PROBABILISTIC BASED DESIGN FOR CONNECTING LINKS IN SINGLE POINT MOORING SYSTEM SUBJECTED TO DYNAMIC SPECTRAL FATIGUE LINE TENSION

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To my beloved family.

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ABSTRACT

Structural reliability theory has been applied to design structural members. A major goal is to achieve a balance between safety and cost (or weight) for a given safety level. It is therefore desirable that optimum design is achieved through probabilistic based design procedures. This study is concerned with optimum design of connecting links frequently found in a single point mooring system, based on probabilistic based design at the component level. Single point mooring systems are subjected to fatigue loading due to environment conditions. The study considered a single point mooring system located in Volve Field in the North Sea, offshore Norway. With the existing deterministic design basis, the probabilistic based design is performed using the design parameters obtained from the design codes used in the deterministic design. The results of probabilistic based design output are checked against the deterministic based design output. The probabilistic based results are obtained from Monte Carlo simulation where the basic input in the Transfer Function value which was obtained from deterministic Finite Element Analysis. As a conclusion, the fatigue life values for the connecting links obtained are compared based on the design method. Through this research study, it has been proved that an economical and safe structure can be designed using probabilistic design method, with respect to fatigue loading. This method can be implemented in the engineering stage.

ABSTRAK

Teori keboleharapan telah diaplikasi untuk merekabentuk strucktur. Matlamat utama adalah untuk mencapai keseimbangan diantara keselamatan dan kos. Oleh itu, secara umumnya, rekabentuk optimum boleh dicapai menerusi prinsip rekabentuk keboleharapan. Objektif utama penyelidikan ini adalah untuk merekabentuk secara optimum penyambung yang terdapat dalam sistem *single point mooring,* dengan menggunakan prinsip rekabentuk keboleharapan di peringkat komponen. Sistem *single point mooring* terdedah kepada beban lesu akibat keadaan persekitaran. Penyelidikan ini tertumpu kepada sistem *single point mooring* yang terletak di sektor *Volve* di *North Sea*, pesisir Norway. Dengan berpandukan pelan rekabentuk konvensional, rekabentuk keboleharapan dibuat dengan menggunakan maklumat daripada kod-kod amalan yang diguna untuk merekabentuk struktur dengan kaedah biasa. Keputusan daripada rekabentuk keboleharapan dibandingkan dengan keputusan daripada rekabentuk biasa. Keputusan rekabentuk keboleharapan diperolehi menerusi simulasi Monte Carlo dimana input utama dalam simulasi ini adalah nilai Fungsi Pemindah, yang diperoleh daripada Analisa Elemen Terhingga. Sebagai kesimpulannya, hayat lesu penyambung yang diperolehi dibandingkan di antara kaedah rekabentuk biasa dan kaedah rekabentuk keboleharapan. Menerusi penyelidikan ini, adalah terbukti bahawa, struktur yang ekonomi and selamat dapat direkabentuk dengan menggunakan prinsip rekabentuk keboleharapan, sekiranya struktur tersebut terdedah kepada beban lesu. Aplikasi kaedah rekabentuk keboleharapan boleh diaplikasikan di peringkat kejuruteraan.

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μ_x	-	mean value
σ_x	-	standard deviation
$\Delta\sigma_i$	-	stress range in stress block i
σ_L	-	local peak stress
γ	-	Poisson ratio
ρ	-	density
γ_{mean}	-	partial safety factor on mean tension
$\gamma_{dynamic}$	-	partial safety factor on dynamic tension
γ_m	-	material factor
β	-	slip angle
n_i	-	applied number of cycles
N_i	-	the predicted number of cycles of failure under stress range $\Delta\sigma_i$
P_f	-	probability of failure
G( )	-	limit state function
D	-	annual fatigue damage
S	-	load
R	-	resistance
x_i	-	random variable
E	-	modulus of elasticity
G	-	shear modulus
S_c	-	characteristic strength
$T_{c\text{-}mean}$	-	mean tension
$T_{c\text{-}dynamic}$	-	dynamic tension
$\bar{a}_1$	-	a constant relating to the S-N curve for N 10^6

$\bar{a}_2$	-	a constant relating to the S-N curve for N > 10^6
m_1	-	the inverse slope of the S-N curve for N 10^6
m_2	-	the inverse slope of the S-N curve for N > 10^6
t	-	thickness through which the potential fatigue crack will grow
t_{ref}	-	reference thickness
k	-	thickness exponent on fatigue strength
F	-	external mooring force
$[TF]_N$	-	nominal transfer function
Var(x)	-	variance
ABS	-	American Bureau of Shipping
ALS	-	accidental limit state
APL	-	Advanced Production and Loading
CDF	-	cumulative distribution function
COV	-	coefficient of variance
DNV	-	Det Norske Veritas
FDF	-	fatigue design factor
FEA	-	finite element analysis
FORM	-	First Order Second Moment
FSO	-	floating storage and offloading
MBL	-	minimum breaking load
PDF	-	probability distribution function
PFL	-	predicted fatigue life
STL	-	Submerged Turret Loading
SCF	-	stress concentration factor
TF	-	transfer function
ULS	-	ultimate limit state

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CHAPTER 1

INTRODUCTION

1.1 General Introduction

Efforts to engineer efficient design methodologies for floating and vessel based offshore structures are one of the greatest challenge for engineers and designers the world over. It has also been a great interest for the oil and gas industry for many years. The current practices on offshore structural design method are largely based on the principle of deterministic methodologies. As a result, the estimation of structural member strength becomes very conservative and uneconomical. Therefore, this research is focused on the development of reliability based optimum design for floating and vessel based offshore structures. Although fixed offshore structures had been a major player in most coastal and shallow water zone of the world, the trend is now is moving towards mobility and reusability of the offshore structures, due to enormous development of marginal fields. As an offshore production system, floating and vessel based offshore structures are also very economical and suitable in the Malaysian shallow waters. This alternative design method will be a supplement method that can be implemented by engineers, owners and certifying bodies to verify the level of optimization on material and cost that the initial design has contributed. Maintaining high reliability of these floating and vessel based offshore structures have become one of the large financial assets for the oil companies, thus an economical design method is required in producing a more economical structures. The main objective of this research is to develop a comparison design model based on reliability theory, against actual existing deterministic design output.

1.2 Background of Problem

The current trend in the oil and gas industry has evoked more vessel based offshore structures to be developed as Minimal Facilities Mobile Offshore Units (MFMOU). MFMOU concept is seen as one of the most appropriate alternative to engineer any offshore platforms (fixed or floating) on the design stage, by optimization using reliability method. In this study, the optimization using reliability method was motivated by factors like current world economy, safety of structures, and the development of marginal fields.

1.2.1 Current World Economy

The unstable current world economy promises little established profit margin to the oil and gas industry. This is due to the price increase of crude oil and construction materials, particularly steel. Deterministic method of designing offshore platforms would create members with uneconomical sizes, thus contributing to additional weight and cost (Lee, 1990). In addition to that, to obtain and process crude oil or crude gas with uncertain return price conditions is considered a business risk (Offshore Engineer, 2004).

1.2.1.1 Crude Price

Underlying the rising cost of oil in recent years has been strong global demand. The International Energy Agency, based in Paris, reported that the world's thirst for oil would be even greater in the rest of 2004 and in 2005 than it previously forecast, increasing pressure on producers to step up output at a time when rising oil prices might slow world economic recovery (Offshore Engineer, 2004).

World energy markets are so concerned about strong demand and possible disruptions of supplies oil prices. Even though Saudi Arabia announced it had the capacity to pump 1.3 million more barrels a day immediately if needed. Low-sulfur crude oil for delivery in October 2004 settled at USD 44.80 a barrel in the United States (Offshore Engineer, 2004). It is reported that the crude oil current price as of November 2005 is approximately USD 53.18 in the United States (Offshore Engineer, 2005)

1.2.1.2 Construction Material Price

With global steel production and consumption running at all-time record highs, steel prices around the world have been showing prodigious gains, with US hot rolled coil at all-time highs (Offshore Engineer, 2004). The US transaction price for hot rolled steel coil is at over USD 700 per ton - a figure that is more than USD 200 higher than the previous record of USD 495 per ton recorded in the third quarter 1988. Conjoined economic recovery in Japan, Europe and US lies behind the sensational increases that have been seen in global steel prices. Additional factors are surging infrastructure and business developments in China, India and some other countries. The most extreme example of steel price increases has been seen in the US, which has seen quite unheard of gains in prices as steel mills have successfully striven to pass on increases in costs for raw materials, energy and transport to their customers.

US coil prices have shot up by more than 125 % in the past 12 months. Since they touched their low point of USD 225 per ton in the third quarter of 2001, coil prices have advanced by a remarkable 215 % (Offshore Engineer, 2004). A proportion is the result of a reduction in import competition. The narrowing of the cost advantage traditionally held by mini-mill sheet producers has resulted in the rise in prices for scrap and the shortage of alternative furnace feeds such as pig iron.

1.2.2 Safety of Structures

Structural reliability theory has been applied to design structural components. A major goal is to achieve a balance between safety and cost (or weight) for a given safety level. It is therefore desirable that the optimum design is achieved through reliability-based procedures.

This study is concerned with the optimum design of connecting link, frequently found in vessel based offshore loading and production system linked to a mooring system, and is based on reliability at the component level. The allowable reliability index and some design requirements drawn from the DNV Recommended Practice RP-C203 – Fatigue Strength Analysis of Offshore Steel Structures (October 2003) design code is used as guidance and main reference. The optimum design derived from a series of fatigue life computation formulae which are used for the design of critical connecting link is shown on a variety of optimum solutions for similar components. The optimum design based on reliability theory is also compared from a safety view point with optimum designs derived by deterministic methods for which there are no safety constraints.

1.2.3 Development of Marginal Field

As a general rule of marginal field development, the budget must be closely controlled. Much has been made in recent years of technologies designed to deliver more oil and gas for less expense. Smaller operators developing marginal fields tend to use what they call as high end technology- with the right price. Shaving costs, of course, is the key to making the most of marginal properties. This includes developing new offshore production system like the sub sea trees and the MFMOU.

The concept of sub sea trees was created as a sort of minimalist approach to field development in which the surface facilities required for conventional dry tree completions are eliminated in order to reduce capital expenditures and make marginal fields more economical (Torgier, Efren, and Wang, 2004). Like the MFMOU, new offshore structures (fixed and floating) can be designed with minimal cost and weight using the probabilistic based design. The least weight platforms would be sought after as the core concept of marginal field is engineer a production facility with the stipulated duration or time frame (Torgier, Efren, and Wang, 2004). For example, based on the rate of production, a typical marginal field would have reserves lasting for about five to ten years. And it is not feasible to design and built an offshore structure similar of the fields with reserves lasting more than twenty years.

1.3 Objective of Study

This research study is of concerned with the optimum design of critical connecting link of the offshore loading system of FSO Navion Saga, based on reliability theory. Similar design requirements drawn from previously referred

DNV Recommended Practice RP-C203 – Fatigue Strength Analysis of Offshore Steel Structures (October 2003) is made as the parametric reference to be considered in the optimization procedure. The main objective of this research study is stated below:

The objective of this research study is to develop a comparison design model based on reliability theory, against actual existing design output, to determine the level of on cost and structural safety achieved.

In this research study the cost is composed of structural cost and the expected failure cost. The structural cost was assumed to be proportional to the structural weight. This may not, however, be true in real structures, where the structural cost should include all costs in construction as well as design for a more complete solution. In spite of this, it is expected that the reliability-based optimization design is likely to yield a design with less total cost, while being more uniformly safe, than the rule-based design.

1.4 Scope of Study

1.4.1 Introduction

The scope of study covered the comparison between deterministic design results and probabilistic design results. In particular, the study considered the fatigue life computation for critical connecting link of the offshore loading system of FSO Navion Saga. The deterministic design results of the connecting link for the system was produced by Advanced Production and Loading (APL) Asia Sdn. Bhd., under the following document title:

1. 1228-APL-N-FE-0003: Turret Assembly – Design Brief
2. 1228-APL-W-RA-0008: Marine Load Summary
3. 1228-APL-N-CA-0008: Turret Connection – Fatigue Analysis

The structural reliability based optimum design methodology is applied to assess the FLF and the PFL for critical connecting link through calculated probability of failure. All parameters required in failure model, which are represented as the statistical probability distributions will be referred to the following design codes:

1. DNV Recommended Practice RP-C203 – Fatigue Strength Analysis of Offshore Steel Structures (October 2003)
2. API Recommended Practice 2A-WSD (RP 2A-WSD) – Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms – Working Stress Design (December 2000)
3. BS 5400 : Steel, Concrete and Composite Bridges, Part 10 : Code of Practice for Fatigue, 1980

ANSYS Structural Version 9.0, a FEA package software is utilized to determine local peak stresses in the connecting link model. A linear static analysis is solved to investigate the structural utilization. Besides that, a transfer function is obtained from the stress plot results.

MATLAB Release 7.0.4 programming software is utilized to run a simulation program based on the Monte Carlo simulation procedure in order to calculate the probability of failure. In the final stage, a reliability-based optimum design's result is compared to the deterministic design methodology's results.

Through out the research, Microsoft Excel spreadsheets will also be used to conduct minor computational tasks.

1.4.2 Navion Saga, Submerged Turret Loading (STL) and Volve Field

Owned fully by Statoil of Norway, The Volve field is situated in the North Sea approximately 200 km west of Stavanger, Norway as a part of the Sleipner PL046 licence. The water depth at the field is 90.5 meters.

The Volve Field will be developed from a Maersk rig of the XL type equipped with production facilities. The stabilised crude oil will be exported via a flexible flow line to the Floating, Storage and Offloading (FSO), Navion Saga for temporary storage. This is done through the STL System provided by APL. This STL system provides a mooring system for the FSO which allow the ship to weathervane with no restrictions, while loading oil through the flow line in the buoy. The FSO will be permanently moored.

The oil will be evacuated from the FSO to tandem moored shuttle tankers, which will further transport the crude oil to the final market place. The FSO is considered a passive vessel, thus no thrusters available for positioning.

The facilities shall be designed to stay on location and maintain production in all environmental conditions up to the 100 year return period without causing damage to any part of the system. The design life for the STL System shall be 10 years.

1.4.3 Fatigue Life Computation

A fatigue life analysis is carried out for the critical connecting link. All these components connect the mooring line to the STL turret structure. These structural components are examined with respect to fatigue durability based on the local peak stresses.

The load spectrum is determined from time series simulations and introduced to the mooring lines. The hot spots (HS) are obtained from the FEA stress plots. The main input to the fatigue life computation is however, given by Transfer Function (TF), defined as the ratio between the maximum principal stress and the corresponding external force.

The fatigue life is predicted by the S-N approach using the Miner linear summation rule for the damage contribution.

The shortest allowable PFL is 100 years, corresponding to FDF of 10 for Target Service Life (TSL) of 10 years.

1.5 Importance of Study

This research study will show an alternative design method using the reliability based optimum design. As mentioned earlier, the study will emphasize in critical connecting link component of the STL system that will be installed within the hull of Navion Saga. The proposed reliability-based optimum design would offer a variety of approach from data statistical analysis, correction method for the errors of the critical connecting link to be designed. The findings from this research are capable in reducing the uncertainties associated with structural failures, enhancing structural strength and improving cost of vessel based offshore structures.

Besides that, the reliability based design approach, and the vessel based offshore structures' potential growth in the near future can be implemented in Malaysia. The proven weathervane capability would make this a cost effective offshore production and loading system, during the monsoon season in offshore Peninsular Malaysia. The flexibility in shallow and deep water can be fully exploited when mobilization is critical. This application is suitable in the Malaysian waters of Sabah and Sarawak.

A probabilistic design method that has proved to be more economical and safe could be established, by using appropriate uncertainty parameters from reliable resources to compute fatigue life estimation for the critical connecting link.

6.2 Further Work

Further research study can be carried out to enhance the findings of this research. The scope of research under structural fatigue reliability is a broad topic. Therefore, several suggestions can be made for the research work in the future.

1. To establish and determine the reliability parameters (variables) for engineering and construction based material, prone to fatigue failure.

2. Strain based fatigue assessment using probabilistic method.

3. Fatigue crack propagation using probabilistic method, covering aspects of fracture mechanics.

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