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The effects of pit corrosions on ultimate strength of spar-type floating offshore wind turbines

*Sajad Rahmdel[1)], Hyerin Kwon[2)], Seonghun Park[3)]

[1), 2), 3)] *School of Mechanical Engineering, Pusan National University, Busan, Republic of Korea*
[1)] *rahmdel.s@gmail.com*, [3)] *paks@pusan.ac.kr*

ABSTRACT

Harsh environmental conditions of Spar-type Floating Offshore Wind Turbines (FOWTs) at oceans raise the issues of structural integrity, fitness for use and reliability of these structures. To overcome these issues, comprehensive ultimate limit state assessments of these structures are required. The purpose of the present study is to evaluate the ultimate limit state (ULS) performance of Spar-type Floating Offshore Wind Turbines (FOWTs) by considering the effects of pit corrosions. 48 spar-type FOWTs plates with different design configurations are selected by a design of experiment (DOE) method. Using ANSYS Design Modeler, these spar-type FOWT plates are modeled, and then the ultimate limit state performance of the models are calculated from ANSYS finite element analysis. Finally, the results of ultimate limit state performance of the spar-type FOWT plate models are used to make a regression model. The results of the current study can provide important design guidelines of ultimate limit state assessment of spar-type floating offshore wind turbines.

KEY WORDS: ultimate limit state; steel plate; spar platform; floating offshore wind turbine; ultimate strength; regression analysis; finite element analysis;

1. INTRODUCTION

It is well known that the ultimate limit state (ULS) is a better approach for design and strength assessment of various types of structures than the conventional allowable working stress approach. The reason is that by determining the limit states of the structures, it is possible to find the true margin of structural safety. While the offshore

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[1), 2)] Graduate Student
[3)] Professor – Corresponding author

industry has previously applied the limit state approach, the floating offshore wind turbine (FOWT) is a new concept and further studies are needed before limit state approach could be used for strength assessments of FOWTs. Also, in maritime industry, it is mandatory to compute the ultimate strength of structural components based on ULS method (IACS, 2006; C. IACS, 2006; ISO, 2006a, 2006b).

Paik et al. did a thorough comparison between three different methods, namely ANSYS nonlinear finite element analysis (FEA), DNV PULS and ALPS to calculate the ultimate strength of the ships and ship-shaped offshore structures. Unstiffened panels, stiffened panels and hull girders were considered as models to evaluate which method is better. Different types of boundary conditions (i.e., simply supported, partially rotational restrained supported and clamped supported) were used. It was concluded that ANSYS nonlinear finite element analysis (FEA) is the most accurate method, while, DNV PULS and ALPS had also acceptable results (Paik, Kim, & Seo, 2008a, 2008b, 2008c).

The hull of most offshore structures (spar platforms, ships, etc.) are built of steel plates and understanding the ultimate strength of these plates help finding the ULS of the whole structure. The aim of this paper is to assess ULS of unstiffened plates.

2. THE SPAR-TYPE FOWT AND ITS STRUCTURAL CHARACTERISTICS

For the present study, a hypothetical spar-type FOWT with a typical stiffened plate structure is considered. Fig. 1 illustrates a stiffened plate with its stiffeners.

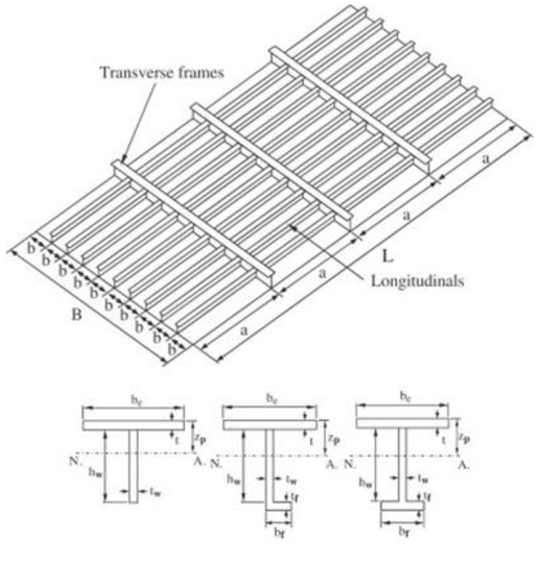

Fig. 1 A stiffened plate with longitudinal and transverse support frames (Paik et al., 2008a)

The spar-type FOWT plates are made of structural steel with yield stress σ_Y of 250 MPa, Young's modulus E of 200 GPa, Poisson's Ratio ν of 0.3, Bulk Modulus of 166.67 GPa, and Shear Modulus of 76.923 GPa. The welding-induced initial deflections of plating and stiffener webs are considered by $\mathrm{w}_{\mathrm{opl}} = \frac{b}{200}$, where $\mathrm{w}_{\mathrm{opl}}$ is the maximum plate deflection and b is the breadth of the plating as shown in Fig. 1.

In the present study, the ULS assessment are made for the unstiffened plate of the hull of a hypothetical classic spar platform. The unstiffened plate is assumed to have simply supported edges and is assumed to be under combined biaxial compression (Fig. 2). The length and the breadth of the plate are $\mathrm{a} = 2400\,\mathrm{mm}$ and $\mathrm{b} = 800\,\mathrm{mm}$, while the slenderness ratio is $\beta = \left(\frac{\mathrm{b}}{\mathrm{t}}\right)\sqrt{\frac{\sigma_Y}{E}} = 2.8284$.

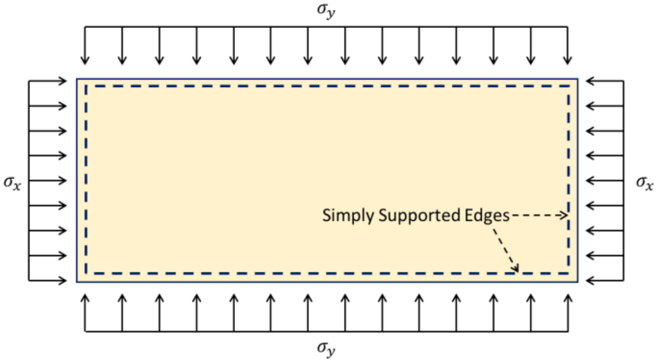

Fig. 2 An unstiffened plate with simply supported boundaries under biaxial compression loading

In this study, the plates are considered to have regular distribution of pit corrosions, however, in reality the distribution of pit corrosions are random. As an example, two of the plates used in the simulation are shown in Fig. 3.

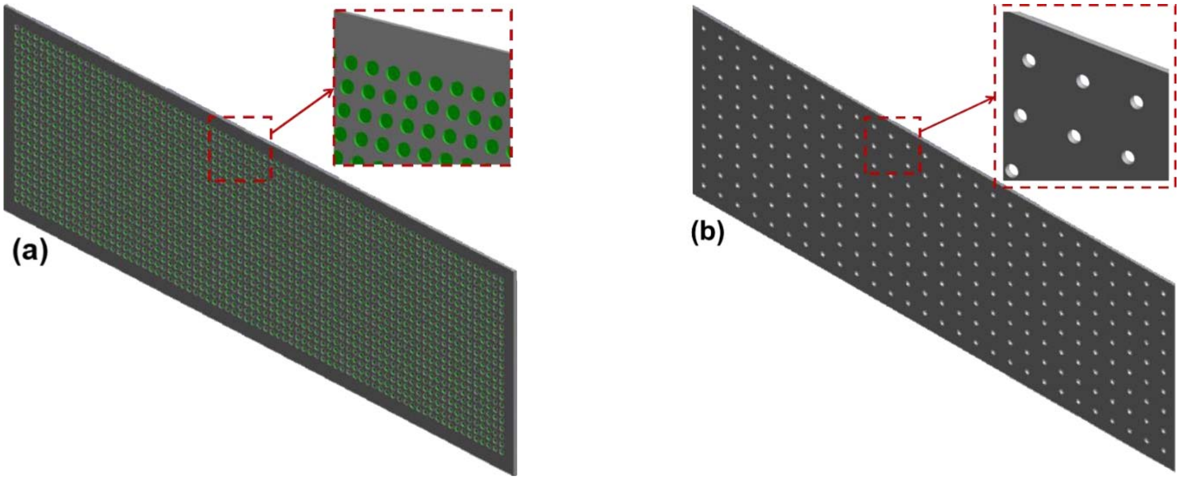

Fig. 3 (a) A plate with 30% DOP and $\mathrm{t}_{\mathrm{pit}} = 0.5t$. (b) A plate with 15% DOP and $\mathrm{t}_{\mathrm{pit}} = t$

3. THE ULTIMATE STRENGTH OF PLATES

Using ANSYS finite element analysis, the ultimate strength of 48 different models under different biaxial compression loadings, density of pit corrosions and corrosion depths were calculated. The results of these analyses are shown in Table 1.

Table 1 Summary of ultimate strength computations

Pit Depth: $\mathrm{t_{pit}} = 0.5t$			Pit Depth: $\mathrm{t_{pit}} = t$		
DOP	$\sigma_x : \sigma_y$	σ_u	DOP	$\sigma_x : \sigma_y$	σ_u
0%	1.0:0.0	209.4	0%	1.0:0.0	209.4
	0.8:0.2	172.98		0.8:0.2	172.98
	0.6:0.4	86.68		0.6:0.4	86.68
	0.4:0.6	56.661		0.4:0.6	56.661
	0.2:0.8	42.041		0.2:0.8	42.041
	0.0:1.0	33.409		0.0:1.0	33.409
7.5%	1.0:0.0	195.43	7.5%	1.0:0.0	176.47
	0.8:0.2	160.11		0.8:0.2	143.5
	0.6:0.4	79.9		0.6:0.4	71.23
	0.4:0.6	52.23		0.4:0.6	46.56
	0.2:0.8	38.75		0.2:0.8	34.545
	0.0:1.0	30.79		0.0:1.0	27.45
15%	1.0:0.0	201.3	15%	1.0:0.0	189.57
	0.8:0.2	165.67		0.8:0.2	156.04
	0.6:0.4	82.975		0.6:0.4	78.162
	0.4:0.6	54.251		0.4:0.6	51.114
	0.2:0.8	40.257		0.2:0.8	38.261
	0.0:1.0	31.994		0.0:1.0	30.41
30%	1.0:0.0	157.97	30%	1.0:0.0	116.84
	0.8:0.2	125.1		0.8:0.2	86.976
	0.6:0.4	61.156		0.6:0.4	42.86
	0.4:0.6	39.917		0.4:0.6	28.231
	0.2:0.8	29.602		0.2:0.8	21.036
	0.0:1.0	23.519		0.0:1.0	16.761

Notes: DOP = density of pit corrosion; σ_x = stress in longitudinal direction; σ_y = stress in transverse direction; σ_u = ultimate strength of the plate

Fig. 4 (a-c) show the deformation and von Miss stresses under different density of pit corrosions. It is found that increase in the density of pit corrosion can significantly reduce the ultimate strength of the plates.

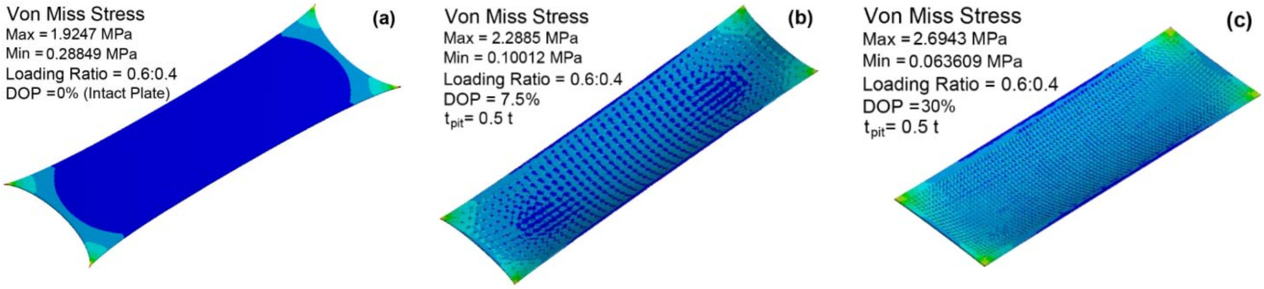

Fig. 4 Deformed shapes and the von Miss stress distributions at the ultimate limit state under biaxial compression ($\sigma_x : \sigma_y = 0.6 : 0.4$) with simply supported edges (free rotational restraints) for (a) intact plate (DOP = 0%); (b) DOP = 7.5%; (c) DOP = 30%

4. REGRESSION ANALYSIS OF ULTIMATE STRENGTH

Using the results shown in Table 1, the ultimate compression strength of the spar platform plate by considering pit corrosion was expressed by the following equation:

$$\sigma_{spu} = k_1 A^2 - k_2 A - k_3 B - k_4 C + 63.97 \tag{1}$$

where σ_{spu} is the ultimate compression strength of the spar platform, A is the loading ratio, B is the density of pit corrosion, C is the depth of pit corrosion. k_1, k_2, k_3, and k_4 are constants with the value of 42.49, -80.73, -17.68, -4.48, respectively. The above equation were obtained by the regression analysis of the computed results as a function of loading ratio, DOP, and depth of pit corrosion. Analysis of Variance (ANOVA) method were used to obtain the accuracy of the Eq. (1). It is seen that the proposed equation can estimate the ultimate strength of the plates with an acceptable accuracy (Fig. 5).

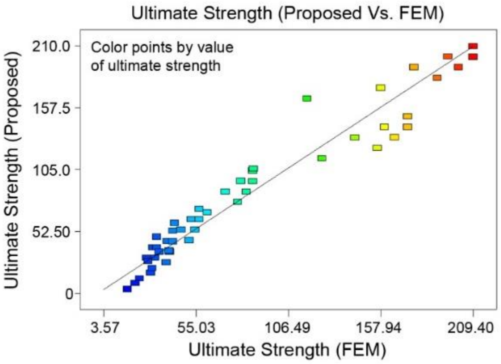

Fig. 5 Eq. (1) in the ultimate compression strength prediction for a plate with pit corrosion

As shown in Table 2, the Model F-value of 168.99 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise. The value of "Prob > F" which is less than 0.05 indicates that model terms are significant. In this case A, B, A^2 are significant model terms, while values greater than 0.1 may indicate that the model terms are not significant. The "Predicted R-Squared" of 0.9241 is in reasonable agreement with the "Adjusted R-Squared" of 0.9346.

Table 2 Summary of Analysis of Variance (ANOVA) for the proposed ultimate strength formula

	Source of variation	Regression model	Residual Error	Total	Adjusted R-squared	Predicted R-squared
Ultimate Strength	DOF	43	4	47	93.46%	92.41%
	SS	1.690E+005	10748.84	1.797E+5		
	MS	42242.09	249.97			
	F-value	168.99				
	Prob>F	<0.0001 (significant)				
	F-table (0.05, 6, 6) = 4.28					

SS stands for Sum of Squares, DOF stands for Degree of Freedom, and MS denotes Mean Square. MS is the SS to DOF ratio, and the F-value is the ratio of the MS of the regression model to the MS of the residual error.

5. CONCLUSIONS

In this study, the ultimate strength of diverse steel plates with different loading ratios, DOPs, and pit depths were obtained by using numerical analysis. Using regression analysis a formula to predict the ultimate strength of the plates were calculated. The accuracy of the proposed formula were then evaluated by using ANOVA method. By considering the evaluation results, it is observed that the proposed formula can predict the ultimate strength of the plates with an acceptable accuracy.

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