Structural Analysis and Modifications - 2 Tankers for Offshore FPSO and FSO Service

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Abstract

This paper addresses the unique structural requirements for successful conversion of tankers for FPSO or FSO service. A description is given of the steps undertaken during two recent and very different conversions of a highly optimized 1980's VLCC to FPSO service, and a typical robust 1970's ULCC to FSO service. The paper describes the steps needed for ensuring the FPSO or FSO requirements are successfully met during conversion of the two tankers – each having its own history, e.g. date of build, original design, material choices, class society, voyage history, and repairs. First, the paper describes the procedure and results of an early initial structural assessment procedure based on an ABS Phase A analysis, past tanker voyage history, and a review of past survey records and thickness gauging data. Secondly, the paper describes the procedure and results of a detailed structural finite element analysis of the two vessels considering past tanker service and future FPSO or FSO service, including the effects of on and off loading of crude oil. Since the abstract was first written, a third FPSO, of similar configuration to the 1980's FPSO described in this paper has been analyzed with the same procedure.

Keywords

FPSO or FSO Vessels; Floating Production Storage and Offloading; Conversion Engineering, Structural Design and Assessment; Spectral Fatigue Assessment; Advanced Finite Element Analysis; Classification Calculations, Repair Methods

Nomenclature

ABS	American Bureau of Shipping
B	Moulded Breadth
BHD	Bulkhead
BT	Ballast Tank
CB	Block Coefficient
CL	Centerline
CT	Cargo Tank
D	Hull Depth
DNV	Det Norske Veritas, FPSO Package
FEA	Finite Element Analysis
FEMAP	Finite Element Pre/Post Processor by UGS
FPSO	Floating Production Storage and Offloading
FSO	Floating Storage and Offloading
HGSA	ABS Hull Girder Strength Program
HHI	Hyundai Heavy Industries
HTS	High Tensile Steel
LBP	Length Between Perpendiculars
LOA	Length Overall
LR	Lloyd's Register of Shipping
NKK	Nippon Kaiji Kyokai
NX	NX Nastran Finite Element Solver by UGS
PHASEA	ABS SafeHull Program, Version 10.0
SAGA	Structural Assessment Graphical Assessment program developed by Viking Software, Inc.
SEAS	ABS Environmental Loading Program
SH	Single Hull
t	Metric tonnes
VT	Void Tank
WT	Wing Tank

Introduction

MODEC International, LLC has recently converted two tankers to operate as FPSO or FSO offshore Brazil, both projects supported concurrently with structural conversion engineering by Viking Systems, Inc. The FPSO vessel was converted from an existing single hull VLCC built at a Japanese shipyard in 1986, and the FSO vessel was converted from a single hull ULCC built at a US shipyard in 1979. As is evident in the next sections of this paper, the results of the conversion analysis procedures are vastly different for the two vessels, primarily due to the differences in design and build histories. The impact on the shipyard conversion process is also vastly different for the two vessels, however, as is seen in the paper a suitable tanker from each of the tanker generations of the 1970's and 1980's can be converted successfully by taking proper detailed care during the inspection, structural analysis, and conversion process. An important lesson learned is that for optimized designs, analysis work should be started as early as possible, and must include feedback from close up inspections.

Description of Conversions

Tanker Vessel Principal Characteristics

The two original tanker vessels are described in Table 1. The VLCC (see Fig. 1) is a typical mid 1980's tanker employing a larger amount of high tensile steel for the longitudinal structure as well as portions of the transverse structure. The tank arrangement uses a typical 5 tank layout in the length direction and three tanks across the breadth. See Fig. 2 for a view of the tanker and converted FPSO tank arrangements.

Table 1: Tanker Basic As Built Data

Tanker	VLCC SH	ULCC SH
Conversion	FPSO	FSO
LOA	322 m	362 m
LBP	310 m	348 m
B	58 m	69.5 m
D	29.5 m	29 m
CB	0.81	0.84
Displacement	300,000 t	460,000 t
Frame Spacing	5.950 m	5.461 m
Longest Tank (CT/WT)	47.6 /59.5m	21.8 /43.6m
Year built	1986	1979
HTS (approximate)	75%	45%
Original Class	NKK	ABS
Yard	Japan	US

The ULCC tanker (see Fig. 3) is of a typical late 1970's type employing high-tensile steel only for the deck and bottom structure and the upper and lower portions of the longitudinal bulkhead and side shell, whereas the transverse structure is built from mild steel of heavy construction.

Fig 1: Spreadmoored FPSO

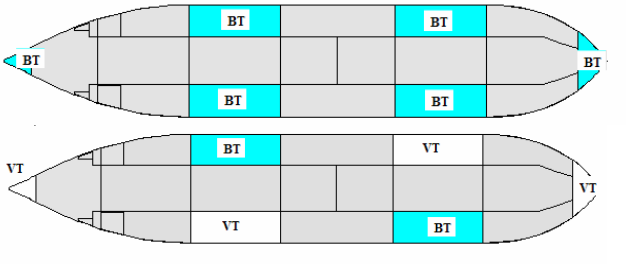

Fig 2: Tank Arrangement (Tanker / FPSO)

In addition, the tank arrangement as shown in Fig. 4 uses 13 short wing tanks in the length direction, and three tanks across the breadth.

FPSO or FSO Vessels Principal Characteristics

The principal characteristics of the two vessels, as converted, are summarized in Table 2.

Table 2: FPSO or FSO Basic Conversion Data

	FPSO	FSO
LOA	322 m	409 m
Topsides	10,000 t	2,750 t
Mooring	Spread-moored	External Bow Turret
Design Life (years)	12	25
Fatigue Safety Factor	1.0	2.2
Class	ABS	ABS
Year Re-delivered	2006	2007

The FSO was fitted with a large SOFEC external turret. See fig. 4 for a photo of the FSO.

Fig. 3: FSO with External Turret

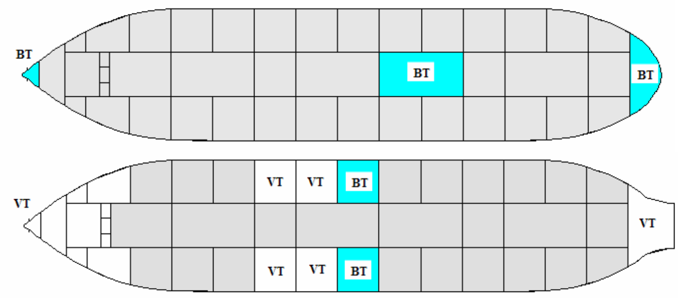

Fig 4: Tank Arrangement (Tanker / FSO)

The FPSO was converted from a tanker with 75% of its construction steel in HTS grades including 100% of the longitudinal structure constructed from HTS. As a contrast, the FSO was converted from a tanker with 45% of its construction steel as HTS with all transverse material of mild steel.

Conversion Engineering Approach

Initial Scantling Assessment Method

Both vessels were initially analyzed using the ABS Phase A program with its supporting environmental loading program SEAS. Phase A was used to assess global and local strength, using the design still water bending moment and the site environmental loads as calculated by the program SEAS. The resulting FPSO scantling requirements are used to develop the renewal scantling at conversion incorporating the future corrosion values expected during the FPSO service life.

The longitudinal strength was assessed with the ABS program HGSA to develop the FPSO allowable shear force and bending moments curves. Generally, the tanker allowable values for still water shear force and bending moment are maintained for FPSO service, except at locations where the ABS rules required a reduction, or where FPSO service required an increase.

In addition, the fatigue strength of longitudinal stiffener end connections is verified by using the Phase A program to calculate the damage expected during the tanker phase of the vessel life as well as the fatigue damage predicted by using the site loads as calculated by the ABS SEAS program. The outcome of the fatigue calculation is a value representing the remaining fatigue life for each longitudinal stiffener.

The Phase A analysis can typically be completed in about a month which allows evaluation of candidate tankers and development of repair and modification plans at an early stage of the projects

Survey Report Data Collection

The authors have used a method to visualize damage reported via class survey reports. Each damage situation is plotted electronically onto a schematic drawing using symbols corresponding to the type of damage (crack in web, crack on bracket, corrosion, buckling, denting, etc). This set of drawings of each major structure group, e.g. bottom, side shell, longitudinal bulkhead, deck and transverse bulkhead proves very useful to ensure that the shipyard conversion team is aware of past damage, and it becomes an invaluable tool for the design and analysis as an easy-to-access visual collection. The engineering team is then able to determine the locations of damage, the type of repair, and whether a repair has been successful. See Fig. 15 as an example.

The survey data is used to correlate the results of both the fatigue screening analysis and the detailed fine mesh FEA based spectral fatigue analysis (see later in this paper for description of fatigue assessment).

FEA Direct Analysis Assessment Method

Both vessels were assessed using a series of advanced FEA based analysis tools consisting of the DNV FPSO Package, Viking Software's computer program SAGA, FEMAP, and NX Nastran.

For each vessel, two Nastran finite element models are constructed using SAGA to represent the tanker vessel in its original configuration using as-built scantlings, and a model representing the FPSO configuration with scantlings equal to those expected at the end of the service life. It is recommended that the entire cargo block is modeled in order to capture the complete effects resulting from FPSO loading cases. This is especially true in the case of the FPSO conversion described in this paper due to the use of non-symmetric loading of ballast tanks. We believe the transition between the cargo block and the end structures are proven in tanker service, so that a full length model is not required for a conversion. The authors develop highly accurate coarse mesh style models using one element between longitudinal stiffeners and approximately five to six elements between transverse frames in order to accurately model web frame tripping brackets, docking brackets, and bilge brackets and to be able to maintain aspect ratios near unity. The models are made with SAGA's shell meshing capability to rapidly and accurately model the entire bottom, side shell and deck structure as defined by the shell expansion and main deck drawings.

Each model is loaded with loading cases representing the tanker's full and ballast loading cases, as well as approximately seven operating cases specific for the FPSO design agreed with class. Unlike tankers, converted FPSO's may have minimum drafts less than those resulting from IMO segregated ballast, and significantly less than the load line draft. See examples, Table 3

Table 3: Tanker vs. FPSO/FSO Drafts

Tanker	VLCC / FPSO	VLCC / FPSO	ULCC / FSO
Min Draft, Tanker (m)	10.090	9.980	13.128
Min. Draft, FPSO (m)	7.876	7.582	6.393
Max. Draft, Tanker (m)	19.880	19.290	22.860
Max. Draft, FPSO (m)	20.242	13.420	20.365

The FPSO design cases are constructed so as to stress each structural member to the maximum 100-year return value of its dynamic loading component at the location of interest by using DNV's frequency domain program WADAM. The loads are obtained by determining the wave height, wave period and wave heading that maximizes the dynamic component. The corresponding loads are applied as pressures for external sea and internal tank loads, as well as six degrees of freedom accelerations. The locations of interest are defined as the locations where the still water loading and the dynamic loading add to produce a maximum design value. Since the model consists of the cargo block only, additional global shear forces and bending moments are applied to the cut sections of the model in both the vertical and horizontal directions. Alternatively, the entire vessel can be modeled with a slight impact to schedule.

For the vessels described in this document, the resulting stresses are assessed against the ABS Steel Vessel Rules for yielding and buckling. This otherwise laborious task has been automated by using the features of SAGA to determine extents of all panels of the model, irrespective of mesh size, to carry out both plate buckling and stiffener buckling calculations. An advanced method to orient the stress tensor in the direction of the panel dimensions allows for an accurate assessment of transverse structure where the majority of the structure is made up from panels that are at angles with the orthogonal coordinate system defined by the length, breadth, and depth dimensions of the vessel. The rules used for the FPSO and FSO are referenced below:

- Plate and Beam Yielding Checks per ABS SVR 5-1-5/3
- Plate and Beam buckling Checks per ABS SVR 5-1-5/5

On other projects, code checks using SAGA's built-in buckling and yielding rules of Bureau Veritas, Lloyds, and DNV have been used.

The fatigue assessment is carried out using the stochastic (e.g. spectral) assessment capabilities of the DNV FPSO package as represented by the STOFAT program. For the two vessels described in this paper, dynamic loads have been developed for four representative FPSO loading cases, each corresponding to four equally spread drafts including and between the full and light displacement cases. Each of the four cases is solved by the DNV FPSO Package for a number of heading and wave periods to be able to allow the use of subsequent STOFAT analysis using heading probabilities and a wave scatter (Hs-Tp) diagram corresponding to each wave heading. The outcome is a calculation of the FPSO damage ratio for the intended design life.

The same procedure is used for the tanker phase of the vessel while trading on its routes. A combined wave scatter diagram is created for the past routes and the fatigue damage ratios are calculated for the tanker phase. The results of the fatigue analysis are correlated with the tanker class survey damage report as produced in graphical format. Correlations are made to ensure that the damage predicted matches the damage recorded.

The on and offloading of the crude is accounted for by using the FPSO strength cases. SAGA is used to determine the maximum principal stress range by subtracting each of the still water cases from one another to obtain the maximum stress range obtained during one on and offloading cycle. We have found low cycle, high stress on and offloading to affect mainly the transverse structure such as cutouts in transverse bulkhead horizontal girder web to allow for vertical bulkhead stiffeners.

The FEA direct analysis assessment method requires a four to six months effort, including iterations to develop practical solutions to problems identified.

Analysis Results

The two ships are built based on very different design methods in place at the time of construction. The results of the initial analysis indicated early that the two vessels have very different structural response against the current ABS class rules in effect in 2005. As such, the two vessels required very different structural modifications for FSO and FPSO service

Tables 4~5 show the modifications implemented during the conversion phase of the FSO and the FPSO, using ABS Rules for screening, FEA to assess response due to site-specific environment loading on operational loading cases, and detailed fine-mesh FEA to site-specific loads and on and offloading to determine requirements for reinforcement in way of structural details.

FPSO Results

The initial screening analysis showed that the wing tank deck transverses required reinforcement for FPSO service. The reinforcement was accomplished by installing on-deck transverse deck beams incorporating the topside stool design. In addition, transverse bulkhead horizontal girder flanges were replaced with stronger members to be acceptable for class.

For the FEA phase six FPSO loading cases were used to ensure that all structure types are loaded to their maximum values considering both static and dynamic loads.

Fig. 5 shows an example of the maximum sagging load case with a maximum wave-induced sagging moment.

Table 4. FPSO Design Modifications

Method	Class Rules	FEA Strength	FEA Fatigue
Deck Transverse Frames	57 t (in way of module supports)	-	-
Deck Longitudinal Reinforcement	-	10 t / 27 locations	-
Transverse Frames	-	35 t / 232 locations	23 t / 1132 locations
Transverse Bulkhead Horizontal Girders	9.8 t	20 t	5 t / 510 locations
Web Frame Cutouts	-	-	7 t / 220 locations
Longitudinal Bulkhead / Side Shell Longitudinal Stiffeners	Reduced corrosion margins	8 t / 4 locations	-
Panel Breakers, Brackets	22 t	45 t 7 t / 54 locations	-
Total	89 t	125 t / 317 loc.	35 t / 1862 locations

Each structure in the cargo block was analyzed for conformance with the ABS Part 5 Rules. For the FPSO, 24 design load cases are processed for conformance to the ABS Rules

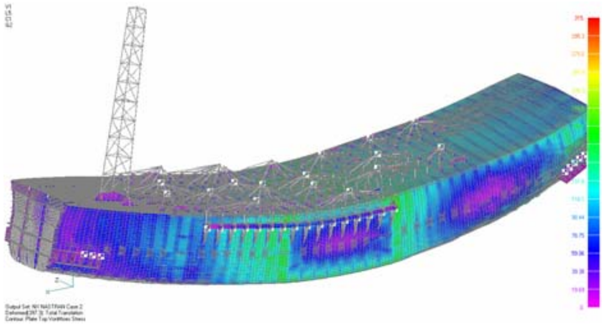

Fig 5: Global Ship Response due to Maximum Sagging

Fig. 6 shows a view of the internal tank structures with empty wing tanks and full center tank during a maximum heave acceleration load.

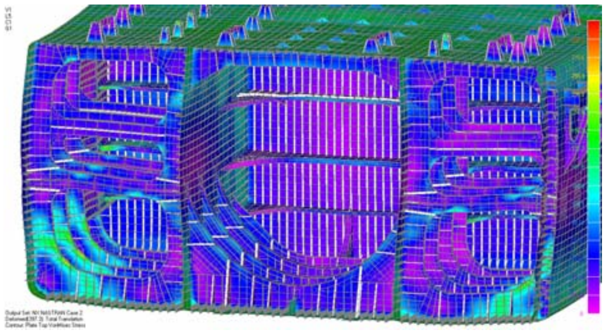

Fig 6: Internal Stress View Showing Tank Structures

As an example, Fig. 7 shows the buckling results obtained for a transverse web frame expressed as a buckling ratio, defined such that a value of 1.0 or less indicates an acceptable structure, and a value greater than 1.0 indicates a structure requiring reinforcement. Several panel breakers were installed as a result of the buckling calculations.

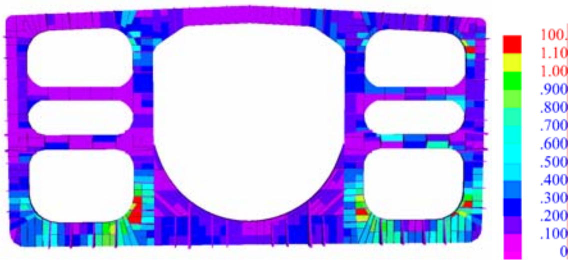

Fig 7: Transverse Frame Buckling Assessment

The FEA strength assessment showed the need for under deck reinforcement in way of a transverse bulkhead that was installed in the center tank only for the tanker.

In addition, a total of 35t of steel at 1862 locations was installed as collar plate modifications to prevent fatigue cracking in way of web frame cutouts for longitudinal stiffeners and at horizontal girder cutouts for vertical bulkhead stiffeners.

The original tanker had experienced cracking in the cutouts for the longitudinal structure as documented by the NKK survey reports. The reason for the cracking is attributed to the extensive use of high tensile steel and the large frame spacing, introducing increased deflection of the web frames in relation to their surrounding bulkheads. The NKK survey reports were very detailed and proved valuable in the correlation of fatigue calculations for the tanker. A lug plate repair as shown in Fig. 8 had been installed during tanker service to prevent further cracking. This repair was shown to be insufficient for FPSO service required and a full collar plate was installed as shown in Fig. 9.

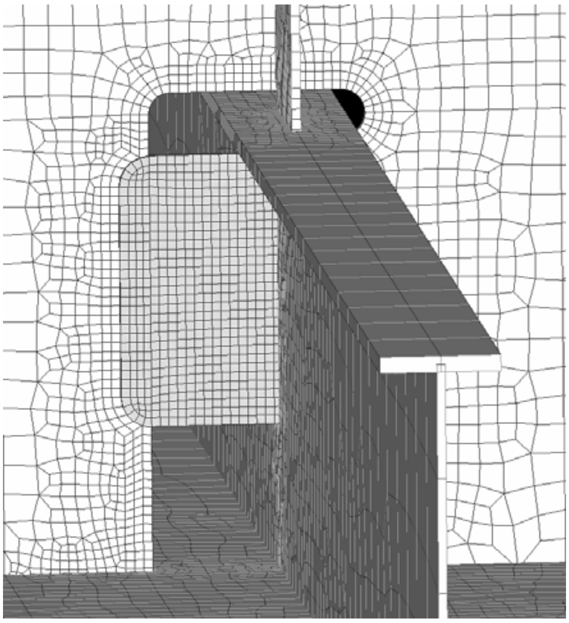

Fig 8: Lug Plate Reinforcement

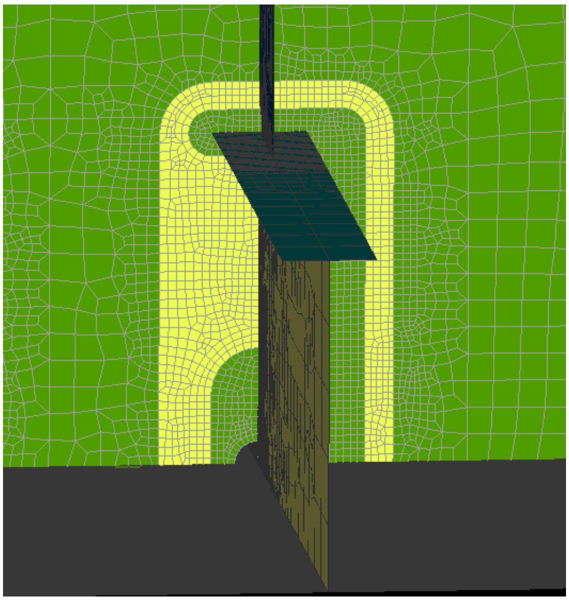

Fig 9: Full Collar Plate Reinforcement

FSO Results

As seen in Table 4, the FSO required significant steel modifications due to strength-related issues, and nearly no modifications due to fatigue strength.

Steel modifications were made to the longitudinal bulkhead, swash bulkhead reinforcements and centerline brackets, in order to provide sufficient strength for the FPSO operation, as required by the 2005 ABS Rules. Two strakes were replaced with HTS steel. The swash bulkheads were converted to oil-tight bulkheads.

Table 5: FSO Design Modifications

Method	Class Rules	FEA Strength	FEA Fatigue
Transverse Frames Reinforcement	-	27 t / 24 locations	11 t / 40 locations
Transverse Bulkhead Horizontal Girders	-	19 t / 16 locations	-
Longitudinal Bulkhead Plating	240 t / 2 strakes	-	-
Panel Breakers, Brackets	100 t / 60 locations	24 t / 68 locations	-
Swash Bulkhead Reinforcement	98 t	-	-
Side and Center Bottom Girder Reinforcement	-	67 t / 20 locations	-
Total	438 t	137 t / 128 locations	11 t / 40 locations

The FEA strength analysis (Fig. 10) showed the need for additional stiffeners to be installed on the longitudinal bulkhead to increase the buckling strength.

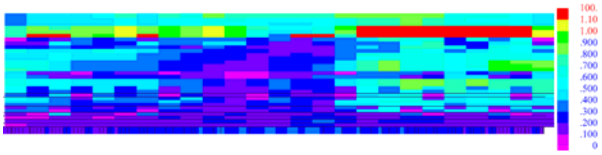

Fig 10: Longitudinal Bulkhead Before Adding Stiffeners

In addition, the FEA strength analysis showed the need for reinforcement on the transverse frames in ballast tanks.

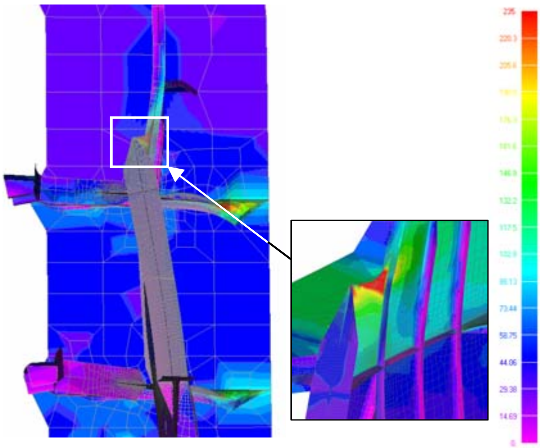

Fig 11: Transverse Frame Bracket Deformation

The original structure was designed with a soft toe and a sniped flange, introducing a highly stressed toe connection. Fig. 11 shows the out-of-plane deformation of the transverse frame bracket and the resulting high stress in the toe of the web. Fig 12 shows the reinforcement installed to prevent overstressing in way of the side shell transverse bracket connection.

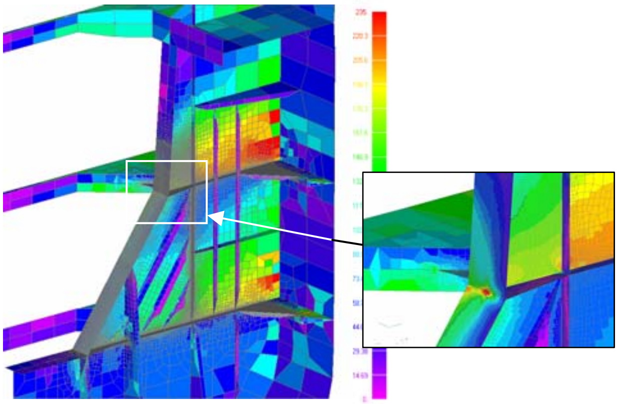

Fig 12: Reinforcement Solution for FSO BT Web Frames

In addition, the transverse bulkhead horizontal girders and the side and center bottom girder structures required reinforcement to reduce stresses below allowable stress levels.

The FEA fatigue analysis showed the need for a smaller reinforcement in the same area show in Fig 12, in way of the cargo tanks.

Stress and Deflection Screening

The authors have been using a longitudinal stiffener end connection fatigue screening method developed by LR (Reference 1) as a method to predict fatigue cracking of longitudinal stiffener end connections before detailed FEA, and as a method to determine the extent of required repair to longitudinal stiffener brackets. This is established by correlating the deflection screening results and the results of a detailed finite element analysis using spectral fatigue methods.

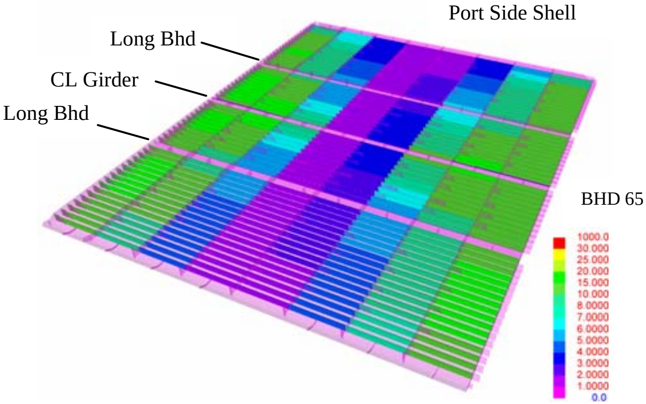

Fig 13: Relative Deflection Plot for Bottom Stiffeners for Predicting Bracket Cracking (mm)

The LR method uses a relative deflection method where the relative deflection of any two neighboring web frames is used to determine whether the end connections of a longitudinal stiffener require special attention during the detailed finite element based spectral fatigue method. The results of this method are shown in pictorial form in Fig 13. As seen in the figure the longitudinals near the transverse bulkheads experience the largest relative deflection matching what is typically experienced in service.

In addition, a web frame cutout cracking prediction procedure has been used similar to the approach used by Mr. D. D. Lee of HHI. This method is used as a tool to determine the required extent of repair by correlating the deflection screening results and the results of a detailed finite element analysis using spectral fatigue methods. The web cracking prediction method is used by determining the actual (as opposed to relative) deflection of web frames as projected to a straight line between the deflected locations of the two neighboring transverse bulkheads.

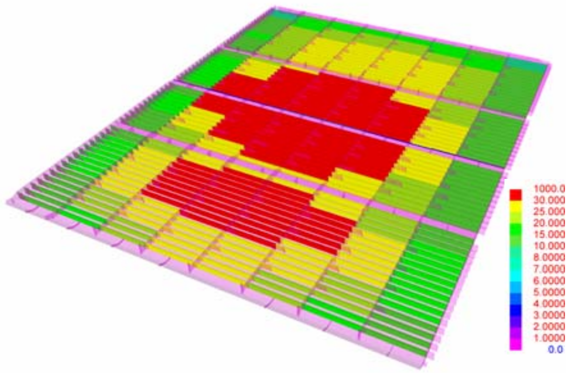

Fig 14: Deflection between Bulkheads for Bottom Stiffeners for prediction of Web Frame cracking (mm)

The outcome is a graphical plot of each stiffener segment (Figs. 13 and 14) as well as a table of deflection values for the relative and actual deflections, which are used in subsequent engineering calculations to determine the extent of repair or reinforcement required to longitudinal brackets and web cutouts, respectively.

As seen in Figure 13 there is strong correlation between the actual cracking seen in the bottom cutouts and the prediction made by the screening procedure (Fig 14).

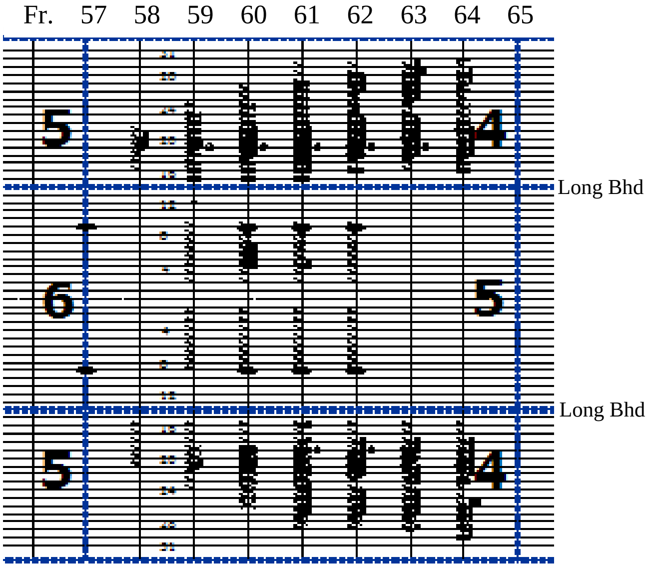

Fig. 15: NKK Survey Data Plotted (Typical)

In addition to deflection based fatigue screening, a stress based fatigue screening is also used to correlate the results of the detailed FEA based spectral fatigue analysis to determine the extent of repair required.

Conclusions

Reliable Initial Scantling Assessment Method

It was found that the Phase A program accurately identified areas requiring FPSO modifications due to strength deficiencies in the original tanker structure, allowing for accurate budget estimation for major steel early in the project. It is especially required that the Phase A program be used with great care to ensure that stiffener end connections and effective length calculations for transverse main supporting members are accurately defined. It was also found that the Phase A program (this is also true for most other class screening programs) was not able to identify cracking in web frame cutouts. It is therefore recommended that alternative methods are employed early in any project to facilitate awareness to problems related to fatigue damage, see next sections. Methods include deflection screening (LR, Ref. 1 and bulkhead-to-bulkhead deflection) and survey data collection.

Survey Report Data Collection

Typically there are accurate class survey damage reports available for the tanker to be converted. It is imperative, but often overlooked, that this data be processed properly to allow the entire conversion team to learn from the past use of the tanker as the FPSO loading will stress the steel in similar ways. The development of a procedure to plot the damage data graphically as early as possible in the project, gave the conversion team the ability to address the structural solutions at all levels of budgeting, shipyard scheduling, and development of adequate conversion engineering solutions.

Strong Value of Direct Strength and Fatigue Analysis

The authors consider the use of an advanced analysis tool set mandatory for FPSO conversion to be able to find adequate solutions to structural deficiencies. This is simply due to the level of detail required to find adequate solutions to problems identified in the early stages by Phase A or by damage reports and inspections. This will become even truer as the trend continues of increasing FPSO design life requirements, and the use of design safety factors. There are no substitutes for the solutions provided by an advanced, accurate, direct analysis of fatigue damage.

Tanker Pool for Future FPSO and FSO Candidates

The pool of candidate tanker have changed away from strong robust mild steel tankers of the early 1970's to 1980's highly optimized tankers using extensive amounts of HT steel, up to 70 to 80% of the steel weight. Compared to the cost of a double hull candidate the 1980's single skin candidates offer a significant savings in cost, and will likely remain an attractive alternative to conversion of double hull tankers and new-built hulls. The conversion of the 1980's tankers will continue to require extensive modifications to structural connections, and it is considered extremely important that powerful tools such as the ones described in this paper be used as early as possible in the project.

Acknowledgement

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