1.0 ABSTRACT
This paper describes the discovery, investigation and repair of local cracking in the tank structures of the FPSO Kuito. The cause of cracking was investigated through a Spectral Fatigue Analysis supported by a fractographic examination. The investigation attributed the cracks to fatigue resulting from a combination of the trading history of the vessel, and high stress ranges experienced during the loading and offloading cycle in FPSO service. The paper also describes the use of the analytical results in developing modifications to the details concerned. The approach adopted was to reduce stress concentration factors and so avoid recurrence of cracking by fatigue. Information is given on the procedures adopted to execute this work offshore. Repair and modification of the connection details will require the addition of 13 tonnes of steel in total.

2.0 INTRODUCTION
Single Buoy Moorings, (SBM), operate a fleet of fifteen FPSO’s & FSO’s worldwide. One of these units, the FPSO Kuito, has experienced local cracking in bottom brackets and in the connections between longitudinal stiffeners and oil tight bulkheads. This paper describes the discovery, investigation and repair of these cracks. Modifications made to the connections to avoid recurrence of the problem are also described.

The vessel was constructed in 1979 by Seatrain Shipbuilding Corporation, Brooklyn Navy Yard, as the SS Bay Ridge. She traded for 16 years as a tanker prior to conversion to an FPSO by SBM. The trading history comprised three main phases:
• 10.5 years on the Trans-Alaska Pipeline System (TAPS) trade route.
• 2 years worldwide trading
• 3.5 years laid up

The conversion of the Bay Ridge into an FPSO took place at Sembawang Shipyard in Singapore during 1998/1999. Since that time the FPSO has been located offshore Angola on Block 14, operating on behalf of ChevronTexaco. The particulars of the Unit are given in Table 1. Production began on the 22nd of December 1999, and at present the production rate is approximately 65,000bbls of oil per day. Oil is offloaded to export tankers via a CALM buoy at approximately 13 day intervals.

Table 1: FPSO Kuito Particulars

| Mooring Lines | 4 groups of 3 lines |
| Water Depth   | 383m |
| Length BP     | 319m |
| Molded Breadth| 43.8m |
| Molded Depth  | 27.7m |
| Displacement  | 264,284 tons |
| Tank Arrangement | 5 center tanks 14 wing tanks |
| Class          | ABS |

Figure 1: FPSO Kuito

The views expressed in this paper reflect those of the author, and are not necessarily those of the American Bureau of Shipping.
3.0 NOMENCLATURE
CaN - Calcium Napthenate
COT - Cargo Oil Tank
L/O - Loading and Offloading
SFA - Spectral Fatigue Analysis
TAPS - Trans-Alaska Pipeline System
WIF - Wave Induced Fatigue

4.0 DISCOVERY AND EXTENT OF CRACKING

4.1 Discovery

During the second quarter of 2001 the Kuito cargo department noted migration between No. 2C COT and No. 3C COT. Inspection in No. 3C COT revealed a weld crack on the centerline girder.

SBM’s Asset department then mobilized to the unit to inspect the crack and prepare a repair procedure, and also performed a detailed inspection of No. 3C COT. This inspection revealed that the tank had a widespread problem with local cracking, and 21 cracks were identified in addition to the weld crack on the centerline girder. The type of defects and locations are detailed in a later section of this paper.

The initial postulation was that the cracking was due to fatigue resulting from high stress concentrations in the poorly designed bracket and connection details, exacerbated by poor construction features. This implied that similar details in other tanks were likely to be exhibiting the same problem. It also seemed probable that in order to prevent recurrence of the cracking, brackets and connection details would need to be modified and construction defects removed.

In January 2002, No. 2C COT became available for inspection and 24 cracks were identified in this tank, supporting the view that cracks would be present in connection details along the full length of the unit.

Further to this inspection, the situation was re-evaluated with the following initial conclusions:

- The emerging defect profile identified a problem potentially extending throughout the cargo block. The initial anticipated total was in excess of 300 defects based on a profile of 20 per tank, but inspection of all tanks would be necessary to ascertain the actual number of defects.
- The type of defects and their location did not compromise the units structural integrity or the safety of the operation, nor did they pose any environmental risks (no defects in the side shell or bottom plate).
- Coupons containing cracks should be removed from the unit to allow the crack surfaces to be examined to confirm that the failure mechanism was indeed fatigue.

- Fatigue analysis should be undertaken to determine the source of the damage, and to assist in determining a scope of work for repairs and modification to the details concerned.
- Loading and Offloading
- Whilst developing the final repair and modification plan, a program of initial repairs should be commenced to address Class and Flag issues. These repairs would be progressed on the basis of repair to as-built, but removing construction defects. Weld quality would also be improved by the use of full penetration welds in-lieu of fillet welds.
- The repair of the know defects would be achievable without loss of production.
- The presence of calcium napthenate (CaN) in the tanks was such that a major cleaning campaign would be required in each tank as part of the repair works.

The development of the scope of the analysis work and the final scope of modifications and repairs are discussed in later sections of this paper.

4.2 Defect Locations and Types

The basic construction form of the FPSO Kuito is a longitudinal ring stiffener system that comprises two deep girders either side of the centerline girder, which are the same depth as the centerline girder. These girders are located at 16’ and 58’ off center, i.e., there are three girders in the center tank and one in each wing tank. The transverse bulkheads are supported by deep girders and the loads are transferred to these bottom and deck longitudinal girders. There are no stringer flats in this construction.

The type of defects experienced can be clearly divided into three major categories: Transverse brackets, longitudinal brackets and bulkhead penetrations.

4.2.1 Transverse Bracket Defects

The transverse bracket defects are located at one of the three brackets locations either side of the centerline on each web frame. These defects are generally toe cracks initiating in way of installation shackle holes that are a common poor construction feature present within the tank structure. Figure 2 shows a typical defect.

The size of cracks at the transverse brackets are generally less than 100mm in length.

Figure 2: Typical Transverse Bracket Defects
The transverse bracket construction detail is particularly stiff in way of the toes with a steep flange snipe angle, indicated in Figure 3.

Figure 3: Typical flange detail on transverse brackets

### 4.2.2 Longitudinal Bracket Defects

The Longitudinal bracket defects are located on the brackets between the deep longitudinal girders and the deep vertical bulkhead girders. These defects are generally toe defects, however in a small number of locations, heel defects are present. Figure 4 indicates typical defects.

![Figure 4: Typical longitudinal bracket defects](image)

The size of the longitudinal defects varied from a few hundred millimeters to the full length of the bracket.

### 4.2.3 Bulkhead Defects

The bulkhead defects represent the most numerous of the defects found on the vessel. These are generally located on the penetration details of the longitudinal stiffeners of both the side shell and longitudinal bulkhead. Defects were also identified on a small number of bottom longitudinal penetrations in way of removed valve penetrations. Figure 5 indicates typical bulkhead defects.

![Figure 5: Typical bulkhead defects](image)

5.0 INVESTIGATION OF CAUSE OF CRACKING

A number of possible causes were postulated for investigation. The first was that the cracks were the result of damage experienced during the trading history of the vessel. The TAPS route has very severe weather, particularly when compared to the benign conditions of the Kuito station on Block 14, and if the fatigue damage was the result of wave loading, this would be more likely to have been a result of the TAPS trade, exacerbated by high stress concentration due to the poor detail design of some of the vessel structural connections.

The second possibility was that the cracking was due to an aspect of FPSO design or operation that was different from the configuration or practice of a tanker. Two possibilities were identified. The first was the influence of the topside weight (4000 tonnes in total), and the second was the effect of the loading and unloading cycle. During operation as a tanker, the vessel was fitted with sluice valves, allowing all tanks to fill simultaneously. For additional...
service as an FPSO, these valves have been removed and the tanks now fill sequentially, causing a differential head on the oil tight bulkheads.

The possible causes of cracking were investigated through the fatigue analysis methodology described in the following section. This analysis was supplemented by a full review of Class records to allow past patterns of cracking to be compared with the pattern of cracking observed on board, and by the removal of coupons containing cracks to allow the crack surfaces to be examined.

5.1 Fatigue Analysis

Inspection of crack surfaces by The Welding Institute in the UK has confirmed the mechanism of crack growth to be fatigue, supporting the appropriateness of fatigue analysis as a means to investigate the root cause of cracking.

5.1.1 Introduction to the analysis

Fatigue analysis of the KUITO was performed with the ultimate objective of supporting efforts to implement robust repairs and modifications. Generally fatigue analysis is undertaken during design, and the methodologies usually applied reflect this. In the present case the focus of the analysis was quite different. This required that the methodologies applied had to be modified and adapted to suit the objectives. In order to establish a level of confidence in the methodologies it was also necessary to demonstrate that the analysis successfully predicted observed fatigue cracking, particularly during the vessel’s life as a trading tanker.

The primary methodology applied was spectral fatigue analysis, which is generally regarded as the most accurate of available techniques for predicting fatigue caused by waves. Spectral methods are used to model the waves, the subsequent loading and the resulting response. Spectral methods were applied in estimating wave-induced fatigue damage of the vessel during both its life as a tanker and as an FPSO facility. The fatigue damage caused by loading and offloading during FPSO operations was also estimated, and for this source of cyclic loads other methods were used to characterize the loading.

The focus of the analysis was connections in the cargo block. The calculation of the stresses relies on a finite element model of the entire vessel, and a limited number of fine mesh models. The latter have very fine meshes in the vicinity of potential crack initiation sites. Every connection has several such sites. Analysis of the fine mesh models ultimately yields estimated fatigue lives for each site considered. These fatigue lives are then used as a starting point for estimating fatigue lives for similar connections elsewhere in the cargo block using spectral fatigue analysis of the entire vessel.

An important input into the analysis was the historical records of fatigue cracking in the vessel. These were important in two respects. First, the records could be used to establish the validity of the methodologies applied in this project and second, the patterns of fatigue cracking could be used as a guide to focus analysis efforts to the regions of primary interest.

Spectral fatigue analysis methodologies comprise many steps and are computationally extensive, and limitations of space do not allow a description in this paper. A detailed description is presented in guidance published by the American Bureau of Shipping [a]. Some modification was made to the standard approach to render it suitable for the present project. Principal among these modifications was the use of the mean S-N curve when comparing predictions with observations of fatigue cracking. (For design purposes the S-N curve is derived by subtracting two standard deviations from the mean of the data, in effect applying a safety factor. This is the basis of S-N curves presented in standards and codes used for fatigue assessment during the design phase of ship and offshore structures).

5.1.2 Scope of Analysis

The following connections were selected for detailed study:

1. Bottom transverse brackets in wing and center tanks
2. Struts in wing tanks
3. Bottom girder longitudinal brackets connections to swash bulkheads in wing tanks
4. Side shell and longitudinal bulkhead stiffener connections to oiltight transverse bulkheads, swash bulkheads, and typical web frames
5. Bottom girder longitudinal brackets and bottom longitudinal stiffener connections to oiltight transverse bulkheads and typical frames in wing tanks
6. Bottom girder longitudinal brackets and bottom longitudinal stiffener connections to oiltight transverse bulkheads and typical frames in center tanks
7. Deck transverse brackets in wing and center tanks
8. Deck girder longitudinal brackets at oil tight and swash bulkheads in center tanks
9. Deck girder longitudinal brackets connections to swash bulkheads in wing tanks

The connections listed above were represented in six local fine mesh models. Part of a typical model is shown in Figure 6 and includes Connection No. 1 listed above. Fatigue lives are calculated for all potential crack initiation sites, indicated by letters in the figure. Once the spectral fatigue analysis is performed for a local model it is possible to extrapolate these results to all other similar connections elsewhere in the cargo block. This process is performed using the spectral analysis performed on the global model together and the stress concentration factors derived from the local model. The results of the extrapolation process for the bottom transverse brackets shown in Figure 6 are illustrated in Figure 7.
The spectral fatigue analysis methodology is only suitable when the loading can be represented in spectral form. This is not the case for fatigue caused by the loading and offloading process associated with FPSO operations. The loading and offloading process was represented by a series of ten stillwater cases from which cyclic stresses were computed for all fatigue sites. Once the cyclic stresses were calculated the usual procedures were applied.

The primary difference between the vessel in the tanker configuration and in the FPSO configuration is the addition of the module structures. Their effect was, of course, taken into account in calculating motion and wave loading. Overall, however, their influence on fatigue performance was negligible.

The same extrapolation procedure used with the spectral fatigue results was applied for the loading and offloading results.

5.1.3 Results and Discussion

The first set of analyses performed was for the vessel as a tanker in which configuration it operated for about 12 years. The results were compared with the crack data gathered during surveys. The agreement can reasonably be characterized as good in the context of fatigue analysis. Compared with other failure modes the prediction of fatigue behavior is the most uncertain. This is mainly because the fatigue of welded connections is known to be sensitive to a large number of parameters, many of which are not explicitly considered in the analysis; the most relevant such parameter is weld quality.

While overall agreement was good there were differences for certain connection types. The analysis predicted that more longitudinal connections to oil tight bulkheads should have failed than in fact did. The general trends, however, are correct. The analysis predicts more failures for side shell connections than for longitudinal bulkhead connections, consistent with observations.

Some of the other discrepancies can be explained by very high stress concentrations factors for several of the details as noted earlier. Even under stillwater conditions certain of the large bottom brackets exhibit high stress levels at bracket toes. While high stress levels above yield are expected in the vicinity of structural discontinuities such as toes of brackets, the analysis indicated that several of the details have large regions of stress in excess of yield. Since the analysis was based on assumptions of elastic behaviour, the precise size of these regions could not be estimated. Nevertheless, it was clear that the high stress regions in some cases were several plate thicknesses in
extent, which is greater than would be expected in a well-designed detail.

The results were used to design modifications taking due account of the distinction between joints that were predicted to fail because of fatigue and those that might be expected to suffer local fracture due to the high stress regime. Therefore, the repair strategy, as explained below, entailed in some cases simple repairs to the as-designed condition, and in others a redesign of the detail to reduce the stress concentration factor.

6.0 SOLUTION ADOPTED

6.1 Conversion of analysis into modification scope

A number of modifications to connection details have been implemented to prevent the recurrence of cracking. The scope and form of the modifications were based primarily on screening of the SFA results, together with industry experience of successful connection modifications [b]. The philosophy adopted was to reduce fatigue damage by reducing stress concentrations. This has been achieved through local modifications to the poor bracket and connection details.

Three criteria employed in the screening:

- Any detail having a life of less than 40 years under TAPS loading using the mean S-N curve, ie approx 14 years on the design S-N curve, should be modified, and the modified detail should be designed to give a minimum life of 10 years under the TAPS loading case.
- Any detail having a life of less than 200 years on the mean S-N curve under the loading and offloading cycles should be modified to give a 200 year life. This high life requirement was selected because of the unreliability of the S-N approach when applied to the high stress ranges determined by the analysis, ie up to 3 times yield.
- Any detail having stresses range above 0.9 of yield under the loading and offloading cycles should be modified to reduce stresses below 0.9 of yield. This approach was taken because as noted earlier, stresses at some bracket toes under these conditions were not localised, but extended over an appreciable zone of the brackets. Low cycle fatigue and ductile tearing are both potential concerns in this situation.

Most details that failed the screening due to the fatigue criteria for loading and offloading also failed under the wave loading criteria. All of these details also failed the criteria for stress levels.

Based on the screening, three principal groups of details required modification: Bottom transverse brackets, bottom longitudinal brackets, and connections of sideshell and longitudinal bulkhead longituqnals to transverse bulkheads. Not unexpectedly, these are the same details that have exhibited cracking.

Three types of modification were developed as described below.

6.1.1 Modification to Wing Tank Transverse Brackets

The flange is cut back and tapered, and a radius added to the web as shown in Figure 8. Finite element modelling demonstrated that this modification reduces the stress at the toe by 45%.

Figure 8: Cut back and tapered flange, radius added to web

6.1.2 Modification to Center Tank Brackets and Wing Tank Longitudinal Brackets

The flange is cut back and tapered, and a rider plate is added to extend and soften the bracket toe, as shown in Figure 9. Finite element modelling demonstrated that this modification reduces the stress at the toe by 60%.

Figure 9: Flange tapered and rider bracket added

6.1.3 Modification to Bulkhead Penetrations

The aft side of the bulkhead connection detail is modified by the addition of a lug plate to provide continuity between the longitudinal stiffener and the transverse bulkhead stiffener, as shown in Figure 10. A soft nosed bracket is added to the fwd side of the bulkhead to further reduce stresses at the penetration, as shown in Figure 11. These modifications together reduce the stress at the critical location by 70%.

Figure 10: Lug plate added
6.2 Work Arrangements onboard

Over the past 30 years SBM has gained considerable experience of hot work and tank repairs on operational FPSO’s & FSO’s, and to date have renewed in excess of 500Té of steel on a variety of units and under a variety of operational conditions.

The feedback from these operations has resulted in the progressive development of hot work procedures defined within SBM’s Safety and Environmental Policy, (SEP), under which all hot work is conducted.

The basis of hot work procedures within the cargo tanks can be summarised as follows:

- **Hot work within a tank at a distance greater than 500mm from a live bulkhead.** The tank must be clean and gas free. The work face and accesses must be safe, well ventilated, and lit to permit safe working standards to be met. This last requirement is applicable to all subsequent cases. In this instance it is not a requirement to address the condition of adjacent tanks.

- **Hot work within a tank within 500mm of a live bulkhead.** The live bulkhead is to be made safe. This can be addressed in a number of ways: The adjacent tank or tanks can be washed and gas freed; washed and inerted; or a water barrier with a surface at least 2m above the hot work site may be used.

- **Hot work on a bulkhead.** In this case both tanks must be clean and gas free. If hot work is within 500mm of other tanks, but entry is not required to these, they may be cleaned, inspected and re inerted.

A further restriction is a maximum personnel limit within a tank of twelve persons. This limit was set on the basis of a risk assessment of emergency evacuation and rescue procedures.

In consequence of these SEP procedures, the workflow in each tank includes the following phases: cleaning, set up, second stage cleaning, modifications and repairs of internal details (primarily brackets); and modifications and repairs of tank corner details (primarily connections of longitudinal stiffeners to transverse oil tight bulkheads).

6.2.1 Project Team Setup

The tank repair work is treated as a project. Project management is performed by SBM Monaco, and offshore supervision is the responsibility of a project supervisor assisted by two shift supervisors, one on day shift and one on nightshift. In addition to the unit safety officer, there are also two independent safety officers dealing specifically with the tank safety issues, one on day shift and the other on night shift. The client also has a safety observer on board.

The onboard team is responsible for the day to day running of the project with support provided by the unit, the shorebase, and SBM Monaco.

36 beds are allocated to the project, allowing for a day shift crew of 19 and nightshift of 17. However, demands on bed space are high, and the full complement of beds is not always available.

6.2.2 Working Practices

The implementation of the repairs and modification follows the same approach on a tank-by-tank basis.

Initial cleaning of a tank is first by crude oil washing followed by water washing, generally in a double cycle. After gas freeing, the cleaning crew and electricians are mobilized along with the scaffolding crew.

The electricians and cleaning crew first locate the fans and lighting to provide safe access to the tank. The cleaners then start demucking the bottom of the tank whilst the scaffolders install safe access ways and scaffold towers to provide access to the bulkhead and items at height. The structural layout of the tank is such that scaffolding and cleaning operations can be conducted simultaneously in a safe manner. Electricians then installing local lighting as required by the supervisors and safety officers.

Once the bottom is cleaned, which has entailed digging out up to 200 m³ of CaN, the cleaning crew is demobilized and replaced by the construction crew. At this time the second stage of local cleaning for hot work is begun in the relevant areas.

On completion of the local cleaning, the construction crew commences the set-up for hot work, running welding cables, air lines and ventilation ducting to the cleaned site, and erecting fire blanket screening for spark control, if required. High performance electric fans suitable for use on an FPSO have been developed in collaboration with a fan manufacturer. These fans operate at 1700Pa and 6m³/s, and the project employs a minimum of two of these fans per tank during the hot work.

Once the set up for hot work is completed and the relevant inspections and verification procedures have been successfully completed, the hot work begins in accordance
with the approved hot work procedure. An integrated plan of repairs and modifications has been implemented, and repairs and modifications to a detail are carried out as part of the same procedure.

On completion of the work in each tank, and also at points during the repairs, inspections are made by ABS and by independent NDE personnel to verify that the repairs have met the required standard.

Once all work in a tank is complete, all scaffolding and materials are removed, and the same process is then followed in the subsequent tank.

During the period of work in each tank there can be a number of stoppages to the hot work, e.g. suspension during offloads, cargo transfers, and bunkering. The cargo transfers and bunkering are usually completed during meal and shift change times to minimize the impact. However, these stoppages can still amount to almost 30% of the total time in a tank.

7.0 SUMMARY AND CONCLUSIONS

The repair and modifications to the tank structures of the FPSO Kuito will result in the addition of approximately 13 tonnes of steel. Despite the technical difficulties associated with hot work within the tanks of a producing FPSO, the repairs and modifications are themselves uncomplicated. The simplicity and repetitiveness of the developed solutions enables a high standard of workmanship to be maintained throughout. All repairs and modifications are subjected to 100% NDE and to date there have been no weld defects identified and only two cases of remedial grinding.

The long term operation of FPSOs and FSOs inevitably requires maintenance interventions to the vessel structures. Industry experience has shown that this is applicable to both newbuildings and converted tankers. However, in order to minimise these interventions, it is important that the experience gained during operation is fed back into the design of future Units.

A number of conclusions of general applicability can be drawn from the experience of cracking on the FPSO Kuito.

- The primary cause of cracking on the FPSO Kuito is the fatigue damage sustained during trade on the TAPS route. Trading history is a primary consideration when selecting a vessel for conversion. Stresses experienced during the loading and unloading cycle have also contributed to this damage. The effect of the loading and unloading cycle on local stresses should be considered, both with regard to fatigue damage, and tearing or fracture.
- Screening methods need to be developed to identify details that will be prone to failure under the loading and unloading cycle.
- The interaction of wave loading and the loading and unloading cycle merits further investigation by the industry.
- 3-D finite element analysis is needed to capture the local stresses in non-standard details for use in fatigue analysis.
- Local stress reduction and large increases in fatigue life can be achieved by local modifications to details.
- Long fatigue lives can be achieved for converted tankers with suitable details.

8.0 ACKNOWLEDGEMENTS

The authors wish to thank ChevronTexaco for their agreement to the publication of this paper.

9.0 REFERENCES
