years to come.

Traditionally, an FPSO consists of a converted tanker with the production facilities, or topsides, mounted on deck. After only a limited conversion the oil tanker will fulfil all functional demands for storage and offloading of the produced oil. The most common project strategy is to contract large blocks of work, such as hull conversion, topsides and mooring system, to independent specialized contractors parallel in time. This is possible since the concept of an FPSO is robust: space on a tanker deck is ample, and mono-hulls are relatively weight insensitive. The downside of this approach is that (contractual) interfaces are created that need to be carefully managed in order not to jeopardise the successful completion of the project. Over the years, two types of FPSO projects have evolved.

Conversions the ‘classic’ approach is to convert a ‘vintage’ tanker. This comprises an extensive Repair and Life Extension (R&LE) program, after which a conversion will take place to accommodate the mooring system, production facilities, utility systems and offloading system. Key advantages of this concept are the low purchase cost of the hull and the short lead-time. A large number of conversion candidates is available, especially now that a major part of the world fleet is being phased out because of MARPOL 13G regulations [1]. Down side of this approach is the high uncertainty embedded in the conversion scope: only after the detailed inspections have taken place in the conversion yard, the exact extent of steel renewals and equipment overhauls / replacements can be determined. This makes such projects very susceptible to budget and, more important, schedule overruns.

To overcome this disadvantage, some project teams have opted for converting a ‘new’ tanker. This can be either a unit that is just delivered, or is still under construction. An example of this approach is described in [2]. When a tanker contract can be secured before start of construction, limited possibilities may exist to tailor the tanker specification to the FPSO requirements, e.g. by increasing scantling or material grades in certain areas. The down sides of converting a ‘new’
vessel are the high purchase costs, while the full conversion scope remains intact.

**New builds** are the most logical approach to take when a tanker conversion can not meet the project requirements for, for instance sea keeping, strength, endurance or size. In theory, a purpose designed new build FPSO can be built by one contracting party, but to date most of these units were contracted out as a number of sub projects, leaving the interface problems intact. Time has proven that purpose designed FPSO units are considerably more expensive, and have longer schedules than conversions. This because their ‘non standard’ specification requires an extensive engineering effort by the shipyard, and because the owner’s requirements, regarding e.g. materials, fabrication and coating, interfere with normal ship production.

An alternative to a purpose designed new build is to opt for a ‘standard specification’ new build. Such a unit would conform to a shipyard’s standard tanker design with only minimal modifications to its specification. Typically these would comprise the omission of the propulsion- and associated auxiliary systems, specification of an improved coating system, increased scantlings and higher material grades in certain areas.

**Interfaces**

As a consequence of the split project execution, contractual interfaces arise. The control and resolution of these interfaces is beyond the scope of this paper but has been the subject of many other publications, for instance [3]. General consensus is to minimise the interfaces between the various parties by contracting systems either fully in the scope of the shipyard, or fully in the scope of the topsides’ fabricator. Moreover, the responsibility for a system should remain with one party and range from design up to (pre-) commissioning. ‘Hand-over’ work should be avoided as much as possible. Noteworthy exceptions to these rules are the safety systems and electric power distribution systems as these are integral to the whole unit.

In this paper it is not so much the system interfaces we consider but the structural interface between the hull and topsides. The topsides are fitted using foundations at a certain elevation above the hull’s upper-deck as shown in Figure 1. For the foundations between the upper-deck and the underside of the topsides, the following functional requirements apply:

- support the topsides modules on the hull,
- provide space for all deck piping and hull equipment,
- provide space for safe (tank) access and mechanical handling operations on the hull’s upper-deck,
- allow for sufficient natural ventilation of the upper-deck in order to prevent build-up of explosive gaseous mixtures,
- create a fire division / barrier between the topsides and hull upper-deck,
- create a division in the hazardous area classification for electrical equipment selection.

The elevation between the upper-deck and the topsides flooring depends on how much clear height is needed underneath the topsides to fulfil the above requirements. For an Aframax size hull, a typical value of 3750 mm at the centreline has proved sufficient but the elevation is dependent on the topside arrangement, i.e. the main girder height of the topsides deck.

**Figure 1: Terminology**

At the start of engineering, neither the arrangement of the topsides nor the arrangement of the hull’s marine systems is determined. One of the most effective engineering instruments to define and maintain control over the hull-topsides interface is the upper-deck combination plan, on which all equipment and piping and cable trays are shown. The basis for this drawing is the shipyard’s ‘as-built’ plan. In case of a conversion this drawing should be brought up to date, as surely equipment and pipe runs will have been added or removed over the vessel’s life. On the combination plan space can be reserved for the topsides support structure, new equipment, pipe runs, escape- and access routes, mechanical handling corridors, and so on. Both parties should agree upon and remain within the boundaries of the physical space allocated to them. During the project, the drawing should be regularly updated and subsequent new design definition should be verified on interference with other structure (clash checks).

Another topic of debate is the type of flooring on the topsides: grating versus plating. This choice is influenced to a large extent by the safety philosophy adopted in the project. The advantage of a steel plated floor is that a protective barrier is created between the topsides and the tanker upper-deck. This will prevent migration of gas, contain liquids on the topsides, and mitigate the effect of a possible jet fire onto the upper-deck. It does require an effective draining system that will be capable to deal oil contaminated water as well as with large volumes rain-, spray- or deluge water, see Figure 2. Disadvantage of a plated topsides deck is that the space between the upper-deck and the topsides becomes more congested, especially in way of the hull’s marine deck piping. This may hinder natural ventilation, increasing the risk on build-up of explosive gaseous mixtures. In the event ignition
should take place, explosion overpressures will be higher than would have occurred with grating type floors.

To hazardous open drain tank

Large volumes directly over board

Figure 2: Typical draining arrangement

Structural Configuration of Topsides

Two types of structural configurations are commonly adopted for the topsides:

Grillage deck, in which a complete new topsides deck is built at an elevation above the hull’s upper-deck. Equipment is at most pre-packaged onto skids and then lifted on the grillage deck, after which it is connected up to its piping-, electrical- and instrumentation systems. This configuration is normally adopted for smaller modules. It results in a weight efficient structure, but forms an integral part of the hull, thereby creating a design interface. Schedule wise, there is limited possibility for pre-fabrication and commissioning, which has an adverse effect on the outfitting time.

Pre Assembled Units (PAU): functional modules are created on larger, mostly single tier ‘pancake’ type structures. The equipment on the PAU is interconnected to its piping-, electrical- and instrumentation systems, to allow (pre-) commissioning. The complete PAU is then lifted onto the hull in one heavy lift operation. Clear advantage of this approach is that the design and fabrication of the PAU can take place independent of the hull and in a different location. The structure will be less weight efficient as the lift case may become dominant. Moreover, an expensive crane is required for the lift onto the hull, see Figure 3. Despite these drawbacks, the majority of FPSO topsides come in the form of PAUs.

Design Considerations

To allow engineering by the topsides contractor in parallel with that of the hull (conversion) contractor, it is required that their common design premises are established early on in the project, and that during their subsequent basic engineering they need as little information from each other as possible. The topsides structural design will be verified in the following conditions:

- fabrication, transport to outfitting yard, lifting and installation,
- on board FPSO, in transit to and from field,
- on board FPSO, operational and extreme environment,
- on board FPSO, exceptional conditions (e.g. explosion, extreme list in damaged condition).

Figure 3: Installation of PAUs onboard FPSO

Topsides Design

The fabrication conditions will require little input from the hull (conversion) contractor. For the final lift of the PAU on board, the vessel draft and trim during outfitting in combination with the crane’s lifting capacity / hoisting height will determine the rigging arrangement with which the PAU will be lifted. The topsides should be checked against installation loads, including Dynamic Amplification Factors (DAF) due to lifting. These loads however are seldom governing for the structural design as the lift operations are normally done in sheltered waters and the PAUs will be ‘dry’ during installation. Design guidance for the installation can be found in the rules and regulations from the warranty surveyors, for instance [4].

The ‘on board’ conditions are governing the structural strength of the PAUs. They mainly involve inertia loads originating from the hull motions. The motions may be predicted accurately with linear ship-motion programs; however, predicting the roll motion is very sensitive to the assumed heading of the FPSO into the waves and the proper assessment of the viscous roll damping. The heading of a single point moored FPSO is determined by the joint effect of wind, waves and current, their respective azimuths, the FPSO’s draft and trim, and the lengthwise position of the turret mooring system. Accurate wind, wave and current records may not be available for the field. What is more, the motion analysis should be done not only for the field location, but also for the transit conditions to and from the field. The determination of the roll motions of an FPSO is so complex, that a new Joint Industry Project (JIP) has been set up to investigate this phenomenon more closely [5]. Thus it is not a practical approach to base the motions and accelerations for
topsides structural design upon the results of a field- and route specific motion calculations based on the spectral analysis. The more the fact that the roll damping is non-linear (i.e. depends on roll amplitude) and invalidates the linear character of the spectral analysis. Better is to revert to ‘tried and proven’, albeit conservative specifications, such as the Classification Societies’ Rules & Regulations for Freight Securing Arrangements. These should be applied in full for the transit to- and from the field when the process equipment is drained from liquids. For the operational conditions, it may be considered to reduce the maximum motions to more moderate values, but then these should be confirmed via a field specific analysis. This should then be performed as early as possible, ideally during the conceptual phase, in order not to jeopardize the progress of the topsides- and hull engineering.

Another source of loading for the topsides is the deformation of the hull. Ships bend as a result of the internal distribution of cargo and ballast over the tank compartments, and as a result of the waves acting on the hull. The main source of deformation is the global bending of the hull girder, but also significant deformations may arise due to flexure of the hull’s primary structure. For the design of the topsides hull interface, it is the elongation of the upper-deck that is governing, and not so much the vertical deflection of the hull. Depending on the material quality used, the Classification Societies’ rules allow a hull girder bending stress of up to $\sigma_{\text{allowable}} = 240$MPa within 0.4L of mid-ship. Assuming a transverse frame spacing of 4.8m, this implies an elongation / shortening amplitude of ~ 5.5 mm per frame spacing. Since the topsides are mounted onto the upper-deck they are subject to these elongations, and not only their structure, but also their piping- and electric cable runs. The flexing of the hull and the precautions this implies for outfitting is a matter understood by naval architects and shipyards, but not so much by topsides structural- and piping designers and fabrication yards.

that covers both the governing design cases with respect to vessel motions and hull deflections. This makes that these calculations are only done as verification, after the design is finalised. An example of an integrated Finite Element Analysis (FEA) model is shown in Figure 4.

**Hull Structure Design**

The scantlings of the hull structure are based upon the Classification Societies’ Rules and Regulations for Tankers, and such units do not furnish for extensive topsides structures on their upper-deck. The scantlings of the upper-deck are determined by the longitudinal stresses originating from the hull girder bending. The structural detailing thereof is so that stress raisers are avoided: penetrations are kept to a minimum in number and size, all corners are suitably rounded, and welded attachments are minimised in projected length and fitted with ‘soft nose’ details. It is common that longitudinal material is of higher tensile steel, such as AH32 or AH36, in order to reduce steel weight. The transverse structure is loaded less onerously, the scantlings determined primarily by hydrostatic tank pressures. Often the web-frames are built of mild steel. Deck longitudinals and webs are welded to deck plating with double fillet type welds. The size of these welds typically corresponds to the rule minimum requirement. Thus the weak points for the topsides support lie under deck: the web frame, with cut-outs for the deck longitudinals, has not been designed for lateral loading. As mentioned earlier, the frames are often fabricated of mild steel. This implies a reduced safety margin against buckling. Last but not least, the fillet weld that transfers the vertical loads from the support into the web is of minimal dimensions. Some designers allow for load transfer in direct contact, but in the authors’ view this is un-conservative, as this load path vanishes when only a small pre-opening is present, see Figure 5. The more the fact that such a pre-opening can not be detected by NDE techniques.

![Figure 4: FEA – integrated shipyard’s and PAU](image)

![Figure 5: Typical weld detail foundation - transverse](image)
The obvious reinforcement techniques will be to ‘beef up’ the web-deck welds and to add buckling stiffeners underneath the supports. For new build hulls, consideration should be given to size the web-plate thickness to rule requirements for mild steel, add an additional margin, and / or specify fabrication in higher tensile steel.

**Construction considerations**

Due to the short schedules allowed for in FPSO projects, the arrangement of the structural supports should be finalised as early as possible. Often the (re-)coating of the cargo and ballast tanks is on the critical path of the conversion schedule. Especially the coating of the deck-heads is critical, as this requires extensive internal scaffolding. When this work is planned for, it creates an opportunity to perform some under deck strengthening at limited costs as scaffolding is already provided for. However, after it is finished, no further hot-work is allowed on the upper-deck as it will damage the tank coating. Thus the chosen support arrangement should be robust and have sufficient spare capacity to allow for the inevitable late changes in topsides reaction loads. Good practice is to provide a sufficient number of doubler plates on the upper-deck that may function as ‘starter points’ for pipe supports. The owner should consider specifying spare supports to allow future expansions of the topsides.

**Topsides support configurations**

Terpstra [6] distinguishes, two types of arrangements that are normally used for PAU supports:

- **Multiple column supports**, in which the PAU or grillage deck is supported on (multiple) rows of columns, fitted in line with the hull’s transverse web frames. The columns are sniped at their ends and gusset plates aligning with the hull’s under deck structure are fitted. Sizing of these should be such that sufficient spreading of the column load is achieved, ideally with no under deck reinforcement. By aligning all the gussets in the transverse plane, flexibility is created in the longitudinal direction, which de-couples the hull deck elongation from the PAU. This support arrangement gives a weight efficient solution and can be used for PAUs up to 500 tons. Problem remains that it is statically indeterminate, and that the column loads are to a large extent dependent on the final arrangement and structural configuration of the PAU. Thus the design of the columns should have a sufficient safety margin to account for uncertainty in reaction force. Interface wise, this arrangement can only be concluded safely when the design of the PAU, its support arrangement and the integration thereof in the hull lies firmly with one party.

- **Support stools** form an alternative PAU support concept. Four box type stools support the PAU, in a similar fashion as modules on a fixed platform. To isolate the hull deformations from the PAU, an array of roller and sliding joints is to be fitted between the strong points and the PAU. These can be detailed to normal civil engineering practice, but due care is to be taken that they can resist uplift and significant transverse loading. Alternatively they can be created with elastomeric pads. These are stiff in compression but flexible in shear. With a suitable arrangement of stoppers and retainers they can be configured so that the PAU will be de-coupled from the hull’s deck elongation, see Figure 6.

![Figure 6: Supporting of PAU on elastomeric pads.](image)

When correctly detailed, the support stool concept will allow support of larger PAUs, however the reactions force on a stool will be far higher than with the multiple column support arrangement and most likely under deck reinforcements will be required. Typically, the support stool is fitted at an intersection of two web frames and a longitudinal bulkhead.

Neto [7] cautions against utilising the longitudinal bulkhead in the topsides support integration, as interaction between direct compression from the support reaction and compression in the bulkhead plating from overall hull girder bending will have an adverse effect on buckling. This may require extensive stiffening of the bulkhead in way of the support stool, necessitating significant in tank scaffolding. When the stools are supported by the web-frames only, their high loads may become governing for their strength, again resulting in under-deck strengthening of the web. This concept is therefore more suitable for purpose built hulls than for converted tankers.

- **Support girder.** A variation on the previous arrangement is the support girder concept, which the authors have seen applied successfully on both conversion and new build projects.

![Figure 7: Support girders.](image)
It consists of two web frames (per PAU) on deck, in line with the hull transverses, extending over the full width of the PAU, see Figure 7. As the torsional rigidity of the hull is an order of magnitude higher than that of the PAU, the arrangement effectively results in two line supports.

The PAU is lifted on top of these girders onto temporary spacers after which fit-up plates are welded over the full length of the structural interface. In effect a transverse bulkhead is created consisting of the hull’s web frame, the support girder and the main transverse of the PAU, see Figure 8. This in turn mitigates bending stresses in the existing web frame.

Figure 8: Transverse section over support girder

The forward girder is anchored to the hull in longitudinal direction by so called ‘pitch stoppers’, which pick up the longitudinal forces acting on the PAU. The aft girder is left free, and is only stiffened against buckling. This allows flexing fore and aft, thereby effectively creating a roller type support in longitudinal direction, see Figure 9. Lightening holes are cut into the web to improve passive ventilation, to mitigate the effects of ‘green water’ on deck, and to allow for passage of the marine pipe runs. As the webs have excess length, the compressive stresses from the PAU reaction forces at upper-deck level will have reduced significantly, and thus no additional under-deck strengthening is required. Down side of this configuration is a higher steel weight when compared with the multiple column supports.

Relative displacement between PAUs. Although every effort is made to de-couple the hull deformation from the PAU structure, relative displacements between adjacent PAUs are unavoidable. These are proportional with the PAU’s length, and with the elevation above the upper-deck. For the design of interconnecting piping and cabling between the PAUs, these displacements need be taken into account. The relative displacements can best be communicated to the piping- and electrical designers via a plan on which, for all elevation of main piping and cable trays, the displacement towards- and away two adjoining PAUs is listed. For the compilation of this plan, a realistic loading condition of the vessel during ‘hook-up’ should be established. The relative displacements of the PAUs towards each other can be determined from the ‘maximum sagging’ condition minus the ‘hook-up’ condition, the relative displacement away from the ‘maximum hogging’ condition minus the ‘hook-up’ condition.

Conclusion
Based on the discussion of the most common structural interface between the hull structure and the topside modules on FPSOs we recommend that the design of the hull conversion and topsides structure are separated as much as possible. The use of support girders yields a manageable and robust structural interface as it:
- loads the hull structure uniformly thereby avoiding the need for under-deck localised strengthening,
- enhances transverse strength by effectively increasing the height of deck webs,
- effectively de-couples upper-deck elongation from the topsides module, creating a statically determinate support condition for its structure,
- forms a fully welded simple plate structure without mechanical or machined parts familiar to shipyards,
- is tolerant to (late) changes in ‘pancake’ structural arrangement.

Only when the design of the hull conversion and the topsides structure lies firmly with one contract party, more integrated foundations concepts can be safely applied.

References
Figure 9: Topsides support principle