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Panel Reliability Assessment for FPSOs

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Abstract

An assessment method is developed for the panel reliability of ship-shaped Floating, Production, Storage and Offloading units (FPSO). Not only axial compressive loads but also internal and external lateral pressures are taken into account in the reliability assessment. Beam-column buckling and flexural-torsional buckling are regarded as two primary failure modes of stiffened panels. Variability of corrosion wastage and material properties are accounted for in modelling the panel's time-dependent ultimate strength. Uncertainty of axial compressive loads induced by hull girder bending is evaluated based on probabilistic characteristics of still-water bending moment (SWBM) and vertical wave-induced bending moment (VWBM). A case study is performed to demonstrate this method and the effects of the lateral pressure, the return period of the

extreme value of VWBM, the environmental severity factor, and the corrosion wastage on the panel reliability are investigated. Sensitivity measures for random variables are also carried out.

Keywords: Floating, production, storage and offloading units (FPSO); stiffened panels; beam-column buckling; flexural-torsional buckling; corrosion wastage; reliability assessment

Nomenclature

σ_a^{exe}	Extreme value of the axial compressive stress on a stiffened panel
γ	$= \frac{s\sqrt{\sigma_y/E}}{t_p}$
χ	Aspect ratio, l/s
ρ	Density of sea water
σ	Scale parameter of Gumbel distribution
λ	Shape parameter of Weibull distribution
α	Unit vector of directional cosines
Γ	Warping constant $\cong mI_{yf}d_w^2 + d_w^3t_w^3/36$
η_a	Amplification factor accounting for the secondary stresses, σ_{L2}
σ_a	Axial compressive stress on a stiffened panel
σ_{ca}	Beam-column critical buckling stress of a stiffened panel
σ_{cL}	Critical buckling stress for the associated plating, corresponding to n -half waves $= \frac{\pi^2 E(n/\alpha + \alpha/n)^2 (t_p/s)^2}{12(1-\nu^2)}$
σ_{ct}	Torsional-flexural critical buckling stress of a stiffened panel
σ_E	Euler column buckling stress
σ_{ET}	$= \frac{E[K/2.6 + (n\pi/l)^2\Gamma + C_o(l/n\pi)^2/E]}{I_o + C_o(l/n\pi)^2/\sigma_{cL}}$
∇g	Vector of partial derivatives of the limit state function $g(\mathbf{X})$ with respect to the design point $\mathbf{x}^{(k)}$
ε_i	Distribution factor around the girth of the installation at location i
α_i	Sensitivity factor of random variable i
σ_{L1}	Primary stresses resulting from hull girder bending
σ_{L2}	Secondary stresses resulting from bending of large stiffened panels between transverse bulkheads
η_{sw}	Model uncertainty factor of SWBM
η_w	Model uncertainty factor of M_w
σ_y	Minimum specified yield stress of a stiffened panel
A	Total sectional area of a stiffened panel
A_e	Area of a stiffened panel accounting for the effective width of the plating attached
a_i	Effective resultant acceleration at the point considered
a_l	Longitudinal accelerations of tank contents (cargo or ballast)
A_s	Area of the stiffener
a_t	Transverse accelerations of tank contents (cargo or ballast)
a_v	Vertical accelerations of tank contents (cargo or ballast)
B	Breath of a FPSO
b_1	Smaller outstanding dimension of flange with respect to centerline of web
b_e	Effective breadth of attached plating in bending for yield
b_f	Width of the flange/face plate
b_t	Breadth of a tank
b_{wL}	Effective width of the plating

	$= 10.75 - \left(\frac{300 - L}{100} \right)^{1.5}$	for $90 \text{ m} \leq L \leq 300 \text{ m}$
C_1	$= 10.75$	for $300 \text{ m} \leq L \leq 350 \text{ m}$
	$= 10.75 - \left(\frac{L - 350}{100} \right)^{1.5}$	for $350 \text{ m} \leq L \leq 500 \text{ m}$
C_b	Block coefficient of a FPSO	
C_{dp}	Parameter of tank shape	
c_m	Moment adjustment coefficient	
c_o	$= Et_p^3 / 3s$	
C_{ru}	Parameter of tank shape	
$\mathbf{C_X}$	Covariance matrix of the vector of random variables $\mathbf{X}$	
C_θ	Weight coefficient for θ	
C_ϕ	Weight coefficient for ϕ	
$d(t)$	Corrosion wastage at time t	
d_m	Long-term corrosion wastage	
d_w	Depth of the web	
E	Young's modulus of a material	
$E[\mathbf{X}]$	Mean matrix of the vector of random variables $\mathbf{X}$	
f	Limit state function	
g	Gravitational acceleration	
h_d	Wave-induced internal pressure head, including inertial force and added pressure head	
h_{de}	Hydrodynamic pressure head induced by waves	
h_s	Hydrostatic pressure head in still water	
h_t	Depth of a tank	
I_e	Moment of inertia of longitudinal or stiffener accounting for the effective width of the plating attached	
I_o	Polar moment of inertia of the stiffened panel, excluding the associated plating, about the stiffener toe	
I_x	Moment of inertia of the stiffened panel about the x -axis, through the centroid of the stiffened panel, excluding the plating	
I_y	Moment of inertia of the stiffened panel about the y -axis, through the centroid of the stiffened panel, excluding the plating	
I_{yf}	$= t_f b_f^3 \frac{1 + 3(1 - 2b_1 / b_f)^2 d_w t_w / A_s}{12}$	
k	Scale parameter of Weibull distribution	
K	St. Venant torsion constant for the stiffened panel's cross section, excluding the associated plating	
k_c	A correlation factor	
k_c	Correlation factor for a specific combined load case	
$k_{EPS/EPP}$	Environmental severity factor (ESF) for external pressure starboard/port	
k_l	Distribution factor along the length of the installation	
k_{lo}	Pressure distribution function	
k_s	Load factor	
k_u	Load factor	
k_{VBM}	Environmental severity factor	
L	Length of a FPSO	
l	Unsupported span of a stiffened panel	
L_n	Most probable extreme value based on unrestricted North Atlantic environment with design return period for the dynamic load parameters	

L_s	Most probable extreme value based on site-specific environment with design return period for the dynamic load parameters
l_t	Length of a tank
m_b	Amplification factor
M_{sw}	Still-water bending moment (SWBM)
M_w	Vertical wave-induced bending moment (VWBM)
$M_{w,c}$	M_w corresponding to the exceeding probability of $1/N$
$M_{w,exe}$	Extreme value of VWBM $M_{w,exe}$ of a FPSO at mid-ship
n	Number of half-waves which yield the smallest σ_{ET}
N	Number of wave cycles
p	Lateral pressure imposed on a stiffened panel
p_e	External pressures imposed on a stiffened panel
P_f	Probability of failure
p_i	Internal pressure
P_r	Proportional linear elastic limit of a material
p_t	Total nominal pressure imposed on a stiffened panel
p_{vp}	Pressure setting of the pressure/vacuum relief valve
r_e	Radius of gyration of area A_e
s	Longitudinal spacing
SM_e	Effective sectional modulus of the longitudinal to flange, accounting for the effective breadth b_e
T_c	Time to coating breakdown
t_f	Thickness of the flange/face plate
t_p	Thickness of the plating
T_t	Transition time
t_w	Thickness of the web
u	Location parameter of Gumbel distribution
ν	Poisson's ratio of a material
W	Hull girder section modulus at the stiffened panel under consideration
w_l	Weight coefficient of a_l
w_t	Weight coefficient of a_t
w_v	Weight coefficient of a_v
$\mathbf{X}$	Vector of random variables
$\mathbf{x}^*$	Final design point
x_o	Horizontal distance between centroid of stiffener, A_s , and centerline of the web plate
$\mathbf{y}^*$	Design point in the standard normal space
y_o	Vertical distance between the centroid of the stiffened panel's cross section and its toe
β	Reliability index
δ_b	Local coordinate adjustments for the point considered
δ_h	Local coordinate adjustments for the point considered
Δh_i	Added pressure head due to pitch and roll motions at the point considered
ζ	Local coordinates for the point considered
η	Local coordinate in the vertical direction for tank boundaries measuring from the top of the tank
θ	Roll amplitudes
μ	Wave heading angle
ξ	Local coordinates for the point considered
σ_b	Bending stress induced by lateral pressures
ϕ	Pitch amplitudes
$\Phi(.)$	Standard normal cumulative distribution function

1. Introduction

Floating, production, storage and offloading units (FPSOs) are widely utilized in offshore oil and gas fields. A FPSO is operated at a specific location and is usually designed to not sail away even during adverse weather conditions. The structural strength assessment, including the reliability-based strength assessment for FPSOs under severe sea conditions during their service life, is of vital importance.

In the past four decades, considerable work has been conducted on hull girder reliability assessment (Abrahamsen et al., 1970; Mansour and Faulkner, 1973; Mansour et al, 1997; Paik et al, 2003; Moan et al, 2006; Harada et al., 2010; Gaspar and Guedes Soares, 2013; Chen, 2016). For panel reliability assessments are much less reported and most of previous work concerns only the failure of deck panels, and thus the applied loads are uniaxial compressive stresses induced predominately by hull girder bending (Mansour et al., 1997; Assakkaf et al, 2002; Gaspar et al, 2011; Bai and Qian, 2013). More information on the state of the art of panel reliability assessment can be found in ISSC reports (Aksu et al., 2012; Ringsberg et al., 2015).

As an extension of the work of Chen et al. (2013) and Chen (2016), this paper aims at developing a methodology for panel reliability assessment of FPSOs considering both axial compressive loads and lateral pressures. Beam-column buckling and flexural-torsional buckling are regarded as two primary failure modes of stiffened panels. Variability of corrosion wastage and material properties are accounted for in modelling panel time-dependent ultimate strength. Uncertainty of axial compressive loads induced by hull girder bending is evaluated based on probabilistic characteristics of still-water bending moment (SWBM) and vertical wave-induced bending moment (VWBM). Lateral pressures imposed on the stiffened panel is calculated based on the external and internal pressures due to sea water, cargo, ballast water, etc. Then, stiffened panels from deck and bottom structures are utilized for a case study to demonstrate the capability of the method developed. The effects of the lateral pressure, the return period of the extreme value of VWBM, the environmental severity factor, and the corrosion effects on the panel reliability are investigated. Sensitivity measures for random variables are also conducted.

2. Ultimate strength of stiffened panel

Ultimate strength of a stiffened panel is evaluated by two primary failure modes, namely, beam-column buckling and flexural-torsional buckling. The critical buckling stresses for the two failure modes are

predicted based on the formulae given in ABS Rules for building and classing: floating production installations (FPI) (2015).

2.1. Beam-column buckling

The critical buckling stress of a stiffened panel corresponding to the failure mode of beam-column buckling is given by:

$$\sigma_{ca} = \begin{cases} \sigma_E & \sigma_E \leq P_r \sigma_y \\ \sigma_y [1 - P_r (1 - P_r) \sigma_y / \sigma_E] & \text{otherwise} \end{cases} \quad (1)$$

where σ_y is the minimum specified yield stress of the stiffened panel. P_r is the proportional linear elastic limit of the material, which is chosen herein to be 0.6 for steel. σ_E is given by:

$$\sigma_E = \frac{\pi^2 r_e^2 E}{l^2} \quad (2)$$

where l is the unsupported span of the stiffened panel. E is Young's modulus of the material. r_e is the radius of gyration of area A_e and it is given by

$$r_e = \sqrt{\frac{I_e}{A_e}} \quad (3)$$

where I_e is the moment of inertia of longitudinal or stiffener accounting for the effective width b_{wL} of the plating attached. A_e is given by:

$$A_e = A_s + b_{wL} t_p \quad (4)$$

where A_s is the area of the stiffener. t_p is the thickness of the plating. b_{wL} is the effective width of the plating (Faulkner, 1975) as given by:

$$b_{wL} = \begin{cases} s(2/\gamma - 1/\gamma^2) & \text{for } \gamma \geq 1.0 \\ s & \text{otherwise} \end{cases} \quad (5)$$

where s is the longitudinal spacing. γ is given by:

$$\gamma = \frac{s \sqrt{\sigma_y / E}}{t_p} \quad (6)$$

2.2. Torsional-flexural buckling

The critical buckling stress of a stiffened panel corresponding to the failure mode of torsional-flexural buckling is given by:

$$\sigma_{ct} = \begin{cases} \sigma_{ET} & \sigma_{ET} \leq P_r \sigma_y \\ \sigma_y [1 - P_r (1 - P_r) \sigma_y / \sigma_{ET}] & \text{otherwise} \end{cases} \quad (7)$$

where σ_{ET} is given by

$$\sigma_{ET} = \frac{E[K / 2.6 + (n\pi / l)^2 \Gamma + C_o (l / n\pi)^2 / E]}{I_o + C_o (l / n\pi)^2 / \sigma_{cL}} \quad (8)$$

where K is St. Venant torsion constant for the stiffened panel's cross section, excluding the associated plating, and it is given by:

$$K = \frac{b_f t_f^3 + d_w t_w^3}{3} \quad (9)$$

where b_f is the width of the flange/face plate. t_f is the thickness of the flange/face plate. d_w is the depth of the web. t_w is the thickness of the web.

I_o is the polar moment of inertia of the stiffened panel, excluding the associated plating, about the stiffener toe, and it is given by:

$$I_o = I_x + m I_y + A_s (x_o^2 + y_o^2) \quad (10)$$

where I_x and I_y are the moment of inertia of the stiffened panel about the x - and y - axis, respectively, through the centroid of the stiffened panel, excluding the plating. m is given by:

$$m = 1.0 - (1 - 2b_1 / b_f)(0.7 - 0.1d_w / b_f) \quad (11)$$

where x_o is the horizontal distance between centroid of stiffener, A_s , and centerline of the web plate. y_o is the vertical distance between the centroid of the stiffened panel's cross section and its toe. b_1 is the smaller outstanding dimension of flange with respect to centerline of web.

C_o is given by:

$$C_o = \frac{Et_p^3}{3s} \quad (12)$$

Γ is the warping constant, given by:

$$\Gamma \cong m I_{yf} d_w^2 + d_w^3 t_w^3 / 36 \quad (13)$$

where I_{yf} is given by:

$$I_{yf} = t_f b_f^3 \frac{1 + 3(1 - 2b_1 / b_f)^2 d_w t_w / A_s}{12} \quad (14)$$

σ_{cL} is the critical buckling stress for the associated plating, corresponding to n -half waves, it is given by:

$$\sigma_{cL} = \frac{\pi^2 E (n / \alpha + \alpha / n)^2 (t_p / s)^2}{12(1 - \nu^2)} \quad (15)$$

where n is the number of half-waves which yield the smallest σ_{ET} . ν is the Poisson's ratio of the material. α is given by:

$$\chi = l / s \quad (16)$$

3. Corrosion wastage model

Mathematical models have been developed to describe the corrosion wastage of ship structures (Guedes Soares & Garbatov, 1999; Melchers, 2003; Paik et al., 2004; Yamamoto & Kobayashi, 2005). The model developed by Guedes Soares & Garbatov (1999) was successfully calibrated to interpret the corrosion wastage of ship crude oil tanks (Guedes Soares et al., 2008) using ABS corrosion wastage data (Wang et al., 2003). Hence, the model of Guedes Soares & Garbatov (1999) is used herein to reflect the corrosion wastage of FPSO panels.

According to their model, the corrosion wastage at time t is assumed to be:

$$d(t) = d_m \left[1 - \exp \left(- \frac{t - T_c}{T_t} \right) \right] \quad (17)$$

where, d_m is the long-term corrosion wastage, T_c is the time to coating breakdown and T_t is the transition time.

In this paper, the long-term corrosion wastage d_m and the coating time T_c are assumed to follow the lognormal distribution. The transition time T_t is assumed to be 4.5 year.

4. Axial compressive stress

The axial compressive stress on a stiffened panel is given by:

$$\sigma_a = \sigma_{L1} + \sigma_{L2} = \eta_a \frac{M_{sw} + M_w}{W} \quad (18)$$

where, σ_{L1} is the primary stresses resulting from hull girder bending, σ_{L2} is the secondary stresses resulting from bending of large stiffened panels between transverse bulkheads, η_a is the amplification factor accounting for the secondary stresses, σ_{L2} . In this paper, η_a is chosen to be 1.05. M_{sw} is the still-water bending moment (SWBM). M_w is the vertical wave-induced bending moment (VWBM). W is the hull girder section modulus at the stiffened panel under consideration.

4.1 Still-water bending moment (SWBM)

The still-water bending moment (SWBM) on a hull girder results primarily from the action of the FPSO's lightweight, cargo, equipment, personnel and buoyancy. The distribution and weight of cargo may be the major contributors to variability in SWBM.

The early publication on probabilistic presentation of SWBM was made by Trafalski (1967), Truhin (1970) (river going ships), Lewis et al. (1973) (tankers), and Ivanov (1973) (general cargo ships and bulk carriers). They stated that there is a need to model the SWBM as a random parameter and a proposal for its presentation with normal distribution was made. Later, Ivanov and Madjarov (1975) investigated eight cargo ships and a normal distribution was used to fit the SWBM with periods from two to seven years for full and partial load conditions. Mano et al. (1977) addressed that the SWBM approximately follows the normal distribution on the basis of the investigation of 10 container ships and 13 tankers.

Guedes Soares and Moan (1988) performed an extensive and systematic study on SWBM. They analyzed about 100 ships with 2000 voyages. The study covers different types of ships belonging to 39 ship owners in 14 countries. Their study shows that the normal distribution might be appropriate to represent the statistical variability of the SWBM on various sections along the ship length. Further studies were carried out by Guedes Soares and Dias (1996), Guedes Soares and Dogliani (2000), and Garrè and Rizzuto (2009) and their results shows, in most cases, normal distributions seem to be appropriate to model the SWBM. Accordingly, it is assumed herein that the SWBM of FPSOs follows a normal distribution based on the previous work on probabilistic presentation of SWBM.

Ideally, it is preferable to use FPSO daily operational records to build the stochastic model for SWBM of FPSOs. If such information is not available, operational manual may be used to build the model of SWBM (Ivanov and Wang, 2008). However, each operational condition in the operational manual is not equally likely happen since the frequency of occurrence of every operational condition is usually not equal.

From the point of view of the structure type, ship-shaped FPSOs are similar to tankers. Therefore, a practical alternative is to use the stochastic model of SWBM of tankers. On the basis of the suggestions of Moan et al. (2006) and Hørte et al. (2007) for tankers, the mean value and the standard deviation of the SWBM of FPSOs are assumed herein to be 70% and 20% of the maximum value stated in the operation manual of FPSOs. In addition, an uncertainty factor η_{sw} is introduced as a multiplier on the SWBM to account for the model uncertainty of SWBM. η_{sw} is defined as a normally distributed random variable with a mean value of 1.0 and a coefficient of variation of 0.1. It is important to note that the coefficient of variation of η_{sw} is an assumed value, possibly not conservative.

4.2. Vertical wave-induced bending moment (VWBM)

The extreme value of the vertical wave-induced bending moment (VWBM) within a given return period is normally calculated by: 1) Rule value, as specified by Classification Society Rules; 2) direct calculation based on wave scatter diagrams and response amplitude operators (RAOs).

4.2.1. Classification Rule value

The ABS Rule value (ABS FPI Rules, 2015) for the extreme value of VWBM $M_{w,exe}$ of FPSOs at mid-ship that can be exceeded by 10^{-8} probability of exceedance, expressed in kN.m, is given by:

$$\begin{aligned} M_{w,exe} &= 0.11k_{VBM} C_1 L^2 B (C_b + 0.7) && \text{for Sagging} \\ M_{w,exe} &= 0.19k_{VBM} C_1 L^2 B C_b && \text{for Hogging} \end{aligned} \quad (19)$$

where L , B , and C_b are length, breath and block coefficient of a FPSO, respectively. k_{VBM} is the environmental severity factor and C_1 is given by

$$\begin{aligned} C_1 &= 10.75 - \left(\frac{300 - L}{100} \right)^{1.5} && \text{for } 90 \text{ m} \leq L \leq 300 \text{ m} \\ &= 10.75 && \text{for } 300 \text{ m} \leq L \leq 350 \text{ m} \\ &= 10.75 - \left(\frac{L - 350}{100} \right)^{1.5} && \text{for } 350 \text{ m} \leq L \leq 500 \text{ m} \end{aligned} \quad (20)$$

4.2.2. Probabilistic presentation of VWBM

VWBM is usually described in two ways, using either short-term or long-term statistics. The amplitude of the VWBM within a short-term duration (typically several hours) corresponding to a steady sea state is usually considered to follow a Rayleigh distribution.

Extensive studies on the long-term VWBM (e.g., Jensen, 2001) show the long-term probability density function and cumulative density function of VWBM $f_{M_w}()$ and $F_{M_w}()$ may be well approximated by a two-parameter Weibull distribution as

$$\begin{aligned} f_{M_w}(M_w) &= \frac{k}{\lambda} \left(\frac{M_w}{\lambda} \right)^{k-1} \exp \left[- \left(\frac{M_w}{\lambda} \right)^k \right] \\ F_{M_w}(M_w) &= 1 - \exp \left[- \left(\frac{M_w}{\lambda} \right)^k \right] \end{aligned} \quad (21)$$

where k and λ are scale and shape parameters of the distribution, respectively. Therefore, the long-term VWBM of FPSOs is assumed herein to follow a two-parameter Weibull distribution.

Since the long-term VWBM is assumed to follow a two-parameter Weibull distribution, a stochastic model is derived herein to represent the extreme value of VWBM $M_{w,exe}$ within a certain return period. In accordance with the extreme value theories, the extreme value $M_{w,exe}$ of VWBM within a given return period could be assumed to follow a Gumbel distribution with a probability density function $f_{exe}()$ and a cumulative density function $F_{exe}()$ given as

$$\begin{aligned} f_{exe}(M_{w,exe}) &= \frac{1}{\sigma} \exp \left[- \frac{(M_{w,exe} - u)}{\sigma} \right] \exp \left\{ - \exp \left[- \frac{(M_{w,exe} - u)}{\sigma} \right] \right\} \\ F_{exe}(M_{w,exe}) &= \exp \left\{ - \exp \left[- \frac{(M_{w,exe} - u)}{\sigma} \right] \right\} \end{aligned} \quad (22)$$

where u and σ are the location parameter and scale parameter of the Gumbel distribution, respectively.

If the number of wave cycles is N during the given return period and the M_w corresponding to the exceeding probability of $1/N$ is $M_{w,c}$, on the principle of the extreme value theories, the mean value and the coefficient of variation of the $M_{w,exe}$ can be derived as (Chen, 2016):

$$\begin{aligned} \mu_{M_{w,exe}} &= M_{w,c} + \frac{0.2124}{N(1-1/N)^{N-1} f_{M_w}(u)} \\ COV_{M_{w,exe}} &= \frac{0.4719}{0.2124 + M_{w,c} N(1-1/N)^{N-1} f_{M_w}(u)} \end{aligned} \quad (23)$$

Because the ABS rule value for $M_{w,exe}$ is primarily calibrated based on the linear strip theory, an uncertainty factor η_w is introduced to multiply with the $M_{w,exe}$ to take into account the uncertainty induced by linear response calculation and nonlinear effects. η_w is assumed to be a normally distributed random variable with a mean value of 1.0 and a coefficient of variation of 0.1 (Hørte et al., 2007).

4.3. Load combination

SWBM and VWBM are two different stochastic load processes that vary with time (Chen et al., 2014). It is unlikely for both maxima of SWBM and VWBM to happen simultaneously in the very same hull girder section. In order to predict the extreme value of the combined two stochastic processes, Turkstra's rule (Turkstra, 1970) is used to combine the SWBM and VWBM to obtain the total bending moment.

According to Section 4.1 and 4.2, SWBM is modelled as a random variable with a Normal distribution and the extreme value of VWBM $M_{w,exe}$ within a certain return period is modelled as a random variable with a Gumbel distribution. So, the extreme value of the axial compressive stress on a stiffened panel is then given by:

$$\sigma_a^{exe} = \eta_a \frac{M_{sw} + M_{w,exe}}{W} \quad (24)$$

5. Lateral pressure

Pressures imposed on the stiffened panel, e.g., bottom panel, may be induced by external and internal pressures due to sea water, cargo, ballast water, etc. In this section, external and internal pressures are predicted based on the formulae given in ABS Rules for building and classing: floating production installations (FPI) (2015).

5.1 External pressure

The external pressures, p_e , imposed on a stiffened panel in a seaway at a specific location can be expressed as:

$$p_e = \rho g (h_s + k_{EPS/EPP} k_u h_{de}) \quad (25)$$

where ρg is the specific weight of sea water. h_s is the hydrostatic pressure head in still water. $k_{EPS/EPP}$ is the environmental severity factor (ESF) for external pressure starboard/port. k_u is the load factor, and is taken as

unity unless otherwise specified. h_{de} is the hydrodynamic pressure head induced by waves and is calculated as follows:

$$h_{de} = k_c k_l \varepsilon_i h_{do} \quad (26)$$

where k_c is the correlation factor for a specific combined load case. k_l is the distribution factor along the length of the installation as given by:

$$k_l = 1 + (k_{lo} - 1) \cos \mu \quad (27)$$

where μ is the wave heading angle, to be taken from 0° to 90° . k_{lo} is the pressure distribution function, equal to 1.0 at amidships. ε_i is the distribution factor around the girth of the installation at location i as given by:

$$\varepsilon_i = \begin{cases} 1.00 - 0.25 \cos \mu & \text{for } i = 1, \text{ at WL, starboard} \\ 0.40 - 0.10 \cos \mu & \text{for } i = 2, \text{ at bilge, starboard} \\ 0.30 - 0.20 \sin \mu & \text{for } i = 3, \text{ at bottomcenterline} \\ 2\varepsilon_3 - \varepsilon_2 & \text{for } i = 4, \text{ at bilge, port} \\ 0.75 - 1.25 \sin \mu & \text{for } i = 5, \text{ at WL, port} \end{cases} \quad (28)$$

h_{do} is $1.36C_1$.

5.2 Internal pressure

The internal pressure, p_i , for a completely filled tank is obtained from the following formulae:

$$\begin{aligned} p_i &= k_s \rho g (\eta + k_u h_d) + p_0 \geq 0 \\ p_o &= p_{vp} - p_n \geq 0 \end{aligned} \quad (29)$$

where p_{vp} is the pressure setting of the pressure/vacuum relief valve ≤ 6.90 N/cm². p_n is 2.06 N/cm². η is the local coordinate in the vertical direction for tank boundaries measuring from the top of the tank. k_s is the load factor. k_u is the load factor and is taken as 1.0 unless otherwise specified. h_d is the wave-induced internal pressure head, including inertial force and added pressure head, and h_d is given by:

$$h_d = k_c (\eta a_i / g + \Delta h_i) \quad (30)$$

where k_c is a correlation factor and is taken as 1.0 unless otherwise specified. g is acceleration due to gravity. a_i is the effective resultant acceleration at the point considered and is approximated by:

$$a_i = 0.71 C_{dp} [w_v a_v + w_l (l_t / h_t) a_l + w_t (b_t / h_t) a_t] \quad (31)$$

where a_v , a_l , and a_t are the vertical, longitudinal and transverse accelerations of tank contents (cargo or ballast). w_v , w_l , and w_t are weight coefficients of a_v , a_l , and a_t . l_t , h_t and b_t are length, depth and breadth of the

tank considered, respectively. C_{dp} is a parameter related to tank shape. Δh_i is the added pressure head due to pitch and roll motions at the point considered and is calculated as follows:

i) For bow down and starboard down ($\phi_e \leq 0, \theta_e \geq 0$)

$$\begin{aligned}\Delta h_i &= \xi \sin(-\phi_e) + C_{ru}(\zeta_e \sin \theta_e \cos \phi_e + \eta_e \cos \theta_e \cos \phi_e - \eta) \\ \zeta_e &= b_t - \zeta \\ \eta_e &= \eta\end{aligned}\tag{32}$$

ii) For bow up and starboard up ($\phi_e \geq 0, \theta_e \leq 0$)

$$\begin{aligned}\Delta h_i &= (l_t - \xi) \sin \phi_e + C_{ru}(\zeta_e \sin(-\theta_e) \cos \phi_e + \eta_e \cos \theta_e \cos \phi_e - \eta) \\ \zeta_e &= \zeta - \delta_b \\ \eta_e &= \eta - \delta_h\end{aligned}\tag{33}$$

where ξ , ζ , and η are local coordinates for the point considered. C_{ru} is a parameter related to tank shape. δ_b and δ_h are local coordinate adjustments for the point considered. θ_e and ϕ_e are given by:

$$\begin{aligned}\theta_e &= 0.71C_\theta\theta \\ \phi_e &= 0.71C_\phi\phi\end{aligned}\tag{34}$$

where ϕ and θ are pitch and roll amplitudes. C_ϕ and C_θ are weight coefficients for ϕ and θ .

5.3 Total nominal pressure

Once the nominal design values of internal pressure p_i and the external pressure p_e are obtained, the total nominal pressure imposed on a stiffened panel is given by:

$$p_t = |p_i - p_e|\tag{35}$$

5.4 Stochastic modeling

It should be noted herein that normally the total nominal pressure p_t is the extreme value during the FPSO design life. The lateral pressure p imposed on a stiffened panel is assumed herein to be a normally distributed variable. The mean value and the coefficient of variation of the p are assumed to be $0.7p_t$ and 0.3, respectively.

6. Reliability assessment

A structural reliability assessment traditionally considers a limit state, or a condition of a structural failure mode. A limit state is reached when the structural response to applied load equals or exceeds a defined criterion. In the panel reliability assessment, two limit state functions are defined corresponding to the two failure modes: beam-column buckling and flexural-torsional buckling.

6.1 Limit state function

6.1.1 Beam-column buckling

The limit state function for beam-column buckling is defined herein as:

$$f = 1 - \frac{\sigma_a^{exe}}{\sigma_{ca}(A_e / A)} - \frac{m_b \sigma_b}{\sigma_y} \quad (36)$$

where A is the total sectional area of the stiffened panel. m_b is the amplification factor as given by:

$$m_b = \frac{1}{1 - \sigma_a^{exe} / \sigma_E} \geq 1.0 \quad (37)$$

σ_b is the bending stress induced by lateral pressures and it is given by:

$$\sigma_b = M / SM_e \quad (38)$$

and

$$M = c_m p s l^2 / 12 \quad (39)$$

where c_m is the moment adjustment coefficient, and is taken as 0.75. SM_e is the effective sectional modulus of the longitudinal to flange, accounting for the effective breadth b_e as specified in Fig. 1.

Introducing factors accounting for the model uncertainty of M_{sw} and $M_{w,exe}$, the limit state function can be rewritten as:

$$f = 1 - \frac{\eta_a(\eta_{sw} M_{sw} + \eta_w M_{w,exe})}{\sigma_{ca}(A_e / A)W} - \frac{m_b \sigma_b}{\sigma_y} \quad (40)$$

6.1.2 Flexural-torsional buckling

The limit state function for the failure mode of flexural-torsional is defined herein as:

$$f = 1 - \frac{\sigma_a^{exe}}{\sigma_{ct}(A_e / A)} \quad (41)$$

Introducing factors accounting for the model uncertainty of M_{sw} and $M_{w,exe}$, the limit state function can be rewritten as:

$$f = 1 - \frac{\eta_a(\eta_{sw}M_{sw} + \eta_w M_{w,exe})}{\sigma_{ct}(A_e/A)W} \quad (42)$$

6.2. Stochastic modelling

The yield stress of material σ_y , still-water bending moment (SWBM) M_{sw} , the extreme value of vertical wave-induced bending moment (VWBM) $M_{w,exe}$, the lateral pressure p , the long-term corrosion wastage d_m , the coating time T_c , as well as the model uncertainty factors η_{sw} and η_w are considered herein as random variables. σ_y , d_m and T_c are considered herein to follow the lognormal distribution. η_{sw} and η_w are assumed to follow the normal distribution. M_{sw} and $M_{w,exe}$ are considered to follow a normal distribution and a Gumbel distribution, respectively. A summary of the assumed probability distributions for these random variables can be referred to Table 4.

6.3 Reliability estimate

A first order reliability method (FORM) (Hasofer and Lind, 1974) is used to predict the panel reliability index. The fundamental idea of the FORM is to find the point on the limit state surface with the minimum distance β to the origin in the standard normal space. This point is traditionally called the design point and β the reliability index. Once the design point is found, the probability of failure P_f is given by

$$P_f = \Phi(-\beta) \quad (43)$$

where $\Phi(\cdot)$ is the standard normal cumulative distribution function.

The method is to apply an iteration procedure to find the design point on the limit state surface. During the k th iteration, the non-normal random variables are transformed into normal variables using the normal tail approximation (Rackwitz and Fiessler, 1978), and then the design point $\mathbf{x}^{(k)}$ is updated by

$$\mathbf{x}^{(k+1)} = E[\mathbf{X}] + \frac{\nabla g(\mathbf{x}^{(k)})^T (\mathbf{x}^{(k)} - E[\mathbf{X}]) - g(\mathbf{x}^{(k)})}{\nabla g(\mathbf{x}^{(k)})^T \mathbf{C}_X \nabla g(\mathbf{x}^{(k)})} \mathbf{C}_X \nabla g(\mathbf{x}^{(k)}) \quad (44)$$

where $E[\mathbf{X}]$ and $\mathbf{C}_X$ are the mean matrix and the covariance matrix of the vector of random variables $\mathbf{X}$ and ∇g is the vector of partial derivatives of the limit state function $g(\mathbf{X})$ with respect to the design point $\mathbf{x}^{(k)}$.

The final design point $\mathbf{x}^*$ is obtained when the iteration procedure is converged. Then, transform the $\mathbf{x}^*$ into the corresponding design point $\mathbf{y}^*$ in the standard normal space and the reliability index β is given by

$$\beta = \sqrt{(\mathbf{y}^*)^T \mathbf{y}^*} \quad (45)$$

6.4 Sensitivity measure

Sensitivity measure is an important part of structural reliability assessment. They can identify not only the random variables that have the most important effect on reliability estimates but also those variables that are not necessary to be considered as random variables in reliability assessment.

According to the definition, the design point $\mathbf{y}^*$ is the point that have the minimum distance β from the origin to the limit state function in the standard normal space ($\mathbf{y}$ space). So the design point can be expressed as

$$\mathbf{y}^* = \beta \boldsymbol{\alpha} \quad (46)$$

where $\boldsymbol{\alpha}$ is a unit vector of directional cosines. Thus the linear and normalized approximation Z to the safety margin can be written as

$$Z = \boldsymbol{\alpha}^T (\mathbf{y}^* - \mathbf{y}) = \beta - \boldsymbol{\alpha}^T \mathbf{y} \quad (47)$$

The variance of Z is then given by

$$\text{Var}[Z] = \sum_{i=1}^n \alpha_i^2 = 1 \quad (48)$$

and thus α_i^2 can be interpreted as the fraction of the total uncertainty caused by the uncertainty described through Y_i . Since the β is the length of $\mathbf{y}^*$, it follows that

$$\alpha_i = \left. \frac{\partial \beta}{\partial y_i} \right|_{\mathbf{y}^*} \quad (49)$$

So the value of α_i is a measure of the sensitivity of the reliability index to inaccuracies in the value of y_i at the design point. Because of this, α_i have often been referred to as a sensitivity factor in the literature (Madsen et al., 1986).

7. Case study

One deck panel and one bottom panel from a ship-shaped FPSO are utilized as case study. The principal dimensions of the FPSO are given in Table 1. The dimensions of the two panels are listed in Table 2 and a sketch diagram of stiffened panels is shown in Fig.2. The bottom panel is selected from a ballast tank whose dimensions are listed in Table 3. Probabilistic characteristics of the random variables used in the panel reliability assessment are listed in Table 4.

In this case study, the effects of the lateral pressure p , the return period of the extreme value of VWBM $M_{w,exe}$, the environmental severity factor k_{VBM} and the corrosion wastage on the panel reliability are investigated and the results are shown in Figs 3-5 and 7-8. Sensitivity measures for random variables are also conducted and the results are listed in Figs.9 and 10.

7.1. Lateral pressure

Fig.3 shows how the panel reliability index β of the bottom panel varies over time with and without the lateral pressure p . The effect of the lateral pressure p on the panel reliability index β is evident since β drops dramatically if p is considered in the reliability assessment. This means that the lateral pressure p has a significant impact on the panel reliability of bottom panel.

7.2. Return period of the extreme value of VWBM

Figs. 4 and 5 show how the panel reliability indices β of the deck and bottom panels are influenced by the return period of the extreme value of VWBM $M_{w,exe}$. The two figures show that β is sensitive to the variation of the return period of the extreme value of VWBM as β decreases significantly with the increase of the return period from 25 to 100 years. However, the figures also show that when the return period is increased from 25 years to 50 years, 75 years, and 100 years, the reductions of the panel reliability indices decrease with the increase of the return period. It can be explained from Fig.6 which clearly shows the increments of the mode of the Gumbel distribution of $M_{w,exe}$ decreases with the increase of the return period.

7.3. Environmental severity factor

The vertical wave-induced bending moment (VWBM) for FPSO specified by ABS FPI Rules (2015) is usually used for design purposes. However, FPSOs are normally operated at specific locations, thus the

design value needs to be adjusted for the specific locations. This can be achieved by calculating environmental severity factors for the service conditions that represent the effect of wave conditions of the specific site.

The environmental severity factor k_{VBM} is often defined as a severity measure of the intended environment relative to the based environment in terms of extreme loads. It is given by

$$k_{VBM} = \frac{L_s}{L_n} \quad (50)$$

where L_s is the most probable extreme value based on site-specific environment with design return period for the dynamic load parameters. L_n is the most probable extreme value based on unrestricted North Atlantic environment with design return period for the dynamic load parameters.

Figs.7 and 8 show the impact of the environmental severity factor k_{VBM} on the panel reliability indices β of the deck and bottom panels. The two figures show that β decreases dramatically with an increase of the environment severity factor k_{VBM} , which means β is very sensitive to the specific service conditions. It is thus important to take into account the wave conditions of the specific location where a FPSO is located in the panel reliability assessment.

7.4. Corrosion effects

As seen from Figs 3-5 and 7-8, the panel reliability indices β of the deck and bottom panels decreases steadily over time due to the corrosion wastage. But it is noted that the corrosion effects on the panel reliability indices β are not as significant as those of the lateral pressure p , the return period of the extreme value of VWBM $M_{w,exe}$, or the environmental severity factor k_{VBM} .

7.5. Sensitivity measure

Figs.9 and 10 show how the absolute values of the sensitivity factors of random variables $|\alpha_i|$ vary with time. As discussed in Section 6.4, α_i is a measure of the sensitivity of the reliability index to inaccuracies in the value of y_i at the design point. Consequently, the absolute value of α_i of a random variable represents the relative importance of this variable.

For the beam-column buckling of the deck and bottom panels and the flexural-torsional buckling of the bottom panel, Fig.9 and 10(b) reveal the highest sensitivity factor in that of $M_{w,exe}$, and then those of η_w ,

σ_y , M_{sw} , and η_{sw} , negligible in those of T_c and d_m . This means that the panel reliability index β in such scenarios is most sensitive to the variation of $M_{w,exe}$, then η_w , σ_y , M_{sw} , η_{sw} but the β is not sensitive to the variation of T_c and d_m .

For the scenario of the beam-column buckling of the bottom panel subjected to the lateral pressure p , Fig.10 (a) shows that that the highest sensitivity factor is that of σ_y or p , and followed by that of η_w , $M_{w,exe}$, M_{sw} , and η_{sw} but those of T_c and d_m are negligible. This indicates that the panel reliability index β in this scenario is most sensitive to the variation of σ_y and p , then η_w , $M_{w,exe}$, M_{sw} , and η_{sw} but the β is not sensitive to the variation of T_c and d_m .

Since the sensitivity factors of T_c and d_m are negligible and the panel reliability index β is not sensitive to the variation of T_c and d_m , as discussed in Section 6.4, T_c and d_m are not necessary to be considered as random variables in the panel reliability assessment.

8. Conclusions

A methodology is developed for ship-shaped FPSO panel reliability assessment. Ultimate strength of a stiffened panel is evaluated by two primary failure modes: beam-column buckling and flexural-torsional buckling. Internal and external lateral pressures induced by sea water, cargo or ballast water are taken into account in the reliability assessment in addition to in-plane compressive loads. Rational stochastic models for corrosion wastage, material properties, still-water and wave-induced loads, and model uncertainties are established.

A case study for deck and bottom panels from a FPSO was performed and some conclusions may be drawn:

- The lateral pressure p has a significant impact on the panel reliability of the bottom panel
- The effects of the return period of $M_{w,exe}$ on the panel reliability decrease with the increase of the return period.
- The panel reliability index β is very sensitive to the environmental severity factor k_{VBM} .
- The corrosion effects on the panel reliability are not as significant as those of p , the return period of $M_{w,exe}$, or k_{VBM} .

- For scenarios of the beam-column buckling of the deck and bottom panels and the flexural-torsional buckling of the bottom panel, the panel reliability index β is most sensitive to the variation of $M_{w,exe}$, then η_w , σ_y , M_{sw} , η_{sw} , but is not sensitive to the variation of T_c and d_m .
- For the scenario of the beam-column buckling of the bottom panel, β is most sensitive to the variation of σ_y or p , then η_w , $M_{w,exe}$, M_{sw} , and η_{sw} , but is not sensitive to the variation of T_c and d_m .
- T_c and d_m are not necessary to be treated as random variables in the panel reliability assessment.

There are only two primary failure modes of stiffened panels, namely beam-column buckling and flexural-torsional buckling, considered in this paper. However, it should be noted herein that global collapse of stiffened panels or interaction between failure modes may occur.

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Table 1. Principal dimensions of the FPSO

Length overall L (m)	274
Breadth B (m)	48.0
Depth D (m)	23.2
Draft d (m)	17.0
Section modulus at deck ($\text{cm}^2.\text{m}$)	422198
Section modulus at bottom ($\text{cm}^2.\text{m}$)	555614

Table 2. Dimensions of the sample deck panel and bottom panel

Unit: mm	Deck panel	Bottom panel
l	4800	4800
s	855	855
t_p	18.5	20
d_w	300	530
t_w	13	11.5
b_f	90	150
t_f	17	20

Table 3. Dimensions of the ballast tank where the sample deck and bottom panels are

Length l_t (m)	33.6
Breadth b_t (m)	24.0
Depth h_t (m)	23.3

Table 4. Probabilistic characteristics of random variables

Symbol			Mean	Coefficient of variation	Distribution
σ_y			378 MPa	0.089	Lognormal
η_{sw}			1.0	0.1	Normal
M_{sw}			$0.7 M_{sw}^{\max}$	0.286	Normal
η_w			1.0	0.1	Normal
$M_{w,exe}$			Eq.(23)	Eq.(23)	Gumbel
p			$0.7p_i$	0.3	Normal
Bottom panel	plate	T_c	5.0 year	0.3	Lognormal
		d_m	1.037mm	0.4	Lognormal
	web	T_c	5.0 year	0.3	Lognormal
		d_m	2.075mm	0.4	Lognormal
	flange	T_c	5.0 year	0.3	Lognormal
		d_m	2.075mm	0.4	Lognormal
Deck panel	plate	T_c	5.0 year	0.3	Lognormal
		d_m	1.037mm	0.4	Lognormal
	web	T_c	5.0 year	0.3	Lognormal
		d_m	1.556mm	0.4	Lognormal
	flange	T_c	5.0 year	0.3	Lognormal
		d_m	1.556mm	0.4	Lognormal

For bending at midspan,

$$b_e = \begin{cases} s[1.219 - 0.965/(cl_0/s)], & \text{when } cl_0/s < 4.5 \\ s & \text{otherwise} \end{cases}$$

For bending at ends,

$$b_e = \begin{cases} s\sqrt{0.124cl/s - 0.062}, & \text{when } cl/s < 8.5 \\ s & \text{otherwise} \end{cases}$$

Figure 1. Effective breadth of plating b_e (ABS FPI Rules, 2015)

Figure 2. Sketch diagram of stiffened panels

Figure 3. The effects of lateral pressure p on the panel reliability index β of the sample bottom panel (failure mode: beam-column buckling)

(a)

(b)

Figure 4. The effects of the return period of the extreme value of vertical wave-induced bending moment (VWBM) $M_{w,exe}$ on the panel reliability index β of the deck panel (a) failure mode: beam-column buckling; (b) failure mode: flexural-torsional buckling

(a)

(b)

Figure 5. The effects of the return period of the extreme value of vertical wave-induced bending moment (VWBM) $M_{w,exe}$ on the panel reliability index β of the bottom panel (a) failure mode: beam-column buckling; (b) failure mode: flexural-torsional buckling

Figure 6. The probability distribution of the extreme value of
VWBM $M_{w,exe}$ at the return period of 25 to 100 years

(a)

(b)

Figure 7. The effects of the environmental severity factors k_{VBM} on the panel reliability index β of the deck
panel (a) failure mode: beam-column buckling; (b) failure mode: flexural-torsional buckling

(a)

(b)

Figure 8. The effects of the environmental severity factors k_{VBM} on the panel reliability index β of the bottom panel (a) failure mode: beam-column buckling; (b) failure mode: flexural-torsional buckling

(a)

(b)

Figure 9. The absolute values of sensitivity factors of random variables $|\alpha_i|$ of the deck panel vary over time:

(a) failure mode: beam-column buckling; (b) failure mode: flexural-torsional buckling

(a)

(b)

Figure 10. The absolute values of sensitivity factors of random variables $|\alpha_i|$ of the bottom panel vary over time: (a) failure mode: beam-column buckling; (b) failure mode: flexural-torsional buckling