Multi-axial fatigue strength assessment of a turret in a FPSO

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Acknowledgements

This thesis will present the final graduation research assignment, where multiaxial fatigue strength of welded details within the turret of a FPSO are assessed. This assignment is carried out for Bluewater Energy services, a company that is specialized in turret designs.

Turret structures within FPSO's are subjected to a variety of repeated loads during their service live, therefore fatigue is a governing limit state in turret structural design. Due to the complexity of these structures and their loading, current fatigue design approaches can be non conservative for welded details subjected to a multiaxial stress state. Within this research these welded joints are identified and selected for proper multiaxial fatigue evaluation.

During the last few months a lot of knowledge is gained on this topic, therefore I would also like to thank Dr.ir. J.H. den Besten, Ir P.S. van Lieshout and Prof.dr.ir. M.L. Kaminski for their guidance and supervision.

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Abstract

Keywords: *Multiaxial fatigue, welded joints, out-of-phase, welded structures, FPSO, turret, maximum load path, Path-Dependent maximum range, non-conservative, arc-welded joints, service life, cycle counting.*

Turret structures within FPSO's are subjected to a variety of repeated loads, due to the harsh environment they operate in during their service live, meaning that fatigue is a governing limit state in turret structural design. Turret structural components are connected by arc-welded joints which are considered particularly susceptible to fatigue damage. Due to the complexity of the structure and its loading, welded details may be subjected to a multiaxial stress state. Currently fatigue design of turret structures is predominantly based on a uniaxial fatigue criteria assuming governing mode I (i.e normal stresses). This design approach can be non-conservative for welded details subjected to a multiaxial stress state, especially when these are non-proportional (i.e. out of phase). The estimation of multiaxial fatigue live for details subjected to a multiaxial stress state is still an extremely complex task. There is still a discrepancy in obtained multiaxial fatigue live between different design rules (i.e. as presented in ISSC), meaning that future work on this topic is required.

Due to the size and complexity of turret structures, identification of welded details (i.e. in the order of hundreds) subjected to a multiaxial (non)-proportional stress state is a rather complicated and laborious task. This thesis proposes a new screening method that identifies sensitive locations where multiaxiality occurs, either geometry or loading induced. Component stresses (i.e. Mode I and III) are determined from finite element models using

a mesh-insensitive structural stress method. The stress state (i.e. multiaxiality and proportionality) of these stress components is determined using the parameters of an ellipse that encloses the stress data (i.e. component stresses) in 2-dimensional stress space. Making this a practical and efficient method to identify sensitive locations within the turret where multiaxiality occurs.

For the multiaxial fatigue damage calculations of welded details subjected to a non-proportional multiaxial stress state, the accumulative Moment of Load Path (MLP) concept is used. Within this concept the multiaxial fatigue damage for any given non-proportional load path is assumed to consist of two parts. The first part can be considered damage due to the effective stress range $\Delta\sigma_e$ (i.e. stress due to direct path), and the second is the "load-path non-proportionality" fatigue damage due to excursion of the reference load path. By implementing the MLP-based method as part of the path-dependent maximum range (PRMD) cycle counting procedure, half cycles and their corresponding MLP-based equivalent stresses ranges are computed. Given the MLP-based stress distributions from PDMR cycle counting, the well know Palmgren-Minor rule is used to determine the accumulation of fatigue damage considering a proper fatigue resistance curve.

By implementing both the screening and the proposed multiaxial fatigue damage method onto a relatively simple Tube-to-Flange connection, a comparison study is used to determine whether the screening method is capable of identifying sensitive locations that may be susceptible to multiaxial fatigue. For five considered load scenarios, the screening method showed to give relatively similar results with respect to the actual fatigue damage calculation, making it a suitable structural screening method. Using the same Tube-to-Flange connection the multiaxial fatigue damage is calculated based on DNVGL and compared with those calculated using the MLP-based concept. For uniaxial proportional loading scenarios similar fatigue damages are observed, however for the non-proportional load scenarios the MLP-based method gives significantly higher fatigue damage results w.r.t DNVGL.

Performing structural screening on complex structural systems like the turret considering each load signal during its service live would be very computationally expensive. Therefore five load scenarios are considered to be sufficient to perform the structural screening. For this thesis a certain domain of the turret of the Aoka Mizu vessel is screened using the defined screening load scenarios. Within the scope (i.e. evaluated domain) details resulting in relative high fatigue damage due to high levels of non-proportionality are not encountered. Even Though details exist with high non-proportionality factors the stress ranges of these details are usually relatively small compared to details subjected to a dominant uni-axial stress state.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 FPSO fundamentals

A turret moored FPSO is composed of a turret system and a mooring system that connects the turret column to the seabed. Two types of turret systems are commonly used for FPSOs - the internal turret system where the turret is mounted within the FPSOs hull, and an external turret system where the turret is mounted on an extended structure cantilevered off the vessel bow. Since all the anchor chains of the mooring system are attached to the turret column, such a system is called a single point mooring system (SPM). This in contrary to the spread moored system, where the vessel is moored by anchor legs from the bow and stern of the vessel, usually in a four-group arrangement.

The turret system contains a bearing system that allows the vessel to rotate freely around the fixed geostatic part of the turret (also known as weathervane). The 360-degree weathervaning feature of a turret moored FPSO significantly reduces the loads on the mooring system. Also, vessel motions, particularly rolling motions, are typically reduced thus allowing more operating uptime during inclement weather conditions. This weathervaning ability is very important for the offloading operation as the headings of the FPSO and the export tanker are both into the predominant sea or winds, thus creating safer approaches and alignments during offloading operations. As the risers are contained within the turret structure, offloading operations are simplified as the FPSO hull is uncluttered with risers or exposed mooring lines.

For offshore areas of the world subjected to harsh environments and where seasonal cyclonic weather systems are predominant but with characteristically mild environments throughout the remainder of the year disconnectable turret are preferred. While the turret enables the vessel to freely weathervane in normal to severe conditions, this type of internal system allow the vessel to disconnect to avoid typhoons, hurricanes, icebergs, and other extreme dangerous conditions. The Aoka Mizo vessel is equipped with a disconnetable turret as shown in Figure 1.1. It should be noted that even thought this FPSO is equipped with a disconnectable turret, it doesn't mean that it currently opperates in a area which might be subjected to seasonal cyclonic weather.

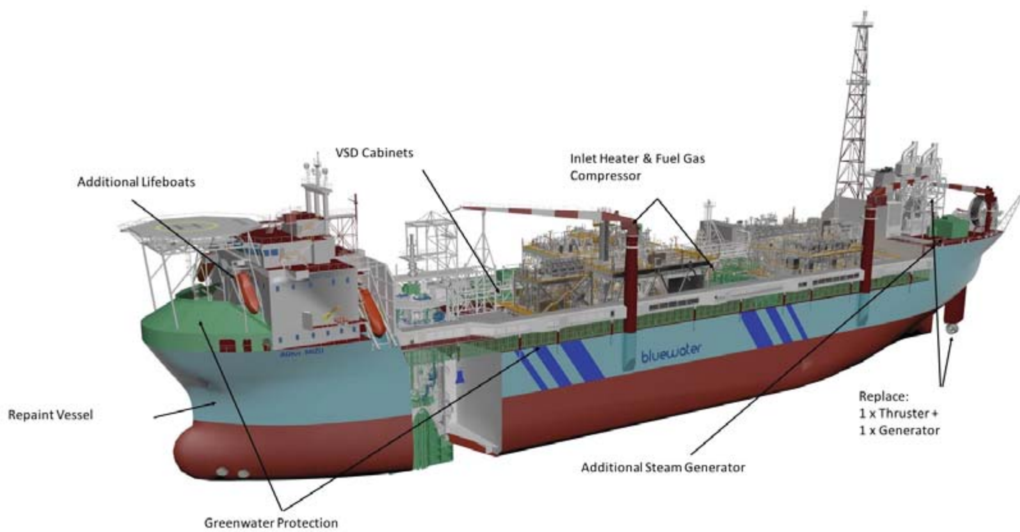

Figure 1.1: The Aoka Mizu FPSO as designed for the Lancaster field. This Turret system will serve as case study throughout this thesis.

FPSOs can be a conversion of an oil tanker or can be a vessel built specially for the application. Although there has been a shift toward newbuild FPSO, especially for developments in harsh environments, very large crude carrier tanker conversions remain the basis for projects in areas where benign environmental conditions (mild sea waves and swells) are predominant, such as off west Africa, southeast Asia, Australia, and Brazil. Providing flexibility and mobility, tanker conversions in some cases offer quicker production of first oil. There are, however, certain drawbacks to converting old tankers, the most important of which is the restriction on the weather conditions and water depth. For these conditions, the demands for integrating the turret into the hull can become quite elaborate and is therefore usually not economically feasible. With the development of turret mooring and new-build ship-shaped hulls the number of FPSOs operating in very deep water and harsh weather conditions has grown substantially.

1.2 Problem description

FPSOs are being recognized as one of the most economical systems to exploit marginal and (ultra) deep-water areas. Due to the world's increasing demand for energy, oil and gas companies continue to move into new and increasingly harsh and remote environment to meet this demand. FPSOs are therefore a important way to accommodate this need in a cost effective, flexible way. Due to the fact that these FPSOs and in particular the turret mooring systems have to operate in harsher environment they increase in size and complexity. The emphasis therefore lies on the optimization of design, building and operations in order to achieve high levels of integrity in term of safety, health and environmental factors, and life-cycle capital (CAPEX) and operational (OPEX) expenditures.

Presently turret mooring system design, construction and operational practices are largely influenced by high-cycle fatigue as a primary degradation parameter. Empirical (inspection) practices are deployed as the key instrument to identify and mitigate system anomalies and unanticipated defects. Current inspection, maintenance and repair are time consuming and quite expensive.

Due to harsher operating environments the loading on the turret becomes higher and more complex. Conventional calculation method using high contingencies may no longer be economically justifiable. BES currently started a in-house FPSO integrity project 'AMON', which stands for Aoka Mizu monitoring. The intension is to gain more insight in the loading and structural response, based on actual measured data from the FPSO. Timely identifying deviations from design conditions allows to take action in case for example the fatigue life is being consumed too fast. Furthermore BES also participates in the 4D fatigue JIP which focuses more on the fatigue capacity of welded joints subjected to multiaxial (non)-proportional loading. This assignment also mainly focusses on the fatigue capacity of welded joints subjected to multiaxial (non)-proportional loading, but taking into account more realistic loading conditions rather then just theoretical loading conditions.

Fatigue design and evaluation of welded joints are typically carried out by weld classification approach in which a family of parallel nominal stress based S-N curves are used according to joint types and loading modes [2]. Therefore the accuracy of the stress range is very important for assessing the fatigue life. The form of the S-N curve indicates that a small change in the estimate of the stress range results in a much larger change in the life because of the equation for the S-N curve, $S = CN^{-1/m}$. For example if the stress range were increased by only 20%, the computed life would be reduced by 42% for m= 3. Therefore, an accurate estimate of stress range is required for fatigue evaluation of a given welded structure. As discussed before this method makes use of several empirical S-N curves that are associated with detail categories and on corrective factors. The selection of a detail class for a welded joint type and loading mode is often subjective and, in many common situations, even skilled engineers might have a hard time choosing a suitable detail class. This is especially true when the geometry of the structure is complex or when the stress state is not reducible to a simple main component. Moreover it must be added that the real structures can develop cracks in locations different to those indicated in the details present in the standards, resulting in several limitations.

The structural members of the TMS are Generally evaluated using finite element analysis, due to it's complexity. From these analysis it is usually difficult to evaluate what is "nominal stress" to be used together with the S-N curves, as some of the local stress due to a detail is accounted for in the S-N curve. In many cases it may therefore be more convenient to use an alternative / extrapolation-based hot spot stress approach. For this approach the hot spot is determined using finite elements calculations at predefined reference points and extrapolated to the fatigue hot spot. The fatigue capacity is described by the D-curve, which can be considered as the hot spot S-N curve. According to [3], the stress at the fatigue hot spot consists of a nominal stress times a stress concentration factor (SCF). With FEA model widely used nowadays, this method gains a lot of attention, making it a widely used method in several design codes. Even though this method is considered a widely used method, the hot spot stress calculated by using different extrapolation procedures and element types varies a lot and besides this the method is also mesh insensitive [4].

To this very moment, the fundamental references in the design of ship and offshore structures and the inherent fatigue resistance are directed from uni-axial and constant amplitude testing **ref**. Furthermore fatigue design of TMS is predominantly based on uni-axial fatigue criteria assuming a governing "Mode I" normal stress. These criteria are then used in combination with damage accumulation hypothesis (e.g. Miner's rule) and cycle counting method (e.g. rain flow counting) or Rayleigh distributed to determine the fatigue life. Nonetheless, during real-life conditions, structures are subjected to multi-axial, variable-amplitude loading including non-proportional characteristics for specific details. Unfortunately, the usability of current multi-axial practices are restrained due to limited validation efforts and finite academic scope in testing, which can be reverted to the general engineering perception that uni-axial loading is the predominant factor [5]. Recent research has shown that conventional uni-axial methods significantly overestimate the fatigue lifetime, and lifetime predictions of multi-axial methods show significant differences [1].

Although all of the above potentially pose relevant and significant problems using current evaluation methods, this research will mainly address the latter (weld details subjected to multiaxial non-proportional loading).

1.3 Scope of Work

Within BES the structural department is responsible for the structural design and structural integrity of structures like the turret within a FPSO. Due to the increasing size of the turret structures, conventional methods may be too conservative or in case of details subjected to a multiaxial non-proportional stress state the conventional method may result in higher fatigue then actually would be the case.

The focus of this thesis will mainly be on welded structural details which are subjected to a multiaxial (non)-proportional stress state. Conventional methods can't properly estimate the fatigue life of these details. Within design codes a attempt has been made to account for the fatigue of details subjected to a multiaxial stress state. The methods from the design codes will be reviewed, determining if these would produce reliable results or if a more advance methods is required to determine the fatigue life of these details.

In addition to the design codes, a literature study is performed on newly developed methods that are not covered by the design codes "yet". Its aim is to provide an understanding of the challenges that still need to be overcome. Also several fatigue experiments are well documented and used for both validation and further research.

The basis of this research is formed by the development of a multiaxial fatigue importance screening tool, which would allow engineers to quickly screen complex structures, selecting only those details subjected to a multiaxial stress state. The structural screening can be performed using the semi-automated post-processing tool, This tool is to be developed within this assignment. Validation of the developed screening tool, will be done using a multiaxial fatigue damage criteria which is capable of properly estimating the fatigue damage of welded details subjected to a multiaxial stress state. This would be done in Phase I of this assignment, as shown in flow-diagram 1.3

As described above a multiaxial fatigue damage criteria should be selected which properly calculates the fatigue life of details subjected to multiaxial stress state. For this a multiaxial fatigue damage criteria from literature is used. Since this is still under development, usually only the mathematical description can be found in papers. Commercial programs are not yet available, and therefore development of a algorithm should also be done in this assignment. This work has been done in phase II, as shown in the flow-diagram 1.3

Validation of the screening tool and the algorithm developed for multiaxial fatigue calculation is done using a simple tube to flange model from which data is available in literature. Furthermore a comparative study is performed to show difference between the results from the screening tool and that of the actual fatigue damage. Also a comparative study has been performed to show the differences between conventional methods and newly proposed methods.

Validation using measured loading data and actual multiaxial fatigue testing may be optional, in case data and machine's are available.

A flow chart is presented in figure 1.2, which gives a better overview of the different steps which will be involved in this assignment.

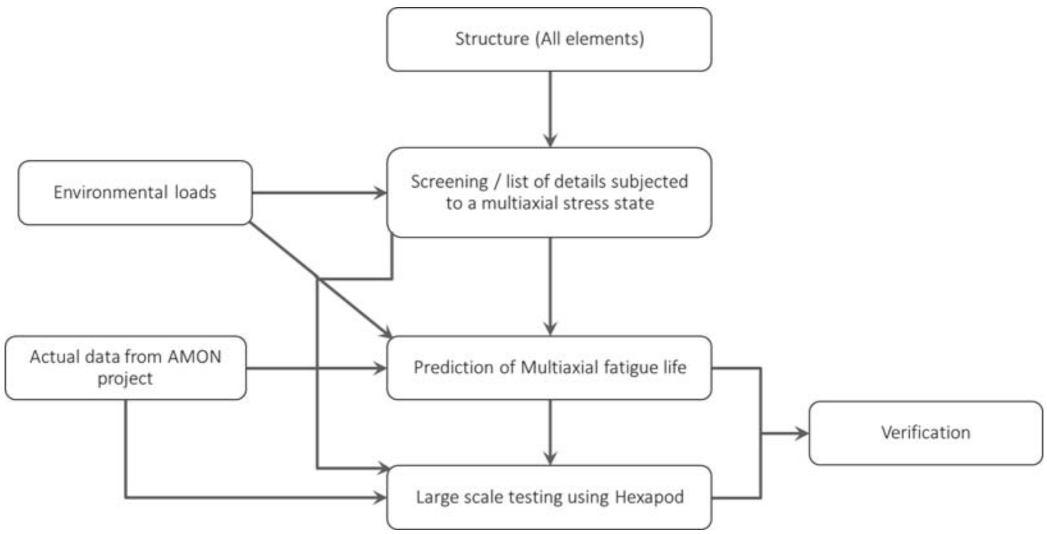

Figure 1.2: High level flowchart of the work which will be performed in this thesis.

1.4 Thesis Structure

The structure of this thesis follows similar steps required for the analysis of welded structural details subjected to a multiaxial (non)-proportional stress state, at least that was intended. Some effort will be made now to describe the outline of this thesis; how it will attempt to achieve the objectives described in section 1.3. Two main parts can be distinguish namely: Phase I "Structural screening" and Phase II "Multiaxial fatigue damage calculation for welded joints". The flow diagram shown in 1.3 represents the steps required to perform a structural screening, the results from the screening are later compared to the considered multiaxial fatigue damage method.

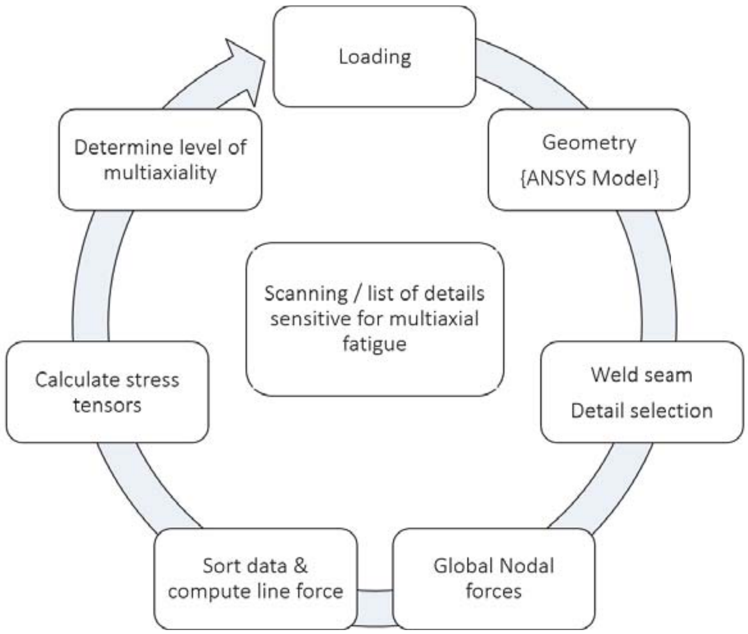

Figure 1.3: Flow-diagram for the evaluation of welded structural details subjected to a multiaxial stress state.

The layout of the thesis is setup as follows:

✓ Chapter 2 focuses on the literature study. Over the last few decades intensive effort have been made to develop multiaxial fatigue approaches which are able to deal with difficulties such as (random) variable amplitude (VA) loading and non-proportionality. With is available in engineering codes and guideline's along with that what is available in open literates will be discussed briefly in this chapter. Special emphasis will be on the methods used for this thesis.

✓ Chapter 3 focuses on Phase I: "Structural screening" following the flow-diagram presented in figure 1.3. The section start with a small introduction, explaining what will be achieved in more details for Phase I. It will then be followed by some subsection explaining the fundamentals of multiaxial fatigue. Further the developed screening method will be described extensively. In order to properly understand and explain the developed screening method, a "Tube to Flange" model is used. All the steps, as shown in the flow-diagram figure 1.3, will be explained in details. This same procedure will be applied to the turret structure, the findings and the results are then presented in the last sections of this chapter.

- ✓ Chapter 4 This chapter is a follow-up on the previous chapter. In this chapter the focus will be more on the multiaxial fatigue ”Damage” of welded components. The same ”Tube to Flange” model is used in this chapter, to explain the considered/ developed methods. This will also provide a in-depth overview of the cycle counting method, which is programmed enabling to count cycles in a stress space, which accounts for multiaxial fatigue. The developed algorithm will the be used to determine the fatigue damage of the selected details from section 3. The development of the required SN-curves is also explained, The results are also presented in the end.
- ✓ Chapter 5 will introduce a review, which is performed to validate the screening method with actual fatigue damage **(basically a combination of section 2 and 3)**. The validation in the sense of structural response and Model validation will be described briefly. This chapter can be seen as a result section, presenting a lot of comparative study results, enabling the author to draw enhance the drawn conclusion and recommendation described in section 6.
- ✓ Chapter 6 will present conclusion and recommendation of this study. Some time will also be spend on some short of reflection (looking back), where the set of goals are evaluated.