

Time-Domain Response-Based Structural Analysis on a Floating Offshore Wind Turbine

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Abstract

As the turbine blade size becomes larger for economic power production, the coupling effect between wind turbine and floating substructure becomes important in structural assessment. Due to unsteady turbulent wind environment and corresponding coupled substructure response, time-domain analysis is required by international electrotechnical commission and class societies. Even though there are a few numerical tools available for the time domain structural analysis based on conventional coupled motion analysis with wind turbine, the application of conventional time domain analysis is impractical and inefficient for structural engineers and hull designers to perform structural strength and fatigue assessment for the required large number of design load cases since it takes huge simulation time and computational resources. Present paper introduces an efficient time-domain structural analysis practically applicable to buckling and ultimate strength assessment. Present method is based on 'lodal' response analysis and pseudo-spectral stress synthesizing technique, which makes time-domain structural analysis efficient and practical enough to be performed even in personal computing system. Practical buckling assessment methodology is also introduced applicable to the time-domain structural analyses. For application of present method, a 15-MW floating offshore wind turbine platform designed for Korean offshore wind farm projects is applied. Based on full-blown time domain structural analysis for governing design load cases, buckling and ultimate strength assessments are performed for the extreme design environments, and the class rule provided by Korean Register is checked.

Keywords Time domain; Structural analysis; Lodal response; Floating wind turbine, Buckling and strength analysis

Article Highlights

- An efficient and practical time domain structural analysis method for a floating offshore wind turbine is introduced.
- Based on lodal response concept, fully coupled transient offshore wind turbine structure response can be obtained in terms of component stress time history.
- Because of high efficiency, full-blown time domain structural analysis for the required large number of design load cases can be performed instantly.
- Structural strength and buckling assessment are performed practically and accurately in time domain with utilizing class rule check software.

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1 Introduction

Floating offshore wind turbine (FOWT) platform experiences transient and periodic loading from irregular wave environments and rotating wind turbine in turbulent wind condition. Due to coupling between wind turbine under transient wind load and floating substructure under irregular wave load, time domain structural assessment on a floating offshore wind turbine platform is required by international regulation societies for safe design and operation (ABS 2020a; ABS 2020b; DNV 2021; IEC 2005; IEC 2019a; IEC 2019b). Compared with a fixed onshore wind turbine system, a FOWT need to consider random wave pressure variation and transient turbulent wind excitation at every simulation time step. For the structural response from random wave excitation, design wave concept has been successfully applied to the offshore floating production platforms in oil and gas industry and documented as recommended practices in API (2000; 2011; 2015) and class societies (ABS 2022a; ABS 2022b; DNV 2017). The design wave ap-

proach is based on the regular wave loading that represents the extreme design wave load on the hull. In this design wave method, only wave load and corresponding motion response are considered to assess the structural response. Other loadings such as transient wind load coupled with floating substructure motion response cannot be correctly considered for a FOWT structural response analysis. For a FOWT platform, the wind turbine load induced by transient turbulent wind environment is dominant to the floating substructure response as well as irregular wave load in harsh environment. Even though there are a few available commercial tools such as BLADED, OrcaFlex and AQWA, it is expensive and requires large capacity of computation resources to perform time-domain structural response analysis. To apply at the initial design stage as well as detail structural analysis stage, presently available tools and methods seem to be impractical to analyze large number of the required design load cases with long duration of simulation time.

To enhance the computational efficiency while keeping accuracy of analysis, present paper introduces a time domain structural analysis based on synthesizing lodal responses. Similar approach has been proposed in previous studies. Kyoung et al. applied the similar approach to a floating offshore production platform for time domain structural strength (Kyoung et al. 2020) and fatigue assessment (Kyoung et al. 2019; Kyoung et al. 2021). Rather than performing finite element analysis by instantaneous load mapping at every time step, present method computes structural responses, or lodal responses, of the floating structure as a complete set of load patterns, which is called as “lodes”, a-priori in pre-processing stage. The spatial distribution of the structural load at any time step can be represented by the linear combination of the pre-computed lodes. Accordingly, the structural responses of the lodes, or lodal responses, can be linearly synthesized to generate structural response in time domain. To enhance the computational efficiency in synthesizing stage, pseudo-spectral response synthesizing (PSRS) technique is applied to combine the linear frequency-domain lodes such as wave loading, and nonlinear time-domain lodes such as wind-turbine and mooring loading. With this approach, computation time and required computation resources can be dramatically reduced compared with the presently available other commercial tools.

In present paper, a 15-MW floating offshore wind turbine substructure (Kim et al. 2022) is used for strength and buckling assessments with full-blown time domain structural analysis. For the assessment and rule check, SeaTrust-HullScan, Korean Register software, is applied.

2 Time domain structural analysis on lodal responses

Present time domain structural analysis is based on lodal responses of the offshore floating turbine structure.

The lodal responses are defined as the structural responses to each load, which are the minimum number of structural load patterns able to generate any structural response by linear combination.

The loads on a floating structure can be categorized into the number of load patterns including hydrodynamic load (wave diffraction and radiation), static pressure, external load (mooring, riser, wind), inertial load, and drag load. For the given unit load patterns, unit structural responses, i.e., lodal responses, can be obtained. Then, the structural response can be obtained by synthesizing the lodal responses with external loading in time domain. The following equation presents the time domain stress response of the given FE model by synthesizing lodal responses at every time step.

$$\sigma_i(t) = \sigma_{ij}^{\text{WD}} \zeta_j + \sigma_{ij}^{\text{WR}} \dot{\zeta}_j + \sigma_{ij}^D V_j + \sigma_{ij}^I a_j + \sigma_{ij}^P F_j + \sigma_i^S \quad (1)$$

where t is time in second. $\sigma_i(t)$ is the time series of stress component at i th element of FE model. σ_{ij}^{WD} is the stress component of diffraction pressure per unit wave amplitude at i th element for j th incident wave component, ζ_j . σ_{ij}^{WR} is the stress component of radiation pressure per unit motion. $\dot{\zeta}_j$ is the hull motion. σ_{ij}^D is the stress component of drag load per unit velocity. V_j is the relative fluid velocity. σ_{ij}^I is the stress component of inertial load per unit acceleration. a_j is the acceleration of hull. σ_{ij}^P is the stress component of unit external load such as mooring, riser and wind. F_j is the external load. σ_i^S is the stress component of static pressure. With present lodal response-based analysis, the time domain structural analysis can be performed with less computational time and required computational resources enough to be executed in personal computer. Application of this method has been validated through comparison between conventional approaches for a floating offshore floating structure in previous studies (Kyoung et al. 2019; Kyoung et al. 2020).

In traditional time domain structural analysis, the loads are computed at every time step considering hull response and external environment loads such as wave, wind and current. Even though this conventional approach can consider nonlinear loading such as instantaneous change of wetted surface area for pressure mapping, it takes huge computational capacity and impractical computation time for structural engineers to design and assess structural integrity and safety of a FOWT. As expressed in Equation (2), conventional time domain approach needs to perform finite element analysis repeatedly at every time step for the transient load patterns.

$$r_j(t) = \sum_{i=1}^{N_m} a_{ij}(t) K^{-1} f_i, \quad j = 1, \dots, N_e \quad (2)$$

where $r_j(t)$ is structural response at time t for j th element, $a_{ij}(t)$ is load amplitude at j th element at time t for i th load pattern, K is the stiffness matrix of FE model, f_i is the nor-

malized loading for i th load pattern, N_m is the number of load pattern, and N_e is the total number of finite elements.

In this paper, the lodal response concept is applied rather than computing all the external loadings repeatedly at every time step. Since the structural response is assumed to be linear and static in general, its time-domain response can be obtained by linearly synthesizing the responses corresponding to the finite number of load patterns. Therefore, only limited number of finite element analyses is necessary for the finite number of load patterns rather than perform finite element analysis at time interval step. Compared with conventional time domain structural analysis, the structural responses to the selected load patterns are separately computed in pre-processing part as express in Equation (3). The time series of structural response can be obtained by simple multiplication of the lodal response with environmental loadings as shown in Equation (4).

$$R_i = K^{-1}f_i, i = 1, \dots, N_m \quad (3)$$

$$r(t) = \sum_{i=1}^{N_m} a_i(t) R_i \quad (4)$$

where $r_j(t)$ is the structural response of all elements at time t . R_i is the lodal response of all elements which is obtained a-priori through the pre-processing to the i th load pattern, $a_i(t)$ is the external loading corresponding to i th load pattern at time t , and f_i is the time series of external load corresponding to i th load pattern, N_m is the number of load patterns.

As shown in Figure 1, the load patterns are intelligently selected according to the characteristics of structure such as conventional offshore floating production platform and floating offshore wind turbine. For a FOWT, they include the wave diffraction and radiation loads, current load, hydrostatic variation, drag load, mooring/riser/power cable loads, wind turbine loads, and hull inertial load.

As a pre-processing stage, finite element analysis is performed with the normalized load of the selected load patterns. For example, the wave diffraction pressure is normalized with unit wave amplitude to the give wave heading. Through this process, a set of lodal responses is generated. The finite element analyses can be performed according to the level of details. In general, a global FE model is applied for yielding and buckling assessment and a detail local FE model for fatigue assessment. In any case, the FE analyses take short in present method compared with the conventional time domain analysis since the finite number, typically less than 2000, of loads will be considered.

To generate the structural response in time domain, the pre-processed lodal responses are synthesized with the time series of external loadings and hull responses. Structural response corresponding to individual load pattern can be obtained. To enhance the computational efficiency, the time series of structural response is obtained by “Pseudo-

spectral response synthesizer (PSRS)” in present method. In PSRS approach, all the structural response is transformed to Fourier space within the same frequency range and interval. Then, by Inverse Fast Fourier Transform (IFFT), the structural response can be obtained at once in terms of the time series of stress components at every element of the given FE model.

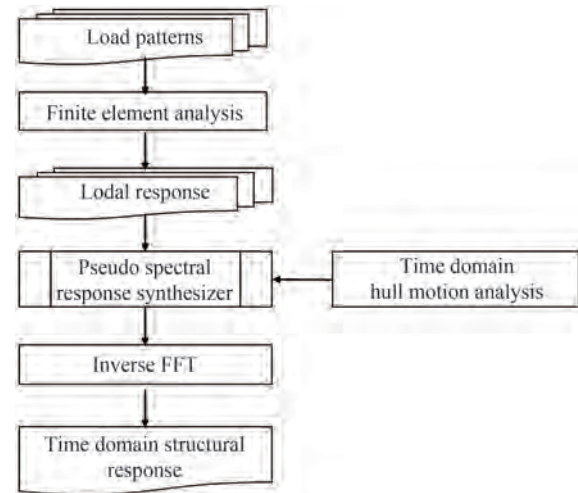


Figure 1 Time-domain structural response through PSRS using lodal response

3 Ultimate strength assessment in time domain

In general (IACS, 2022) the geometry of the hull structure is represented by the finite element model including all main structural elements. Plate structure is modeled by shell elements. The aspect ratio of the shell elements is required not to exceed three. Mostly quadrilateral element is recommended for the shell element model and the minimum use of triangular shell elements is recommended. It is also recommended to keep the aspect ratio of shell elements close to one in the areas where there are likely to be high stress or a high stress gradient. For the areas, the use of triangular elements is not recommended. The shell element mesh can be also applied to the stiffening system such as actual plate panels between stiffeners. All stiffeners are modelled with beam elements having axial and bending stiffness. The eccentricity of the neutral axis also needs to be modelled.

For shell element, all stress components can be also obtained on the top and bottom surfaces of each shell element. In general, the von Mises (VM) stress of shell elements at middle layer are used for the assessment ultimate strength assessment. In case of buckling assessment, reference stresses for compression and shear over the buckling panel are compared with the critical buckling stress which

is required by the class rule for the buckling check.

The followings summarize the procedure and requirements for ultimate strength and buckling strength assessment using the obtained time domain structural response. Figure 2 shows the procedure for calculating the ultimate stress based on the von Mises stress (VM) of shell element for the design sea state. For shell elements, von Mises stress, σ_{vm} , is calculated using the normal and shear stress-

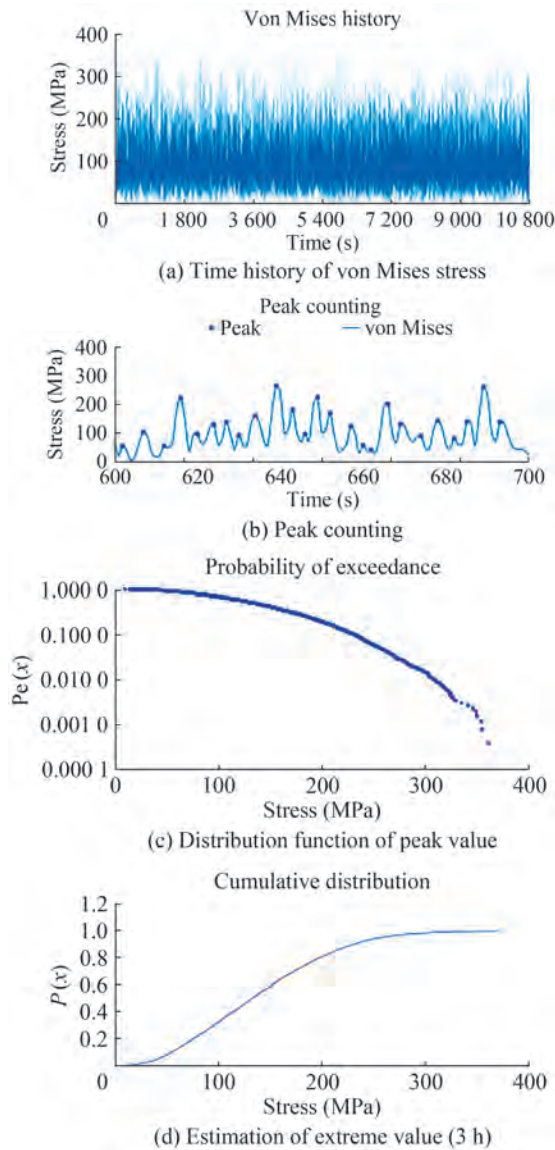


Figure 2 Calculation procedure for ultimate strength from time domain analysis

es as shown in Equation (5) and is evaluated at each shell element centroid of the middle layer.

$$\sigma_{vm} = \sqrt{\sigma_x^2 - \sigma_x \sigma_y + \sigma_y^2 + 3\tau_{xy}^2} \quad (5)$$

where σ_x and σ_y are the element normal membrane stress

in N/mm^2 . τ_{xy} is the element shear stress in N/mm^2 . Since VM stress is non-negative value, the peak values for the given time duration can be found using the peak-counting method. The selected peak values can be fitted into a probability distribution function. From that, the extreme VM stress can be obtained at a specific probability level for the given design sea state.

For beams and rod elements, the axial stress, σ_{axial} , is to be calculated based on the axial force alone. The axial stress is to be evaluated at the middle of element length. The structural strength can be evaluated by the following criteria shown in Equation (6).

$$\lambda_y \leq \lambda_{yperm} \quad (6)$$

where λ_y is the yield utilization factor. $\lambda_y = \frac{\sigma_{vm}}{R_y}$ is defined

for shell elements in general and $\lambda_y = \frac{|\sigma_{axial}|}{R_y}$ is defined for

rod or beam elements in general. σ_{axial} is the axial stress in rod or beam element. λ_{yperm} is the coarse mesh permissible yield utilization factors. R_y is the nominal yield stress. In general, λ_{yperm} is 1.0 when both static and dynamic loads are considered. Since the stresses in the fine-meshed area have high stress gradient due to mesh size, the extreme stresses in the refined area need to be re-evaluated according to the adjusted allowable stress criteria.

4 Buckling strength assessment in time domain

‘Buckling’ is a generic term to describe the strength of structures under in-plane compressions and/or shear and lateral load. The buckling strength or capacity considers the internal redistribution of loads depending on the load situation, slenderness and type of structure. Buckling capacity gives a lower bound estimate of ultimate capacity or the maximum load that the panel does not have any major permanent deformation. Buckling capacity assessment is conducted based on the positive elastic post-buckling effect and load redistribution between plating and stiffeners. An example of buckling panel is shown in Figure 3.

For the buckling strength assessment, the utilization factor, η , is defined as the ratio between the applied loads and the corresponding ultimate capacity or buckling strength. The utilization factor, η_{act} , is defined as the ratio of the equivalently applied stress over the corresponding buckling capacity as shown in Equation (7).

$$\eta_{act} = \frac{W_{act}}{W_u} = \frac{1}{\gamma_c} \quad (7)$$

where W_{act} is an equivalent applied stress in N/mm^2 for buckling assessment by prescriptive and direct strength

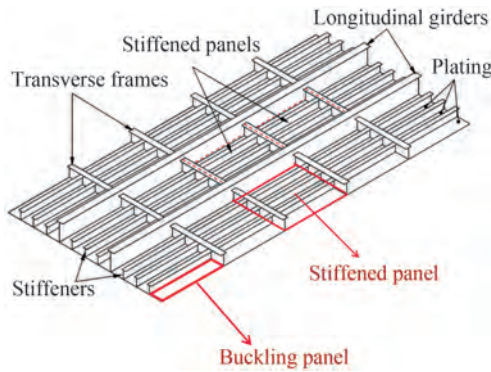


Figure 3 Example of buckling panel

analysis. W_u is an equivalent buckling capacity in N/mm^2 for plates and stiffeners. γ_c is the stress multiplier factor at failure for each different limit states. γ_c is obtained from the following criteria.

$$\left(\frac{\gamma_{c1} \sigma_x S}{\sigma'_{cx}} \right)^{e_0} - B \left(\frac{\gamma_{c1} \sigma_x S}{\sigma'_{cx}} \right)^{\frac{e_0}{2}} \left(\frac{\gamma_{c1} \sigma_y S}{\sigma'_{cy}} \right)^{\frac{e_0}{2}} + \left(\frac{\gamma_{c1} \sigma_y S}{\sigma'_{cy}} \right)^{e_0} + \left(\frac{\gamma_{c1} |\tau| S}{\tau'_c} \right)^{e_0} = 1 \quad (8)$$

$$\left(\frac{\gamma_{c2} \sigma_x S}{\sigma'_{cx}} \right)^{2/\beta_p^{0.25}} + \left(\frac{\gamma_{c2} |\tau| S}{\tau'_c} \right)^{2/\beta_p^{0.25}} = 1 \quad \text{for } \sigma_x \geq 0 \quad (9)$$

$$\left(\frac{\gamma_{c3} \sigma_y S}{\sigma'_{cy}} \right)^{2/\beta_p^{0.25}} + \left(\frac{\gamma_{c3} |\tau| S}{\tau'_c} \right)^{2/\beta_p^{0.25}} = 1 \quad \text{for } \sigma_y \geq 0 \quad (10)$$

$$\frac{\gamma_{c4} |\tau| S}{\tau'_c} = 1 \quad (11)$$

$$\gamma_c = \min(\gamma_{c1}, \gamma_{c2}, \gamma_{c3}, \gamma_{c4}) \quad (12)$$

where σ_x and σ_y are the applied normal stress to the plate panel in N/mm^2 . τ is the applied shear stress to the plate panel in N/mm^2 . σ'_{cx} and σ'_{cy} are the ultimate buckling stress in N/mm^2 in direction parallel to the longer and shorter edge of the buckling panel, respectively. τ'_c is the ultimate buckling shear stresses in N/mm^2 . γ_{c1} , γ_{c2} , γ_{c3} and γ_{c4} are the stress multiplier factors at failure or each of different limit states. B and e_0 are coefficient specified in the class rule (DNV 2015; Korean Register 2010; Korean Register 2021). β_p is the plate slenderness parameter.

Figure 4 illustrates the buckling capacity and the buckling utilization factor of a structural member subject to longitudinal and transverse stresses. The buckling strength of elementary plate panels should satisfy the following criterion.

$$\eta_{\text{act}} \leq \eta_{\text{all}} \quad (13)$$

where η_{act} is the buckling utilization factor based on the ap-

plied stress. η_{all} is the allowable buckling utilization factor.

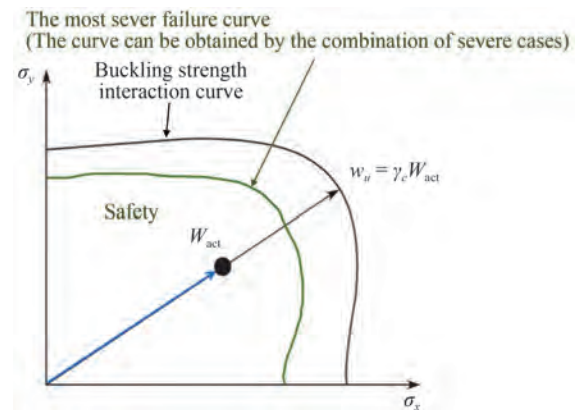


Figure 4 Example of buckling capacity and buckling utilization factor

For a slender body such as a ship, the yield and buckling evaluation are performed based on the equivalent design wave method (EDW) in the frequency domain. But a FOWT is required to perform a coupled global motion analysis in the time domain. Conventionally in time domain analysis, the buckling stress can be calculated at every time step to evaluate the buckling capacity of the plate in terms of snapshot stress distribution. Considering the number of buckling panels (more than 20 000), total simulation time (more than 1 h) and time interval (normally 0.1 s), the application of conventional procedure is inefficient and impractical in the design stage.

To perform the buckling evaluation efficiently in time

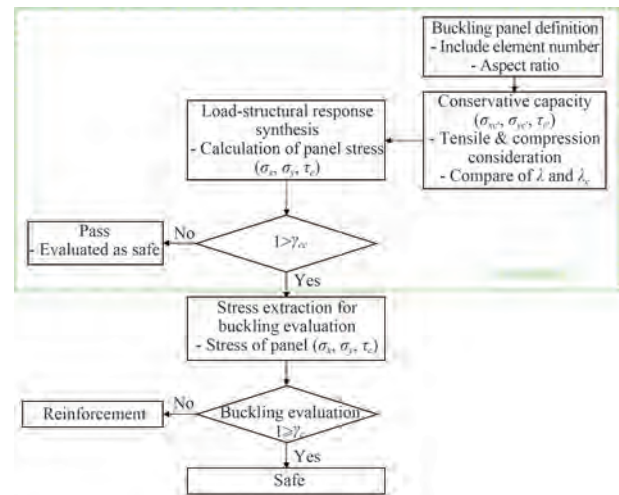


Figure 5 Buckling evaluation procedure using buckling capacity screening technique

domain, a screening technique is implemented in present paper as shown in Figure 5. In the screening technique, a ‘conservative capacity’ for the buckling panel ($W_u < W_{u,c}$) and corresponding approximated stress multiplier factor

(γ_{cc}) is predefined by applying conservative parameters to tensile or compression modes in the buckling panel. Using the predefined conservative buckling capacity, an efficient screening can be performed to find the critical stress conditions at every time step in time domain structural analysis. Through this screening process, limited number of buckling events can be obtained and reduce computation time and resource requirement dramatically compared with the conventional buckling assessment based on snapshot at every time step. In post-processing stage, accurate evaluation of the buckling capacity for the screened events can be performed using tools provided class societies such as HullScan-SeaTrust.

5 Application to a floating offshore wind turbine

As an application, 15-MW floating offshore wind turbine is used to perform strength and buckling assessments in time domain. Figure 6 shows the wind turbine and tower,

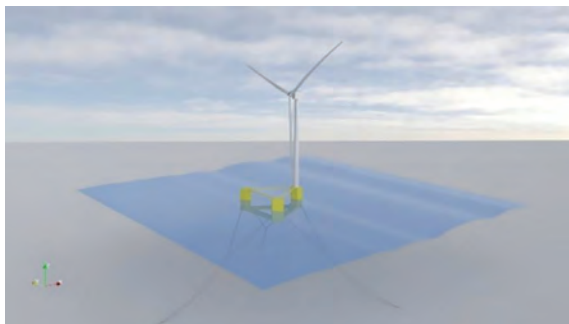


Figure 6 15MW floating wind turbine

floating substructure, and mooring configuration. Figure 7

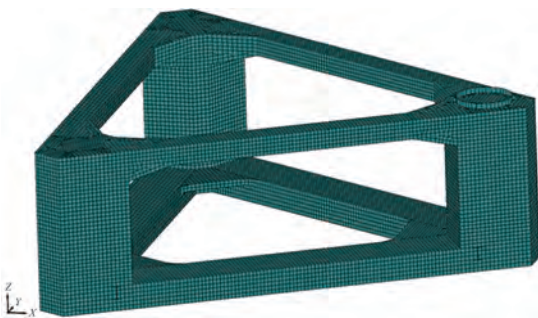


Figure 7 Finite element model of 15MW floating wind turbine substructure

shows the corresponding finite element model of substructure. In present strength and buckling assessment, global structural model is applied, which has coarser mesh than local structural model which is usually applied for fatigue

assessment.

For yield and buckling assessment, two design load cases (DLC) are considered as summarized in Table 1. The DLC 1.6 represents the extreme operating condition. In the DLC, it is assumed that power keeps produce normally even in severe environment conditions. Rated wind speed of 11 m/s to generate maximum thrust and cut-out speed of 25 m/s are considered. The rated wind speed causes the maximum moment of wind tower as well as maximum thrust. The severe sea state is considered with associated wind speed.

DLC 6.1 represents parking condition in extreme wind

Table 1 Design load cases for strength and buckling

Design load case	DLC 1.6	DLC 1.6	DLC 6.1	DLC 6.1
	$V_{MaxThrust}$	V_{out}	$Tp = 13.4\text{ s}$	$Tp = 16.4\text{ s}$
Wind	Turbulence model	NTM	NTM	EWM
	V_{hub} (m/s)	11	25	50
	Spectrum	JONSWAP	JONSWAP	JONSWAP
Wave	H_s (m)	4.5	10.7	10.7
	Tp (s)	9	14.1	16.4
	Gamma	2.4	2.5	2.5
Current	speed (m/s)	0.79	0.79	0.79

and wave environment of 50-year return period. In this DLC, turbine rotation is set to free with keeping 90° of blade pitch angle. Therefore, in this condition, the wave environment governs the extreme response of substructure. Tower inertial loading due to hull motion response imposes higher load at the tower connection. In this paper, wave peak period of 13.4 s and 16.4 s are considered representatively.

The considered design load conditions are summarized in Table 1. Time domain simulation of coupled motion response was performed by OpenFast, open-source program by NREL. Though the OpenFAST analysis for coupled motion takes less than 1.5 h for 3-hour simulation in typical personal computer system, present time domain structural analysis takes less than 30 minutes in typical windows-based multi-core personal computer for 45 000 structural finite elements. At the design refinement stage, the limited number of elements in the critical area identified in the previous refinement stage is considered generally. In this case, the computation time for time domain structural analysis can be drastically reduced. As an example, it is found that present time domain structural analysis for the 400 elements takes less than 30 seconds for each DLCs.

Figures 8 to 9 show the results of ultimate strength assessment based on extreme VM stresses for DLC 1.6 and DLC 6.1 using full-blowing time domain structural analyses.

In Figure 8(a), a snapshot of VM stress distribution over all substructure is shown. From all the BINs in DLC 1.6,

the extreme VM stresses is plotted in the Figure 8(b). From the contour plot, it is found that the extreme stress response occurs at 60° heading and rated wind speed (11 m/s).

In Figure 9, an extreme VM stress contour is shown for DLC 6.1 parking condition. Stress response at hotspot points is found from all the BINs corresponding DLC 6.1. The stress variation for each BINs (different heading) can be obtained as shown at each hotspot point such as corner pontoon, connection point of pontoon and column supporting tower, and tower connection. Additionally, governing environment can be found for the specific hotspot point.

Conventional structural analysis based on design wave

concept does not consider the fully coupled motion effect between floating substructure and wind turbine. Therefore, the critical environment and corresponding load pattern can be inaccurate. But in this time domain analysis based on full-blown coupled analysis, accurate results can be obtained for the structural assessment of a floating offshore wind turbine. With a short computation time, present time domain analysis methodology can provide the trend in the extreme stress distribution and critical environment condition as shown in Figure 8(b). Therefore, an improvement in structural design can be quickly achieved with far less uncertainties.

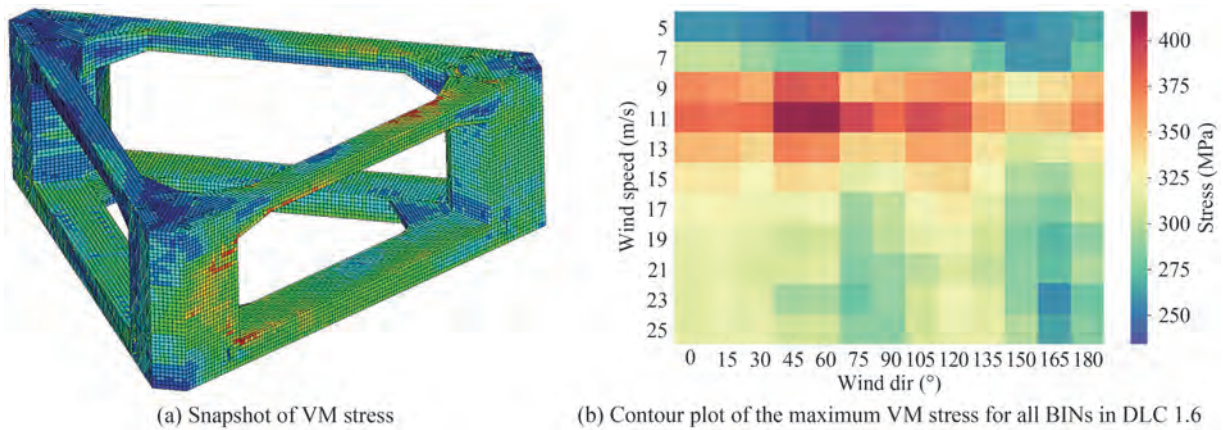


Figure 8 Contour plot of extreme VM stress for wind speeds and wind heading for DLC 1.6

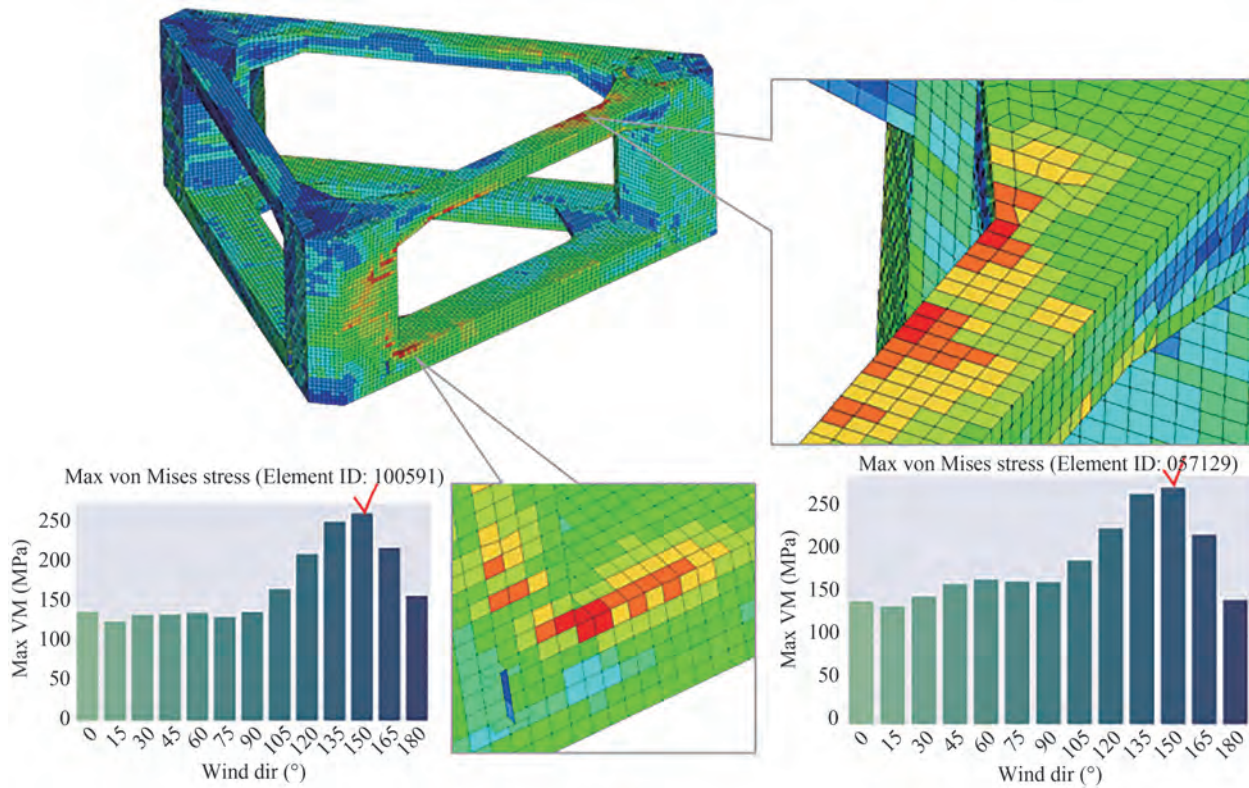


Figure 9 Extreme VM stress at hotspot points for different wind heading for DLC 6.1

For buckling assessment, buckling panels are generated using SeaTrust-HullScan, KR software, which can generate panels from finite elements model and visualize the buckling assessment results on each panel. The reference stresses of each generated buckling panel were calculated by interpolating stresses from the finite element elements in each panel. For each buckling panel, approximate buckling utilization factor is obtained based on the conservative buckling capacity \check{W}_u .

In time domain analysis, buckling utilization is computed at every time step and compared with the given approximate utilization factor. When an incidence of extreme utilization factor was detected for each buckling panel, the

screened critical buckling events is stored for the final assessment.

A snapshot of detected buckling incidence is shown in Figure 10(a). The snapshot event is based on the approximated buckling utilization factor. In final assessment using class tools such as HullScan/SeaTrust, the plate buckling capacity, overall stiffened panel capacity and ultimate buckling capacity were evaluated and reviewed through detail calculation sheets. Figure 10(b) shows result of final buckling assessment. Compared the screened results directly from time domain analysis Figure 10(a) and detail assessment based on snapshot using class tools, the utilization (named “Eta”) and stress multiplier factors (named “Gamma_c”) show a good agreement.

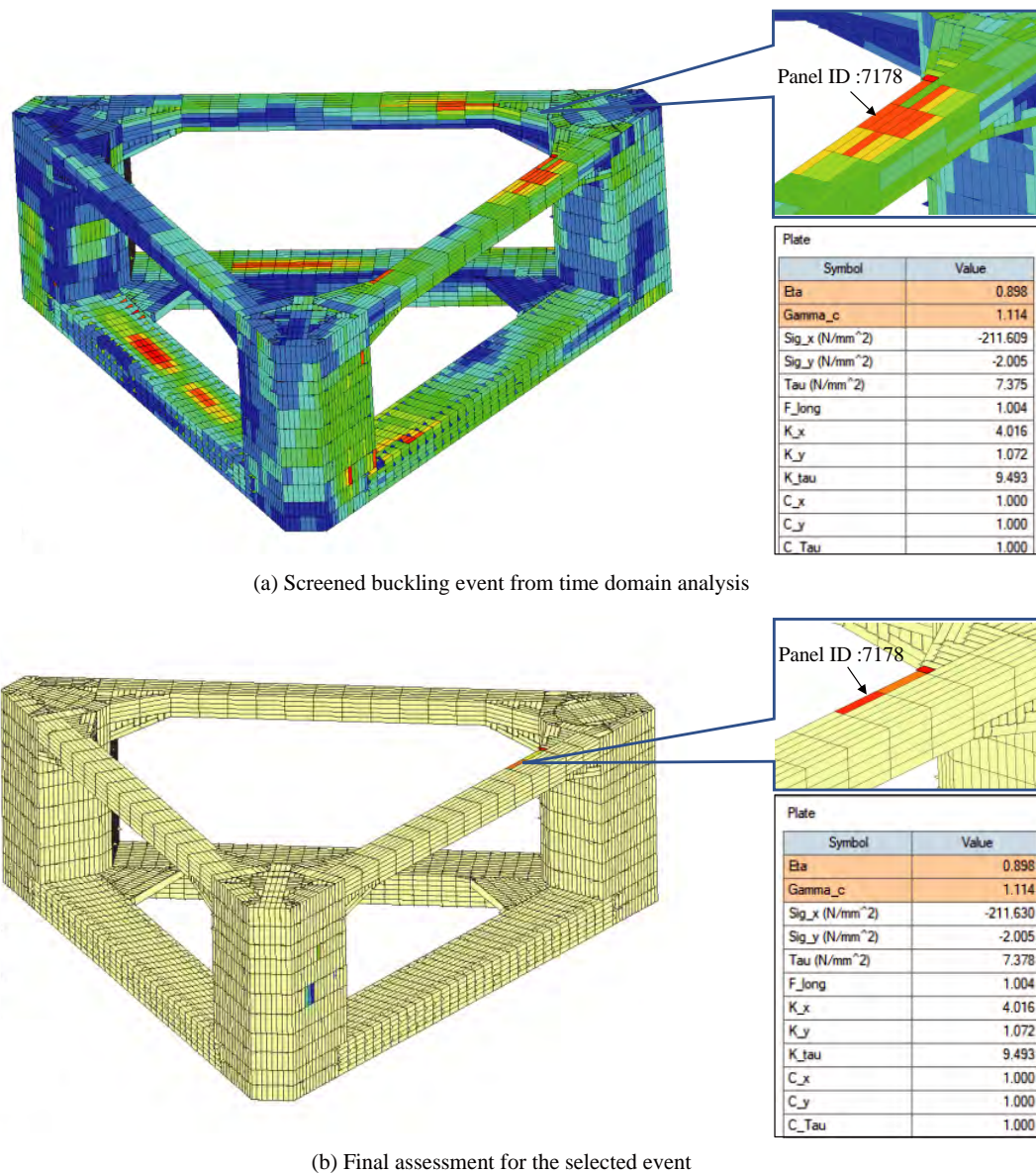


Figure 10 Buckling assessment and utilization factor for selected extreme snapshot

6 Conclusion

Present paper introduces an efficient and practical time domain structural analysis method for a floating wind turbine in extreme wind and wave environments. Based on local response concept, present method can produce the time history of stress components considering coupled effect between wind turbine in transient wind loading and floating structure in irregular wave loading. Due to high numerical efficiency, full-blown time domain structural analysis corresponding design load cases can be performed instantly. Through application to a 15-MW floating offshore wind turbine, it is demonstrated that structural strength and buckling assessment can be practically and accurately performed in time domain with utilizing class rule check software.

Nomenclature

DLC	Design load case
EDW	Equivalent design wave
EWM	Extreme wind speed model
FE	Finite element
FEA	Finite element analysis
FOWT	Floating offshore wind turbine
HPC	High performance computing
Hs	Significant wave height
IFFT	Inverse fast Fourier transform
KR	Korean Register
LC	Load case
NTM	Normal turbulence model
RAO	Response amplitude operator
PR	Principal stress
PSRS	Pseudo spectral response Synthesizer
Tp	Peak period
TRUST	Time-domain response-based ultimate structural analysis
VM	Von Mises stress

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