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TIME-VARIANT RELIABILITY ASSESSMENT OF FPSO CONSIDERING CORROSION AND COLLISION

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ABSTRACT

Floating production, storage, and offloading (FPSO) system has been widely used in the offshore oil and gas exploitations. Since it has long intervals of docking for thorough inspection and maintenance, and is exposed to collision risk at sea, the time-variant reliability of FPSO becomes very important as for the risks of corrosion and collision. The corrosion defect is modeled as the exponential function of time. The Idealized Structural Unit Method is also proposed to predict ultimate strength of hull girder. Still water and wave-induced bending moments are also combined into stochastic processes. Reliabilities of intact hull during the service are calculated as references to those of collided hulls with effect of corrosion defect. Collision condition is a focus in this paper, where collided hulls are modeled according to ABS instructions. According to the instructions, the section with highest bending moment, which almost locates at the mid ship, should be noticed. Therefore still water bending moments of mid section of collided hulls are achieved and divided into two groups based on collision positions. One is that the mid section is broken, which is named as “direct damage”. Another is that other else section is broken, which is named as “influence”. Result shows that “influence” condition has higher still water bending moment than “direct damage”, which is usually neglected in previous researches. Finally, reliabilities of collided hulls throughout the service life are obtained, which can become references to further inspection and maintenance plan.

INTRODUCTION

FPSO (Floating Production, Storage, and Offloading) needs to be moored near oil/gas field within rather long time. Because of its tough working environment, the long interval of docking between thorough inspections and maintenances, which is designed as 10 years, and the possibilities of collision with shuttles or supply ships, it will be very important to estimate the reliability of the hull girder in order to forecast the safety level of the FPSO during its lifetime.

There are many factors acting on FPSO during its lifetime, e.g., corrosion and fatigue. Ultimate strength decreases with the elapse of time, and the hull may encounter rather high still water and wave-induced load, which are caused by frequently changed loading conditions and unpredictable sea storms. These factors combined together make the reliability of FPSO going down and push the platform and the staff working on it into various dangerous situations. In order to make reasonable measures to reduce the risk and forecast the reliability of FPSO at different service years, it is necessary to perform time-variant reliability analysis. All previous pollution disasters caused by hull crack and consequent oil leaking have raised the alarm in maritime and offshore industry, simply because they made tremendous threats to ocean environment. Therefore, not only the reliability of intact hull but also that of damaged hull should be studied throughout their whole lifetime. ABS brought forward the guide of residual strength assessment [1] in 1995. After that, Jeom Kee Paik [2] and Ge Wang [3] did corresponding researches and theoretical analysis.

By using the previously mentioned methods, time-variant reliability of FPSO hull is studied in this paper, which includes reliability analysis for both intact and damaged hulls. The influence of corrosion and collision is also discussed. Especially, the situation of collided section not coinciding with the section to be studied, of which the influence to reliability is usually ignored before, is discussed and the example is given. The result of this study can form the foundation for further research about proposing inspection, repair decision and sensitivity analysis of FPSO.

NOMENCLATURE

B, ship breadth
C_B, block coefficient
C_W, wave coefficient
COV coefficient of variance
$d(t)$, corrosion depth
d_∞, long-term thickness of the corrosion wastage
F_{Xs}, extreme cumulative distribution function of SWBM
F_{Xw}, extreme cumulative distribution function of VWBM
h_w, site-specific parameter
ISUM, Idealized Structural Unit Method
L, ship length
M_s, SWBM of individual load condition
$M_{s,0}$, specified maximum of SWBM
$M_{s,T}$, time-variant SWBM
$M_{t,T}$, combination of SWBM and VWBM
M_u, ultimate strength
M_w, extreme VWBM
$M_{w,0}$, specified maximum of VWBM
$M_{w,T}$, time-variant VWBM
$r(t)$, corrosion rate
SWBM, still water bending moment
t, service year
T, interval between new state and checking point
T_0, designed lifetime
VWBM, vertical wave-induced bending moment
α_s, μ_s, parameters of extreme cumulative distribution function of SWBM
α_w, μ_w, parameters of extreme cumulative distribution function of VWBM
τ_c, coating life
τ_t, transition time
υ_s, mean arrival rate of one loading condition
υ_w, mean arrival rate of one wave cycle
φ_w, load reduction factor
χ_u, model uncertainty of predicting ultimate strength
χ_s, model uncertainty of predicting SWBM
χ_w, model uncertainty of predicting VWBM

ULTIMATE STRENGTH

ISUM

Since the accident of “Energy Concentration” happened in Rotterdam, the importance of ultimate strength of hull girder has been one of the focuses in maritime industry. Now there are three main methods to calculate the ultimate strength of hull girder. The first one is based on the discrete analytical model of hull cross-section initially presented by Caldwell. A further simplified method was developed by Smith C.S. [4], which has been proved to be simple and adequately accurate. The second method to calculate the ultimate strength of hull girder is the traditional FE analysis [5]. But it took too much computing time and manpower at the time when the computing technologies were not advanced as now. To improve the efficiency of modeling and computation and keep the general characteristics of FEM, Ueda Y and Rashed SMH [6] presented a new method - ISUM, Idealized Structural Unit Method, which is more convenient and efficient than the traditional FE method. Jeom Kee Paik [7] put this method into use and programmed software. After that, Jeom Kee Paik et al [8,9] calculated the ultimate strength of different types of ships under different working conditions by using ISUM. This study also takes the ISUM as the tool to calculate the ultimate strength, which can take corrosion and collision into account.

Corrosion Model

Corrosion is a main factor to diminish the ultimate strength of hull girder. Many researches have been carried out to simulate corrosion process of ship and offshore structures. The corrosion rate is assumed to be uncertain but constant in most corrosion models, which leads to a linear relationship between corrosion wastage and time. Southwell et al. proposed a linear and a bilinear model in 1979. Melchers [10] extended these two models by interpreting original parameter as mean value of statistical analysis in 1999. The extended Southwell’s models are given as below,

The linear model is

$$\begin{aligned}\mu_d(t) &= 0.076 + 0.038t \\ \sigma_d(t) &= 0.051 + 0.025t\end{aligned} \tag{1}$$

The bilinear model is

$$\begin{aligned}\mu_d(t) &= \begin{cases} 0.09t, & 0<t<1.46 \text{ years} \\ 0.076+0.038t, & 1.46<t<16 \text{ years}\end{cases} \\ \sigma_d(t) &= \begin{cases} 0.062t, & 0<t<1.46 \text{ years} \\ 0.035+0.017t, & 1.46<t<16 \text{ years}\end{cases}\end{aligned} \tag{2}$$

Joem Kee Paik [11] also proposed a model, which is

$$r = c_1 t_1^{c_2} \tag{3}$$

where t_1 is the time after coating invalidation. If the parameter c_2 is taken as constant 1.0, c_1 can be regarded as corrosion rate. Yamamoto, Kumano and Matoba [12] found that c_1 can be simulated by Weibull distribution and two parameters can be calculated by the method of least squares.

However the experimental evidence shows that non-linear model is more appropriate. Nowadays, one of the widely accepted models is proposed by Guedes Soares and Y. Garbatov [13], which is also used in this study. The equation of this model is

$$\tau_t r(t) + d(t) = d_\infty \tag{4}$$

The solution of Eq.(4) is

$$d(t) = \begin{cases} 0, & t \le \tau_c \\ d_\infty (1 - e^{-(t-\tau_c)/\tau_t}), & t \ge \tau_c \end{cases} \tag{5}$$

Collision Model

Since many FPSO are converted from oil tankers and newly-built FPSO still has similar shape to tankers, it is acceptable to set up collision model based on corresponding guide for tankers. According to the guide document proposed by ABS [1], the possible position of collision is defined between 0.2L forward from A.P. and 0.15L aft from F.P. Within this length, two sections should be studied at least. One is the midship section and the other one with high value of shear force. The following members should be assumed to be damaged and excluded totally or partially from section modulus calculations.

- side shell plating for vertical extent of 4m or D/4, whichever is greater, down from the upper edge of shear strake, where D is the depth;
- strength of deck plating including the stringer plate extending from side shell to inner skin;
- side stringers and platforms, within the damaged zone extending for 75% of double-side width;
- all deck and side longitudinals and longitudinal stiffeners attached to damaged plating.

SWBM

The peak value of SWBM (still water bending moment) of the FPSO can be fitted by Rayleigh distribution for sagging condition and exponential distribution for hogging condition by former research of Moan, Jiao and Wang.

The extreme cumulative distribution function of SWBM can be taken as Type Ⅰ distribution for total of $\upsilon_s T$ repetitions during its lifetime [14]:

$$F_{X_s} = \exp[-e^{-\alpha_s (X_s - \mu_s)}] \tag{6}$$

where $X_s = M_s / M_{s,0}$, and the two parameters α_s and μ_s are separated by conditions:

$$\mu_s = \sqrt{\frac{\ln(\upsilon_s T)}{\ln(\upsilon_s T_0)}} \qquad \text{sagging} \tag{7}$$

$$\alpha_s = 2\sqrt{\ln(\upsilon_s T_0)\ln(\upsilon_s T)}$$

$$\mu_s = \frac{\ln(\upsilon_s T)}{\ln(\upsilon_s T_0)} \qquad \text{hogging} \tag{8}$$

$$\alpha_s = \ln(\upsilon_s T_0)$$

Usually $M_{s,0}$ is defined by IACS requirement as

$$M_{s,0} = \begin{cases} -0.062 C_w L^2 B(C_B + 0.7) & \text{sagging} \\ C_w L^2 B(0.1225 - 0.015 C_B) & \text{hogging} \end{cases} \tag{9}$$

and C_w in Eq.(9) is given by following function:

$$C_w = \begin{cases} 10.75 - ((300 - L)/100)^{3/2} & 100 < L \le 300 \\ 10.75 & 300 < L \le 350 \\ 10.75 - ((L - 350)/150)^{3/2} & L > 350 \end{cases} \tag{10}$$

Equation(6), (7) and (8) will be adopted in following reliability assessment.

VWBM

Since the disconnectable turret system makes the FPSO headed coming wave, only VWBM is considered in this study.

Long-term distribution of VWBM can be fitted by Weibull distribution:

$$F_{M_w}(M_w) = 1 - \exp[-\ln(\upsilon_w T_0)(\frac{M_w}{M_{w,0}})^{h_w}] \tag{11}$$

And $M_{w,0}$ in Eq.(11) is defined by IACS,

$$M_{w,0} = \begin{cases} -0.11 C_w L^2 B(C_B + 0.7) & \text{sagging} \\ 0.19 C_w L^2 B C_B & \text{hogging} \end{cases} \tag{12}$$

Because the location of studied FPSO is in South China Sea, where has severe climate, it needn't to introduce environmental severity factors into account for this study.

The extreme cumulative distribution function of VWBM can also be modeled similar to that of SWBM for a total of $\upsilon_w T$ repetitions.

$$F_{X_w} = \exp[-e^{-\alpha_w (X_w - \mu_w)}] \tag{13}$$

where $X_w = M_w / M_{w,0}$, and the two parameters α_w and μ_w are :

$$\mu_w = [\frac{\ln(\upsilon_w T)}{\ln(\upsilon_w T_0)}]^{h_w}, \quad \alpha_w = [\frac{\ln(\upsilon_w T_0)}{(\ln(\upsilon_w T))^{1-h_w}}]^{1/h_w} \tag{14}$$

Equation(13) and (14) will be used in the process of reliability assessment.

LOAD COMBINATION

Because SWBM and VWBM can be modeled as a Poisson rectangular pulse process and a Poisson spike process, respectively, they will not reach peak values at the same time. Therefore the way of load combination should be researched. Ferry-Borges method is widely used for its efficiency and accuracy. For practical usage, the combination load is expressed as

$$M_{t,T} = M_{s,T} + \varphi_w M_{w,T} \tag{15}$$

$M_{s,T}$ and $M_{w,T}$ are defined by

$$M_{s,T} = \begin{cases} \dfrac{\sqrt{\ln(\upsilon_s T)}}{\sqrt{\ln(\upsilon_s T_0)}} M_{s,0} & \text{sagging} \\ \dfrac{\ln(\upsilon_s T)}{\ln(\upsilon_s T_0)} M_{s,0} & \text{hogging} \end{cases} \tag{16}$$

$$M_{w,T} = [\frac{\ln(\upsilon_w T)}{\ln(\upsilon_w T_0)}]^{1/h_w} M_{w,0} \quad \text{sagging and hogging} \tag{17}$$

Referring to the work of Haihong Sun and Yong Bai[14], load reduction factor can be expressed by

$$\varphi_w = \frac{0.83 M_{w,T} - 0.17 M_{s,T}}{M_{w,T}} \tag{18}$$

To evaluate the reliability of FPSO working in harsh environment, both sagging and hogging conditions are considered in the case of extreme load.

TIME-VARIANT RELIABILITY METHOD

Method of time-variant reliability assessment is well developed and accepted by maritime industry. The widely used limit state function at instant t relative to ultimate strength of hull girder is listed below

$$Z(t) = \chi_u M_u(t) - [\chi_s M_s(t) + \varphi_w \chi_w M_w(t)] \qquad (19)$$

Failure domain is defined as $Z(t)<0$ for $t>0$. As soon as distributions and parameters of all above variables in Eq.(19) are achieved, the probability of failure at time t can be calculated by Monte Carlo method.

NUMERICAL EXAMPLE

The studied FPSO was built in 2001 and has been put into service in South China Sea since then. The time-variant reliability analysis of FPSO hull girder subjected to effects of corrosion and collision is carried out. The principal dimensions of the FPSO are listed in Table 1 and mid section is plotted in Fig.1.

Table 1. Principal Dimensions of FPSO

Description	Value
Length (LPP) /m	250.00
Breadth (MLD) /m	46.00
Depth (MLD) /m	24.60
Draft (design) /m	16.50
Coefficient of Block	0.9002

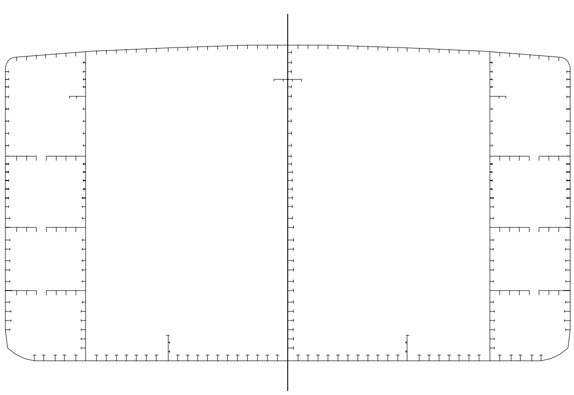

Figure 1. Mid Section of FPSO

Corrosion data

Since the target is newly-built FPSO, there is no measured corrosion data of it, especially the long-term thickness of the corrosion wastage, d_∞. Considering its ship-like shape, the data of an oil tanker presented by Unyime O.Akpan, T.S.Koko, B.Ayyub and Dunbar T.E.[15] is taken as replacement. The d_∞ used in Eq.(5) can be obtained from the mean values of corrosion rates in Table 2. The relationship between d_∞ and mean value given by Unyime O.Akpan etc. is expressed in

$$d_\infty = mean \times T_0 \qquad (20)$$

T_0 is designed lifetime, which is 20 years, and the "mean" in Eq. (20) is gotten from Table. 2.

Table 2. Corrosion Rate

Location	Mean(mm/y)
Deck plating	0.065
Deck longitudinals (web)	0.065
Side shell plating	0.03
Side shell plating longitudinals (web)	0.03
Bottom shell plating	0.17
Bottom shell longitudinals (web)	0.065
Longitudinal bulkhead plating	0.065
Longitudinal bulkhead longs. (web)	0.065

Considering the improved anticorrosive method, τ_c is set to 5 years and τ_t to 20 years, which are little bit longer than previous research and inspection results.

Although the designed lifetime T_0 is 20 years, corrosion data is derived within the interval of 25 years in case of exceeded service. Therefore, corrosion wastage is derived and plotted in Fig.2 in terms of different d_∞, which comes from different value in Table 2.

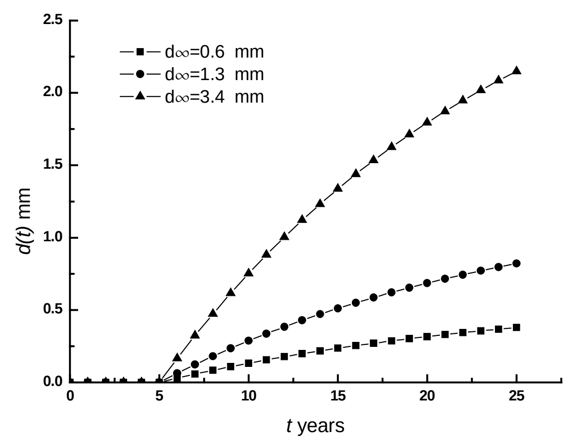

Figure 2. Corrosion Wastage

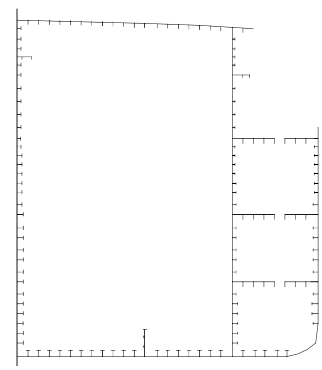

Figure 3. Collision Model

Collision model

Based on mid section of FPSO and the rules from ABS, collision model is determined as shown in Fig.3. The side shell plating for vertical damaged extent is 6.15 meters and the damaged zone of deck plating is 4.9 meters from the side shell to the inner skin. And all attached structural members of these plates are taken away. Because the studied FPSO has long parallels, the model can be applied to all the five ballast tanks. Therefore, not only the situation that the mid section is broken, but also the status that other else section is broken, can be proceeded to get SWBM under damaged condition at mid section of hull girder.

Since ultimate strength is usually focused at the mid section of ship, the situation of collision influence to the section with higher shear force is not discussed in this paper.

Ultimate Strength

Ultimate strength of FPSO hull girder can be derived using ISUM since corrosion data and collision model are achieved. Considering influence of corrosion only, intact ultimate strength of mid section can be gotten and plotted in Fig 4. Damaged ultimate strength of mid section affected by both corrosion and collision is plotted in Fig 5. In order to simplify the plot figure, ultimate strength of sagging condition is taken as absolute value.

Both hogging and sagging condition are calculated. It is obvious that ultimate strength degrades with time elapsing and effect of collision.

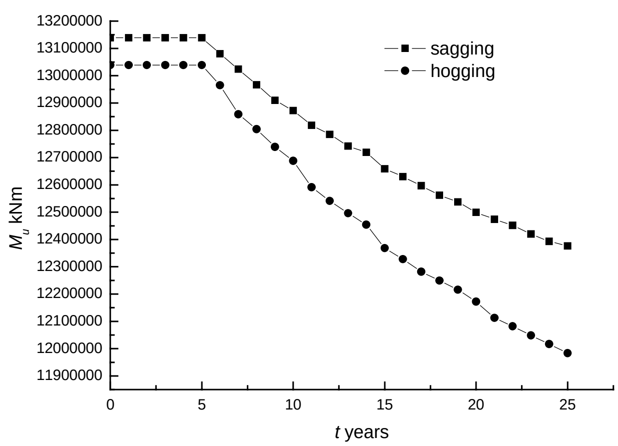

Figure 4. Intact Ultimate Strength of Mid Section

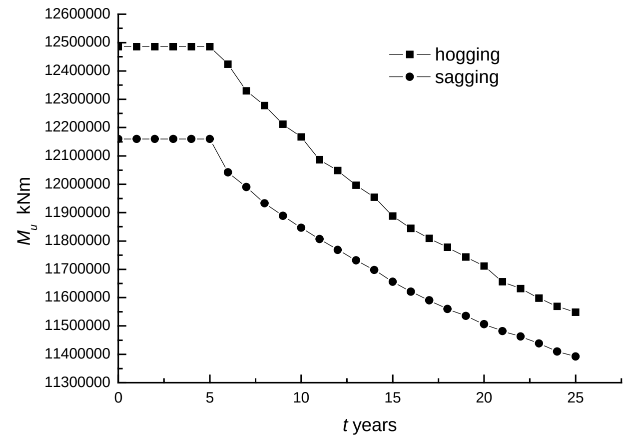

Figure 5. Damaged Ultimate Strength of Mid Section

SWBM

According to Eq.(9) and (10), $M_{s,0}$ of intact hull regulated by IACS requirement is

$$M_{s,0} = \begin{cases} -2951048 \text{ kNm} & \text{sagging} \\ 3242088 \text{ kNm} & \text{hogging} \end{cases}$$

But calculation book presented by shipyard gives specific values of all typical loading conditions, of which the highest value is -3525595 kNm for sagging condition and 3101881 kNm for hogging condition. Therefore, $M_{s,0}$ of intact hull is taken as the specific values listed in calculation book, within which the peak values are presented as mentioned above.

Collision will break the integrity of hull girder, which leads to ballast water leaking or filling in. $M_{s,0}$ of collided hull is derived from direct calculation considering the changes of ballast water.

Referring to Eq.(6), (7) and (10), mean value and deviation of M_s can be expressed by

$$\mu_{M_s} = M_{s,0} \times [\sqrt{\frac{\ln(\upsilon_s T)}{\ln(\upsilon_s T_0)}} + \frac{0.577}{2\sqrt{\ln(\upsilon_s T)\ln(\upsilon_s T_0)}}]$$
$$\sigma_{M_s} = M_{s,0} \times \frac{1.283}{2\sqrt{\ln(\upsilon_s T)\ln(\upsilon_s T_0)}} \quad \text{sagging (21)}$$

$$\mu_{M_s} = M_{s,0} \times [\frac{\ln(\upsilon_s T)}{\ln(\upsilon_s T_0)} + \frac{0.577}{\ln(\upsilon_s T_0)}]$$
$$\sigma_{M_s} = M_{s,0} \times \frac{1.283}{\ln(\upsilon_s T_0)} \quad \text{hogging} \qquad (22)$$

where average arrival period($1/\upsilon_s$) is 20 days, which is derived from calculation book and daily output of the oil field.

VWBM

The extreme cumulative distribution function of VWBM is used to simulate the most dangerous wave-induced load. Equation(13), (14) can be used to get the mean and deviation of extreme VWBM, which follows the Type Ⅰ distribution.

The mean and deviation of M_w can be written as,

$$\mu_{M_w} = M_{w,0} \times \{[\frac{\ln(\upsilon_w T)}{\ln(\upsilon_w T_0)}]^{h_w} + 0.577 \Big/ [\frac{\ln(\upsilon_w T_0)}{(\ln(\upsilon_w T))^{1-h_w}}]^{1/h_w}\}$$
$$\sigma_{M_w} = M_{w,0} \times \frac{1.283}{[\frac{\ln(\upsilon_w T_0)}{(\ln(\upsilon_w T))^{1-h_w}}]^{1/h_w}} \quad (23)$$

Usually the parameter h_w varies from 0.9 to 1.1, and it can be reasonably taken as 1.0. Then, the Eq.(23) can be simplified as

$$\mu_{M_w} = M_{w,0} \times \frac{\ln(\upsilon_w T) + 0.577}{\ln(\upsilon_w T_0)}$$
$$\sigma_{M_w} = M_{w,0} \times \frac{1.283}{\ln(\upsilon_w T_0)} \quad (24)$$

where the average arrival rate υ_w is $10^{8.7}$ in 100 years.

$M_{w,0}$ is calculated by Eq.(12) and presented below:

$$M_{w,0} = \begin{cases} -5235730 \text{ kNm} & \text{sagging} \\ 5087483 \text{ kNm} & \text{hogging} \end{cases}$$

Load Combination

Since h_w is taken as 1.0, Equation(17) is predigested and the load reduction factor φ_w of intact hull and collided hull can be achieved, as plotted in Fig. 6 and 7.

Conditions of "direct damage" and "influence" are also distinguishable in Fig.7

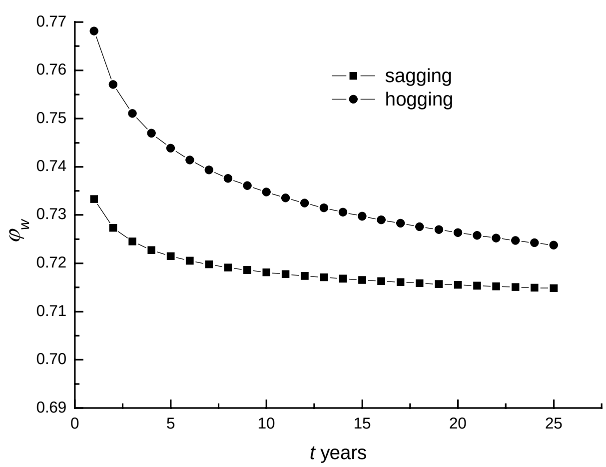

Figure 6. Load Reduction Factor of Intact Hull

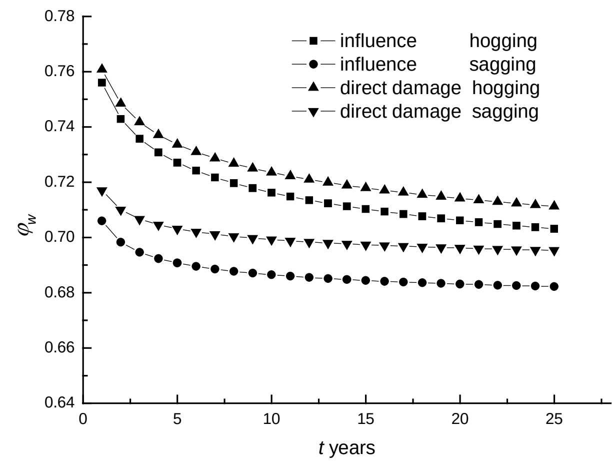

Figure 7. Load Reduction Factor of Collided Hull

Reliability Calculation

After necessary variables being obtained, the time-variant reliability can be calculated by using certain reliability assessment method. Equation(19) will be applied in this process to get reliability index using those parameters calculated above, of which some are variables of time.

The ultimate strength $M_u(t)$ at time t follows the normal distribution, where *COV* is taken as 0.12. The values of $M_u(t)$ degraded by effect of corrosion are derived according to intact and collided condition, see Figure 4 and Figure 5. $M_s(t)$ is SWBM with Type Ⅰ distribution at time t, of which the mean and the deviation are given in Eq.(21) and (22) according to the working condition. And it should be noticed that the values of $M_s(t)$ under intact condition, direct damage condition and influence condition are quite different even at the same time t because of different $M_{s,0}$. $M_w(t)$ is VWBM with Type Ⅰ distribution at time t, of which the mean and the deviation are given in Eq.(23) and (24).

As mentioned above, the load reduction factor φ_w has been derived from Eq.(18) and plotted in terms of hull integrity or not, which can be seen in Figure 6 and Figure 7.

Considering the uncertainty of predicting the ultimate strength, SWBM and VWBM, three uncertainty parameters are introduced into the assessment, which are χ_u, χ_s and χ_w in correspondence with variables' sequence. Three uncertainty parameters χ_u, χ_s and χ_w are normal variables with the mean value 1.0. And their *COV*s are 0.1, 0.05 and 0.2, respectively.

Reliability index can be calculated by applying the Monte Carlo method based on Eq.(19). The results of simulation throughout the service cycle of the FPSO are plotted in Fig. 8 to Fig. 11.

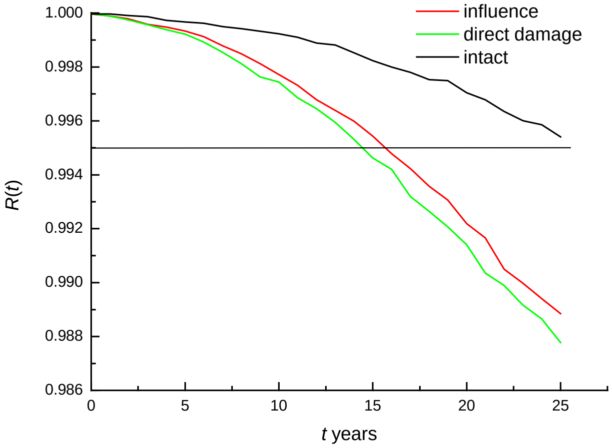

Figure 8. Time-Variant Reliability of Hogging

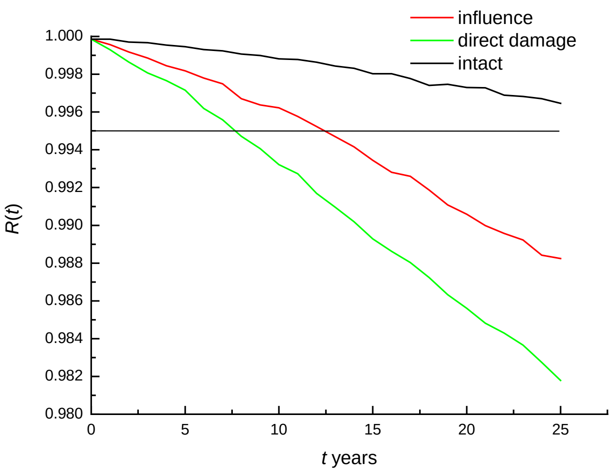

Figure 9. Time-Variant Reliability of Sagging

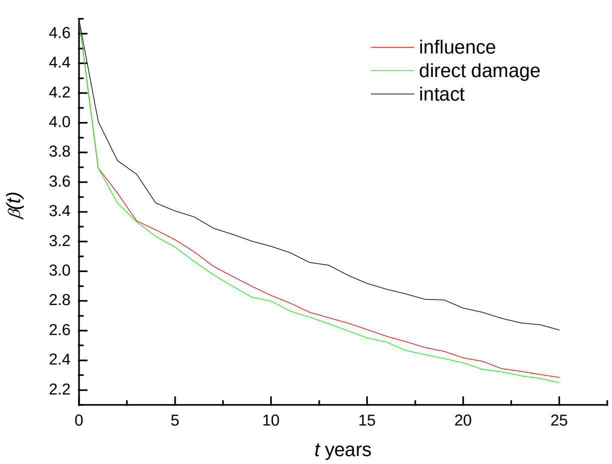

Figure 10. Reliability Index of Hogging

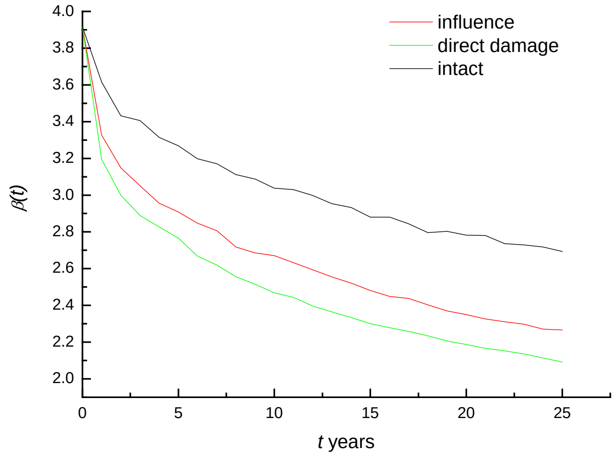

Figure 11. Reliability Index of Sagging

Time-variant reliabilities of hogging and sagging condition are plotted in Fig.8 and Fig. 9, respectively. And reliability indexes of hogging and sagging condition are shown in Fig. 10 and Fig. 11. Within the Fig.8 and Fig. 9, horizontal line with reliability value of 0.995 is added to set the lowest acceptable reliability level.

CONCLUSION

Obviously the sagging condition has higher reliability than hogging condition when the hull is intact. When "direct damage" happens, reliability of hogging condition is higher, for which partial deck and top side shell structural members are destroyed by collision and compression load-carrying ability of deck degrades under sagging condition. While one another section is collided, changed still water load contributes to hogging reliability, which is higher than sagging reliability.

Taking 0.995 as the lowest acceptable reliability level, intact hull has satisfactory safety margin within 25 years. But the reliability of collided hulls after servicing for several years is unacceptable, which is lower than 0.995 and regarded as invalidated. The invalidation time of collided hull under sagging and hogging condition are listed in Table 3.

Table 3. Invalidation Time

	Direct damage	Influence
Hogging	14.43 years	15.64 years
Sagging	7.64 years	12.37 years

It should be noticed that the influence of other sections' collision to intact mid section is remarkable, especially under hogging conditions when the level of reliability is nearly equal to that of "direct damage". This phenomenon proves the importance of considering such situation of "influence" during process of design, evaluation and research, which is usually neglected before when analyzing the reliability.

Based on obtained reliability data, the decision of inspection and maintenance can be made to update the reliability when a target level is defined. It contributes greatly to reducing the risk level of FPSO and guaranteeing the safety of staffs, equipments under ocean environment.

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