International Conference on Mechanical, Industrial and Materials Engineering 2024 (ICMIME2024)
11-13 December, 2024, RUET, Rajshahi-6204, Bangladesh.

Paper ID: 485

GEOMETRICAL EFFECTS OF PITTING CORROSION ON RELIABILITY OF UNSTIFFENED SHIP PANEL

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Abstract

Reliability analysis of pitted unstiffened ship panel at the deck and bottom of a capesize bulk carrier, focusing on effects of real pit geometries (conical and ellipsoidal) has been performed in this study. Two limit state functions are developed to evaluate scenarios with and without buckling effects, while examining the tertiary failure mode of plates between stiffeners under environmental bending loads (hogging and sagging). Although pitting corrosion has been extensively studied by previous researchers, limited studies have considered the reliability implications of actual pit shapes. This research addresses this gap by considering two real pit shapes namely conical and ellipsoidal that was observed by other researchers for investigating the pit geometry effect on reliability of structure. The objectives of this study are to evaluate the reliability of pitted unstiffened ship panels used in marine environments and to investigate the influence of real pit geometry at the deck and bottom positions with and without buckling effects. The findings explore whether ellipsoidal pits have a significant impact on the reliability index than conical pits, considering changes in location, load conditions, and buckling effects, while identifying potential vulnerabilities arising from geometric influences. The study provides deeper insights into the behavior of ship panels under varying load conditions and locations, aiding structural design optimization and enhancing predictive models for assessing the safety and integrity of marine structures.

Keywords: Reliability Analysis, FORM, Pitting Corrosion, Pit Geometry, Damage, Ultimate Strength, Buckling

1. Introduction

Corrosion is the degradation of materials due to the natural tendency for most of the metals to react with their environment. General and pitting corrosions are considered the most prevalent forms of corrosion among the basic four types of corrosion (i.e., general corrosion, pitting corrosion, grooving corrosion, and edge corrosion [1]. Because of pitting corrosion, metal deteriorates locally in the forms of pits with the effect of strength and deformability reduction. These reductions are very crucial for the integrity of marine structures [2]. Chemistry has no role to play when the effect of corrosion on structural integrity is discussed; rather, it mostly has a geometric influence [3]. The damage of a structure due to pitting results from a reduction in cross-sectional area, and this damage intensifies with increasing pit depth and the formation of multiple pits in the same cross-section. The shape of the pit also directly affects the extent of damage. Hence, considering the actual geometry of pits is crucial for accurately studying the effect of pitting corrosion. Time is a dominating variable in progression of a pit, i.e., damage increases with the ageing of structure. On the other hand, an efficient and safe design of any structure can be ensured by measuring the reliability which is essential in ship design. Reliability assessment tells about a structure's ability to perform with the desired performance under the targeted environmental or loading condition. The deterministic rule based designs fail to ensure efficiency and safety when uncertainty arises. Consideration of uncertainties is the main merit of reliability analysis. In case of failure probability of an unstiffened ship panel under marine environmental load due to pitting corrosion, uncertainties arise due to random initiation of pit location and random characteristics of material properties and environmental loads.

Despite extensive research on pitting corrosion, limited studies have explored the reliability implications of real pit geometries, such as conical and ellipsoidal shapes, in marine structures. This study aims to fill this gap by performing a time-dependent reliability analysis of unstiffened ship panels considering the variability of these pit shapes under vertical bending loads in a marine environment. The load is comprised of still water bending moment and wave induced bending moment in hogging condition whereas slamming induced dynamic moment is also considered in sagging condition. Two different limit loads have been considered in this study. The ultimate strength of panel is considered as average yield strength with the effect of buckling mode and then disregarding the effect of buckling. The reduction in strength with incremental damage due to pit has been assessed by assuming the linearity of material properties till yielding in case of without buckling analysis whereas an empirical formula proposed by Paik et al. [4] has been used for the case with buckling analysis. The considered cross section of unstiffened panel is 880×16 mm and it has been considered that the panel is corroded by two different pit shapes (conical and ellipsoidal). The corrosion model used was suggested by Yamamoto and Ikegami [5]. To analyze the reliability, the limit state function and the associated random variables for loads in marine environment are obtained and then the First-order Reliability Method (FORM) has been used. The vessel under investigation in

this study is the capsized single side skin bulk carrier (ISSC-2000) which has been frequently used as a reference ship in various research studies and the change in reliability index has been investigated at bottom and deck.

2. Method of reliability analysis

During reliability analysis, various variables are treated as random variables with probability distributions and the probability of failure of the structural is evaluated in terms of Reliability Index (β). Several methodologies, including First Order Reliability Method (FORM), Second Order Reliability Method (SORM) and Monte Carlo Simulation (MCS) have been employed in various domains to assess the reliability or probability of failure of structures [6-7]. Fig. 1 shows the process of structural reliability analysis that has been followed in this study. First several variables associated with the analysis have been identified and then they have been estimated by following appropriate guidelines which is discussed later in this paper. After the identification of the variables, a limit state function for the structural reliability analysis was constructed for the target ship panel. For the calculation purpose, ISSC-2000 bulk carrier was selected as it satisfies the requirement of this study. Bending loads from marine environment has been estimated for the two furthest possible locations from the neutral axis of a ship section and those are deck and bottom of the selected vessel.

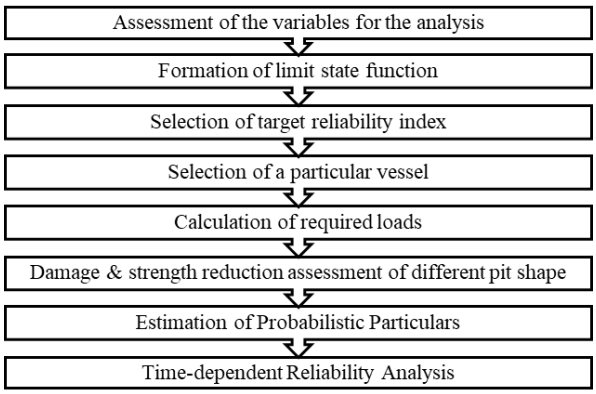


Fig. 1. Flow chart of time-dependents reliability analysis

The strength reduction due to damage of marine pitted steel plate was assessed by Islam and Sumi [8] considering the real pit shape (conical and ellipsoidal). The same damage data has been used in this study. This variation in cross section has been accommodated by considering the same ratio of damage in the extended part. The probabilistic parameters that involve the uncertainties have been estimated following the guideline provided by P.K Das and W. Zhang [9]. The final step is performing time-dependent reliability analysis for both the conical and ellipsoidal pit shape using the limit state function and probabilistic particulars estimated in the previous steps. The first order reliability method (FORM) is used for the analysis. The panel is considered as subjected to compressive stress induced predominantly by vertical still-water bending moment and wave induced bending moments. The performance function g associated with a corroded unstiffened ship panel in compression can be expressed as [9]:

With effect of buckling mode

$$g = x_r.\sigma_u - \sigma_L \quad (1)$$
$$= x_r.R_u(t).\sigma_u - \frac{M_{sw}+k_w M_{wv}}{SM} \quad \text{(Hogging)}$$
$$= x_r.R_u(t).\sigma_u - \frac{-M_{sw}+k_w(M_{wv}+k_d M_d)}{SM} \quad \text{(Sagging)}$$

Without effect of buckling mode

$$g = x_r.\sigma_y.A(t) - A_0\sigma_L \quad (2)$$

where, x_r is the model uncertainty factor, σ_u is the ultimate strength and σ_L is the induced stress, R_u is the Strength Reduction Factor, M_{sw} is still water bending moment, k_w is a factor to combine the wave-dynamic composite moments with the still water moment, M_{wv} is wave induced bending moment, SM is the appropriate section modulus depending on desired location, k_d is a factor to combine the wave-induced and dynamic moments. M_d represents the slamming-induced moment which is sagging in nature and only need to be considered in sagging condition. When buckling effect is disregarded (Equation 2), σ_y is the material yield strength, $A(t)$ is the time-variant minimum cross-sectional area and A_0 is the initial cross-sectional area (880×16 mm) of the ship panel.

3. Bending load in marine environment

In this study, both hogging and sagging in head sea condition with unrestricted navigation is considered for conducting the reliability analysis. According to Bureau Veritas (BV) [10], still water bending moment, M_{sw} is estimated as follows:

$$M_{sw} = f\left(190\frac{1+n}{2}C.L^2.B(C_B+0.7)10^{-3} - M_{wv-h-mid}\right)\text{[for Hogging]} \quad (3)$$

$$M_{sw} = -f\left(190\frac{1+n}{2}C.L^2.B(C_B+0.7)10^{-3} + M_{wv-s-mid}\right)\text{ [for Sagging]} \quad (4)$$

and, wave-induced bending moment, M_{wv} is estimated as follows:

$$M_{wv-h} = 190\, f\, f_{ps}\, n\, C\, L^2\, B\, C_B\, 10^{-3}\text{ [hogging]} \quad (5)$$

$$M_{wv-s} = -110\, f\, f_{ps}\, n\, C\, L^2\, B\, (C_B+0.7)10^{-3}\text{ [sagging]} \quad (6)$$

where, f is a distribution factor along the ship length (which is 1.00 for midship as for the case of this study), n is the navigation coefficient (equal to 1.00, for unrestricted navigation) C is a wave coefficient, L, B and C_B are ship length, moulded breadth and block coefficient respectively, f_{ps} is the coefficient for strength assessments which is a function of applicable design load (equal to 1.00, for extreme sea design load). $M_{wv-h-mid}$ and $M_{wv-s-mid}$ represents vertical wave bending moment at amidship in hogging and sagging condition respectively. The wave coefficient C can be estimated by:

$$\begin{aligned} C &= (118-0.36L)\frac{L}{1000} && \text{for 65 m} \le L \le 90\text{m} \\ &= 10.75-\left(\frac{300-L}{100}\right)^{1.5} && \text{for 90 m} \le L \le 300\text{ m} \\ &= 10.75 && \text{for 300 m} \le L \le 350\text{ m} \\ &= 10.75-\left(\frac{L-350}{150}\right)^{1.5} && \text{for L} > 350\text{ m} \end{aligned} \quad (7)$$

4. Strength of unstiffened ship panel

In the failure analysis of a ship structure, three different modes are usually considered besides fatigue failure [9]. The tertiary mode of failure i.e., with or without the effect of buckling in failure has been considered in this study. The limit state function for with or without buckling is described later. The ultimate strength (σ_u) of the unstiffened ship panel was formulated by following SSC 398 report where the influence of critical buckling stress has taken into consideration. The strength of an unstiffened plate subjected to in-plane load acting on the plate width can be estimated by:

a. For $\frac{a}{b} \ge 1.0$

$$\frac{\sigma_u}{\sigma_0} = \begin{cases} = \left(\frac{\sigma_{cr}}{\sigma_0}\right)^{\frac{1}{2}} & if\ \beta \ge 3.5 \\ = \frac{2.25}{\beta} - \frac{1.25}{\beta^2} & if\ 1.0 \le \beta < 3.5 \\ = 1.00 & if\ \beta < 1.0 \end{cases} \quad (8)$$

where, $\frac{\sigma_{cr}}{\sigma_0} = \frac{4\pi^2}{12(1-\nu^2)}.\frac{1}{\beta^2} = \frac{3.612}{\beta^2}$

b. For $\frac{a}{b} < 1.0$

$$\frac{\sigma_u}{\sigma_0} = \alpha C_u + 0.08(1-\alpha)\left(1+\frac{1}{\beta^2}\right)^2 \le 1.0 \quad (9)$$

where, $C_u = \begin{cases} = \left(\frac{4\pi^2}{12(1-\nu^2)}.\frac{1}{\beta^2}\right)^{\frac{1}{2}} & if\ \beta \ge 3.5 \\ = \frac{2.25}{\beta} - \frac{1.25}{\beta^2} & if\ 1.0 \le \beta < 3.5 \\ = 1.00 & if\ \beta < 1.0 \end{cases}$

Here, a and b are panel length and width respectively, σ_0 is the average yield stress in compression, σ_{cr} is the critical buckling stress, $\beta = \frac{b}{t}\sqrt{\frac{\sigma}{E}}$ represents the slenderness ratio of the unstiffened ship panel with σ as the normal stress and E as the modulus of elasticity, $\alpha = a/b$ is the aspect ratio and ν is the Poisson's ratio. In this study SM490A steel [2] is considered which has a modulus of elasticity of 206.9 GPA.

5. Statistical characteristics of associated variables

The level of uncertainty in the magnitude of any variable can be represented by coefficient of variance (COV) and probability distribution which tells about the likelihood of different outcome of an uncertain variable. The uncertain variables that are associated with this analysis are of different types like material properties, environmental loads, geometry of structure (section modulus) etc. The steel material used for the study is SM490A, with a yield strength of 365 MPa. Its composition includes carbon (0.16%), manganese (1.43%), silicon (0.36%), phosphorus (0.017%) and sulfur (0.005%). The different types of bending loads in marine environment for the reference ship have been estimated by using Equations (3) to (7). Then, the mean value, COV and probability distribution for associated variables are determined by following guidelines of Das and Zhang [9]. The summary of statistical characteristics of uncertain variables that are involved in this analysis is shown in Table 1.

Table 1. Summary of statistical characteristics of variables associated with current study [9]

Variables	Mean	COV	Distribution
Model uncertainty factor (x_r)	1.0	0.15	Normal
Yield Strength (σ_y)	365 MPa	0.05	Log-normal
Ultimate Strength (σ_u)	270 MPa	0.15	Log-normal
Still water bending moment (M_{sw})			
for sagging condition	3201 MPa	0.25	Normal
for hogging condition	3465 MPa	0.25	Normal
Wave-induced bending moment (M_{wv})			
for sagging condition	3668 MPa	0.10	Gumbel
for hogging condition	3448 MPa	0.10	Gumbel
Section Modulus (SM)			
deck	42.965	0.04	Normal
bottom	61.872	0.04	Normal
Wave-dynamic composite moments and still water moment combination factor (k_w)	1.0	0.05	Normal
Wave-induced and dynamic moments combination factor (k_d)	0.7	0.15	Normal
Dynamic Slamming bending Moment (M_d)	1467 MPa	0.03	Gumbel

6. Strength reduction considering real pit geometry

Paik et al. [4] derived the following empirical formula for predicting the reduced ultimate strength for compressive load and shear load basing on damage (D_m) where damage is the ratio of maximum diminution in cross sectional area due to surface pit to intact cross-sectional area:

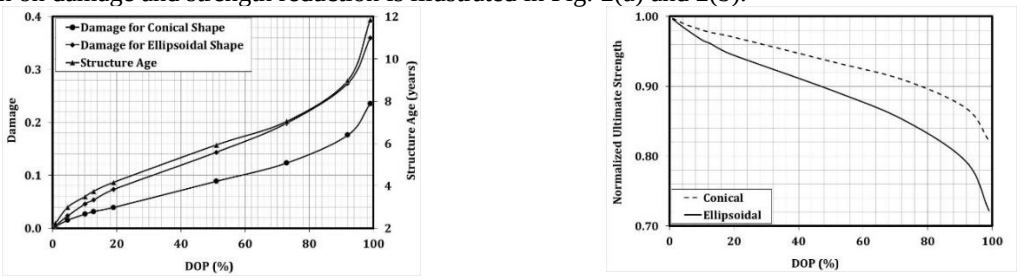
$$R_u = (1 - D_m)^{0.73} \quad (10)$$

Here, R_u is the ultimate strength of pitted plates normalized by that of an intact plate. Ahmmad and Sumi [11] validate equation (10) for tensile strength reduction due to conical pit whereas Islam M. R. and Sumi [2] proves the applicability of the same for semi-ellipsoidal pit. Yamamoto and Ikegami proposed a corrosion model (used in this research) by dividing the total life of a pitted structure into three different life spans and all these lives are random variables (Table 2).

Table 2. Statistical characteristics of variables associated with corrosion model

Life Span	Distribution
Life of paint coating	Log-normal
Transition time between active and progressive pitting	Exponential
Progression of pit depth	Log-normal

The level of pitting is represented by Degree of Pitting intensity (DOP) which can be defined as the ratio of pitted surface area to the total surface area. This study evaluates the effect of pit geometry (conical and ellipsoidal) on reliability, using the same DOP, spatial pit distribution, and probabilistic parameters. The impact of pitting corrosion on damage and strength reduction is illustrated in Fig. 2(a) and 2(b).



(a) (b)

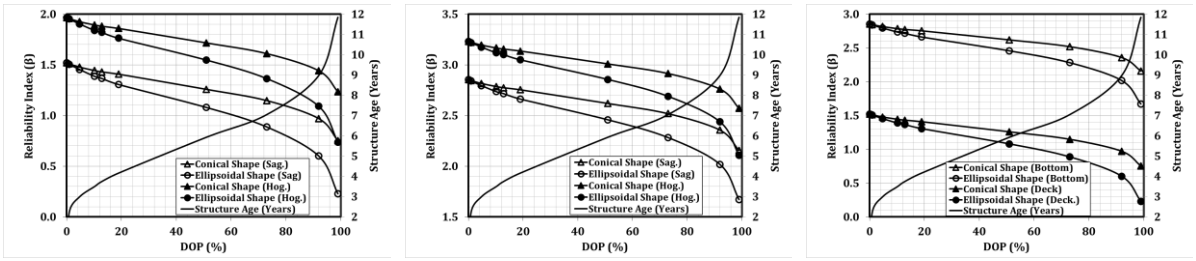
Fig. 2. Geometrical effect of pitting corrosion on (a) damage, (b) strength reduction

7. Effect of pit geometry on reliability index

This study uses the First Order Reliability Method (FORM), which considers the actual probability distributions of the random variables. It extends the Hasofer-Lind reliability method [12]. The procedure is as follows (all the random variables in this study are considered independent):

1. Transformation of basic random variables into standard normal variables: $F_{X_i} = \Phi(u_i)$ i = 1,2,3 …. N
   where, $F_{X_i}(x_i)$ is the CDF of X_i with $x_i = F_{X_i}^{-1}[\Phi(u_i)]$ and $u_i = \Phi^{-1}\left[F_{X_i}(x_i)\right]$;

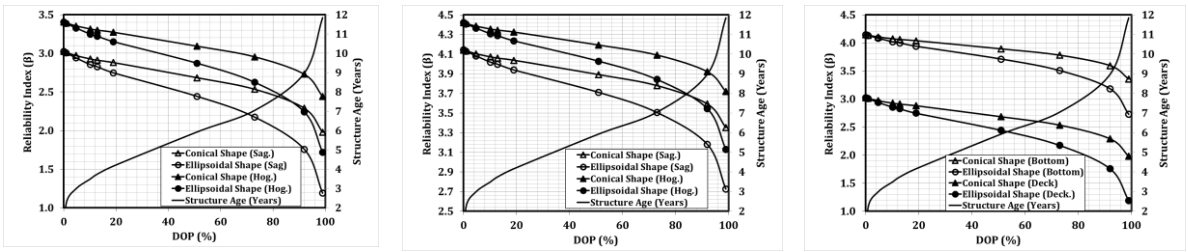
2. The failure surface: $g(x) = g\{F_X^{-1}[\Phi(u)]\} = \acute{g}(u) = 0$;
3. Optimization for the most probable failure point (MPFP) by linearization of failure surface;
4. Coordinates of MPFP: $u^* = \beta\alpha^*$where, β = reliability index that represents the minimum distance between origin of standardized surface and the MPFP and α^* = unit vector normal to the failure surface at $u = u^*$.
5. The probability of failure is approximated by $P_f = \Phi(-\beta)$



(a) (b) (c)

Fig. 3. Pit shape effect on reliability of unstiffened ship panel (with buckling effect) (a) at deck, (b) at bottom, (c) at deck and bottom for sagging condition

The variation in reliability due to geometrical effects of two types pit shape (conical and ellipsoidal) on ship unstiffened panel with buckling effect for both the hogging and sagging moment at deck is shown in Fig. (3a) and at bottom is shown in Fig. (3b). From figure it is evident that, ellipsoidal pit is more vulnerable than the conical shape pit and also the sagging moment is crucial for the unstiffened ship panel with buckling effect in failure. The slamming induced sagging moment plays the vital role behind this severity of sagging condition. Fig. (3c) compares the decrease in reliability index (β) for the real pit shapes effect on unstiffened ship panel between deck and bottom considering sagging moment. It is observed that unstiffened ship panel at deck is less reliable than the bottom and most severe case will arise for the ellipsoidal pit shape. This vulnerability of deck arises due to the higher distance from the neutral axis as can be seen in Table 2.



(a) (b) (c)

Fig. 4. Pit shape effect on reliability of unstiffened ship panel (without buckling effect) (a) at deck, (b) at bottom, (c) at deck and bottom for sagging moment

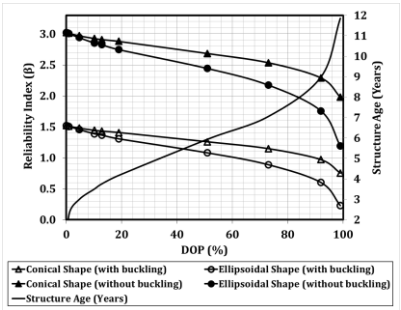


Fig. 5. Effect of buckling load on steel pitted plate with the variation in pit shape

Fig. (4a) to (4c) schematically represent the condition of reliability with the real pit shape effect where now the failure of unstiffened ship panel is considered without buckling effect. Reliability index values are higher in these figures than the Fig. (3a) to (3c). The reliability index at 0% DOP reported by Hu Han et al. [13] aligns with the findings of this study under sagging condition without buckling effect, serves as the validation of the methodology and results of this research. Their study reported a reliability index of 4.0, compared to 4.14 in this analysis. The difference arises due to variation in section modulus, loading, and material properties.

This is a desirable result as the buckling effect is disregarded in the later cases. In these cases, it is also observed that deck location is more vulnerable with the ellipsoidal pit effect. The analysis result for buckling effect is visible

in Fig. 5. Without initiation of pitting the reliability index is 47% less when buckling effect is considered in failure mode. The reduction is 58% in the case of conical pit and 75% in case of ellipsoidal pit at DOP 100%. For all the cases ellipsoidal pit shape shows more vulnerability. This is reasonable as the material degrades more due to ellipsoidal shape than the conical shape even for the case of same pit spatial distribution with the same rate of change in pit diameter.

8. Conclusion

Reliability of a structure decreases or probability of failure increases with the progression in pit depth that is reliability of a pitted structure is time variant. But the rate of change in reliability is not the same for different pit shapes. In this study the effect of conical pit shape and ellipsoidal pit shape on time variant reliability of pitted unstiffened ship panel has been analyzed by using First Order Reliability Method. The concluding remarks from this study are as follows:

1. Material degradation as well as strength reduction depends on pit shape and so consideration of real pit shape is an essential part in reliability analysis of ship structure;
2. Ellipsoidal pit shape shows more vulnerability than the conical pit shape as the material degrades more due to ellipsoidal shape for the case of same pit spatial distribution with the same rate of change in pit diameter;
3. Still water bending moment and wave induced bending moment take part in total moment of hogging condition whereas an extra component namely slamming induced moment takes part in total moment of sagging condition making the sagging moment more vulnerable form reliability point of view;
4. Reliability of unstiffened pitted ship panel depends on the location with respect to the location of neutral axis especially when bending load is concerned;
5. Buckling mode severely affect the ultimate strength of an unstiffened ship panel which in turn has remarkable effect on magnitude of reliability index.

9. Acknowledgements

The data used for corrosion modeling in this research is a part of doctoral dissertation of Dr. Muhammad Rabiul Islam (who is also an author to this paper) which was supported by a Japanese Government Scholarship.

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