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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.

## 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 [1,28,29,33,31,42,11,6]. 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 [29,4,12,5]. More information on the state of the art of panel reliability assessment can be found in ISSC reports [3,35].

As an extension of the work of Chen et al. [8] and Chen [6], 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 FPI [36].

### 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:

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

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## Nomenclature

| | |
|---|---|
| $\sigma_a^{exe}$ | extreme value of the axial compressive stress on a stiffened panel |
| $\gamma$ | $= \frac{s\sqrt{\sigma_y/E}}{t_p}$ |
| $\chi$ | aspect ratio, $l/s$ |
| $\rho$ | density of sea water |
| $\sigma$ | scale parameter of Gumbel distribution |
| $\lambda$ | shape parameter of Weibull distribution |
| $\boldsymbol{\alpha}$ | unit vector of directional cosines |
| $\Gamma$ | Warping constant $\cong mI_{yf}d_w^2 + d_w^3t_w^3/36$ |
| $\eta_a$ | amplification factor accounting for the secondary stresses, $\sigma_{L2}$ |
| $\sigma_a$ | axial compressive stress on a stiffened panel |
| $\sigma_{ca}$ | beam-column critical buckling stress of a stiffened panel |
| $\sigma_{cL}$ | critical buckling stress for the associated plating, corresponding to $n$-half waves $= \frac{\pi^2 E(n/\alpha+\alpha/n)^2(t_p/s)^2}{12(1-v^2)}$ |
| $\sigma_{ct}$ | torsional-flexural critical buckling stress of a stiffened panel |
| $\sigma_E$ | Euler column buckling stress |
| $\sigma_{ET}$ | $= \frac{E[K/2.6+(n\pi/l)^2\Gamma+C_o(l/n\pi)^2/E]}{I_o+C_o(l/n\pi)^2/\sigma_{cL}}$ |
| $\nabla g$ | vector of partial derivatives of the limit state function $g$ ($\mathbf{X}$) with respect to the design point $\mathbf{x}^{(k)}$ |
| $\varepsilon_i$ | distribution factor around the girth of the installation at location $i$ |
| $\alpha_i$ | sensitivity factor of random variable $i$ |
| $\sigma_{L1}$ | primary stresses resulting from hull girder bending |
| $\sigma_{L2}$ | secondary stresses resulting from bending of large stiffened panels between transverse bulkheads |
| $\eta_{sw}$ | model uncertainty factor of SWBM |
| $\eta_w$ | model uncertainty factor of $M_w$ |
| $\sigma_y$ | 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 |
| $C_1$ | $= 10.75 - \left(\frac{300-L}{100}\right)^{1.5}$ for 90 m $\leqslant L \leqslant$ 300 m<br>$= 10.75$ for 300 m $\leqslant L \leqslant$ 350 m<br>$= 10.75 - \left(\frac{L-350}{100}\right)^{1.5}$ for 350 m $\leqslant L \leqslant$ 500 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 |
| $\mathrm{C}_{\mathbf{X}}$ | covariance matrix of the vector of random variables $\mathbf{X}$ |
| $C_\theta$ | weight coefficient for $\theta$ |
| $C_\phi$ | weight coefficient for $\phi$ |
| $d(t)$ | 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 $\sigma_{ET}$ |
| $N$ | 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 |