Structural Safety and Design Requirements of CFMP based Offshore Wind Substructure System

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***Abstract*-Offshore wind substructure system should have a structural safety against to the harsh offshore conditions of wind, wave, and tidal. Also, in order to satisfy overturning stability, gravity based substructure system should be required to have sufficient foundation resistance and weighting resistance to efficiently resist to the overturning. In this study, structural safety for the CFMP based offshore wind substructure system was evaluated. CFMP based substructure system of this study was designed to improve structural safety against to the harsh offshore condition and to reduce constructional cost. In order to investigate ultimate structural safety and serviceability, integrated static structural analysis was carried out and structural behaviors of the strength and deformation were evaluated. Also, in order to investigate dynamic modal safety, modal analysis was carried out and natural frequency and resonance possibility were evaluated. As the results of this study, it was found that the CFMP based offshore wind substructure system of this study satisfied structural safeties in respect of ULS (ultimate limit state) and SLS (serviceability limit state). Also, this system satisfied vibration safety, namely resonance was not occurred. However, if the total weight and stiffness of substructure system increased, it was respected that vibration safety should be improved.**

Keywords-substructure; offshore wind; safety; strength; CFMP; frequency

I. INTRODUCTION

Offshore wind substructure system should have a structural safety against to the harsh offshore conditions of wind, wave, and tidal. Also, in order to satisfy overturning stability, gravity based substructure system should be required to have sufficient foundation resistance and self-weighting resistance to resist to the overturning efficiently.

In order to improve structural safeties of offshore wind substructure system, it is very important to reduce wave-induced hydrodynamic force subjected to the substructure system and to improve strength, stiffness, and vibration resistance of substructure system [1,2]. However, since the increasing of the size of substructure system to improve strength and stiffness disadvantages to the wave-induced hydrodynamic forces subjected to the substructure system, it needs to optimally arrange cross-section of substructure system so as to satisfy both low-hydrodynamic force and high-structural capacity of strength, stiffness, and vibration resistance. Also, in order to improve overturning stability of substructure system, it is advantage to increase self-weight of substructure system [3,4]. However, since the increasing of self-weight of substructure system influence on the construction costs, it needs to optimally control the self-weight of substructure system.

In this study, structural safety of CFMP (Concrete Filled Multi-Piles) based offshore wind substructure system was evaluated. CFMP based substructure system of this study was designed to improve structural safety against to the harsh offshore condition and to reduce constructional cost. In order to investigate ultimate structural safety and serviceability, integrated static structural analysis was carried out and structural behaviors of the strength and deformation were evaluated. Also, in order to investigate dynamic modal safety,

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modal analysis was carried out and natural frequency and resonance possibility were evaluated.

II. CFMP BASED SUBSTRUCTURE SYSTEM

CFMP based Substructure System

CFMP based substructure system of this study, as presented in Fig. 1, was designed to improve structural safety against to the harsh offshore condition and to reduce constructional cost. In order to reduce wave-induced hydrodynamic force subjected to the substructure system, multi-piles system was adapted. Also, in order to improve strength, stiffness, and vibration resistance of substructure system, multi-piles system filled with the concrete. Therefore, CFMP system was designed so as to satisfy both low-hydrodynamic force and high-structural capacity of strength, stiffness, and vibration resistance.

Fig. 1: CFMP based offshore wind substructure system

Also, to improve overturning stability of substructure system, the bottom part of substructure system consists of gravity based concrete cone. The gravitational restoring force of the concrete cone resist to the overturning combined with the foundation piles. Namely, combining force of the concrete cone and foundation piles resist to the overturning moment. This concept has an advantage that two components of gravitational restoring force and foundation piles resistance can be apply alternatively according to the seabed condition from the soft soil to the rock.

The CFMP and the concrete cone connect with the grouting at the sea condition. This modular installation method can become possible substructure installation by using only small capacity's offshore crane, instead of large capacity's offshore crane which is very expensive and too difficult to rent, and resulting in reduce total construction cost.

Limit States Design of Substructure System

In general, offshore wind substructures have been designed by limit states design concept. Limit states of substructure are detailed four sub-items of ULS (Ultimate Limit State), SLS (Serviceability Limit State), FLS (Fatigue Limit State), and ALS (Accident Limit State). ULS is design requirement for the structural strength, displacement and overturning at the extreme environmental loads condition. SLS is the design requirement for the structural deformation, vibration, and cracks. FLS is design requirement for the structural fatigue resistance at the normal environmental loads condition. ALS is the design requirement for the structural safety at the ship impact, seismic, and explosion.

In respect of structural safety of substructure system, among the four limit states design requirements, two limit states of ULS and SLS should be analyzed firstly. Where, extreme environmental conditions (wind, wave and current) of return period 50 years are used at the ULS and SLS analysis of the substructure system.

III. STRUCTURAL SAFETY ANALYSIS

Offshore Wind Model and Environmental Loads

NREL 5.0MW turbine model was selected for the structural safety analysis of CFMP based substructure system. The details of NREL 5.0MW turbine were provided in TABLE 1. Also, the details of tower system were provided in TABLE 2. In this study, tower model resulting from Upwind project [5], which was designed corresponding to the NREL 5.0 MW turbine model, was applied. The total weights of turbine and tower models were about 350 and 220 ton, respectively.

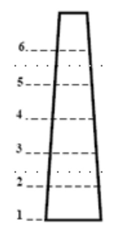
The hub height is 82.5m from MSL (Mean Sea Level) and the tower length is 68.0 m. The height of substructure is 32.0 m from seabed and the water depth is 20.0 m. The total height of total system of tower to substructure is 100.0 m, as presented in Fig. 2.

At the structural safety analysis, design code IEC 61400-3 was adopted and structure analysis was carried out according to the ultimate design loads condition 6.1(a) and 6.2(a), as presented in Table 3. DLC 6.1(1) and 6.2(a) present ultimate limit states for the parked (standing still or idling) state and grid loss state, respectively.

TABLE 1 DETAILS OF NREL 5.0MW TURBINE MODEL

Turbine Parameter	Unit	Value
Rated power	MW	5.0
Rotor diameter	M	126.0
Mass of rotor and nacelle	Ton	350.0
Cut-in wind speed	m/s	3.0
Rated wind speed	m/s	11.4
Cut-out wind speed	m/s	25.0
Nominal rotor speed	rpm	12.1
Lower bound rotor speed	rpm	6.9
Upper bound rotor speed	rpm	12.1

TABLE 2 DETAILS OF TOWER

	Section	Height (m)	D_out at top (m)	D_out at bottom (m)	Thick Ness (mm)	Flange (kg)
	80.0	75.0	4.000	4.118	30	1,000
	75.0	66.0	4.118	4.329	20	0
	66.0	56.0	4.329	4.565	22	0
	56.0	46.0	4.565	4.800	24	0
	46.0	34.0	4.800	5.082	28	1,400
	34.0	24.0	5.082	5.318	30	0
	24.0	12.0	5.318	5.600	32	1,900

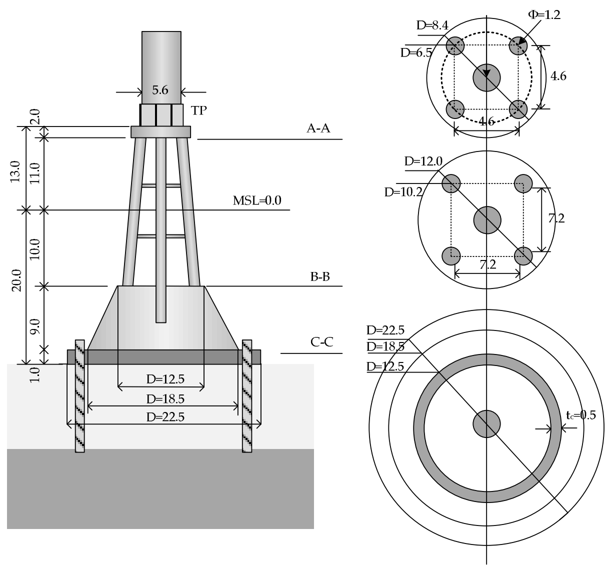


Fig. 2: Structure safety analysis model

TABLE 3 DESIGN LOAD CASES (DLC) FOR ULTIMATE LIMIT STATE

DLC	Condition	Wave	Wind
IEC 61400-3-(6.1a)	Parked Standing still or idling	Extreme	Extreme
IEC 61400-3-(6.2a)	Grid loss	Extreme	Extreme

Environmental loads of wind, wave, and current for the southern-western sea of the Korea peninsular were processed and summarized in TABLE 4. Extreme wind loads subjected to the blade, nacelle, and tower were calculated based on the wind speed of return period 50 years. Extreme wave force subjected to the substructure was calculated based on the wave height and period of return period 50 years.

TABLE 4 ENVIRONMENTAL LOADS

	Wind	Wave	Limit state
Normal	7.7 m/s	H_w=1.52m, P_w=6.2sec	FLS
Extreme	41.6 m/s	H_w=13.76m, P_w=15.0sec	ULS

Wave forces subjected to the substructure were calculated from both the Morison equation and diffraction theory. These wave forces were compared with each other as presented in Fig. 2. As the result of the comparison, since there is some error between the two sets of wave forces at the normal condition, which is necessary for the FLS design, the wave force from diffraction theory was selected for the structural safety analysis.

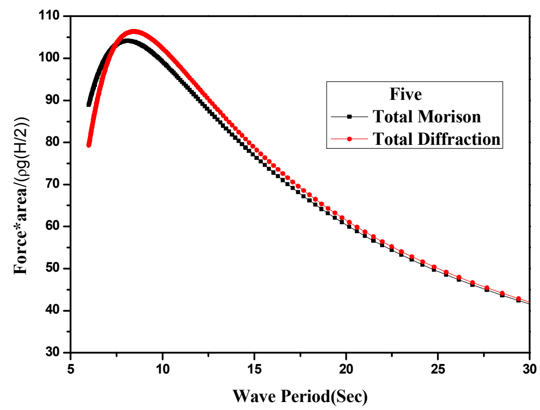


Fig. 3: Wave forces from Morison and diffraction

Structural and Modal Analysis

In order to investigate ultimate structural safety and serviceability of CFMP based substructure system of this study, integrated static structural analysis was carried out and structural behaviors of the strength and deformation were evaluated. Structural analysis carried out using the structural analysis package ANSYS mechanical [6]. The CFMP and the concrete cone members were modeled by using 3D-Solid element. It assumed that the boundary condition to the seabed was fixed condition. Dynamic environmental loads were converted to the static loads, as presented in TABLE 4, and applied to the substructure system as the pressure loads.

In order to investigate dynamic modal safety, modal analysis was carried out to the tower-to-substructure system and natural frequency and resonance possibility were evaluated.

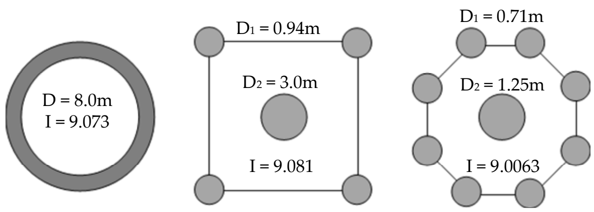
IV. STRUCTURAL SAFETY AND REQUIREMENT

Wave-Induced Hydrodynamic Forces

As the results of diffraction analysis for the three cases arrangement of multi-piles as presented in Fig. 4, wave forces subjected to the substructure were plotted in Fig. 5. Wave force of multi-piles cases indicated about 35% lower level than that of mono-pile. Therefore, the reducing of wave force subjected to the substructure system should be contributed to reduce bending stress and to improve overturning stability of substructure system.

Structural Bending Moment and Displacement

As the results of structure analysis, structural stress and deformation were plotted at the Fig. 6. There were large variance of bending stress at the two connection parts of tower to substructure and CFMP to concrete cone connection part. The maximum bending stresses excepting these parts were about 23.0 MPa for the CFMP and 3.0 MPa for the concrete cone, respectively. Therefore, it was found that the ultimate strength of CFMP based substructure system satisfied ULS design condition. However, structural details at the two connection parts, tower to substructure and CFMP to concrete cone, should be decided carefully to satisfy large variance of bending stress about 100.0 MPa. Bending moment was converted from bending stress resulting from structure analysis. Maximum bending moment was occurred at the seabed.



(a) Mono (b) Five (c) Nine

Fig. 4: Arrangement of CFMP (Concrete Filled Multi-Piles)

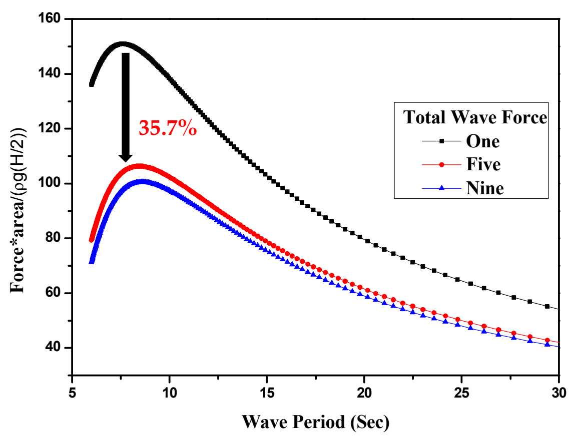


Fig. 5: Wave forces according to the arrangement of multi-piles

Maximum displacements were about 0.793m at the tower top. The gradient of tangent line was 0.454° for the total length 100.0m of the substructure from seabed. Considering design requirement for the transverse displacement 1/100 or 0.50° for the total length L, it was found that the ultimate deformation of CFMP based substructure satisfied ULS and SLS design condition. However, in case of soft seabed condition, as the transverse deformation of the substructure was affected by seabed condition, the detailed seabed condition or foundation resistance should be included at the structure analysis.

Natural Frequency and Resonance

Based on the modal analysis results, resonance possibility was evaluated. Natural frequency of the tower to substructure system from modal analysis was plotted against to the spectrum density of the turbine and environmental loads. As the results of plotting, it was found that the natural frequency of CFMP based substructure system was located between the turbine's natural frequency of 1P and the blade's passing frequency of 3P. Therefore, it was concluded that the there is no possibility of resonance.

However, considering uncertainties at the modeling, boundary condition, and environment loads condition, it was induced that there may be a possibility of resonance. Therefore, it is recommended to be designed including DMF (Dynamic Magnitude Factor) requirement.

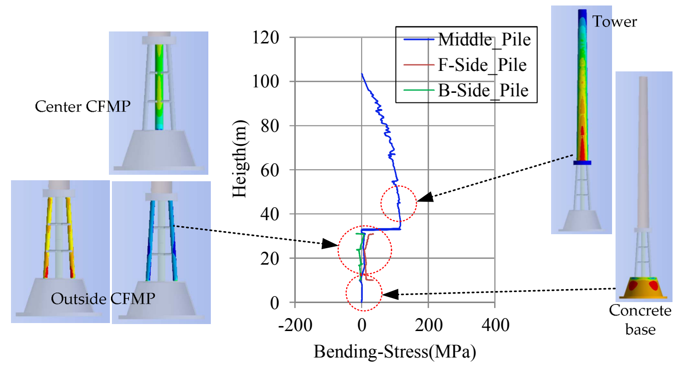
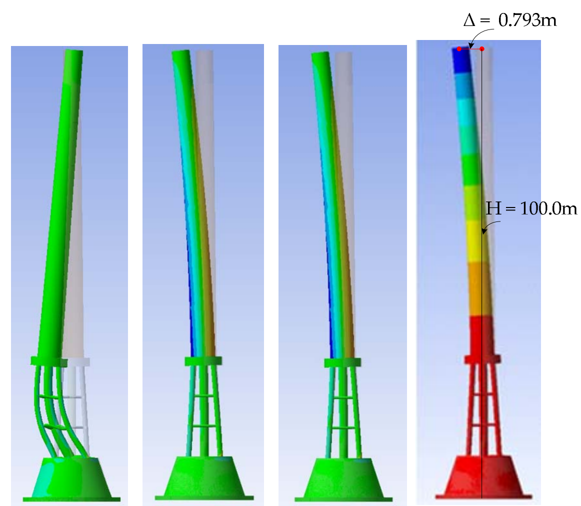


Fig. 6: Bending stresses of CFMP based substructure system



(a) Wave (b) Wind (c) Integrated (d) Displacement

Fig. 7: Structure deformation by loading conditions

V. CONCLUSIONS

In this study, structural safety for the CFMP based offshore wind substructure system was evaluated. CFMP based substructure system of this study was designed to improve structural safety against to the harsh offshore condition and to reduce constructional cost.

In order to investigate ultimate structural safety and serviceability, integrated static structural analysis was carried out and structural behaviors of the strength and deformation were evaluated. Also, in order to investigate dynamic modal safety, modal analysis was carried out and natural frequency and resonance possibility were evaluated.

As the results of this study, it was found that the CFMP based offshore wind substructure system of this study satisfied structural safeties in respect of ULS (ultimate limit state) and SLS (serviceability limit state). Also, this system satisfied vibration safety, namely resonance was not occurred.

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