11th International Conference on Marine Technology
MARTEC 2018

PROBABILISTIC APPROACH IN MARINE STRUCTURE STRENGTH ASSESSMENT

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ABSTRACT

Most of the commercial ships were design and build according to standard stipulated by Classification Society Rules. The rules were to ensure safety of the ships while performing functional requirements. The international Convention for the Safety of Life at Sea (SOLAS) and International Convention of Load Lines recognise the role of Classification Societies towards implementing Conventions recommendation. The new direction in ship structural regulation and assessment suggest on the improvement of the load and strength models. Probabilistic design approach is found to produce more rational models in replicating load and strength condition in contrast to deterministic base of Class Rules. In probabilistic design approach, limit state function is used in strength assessment. Deterministic formulations in resistance and load are made probabilistic by understanding the probability characteristics of the data. Corrosion degradation is assumed to follow normal distribution for a given range of resistance over time. Taking into consideration the probabilistic nature of both resistance and load, it is expected that strength assessment result will improve. The paper proposes a method in implementing ultimate limit state and probabilistic approach to determine reliability of structures emphasising on the strength of deck components.

Keywords: *Limit state, Probability, Ship Structure, FPSO.*

1.0 INTRODUCTION

Strength assessment of ship structures has never been considered as crucial during the early age of wooden ship history. However, situation becomes different when designers began to replace wood with steel in the making of ship hull-frame during the industrial revolution back in mid-19th century. Buckling was not considered as an issue in the early constructed steel ship as main components such as deck and hulls were made of woods. The local strength issues associated with material properties [1] began to get more attention after new steel ship with high volume of steel was constructed. Ship Structure Committee was then established in 1943 to investigate the cause of brittle fracture of merchant ships. Since then, many theories and researches have been deliberately proposed to provide safer and reliable sea voyage ship.

There are several approaches available in designing and constructing seaworthiness ships and offshore structures. The first strength evaluation of iron ships was performed by

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William Fairbairn in 1890 [2] by applying ultimate load concept and later followed by Rankin who then published the correct formulation in calculating longitudinal bending moment for the ship [2]. Schnadel then added post buckling behaviour in investigating thin deck plating strength [2]. The classical theory of elasticity becomes a dominant theory in evaluating ship's structural strengths under the formulation of Classification Society [2]. Classification Society like the Germanisher Lloyd (GL), American Bureau of Shipping (ABS), Bureau Veritas (BV), Llyods Register (LR) and others developed guideline based on the classical elastic theory tailored to specific requirements, dedicated areas and conditions. Nevertheless, the safety and serviceability of the structure were found to rely on plastic behaviour rather than linear-elastic estimation [1] as in Class rules. The ambiguity in Class rules appears as an opportunity for further improvements in both safety and economy.

There are different outcomes in term of scantling between each Classification Society formulations [1] but they serve the purpose in reducing risk of failure [4] during sea-time. The Common Structures Rules (CSR) for tanker and bulk carrier initiated by the International Association of Classification Society (IACS) are to synergise rules and definitions among classification societies. The goal-based standard maintains classification societies status quo to ensure a safe operating life of ship over a specific period in certain persistent sea conditions [7].

The new direction in ship structural regulation and assessment will focus more on the improvement of the load and strength models as well as to unleash optimal potential of probabilistic models. Hence, the recent development in safety-based rules suggests variability on the load states such as serviceability, accidental and ultimate limit states in measuring acceptability [8] of rules.

The development of scientific analyses and design tools for offshore structure is essential to cater future needs and trends. The tools should be able to investigate essential areas such ultimate strength calculation associated with uncertainty and reliability analysis [6]. Furthermore, probabilistic and uncertainty methods are capable to produce better accuracy in design problems compared to deterministic approaches [5]. This paper employs probabilistic approach to explore possibility of enhancing inspection schedule of large maritime structure and the corresponding maintenance strategy.

2.0 BENDING STRESS

Most of the structural systems are designed deterministically. The elements in strength analysis consist of resistance and load, which are assume deterministic. Class Rules evaluate the strength of the structures by ensuring that resistance should exceeded summation of all possible loads with a certain margin, called safety factor. Safety factor is a ratio of allowable load to the strength, and usually refer to material strength in elastic region. The structure is said as more reliable when higher safety factor is in place. The safety factor ratio is based on past experiences and some engineering judgements but sometimes these lead to an excessive of material usage.

Bending stress is a major concern in establishing safe and reliable marine structures. The action of wave is exposing ship's hull to experience hogging and sagging; creating bending stresses. Typically bending moment is higher in the midship section. The elastic flexural formula in equation (1) quantifies deck and hull girder bending stress.

$$\sigma = \frac{My}{I} \tag{1}$$

The study of on-the-deck component is considered important, albeit the case of deck failure hardly exists. The failure of deck panel structures under compressive loads can affect a major portion of the cross-section that is assume equivalent to hull failure mode [12], which will lead to failure of the ship. The risk of failure is higher since deck is experiencing higher bending moment which is as much as that of hull girder. Furthermore, the number of research on the reliability of deck components is considered much lesser in contrast to that of hull girder [11].

3.0 RESISTANCE IN DECK

The construction of the hull deck is made by combining deck panels, and carefully weld them together to become one single piece. Deck panels are made of plates and stiffeners. The failure mode of the deck will come from the failure of any individual structural element possibly due to buckling and torsional loads. Only compressive stress of deck is considered due to bending of the ship in sagging condition, while hogging which cause the deck to be in strain will not be considered in this paper.

The resistance of the deck is determined in terms of yield and ultimate strengths associated to hull bending moment in sagging. Two different limit states are considered for analyses and the results will be compared between each other. The limit state is then used to determine failure probability which is caused by either increase in load or reduction in strength. Both cases will be analysed for comparison.

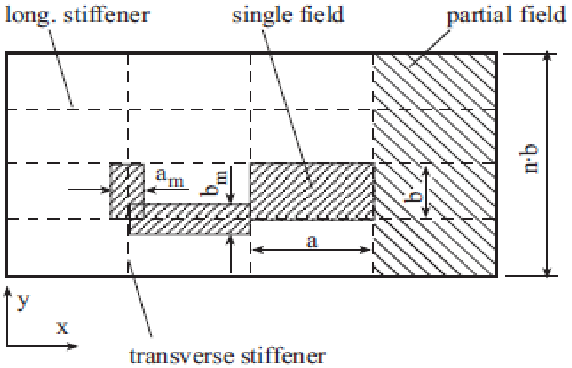

Figure 1: General arrangement of panel [13]

Several possible general arrangements of deck panels are shown in Figure 1. In this paper, deck panel is taken as a single field with length and width is given as *a* and *b*, respectively.

3.1 Yield strength

Design yield strength is resistance related to serviceability limit state (SLS). The principle of SLS deals with unacceptable deformation and local damage condition that reduce the durability of the structure [14] due to corrosion or any permanent structural compromise. Under normal operation condition, deck maximum loading shall not exceed design yield strength to avoid unacceptable deformation.

Design yield strength, σ_{yD} is related to hull bending moment M_y according to equation (2)

$$\sigma_{yD} = \frac{M_y}{Z_d} \tag{2}$$

where

$Z_d = \frac{I}{y}$ is section modulus of deck panel, σ_{yd} is material yield stress, I is moment of inertia and y is distance to centroid.

3.2 Ultimate strength

The ultimate strength is a measure of resistance against maximum load carrying capacity of hull girder bending namely buckling and torsional stresses. Sagging is causing the deck to experience uniaxial compression in longitudinal direction induced by hull girder bending moment.

Deck structure elements such as stiffened panel, plate and stiffeners are exposed to failure mode associated to compression. For both yield and ultimate resistance, deck component of unstiffened and stiffened panel will be considered.

For unstiffened plate, there would only ultimate strength, $\sigma_{ul\text{-}plate}$ in action. The minimum requirement for $\sigma_{ul\text{-}plate}$ must at least equal to critical buckling stress. For stiffened panel, ultimate buckling, $\sigma_{ul\text{-}bc}$, and ultimate torsional, $\sigma_{ul\text{-}tor}$ strengths [11] are given by equation (3) and (4),

$$\sigma_{ul\text{-}bc} = \eta_{allow}\sigma_y - \sigma_b \quad (3)$$

$$\sigma_{ul\text{-}tor} = \eta_{allow} C_T \sigma_y \quad (4)$$

For stiffened panel situated above 0.5D where *D* is ship depth, ηallow is taken equal to 1.0 while it is equal to 0.9 for other position. σ_y is material minimum yield stress and σ_b is component bending stress without any interference from lateral load. C_T is torsional buckling coefficient which value depend on degree of slenderness.

3.3 Strength degradation

Deck panel is expected to experience corrosion degradation over time. Corrosion appears to reduce structural strength by reducing the section modulus of component. The reduction of thickness is given as a function of time is denoted by, $t_{cor}(T)$ (5):

$$t_i(T) = t_0 - t_{cor}(T) \quad (5)$$

where $t_i(T)$ is updated thickness and t_0 is the design thickness. The thickness reduction is taken as random variable and follows normal distribution with mean, $\mu_{Z_d}(T)$, and standard deviation, $\sigma_{Z_d}(T)$, of section modulus at time *T*, as shown in equation (6) and (7) :

$$\mu_{Z_d}(T) = \frac{\mu_I(T)}{\mu_y} \quad (6)$$

$$\sigma_{Z_d}(T) = \frac{\sigma_I^2(T)}{(\mu_y)^2} + \frac{\left(\mu_I(T)\right)^2}{(\mu_y)^4}\sigma_y^2 \quad (7)$$

where μ_I and σ_I^2 are mean and variance of inertia of panel.

4.0 PROBABILISTIC MODEL OF LOADING

This section discusses the probabilistic model of typical loads on FPSO. Three types of load are discussed, still water bending moment, wave bending moment and extreme loads.

4.1 Still Water Bending Moment (SWBM)

The loading of floating ships is evaluated from the still water bending moment and wave bending moment. Still water load is formed due to the variation in distribution of mass and buoyancy. For a certain type of hull, there are certain requirements that must be fulfilled. The ABS FPI takes SWBM of an FPSO according to Steel Vessel Rules (2014) with consideration of load case. The ABS Safehull (2014) emphasises tankers to have five different loading conditions in performing strength analysis. The conditions are at full loading, partial load of

67% full, partial load of 50% full, partial load of 33% full, and full ballast condition. Valenzuela et.al (2004) suggests considering hull loading near to full loading to obtain best and compatibility in satisfying ABS requirement. The highest still water loading is assumed to occur at midship section.

Since still water load is varying with loading patterns which in response to operational requirement, a single value will not satisfy to explain the actual condition. Mean value, standard deviation and covariance of still water bending moment use to explain distribution of these loading. For instant, Wirsching et. al. (1997) was using mean value and standard deviation of several tankers in similar loading. The mean and standard deviation are as per equation (8) and (9), respectively.

$$\mu_{Ms} = -0.124 f_a \tag{8}$$

$$\sigma_{Ms} = 0.213 f_a \tag{9}$$

where f_a nominal yield strength with negative value refers to sagging condition. The SWBM variation is assumed to have a normal distribution.

4.2 Wave bending moment (WBM)

The randomness of wave condition is treated as a stochastic process. The waves induce a maximum bending moment, M_{wv}, to occur randomly at any time during the structure service life, T_s. The ABS vertical wave bending moment equation is deterministic and varies with ship principle dimensions. The WBM for hogging and sagging are given in equation (10) and (11), respectively.

$$M_{wh} = +190\beta_{VBM} C L^2 B C_b \times 10^{-3} \tag{10}$$

$$M_{ws} = -110\beta_{VBM} C L^2 B (C_b + 0.7) \times 10^{-3} \tag{11}$$

where L, B, C_b are length, breadth and block coefficient of the hull, respectively and β_{VBM} is environmental severity factor for long-term environmentally induced load. The vertical bending moment is taken for β values in sagging condition and given as (12);

$$\beta = \frac{L_s}{L_u} \tag{12}$$

where:
L_s: most probable extreme value based on [100 years return period for the intended site; 10 years return period for transit; one-year return period for repair/inspection], and
L_u: most probable extreme value base in North Atlantic environment.

Coefficient C which vary with hull length given as in equation (13) below:

$$\begin{aligned} C &= 10.75 - \left(\frac{300 - L}{100}\right)^{1.5} && \text{for} \quad 90 \le L \le 300 \text{ m} \\ C &= 10.75 && \text{for} \quad 300 < L \le 350 \text{ m} \\ C &= 10.75 - \left(\frac{984 - L}{328}\right)^{1.5} && \text{for} \quad 350 < L \le 500 \text{ m} \end{aligned} \tag{13}$$

This paper considers only sagging condition to show the compressive axial stress on the deck.

The maximum wave bending moment, M_{ws}, may occur at any time during the service life, T_s. The approach used by Wirshing et. al. (1997) will be used in modelling probabilistic of wave-induced bending moment. The model considers M_{ws} as a random variable in a set of single wave bending moment, M_i, in service life time, T_s. Individual wave bending moment, M_i, is assumed to follow Weibull distribution and all sets are having similar type of distribution. It is assumed that the total sample size is N. The cumulative distribution function (cdf) of Weibull with two parameters is given as in equation (14) below;

$$F_{M_i}(x) = 1 - \exp\left[-\left(\frac{x}{\alpha}\right)\right]^{\beta} \tag{14}$$

where α is scale parameter and β is shape parameter. The common value of β for tankers ranges from 0.9 to 1.10. In this case, value of β is taken equal to 1.0.

In a sample set of large cycle where N is approaching infinity, the Weibull distribution is approaching an asymptotic distribution. The extreme value in N which is M_{ws} is dependent on is also approaching asymptotic distribution. The extreme value distribution type-I (EVD-I) is considered as asymptotic distribution for M_{ws} with parameters of EVD-I. The CDF and its components are given by equation (15) to (17) as follow;

$$\mu_{M_{ws}} = \mu_{wb} + 0.577\sigma_{wb} \tag{15}$$

$$\sigma_{M_{ws}} = 1.283\sigma_{wb} \tag{16}$$

$$COV = \frac{\sigma_{M_{ws}}}{\mu_{M_{ws}}} \tag{17}$$

where μ_{M_w} is mean value of maximum wave bending moment, μ_{wb} is mean value of wave bending moment in Weibull distribution and COV is coefficient of variation of WBM and σ_{wb} is standard deviation of wave bending moment in Weibull distribution. The relationship between Weibull and EVD-I parameters are related [17] as in equation (18) and (19),

$$\mu_{wb} = \beta\left[\ln(N)\right]^{\frac{1}{\alpha}} \tag{18}$$

$$\sigma_{wb} = \frac{\beta}{\alpha\left[\ln(N)\right]^{1-\left(\frac{1}{\alpha}\right)}} \tag{19}$$

4.3 Extreme Load

The estimation of design loads is very important to provide ship with adequate strength in desired service area. IACS (2016) requires wave load estimation to have 25 years of design life with average operating speed of 5 knots in North Atlantic wave environment. The probability of 10^{-8} of load cycles by using $N = 10^8$ for total number of response peaks during 25 years life time period [19]. The value is reasonable in predicting extreme responses for various wave loads within safe-side estimation with slightly over estimated tolerance.

The extreme WBM in service life of 25 years distributed following EVD-I is obtained by substituting equation (11) into distribution characteristic as in equation (15) and (16). The difference between the extreme WBM in 20 years cycles and design WBM is recorded within 10% [17]. Hence the class WBM is treated as mean of extreme WBM.

5.0 Limit State Function and Failure Probability

Two limit states are used to explain failure of structures. The serviceability limit state (SLS) and ultimate limit state (ULS) are describing failure mode against yielding and ultimate buckling and torsional as shown in equation (20) and (21) respectively.

$$g\left(\sigma_{yD}\right) = \sigma_{yD} - M_T \tag{20}$$

$$g\left(\sigma_{bc}\right) = \sigma_{bc} - M_T \tag{21}$$

where M_T is total load and $\sigma_{bc} = \min(\sigma_{ul\text{-}bc}, \sigma_{ul\text{-}tor})$

For a safe structure, $R = P[g(\sigma_{yb})$ and $g(\sigma_{bc})] > 0$ which is reliability of the structure. Reliability is denoted as probability of strength exceeding load. Reliability is expected to decrease gradually and progressively when serviceability criteria and ultimate strength criteria is violated, respectively. The complement of reliability is probability of failure as shown in equation (22):

$$R = 1 - P_f \tag{22}$$

6.0 WAY FORWARD

There are still lot more considerations should be established to enhance the outcome. However, limitation of data is among the constraint in establishing more samples being investigated. The research will continue to explore information and consider more data on FPSO equivalence to improve approximation. The uncertainty measures of load and resistance will be investigated to reduce the error in estimation. Three different scopes are expected to be investigated for uncertainty measures, which are, characteristic of variable parameters, adequacy of statistical data and model uncertainty. The increase of life operation is believed will increase failure probability hence will required extensive maintenance and scheduling to keep it floating safely.

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