Experience Based Data for FPSO’s Structural Design
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Abstract
There is a lack of systematic data suitable for conceptual and preliminary design of ship-shaped FPSOs. At the same time, there is an increasing interest in their applications, and the number of FPSOs is growing. This combination makes the development of relevant design data both necessary and very useful. The ever growing interest in applying risk and reliability approaches in designing and inspecting FPSOs, also calls for many data inputs, ranging from corrosion rates to proven designs. Based on this, design approaches can be refined and inspection plans can be rationalized or optimized.

This paper presents some structural strength related data from trading tankers that may be used in the structural designs or selections for FPSOs. These include main dimensions of hull, design loads for different installation sites, scantlings of primary structural members, corrosion wastage and the hull girder properties of corroded hulls.

Corrosion wastage data for FPSOs is either scarce or in a format that is not very usable. The experience gained from trading tankers can be used to establish design standards and planning inspection and maintenance before sufficient corrosion data becomes available. A corrosion measurement database of 140 trading tankers is introduced. Trends are analyzed as well as discussions related to the reduction in hull girder strength over time. Some of the potential limitations of the data presented are due to the differences between tankers and FPSOs. The influences of FPSOs’ aging on the local and global strength are demonstrated, taking into account buckling and ultimate strength. Implications of corrosion on FPSO’s safety and inspection planning are presented based on time variant reliability approaches.

The collected experience based data will facilitate the development of rationalized approaches to the decision-making, FPSO selection, and inspection.

Introduction
There are approximately 85 FPSOs currently operating around the world [7, 8]. There are between 8 and 10 FPSO units coming on-line per year worldwide and 80 or more FPSOs planned or under study for future field developments [2]. Of this fleet of FPSOs, approximately 65% are converted from trading tankers, primarily older vintage single hull tankers.

Compared to the trading tankers, FPSOs have very limited experience, with an estimated total cumulative operating experience in the range of only 500 – 600 years. This is compared to other offshore installations such as fixed platforms, which have well over 100,000 combined operating years of experience with many platforms still in operation 10-20 years after their 20-year life. In comparison, FPSO installations tend to be in their infancy, with only 15% of the fleet having been in operation for more than 10 years. Because of this, there is a lack of systematic experienced based data for conceptual and preliminary design, as well as assisting in the evaluation of the long-term performance specific to ship-shaped FPSOs. At the same time, there is an increasing interest in their application, and the number of FPSOs is growing. This combination makes the development of relevant design data both necessary and very useful.

Additionally, the ever growing interest in applying risk and reliability approaches in the design and inspection of FPSOs also calls for many data inputs ranging from corrosion rates, fatigue life and coating performance. Without this detailed, high-quality data, it is difficult to assess the applicability and suitability of current design practices and maintenance schemes. Furthermore, implementation of risk and reliability based inspection techniques, which provide the scientific basis for more rational approaches to inspection planning, is currently hampered by limited data since these techniques require detailed information to develop statistical means, variances and correlations. With better data specific to FPSO’s, design approaches can be refined and inspection plans can be rationalized or optimized.

To supplement limited service performance data, trading tanker experience has provided much of the basis and framework for FPSO design, maintenance and inspection planning. By and large, the use of such data from the tanker industry applied to FPSO construction and conversion has been successful. Integrity issues such as corrosion rates, construction detail performance, coating
performance, inspection frequencies and inspection techniques are all drawn upon from trading tanker experience.

This paper presents some data drawn from an extensive collection effort of trading tankers that can be related to structural designs of FPSOs. It aims to provide reference material that can be used in design and inspection planning of FPSOs.

Principal Dimensions
The principal dimensions are determined by the application, required capacity, shipbuilder’s capacity, etc. Figure 1 shows ship length, breadth and depth of 140 single hull tankers and 46 double hull tankers, which constitute the primary data set, presented in this paper. The single hull tankers are shown as solid circles. Most of the ships are still in service and some have been or will be converted to FPSOs. The ship length ranges from 170 m to 400 m. The majority of this fleet was built in the 1970s and 1980s. Some were built in the 1960s. Those still in service are approximately 15 to 33 years old. The 46 double hull tankers are denoted by circles on Figure 1 and most were constructed in the 1990s.

For new build FPSOs, dimensions are driven by specific storage and production requirements. In Figure 1, the principal dimensions of 35 new build FPSOs [7] are shown, denoted as triangles. Except for the two small FPSOs, which fall below 120 meters in length, the breadth of the new build FPSOs tends to fall inline with the band of trading tankers. The similar breadth dimension may be attributed to shipyard experience, drawing from past tanker designs, as well as shipyard capabilities.

When reviewing the vessel depth comparisons, it is noteworthy to point out that the majority of new build FPSOs, constructed to date, tend to be slightly deeper than their trading tanker cousins. The deeper depth of the new build FPSOs is irrespective of locations (e.g., North Sea, Africa, Asia) or hull type (double hull, double sided or single hull). As one would expect, double hulls, which make up the majority of the new build FPSO fleet, are deeper than their single hull tanker predecessors. This is driven by MARPOL and ballast water requirements that must be met, and the vessel depth has to be increased. However, most of the double sided, as well as the few single hull new build FPSOs that have been constructed, tend to have slightly deeper depth than the average trading tankers. Of the two new builds that fall well below the trading tanker average depth, one vessel is operating in very shallow water depth [7] and thus it is likely that this is the primarily drive for the shallower depth.

Obviously there are no hard and fast conclusions that can be made simply by reviewing the vessel depth data; particularly since each new build FPSO represents a design that evolved from specific design site-specific conditions. However, the data does provide some upper level insight into some very general trends and many of the similarities between tankers and FPSOs.

One other observation is that, to date, no new build FPSO has had the economics to require storage capacity equivalent to the Ultra Large Crude Carrier (ULCC) which are part of the current trading tanker fleet. ULCCs are typically considered vessels in excess of 300,000 deadweight tons, which equates to vessel lengths upward of 400 m.
Hull Girder Capacity

Figure 2 shows the section modulus to the deck and sectional area of midship of the 140 trading single hull tankers and 46 double hull tankers. Section modulus to the deck is determined by the requirements for vertical bending, and is the single most important measurement of the hull girder strength of ship-shaped vessels.

The sectional area at midship, also shown in Figure 2, is based on 140 single hull tankers and 25 double hull tankers. The steel weight of a vessel can be roughly estimated by multiplying section area at midship, ship length and mass density of steel. Double hull tankers tend to be heavier than single hull tankers. The information on the midship section area, presented in Figure 2, is useful when selecting tankers for FPSO conversion candidates.

Both of these properties should be changed when a vessel is designed for designated locations, as is the case for FPSOs. As the loads of an FPSO can be determined as discussed in the Loads section, these properties change accordingly. Nevertheless, the information presented can be used as a reference, especially for converted tankers.

Taking the load issue above into account, section area of FPSOs may be different from that of tankers.

Loads

Generally, a FPSO is designed for a specific location, while trading tanker designs are based on a 20-year service in the North Atlantic. As a result, FPSOs are designed for site-specific loads.

Because of the limited experience of FPSO design, the concept, methodology, etc. of trading tankers can generally be used for FPSOs too. The site-specific loads can be formatted as percentage of those in the North Atlantic. On this comparative basis, FPSOs can be scaled to a trading tanker. Load comparisons between FPSOs and trading tankers are realized using the concept of environmental severity factors [1]. The ABS Guide for FPSOs uses environmental severity factors for 13 dominant loading parameters to address hull girder loads, ship motions, and external pressures, and 6 parameters to address the fatigue loads.

Figure 3 shows the influences of the site-specific environment on the vertical bending moments on the ship’s hull girder, based on 44 trading tankers. The 44 tankers represent both double hull and single hull types constructed in the 1980s and 1990s and are currently still in service. By varying the wave-induced vertical bending moment, environment of different installation sites is represented, and the total vertical bending moment, the sum of still-water bending moment and the wave-induced bending moment, are calculated and scaled with respect to North Atlantic environmental criteria.

The wave load is varied to 0.5, 0.6, 0.7 and 0.8 times that determined according to IACS unified wave-induced vertical bending moment for tankers. The IACS wave bending moment corresponds to a 20-year service of tankers in the North Atlantic. The still-water bending moments are based on the loading manual or design specifications of these vessels.

The total vertical bending moments are approximately 65 to 72% of the total bending moment for trading tankers for site of 0.5 wave-induced bending moment, 72 to 78% of trading tankers for site of 0.6 wave-induced bending moment, 79 to 83% of trading tankers for sites of 0.7
wave-induced bending moment, and 86 to 89% of trading tankers the FPSO total bending moment for sites of 0.8 wave-induced bending moment.

Based on analyses of wave-induced vertical bending moment developed from the select trading tankers general ranges for specific regions of the world can be developed. Some examples are provided below.

- In North Sea, the wave-induced bending moment is about 1.1 to 1.7 times that of trading tankers (or North Atlantic).
- In Gulf of Mexico, the wave-induced bending moment is about 0.8 to 1.1 times that of trading tankers.
- In Offshore Brazil, the wave-induced bending moment is about 0.5 to 0.7 times that of trading tankers.
- In West Africa, the wave-induced bending moment is about 0.3 to 0.7 times that of trading tankers.

The environment severity factor varies depending on the sites, weather conditions, etc.

Requirements for hull girder section modulus are determined based on the maximum bending moment, sum of still-water bending moment and wave-induced bending moment, and allowable vertical bending stress. This allowable bending stress of FPSOs is based on trading tanker – another example of transferring tanker experience to FPSO structural designs.

In addition to these loads, which are calculated using shipmotion programs with particular wave scatter diagrams, design limits to the minimum allowable hull girder section modulus have been specified in FPSO design standards. This concept of minimum hull girder section modulus is also derived from trading tanker design practice. IACS specifies that ships should maintain a section modulus above a minimum value that is determined by the ships’ principal dimensions. This IACS requirement is not tied with the total bending moment on a ship’s hull.

Additionally, it is necessary to introduce limits to keep the design parameters from going “too low”. These limits should reflect successful experience, not to inadvertently create a reordering of the dominant structural failure modes, and to avoid the introduction of new controlling limit states (unacceptable deflections, vibrations, etc) [1]. Establishing this limit also takes into account the transit condition when the hull is shipped from shipyard to the installation site. ABS specifies that FPSOs should not be designed below 85% section modulus required for trading tankers.

**Structural Scantlings**

Figure 4 shows the plate thickness deck plating for varying ship lengths based on the tanker fleet mentioned in the “principal dimensions” section.

Deck plating carries the stress due to hull girder bending. Scantlings of deck plates are to a large extent determined by the requirements of hull girder strength. Stresses at deck should not exceed specified allowable stress and buckling capacity of deck plates. Usually the allowable stress for vertical bending can be used for FPSOs. Generally, larger ships have thicker deck plating, as shown in Figure 4.
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The use of high tensile steel (also known as high strength steel) also has an impact on the thickness of deck plates. For ships of similar size, thinner plates can be used if the steel is of higher strength. Partly due to the extensive application of high tensile steel in the top area of tankers, double hull tankers usually have deck plates thinner than single hull tankers of similar size.

Other factors influencing scantlings include longitudinal spacing and special requirements of owners.

By combining information from Figures 3 and 4, the deck plate for a FPSO may be approximately estimated as a starting point before embarking on a detailed structural design. Given the total bending moment for a specific site, the deck plate thickness can be approximately scaled from that of a tanker. For example, assuming the total bending moment is 85% that of a trading tanker, the deck plate of the FPSO may be about 85% that of the deck when it is a tanker.

Figure 5 shows bottom and side plating thickness for varying ship lengths based on the tanker fleet database. Bottom shell plating carries the stresses induced by hull girder bending, and stresses induced from external seawater pressure and internal pressure of ballast water or oil. Combining the effects of both global and local loads, bottom and side shell thickness may also be roughly estimated, using similar approximations as described above as an initial design starting point.

Corrosion Wastage
One of the major challenges to FPSO design and operations is asset integrity management (i.e., inspection, maintenance and repair). To date there is only limited experience-based information to draw upon specific to FPSO vessels. Data related to corrosion rates, fatigue lives, coating performance and on-site repairs is limited and not generally shared among operators.

Before sufficient corrosion data becomes available on these structures, trading tanker experience provides a good starting point and source that can be used as references for FPSOs. The internal corrosion environment may be close to FPSOs, and the corrosion data from trading tankers is therefore very useful.

For trading tankers, a collective effort has been made by industry to collect experienced-based data, which has helped enhance the understanding of degradation mechanisms and improve data collection and reporting. An example of such cooperative effort is the Tanker Structural Cooperative Forum (TSCF), which has published very useful experienced based data on detail performance, repairs and observed wastage rates for different structural components and exposure environments. Similar efforts, with particular focus on corrosion wastage, have been put forth by ABS. Large amounts of gauging data for trading tankers have been collected, organized and analyzed and recently published in References 4 and 5. This collection effort is unique since it represents one of the largest corrosion databases since the TSCF collection and publications. The new database supplements the TSCF work.

Table 1 presents some general results from the corrosion database for trading tankers. The table lists the wastage of major structural members at the 20-year service life and estimated corrosion rates based on a corrosion measurement database [4, 5].
Experience-Based Data for FPSO Structural Design

The corrosion observations, such as those presented in Table 1, provide a useful starting point in predicting corrosion performance of FPSOs; however, there are noteworthy differences between a FPSO and a trading tanker. Specifically, the operating conditions of an FPSO can differ significantly from a trading tanker. Some differences between an FPSO and trading tanker that may influence degradation mechanisms such as corrosion include:

- Higher offloading frequencies
- Greater potential for continual cargo issues (e.g., wax build-up or high hydrogen sulfide content, etc.).
- No scheduled dry-docking for inspection, maintenance and repair (IMR).
- Different loading conditions and ballasting requirements.
- Potential thermos bottle effects for double hull vessels.

Furthermore, limits to the minimum allowable hull girder strength also provide a means to take into account the inevitable corrosion risks. Trading tankers have exhibited possible strength reduction of about 10 to 16%, as shown in Figure 6. The same level of strength reduction may also need to be taken into account at the design stage for new build FPSOs [4].

![Figure 7. Annual reliability index of a stiffened panel at a tanker’s bottom for different corrosion levels [4]](image)

Figure 7 is the estimated time-dependent annual reliability index of a stiffened panel [4]. This panel is at the bottom of a cargo hold of a single hull tanker, 232 meters in length. The assumed three corrosion levels are based on corrosion wastage measurements.

The loads acting on the bottom panel are in-plane compression due to vertical bending and lateral loads due to water pressure. The ultimate strength of the panel is calculated and compared with the external loads. It is assumed that the plates are replaced at special surveys.

### Table 1  Corrosion wastage of structural members in oil tankers [4, 5]

<table>
<thead>
<tr>
<th>Structure</th>
<th>Tank</th>
<th>Wastage at 20 year (mm)</th>
<th>Corrosion rates (mm/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean value</td>
<td>Deviation</td>
</tr>
<tr>
<td>Deck plating</td>
<td>Cargo</td>
<td>1.096</td>
<td>1.564</td>
</tr>
<tr>
<td></td>
<td>Ballast</td>
<td>1.020</td>
<td>0.771</td>
</tr>
<tr>
<td>Side shell</td>
<td>Cargo</td>
<td>0.789</td>
<td>1.048</td>
</tr>
<tr>
<td></td>
<td>Ballast</td>
<td>0.662</td>
<td>0.504</td>
</tr>
<tr>
<td>Bottom shell</td>
<td>Cargo</td>
<td>1.678</td>
<td>1.795</td>
</tr>
<tr>
<td></td>
<td>Ballast</td>
<td>1.099</td>
<td>0.984</td>
</tr>
<tr>
<td>Longitudinal bulkhead plating</td>
<td>Between cargo</td>
<td>0.704</td>
<td>0.623</td>
</tr>
<tr>
<td></td>
<td>Others</td>
<td>0.701</td>
<td>0.564</td>
</tr>
</tbody>
</table>
when falling below thickness requirements of classification societies. The spikes in Figure 7 reflect the effects of plate renewal.

If corrosion remains low, inspections at five-year intervals will be sufficient, and no plate renewals are needed for more than 30 years. When experiencing a moderate level of corrosion, inspections at five-year intervals appear to be sufficient for maintaining the reliability index at a reasonable level, though plate renewals are expected after 30 years in service. When experiencing a severe level of corrosion, inspections at five-year intervals may not prevent the reliability index from becoming too low. The reliability index can decline quickly, and the drop during a 5-year period can be significant, as shown in Figure 7. In order to maintain enough margin when severe corrosion is anticipated, inspection intervals shorter than 5 years may be warranted.

For FPSOs, managing corrosion is critical, for unlike trading tankers that undergo scheduled dry-docking; an FPSO must remain on site for the duration of the field life, generally 20-30 years without dry-docking. If “severe” corrosion occurs, similar to what is depicted in Figure 7, the repair costs can easily soar in excess of 5 times that of similar repair costs at a dry-dock or more depending on the difficulty of the repair while afloat. Compounding this is the fact that such repairs can impact production operations by reducing storage capacity and restricting activities during the repair. Therefore, initiating plating renewals while on site for an FPSO, such as what is shown in Figure 7, would be an undesirable response to managing corrosion. For FPSOs, planning and contingencies to prevent such events must be implemented during the design and construction phase of a new build or conversion. This may include the implementation of a stringent coating program (e.g., strict surface preparation requirements, well defined and enforced application conditions, appropriate coating application schedules [i.e., sequencing and amount of time to complete work], etc.) as well as possibly the use of more steel (i.e., increased wastage allowances) at specific locations in the case of a new build FPSO.

Conclusions
This paper presents some structural strength related information drawn from an extensive collection of experience based trading tanker data that may be useful for the design of new build FPSOs or in the selection of conversion candidates. These include main dimensions of hull, design loads for different installation sites, scantlings of primary structural members, corrosion wastage, and hull girder properties. It aims to facilitate, with useful experience data, the development of rationalized approaches to the decision-making, FPSO selection, and inspection. The paper also highlights the current need for a more concerted effort within industry of the collection and dissemination of experience based data specific to FPSOs, similar to the works that have been done on trading tankers. Because of the similarities between tankers and FPSOs, the application of tanker data has been generally successful however, just as tanker designs have evolved over the years, drawing upon actual operational experience, so will FPSO designs. As information on the in service performance of these structures becomes available and is organized and presented in useful forms, more informed decisions and optimizations can be made related to FPSO design and integrity management.

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References