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Design Considerations for Offshore Wind Turbines in US Waters - The American Way

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Abstract

This paper addresses unique design considerations for the support structure of an offshore wind turbine in US waters and how the Working Stress Design (WSD) approach can be applied. The Load and Resistance Factor Design (LRFD) criteria specified in IEC 61400-3 are primarily developed based on the experience from offshore wind turbines installed in European coastal areas. Due to the higher variability of the wind and wave climate in hurricane-prone areas, offshore wind turbines in US waters would not achieve the same level of safety as those in European waters if the existing IEC design criteria were applied. To address this, a set of acceptance criteria, accounting for the unique design consideration related to tropical storms, has been developed and are published in the ABS *Guide for Building and Classing Offshore Wind Turbine Installations.* Extensive calibrations have been carried out to verify the adequacy of design load conditions and structural design requirements of the ABS WSD-based design criteria. Metocean conditions in the US Gulf of Mexico (GoM) and East Coast were used in the calibrations to calculate the aerodynamic and hydrodynamic loads as well as the structural responses of the typical designs of offshore wind turbines.

Introduction

The US offshore oil and gas industry has extensive experience with hydrocarbon-related offshore structures installed on the US Outer Continental Shelf (OCS). A series of Recommended Practices (RP) has been published through American Petroleum Institute (API) under its Subcommittee on Offshore Structures. The main document is API RP 2A-WSD [2], which provides a comprehensive basis for the design of offshore structures subjected to wave, wind, current and earthquake loading conditions on the US OCS. What is not included in API RP 2A-WSD, however, is the definition of environmental and load conditions that can account for unique response characteristics of offshore wind turbines.

Several design and certification guidelines have been developed primarily based on the experience from offshore wind turbines installed in European coastal areas. Of these guidelines, the International Electrotechnical Commission (IEC) 61400-3 *Wind turbines – Part 3: Design Requirements for Offshore Wind Turbines* [12] embodies the industry's state-of-the-art knowledge for offshore wind turbines. Although a framework to define the site-specific Class S wind turbines is included in IEC 61400-1 *Wind turbines – Part 1: Design Requirements* [11] and further referred to by IEC 61400-3, the applicability of IEC standards to the offshore areas subject to the risk of tropical storms remains unanswered. Further validations and possible modifications are important to determine to what extent the IEC61400-3 design criteria can be adopted for the US OCS.

A number of studies have been undertaken from various perspectives to examine the gaps between the existing offshore wind turbine design requirements and the common practices of designing hydrocarbon-related offshore structures deployed on the US OCS [4][14][15][16][18]. ABS recently reevaluated the design criteria in IEC 61400-3 for its development of ABS *Guide for Building and Classing Offshore Wind Turbine Installations* [1], which provides design guidelines for the support structures of bottom-founded offshore wind turbines. A new set of design acceptance criteria based on the WSD approach was specified in the ABS *Guide for Building and Classing Offshore Wind Turbine Installations*. Extensive calibration studies were carried out to verify the adequacy of design load conditions and structural design requirements of the ABS WSD-based criteria. This paper presents the development of these WSD-based acceptance criteria for the support structures of bottom-founded offshore wind turbines as well as part of the results of calibration studies.

Return Period of Extreme Storm Conditions

One of most debated topics on adapting the IEC 61400-3 design criteria for the US OCS is the return period of extreme storm conditions, i.e., 50-year as required by IEC 61400-3 versus 100-year commonly used for high consequence (L-1) hydrocarbon-related offshore structures. Instead of directing the discussion solely toward the return period of design environment conditions, a review of the overall design approach (i.e., 'design recipe') is imperative for developing rational design criteria for offshore wind turbines in US waters, where the impact of hurricanes has to be considered.

For a hydrocarbon-related offshore structure designed to well-established standards such as API RP 2A-WSD [2], the following items are important factors in determining its safety level:

- Prescribed safety factors in the design standard
- Return period of design environment conditions
- Load models of environmental and operational loading
- Strength and fatigue capacity models of materials, structural members and joints and foundation elements
- Statistical variation of environmental conditions at the site where the offshore structure will be installed

In the design of a support structure of an offshore wind turbine, in addition to the above-listed items, the following items which are unique to offshore wind turbines will also affect the safety level of a turbine support structure:

- Wind load generated by aerodynamic response of turbine rotor – it can be a major, often dominant, part of base overturning moment. This is in contrast to the fixed hydrocarbon-related offshore structures where wind loads are normally due to the drag effect and affect mostly the design of local topside structures.
- Effects of turbine control and safety systems, which play a significant role in regulating the aerodynamic loads by adjusting blade pitch angle and yawing angle between rotor rotating plane and wind direction. The loads generated by a turbine in the power production mode can potentially be higher than those inflicted by design storm wind and wave when the same wind turbine is in parked condition (standstill or idling). The definition of "Operating" and "Extreme" design conditions in API RP 2A-WSD is therefore not directly applicable to offshore wind turbines.
- With the change to load modeling and the effect of wind turbines control and safety system, the slope of global loads (base shear and overturning moment) versus return period curve is different than those that are normally perceived in the design of hydrocarbon-related offshore structures. Applying the same design approach valid for hydrocarbon-related offshore structures to offshore wind turbines will not result in the anticipated safety level.

The design criteria specified in IEC 61400-3 are mainly developed and calibrated based on the environmental conditions and load combinations for offshore wind turbines installed in European coastal areas, where the variation (not magnitude) of environmental conditions is relatively small [7][17][18]. Assuming the return period is still 50 years for the extreme storm condition and the turbine support structure is targeted to be designed to the same safety level as those in Europe, Clausen, et al. [5][6] indicates that the load factor of the LRFD-based criteria in IEC61400-1 needs to be increased by approximately 25% to 50% for the regions subject to typhoons in the Philippines. Garciano and Koike [7], on the other hand, propose to increase the resistance factor by as much as 74% for those turbine support structures designed for surviving typhoon winds while maintaining the same IEC load factor and 50-year return extreme storm condition. Note that although these studies were conducted for land-based wind turbines, the conclusions illustrate the approximate magnitude of the increase in safety factors that may be needed to reach the same safety level as that of wind turbines designed to IEC 61400 in Europe.

In order to account for the effect of the environmental conditions in the hurricane-prone US waters, where the variation and, therefore, uncertainty of environmental conditions are much higher than those implied in the IEC 61400-3, the design requirement for the support structure of an offshore wind turbine has to be increased [5][14][16]. This increased design requirement may be achieved by requiring a higher return period, a larger load factor in the LRFD format or a larger factor of safety in the WSD format.

Conceptually, it is more appealing to use the same return period, i.e., 50 years, and increase the regional, or even site-dependent, load factors (LRFD) or factors of safety (WSD). The advantage of this approach is that the existing design criteria in IEC61400-3 can be mostly retained. However, the main difficulties of this approach are:

- To increase the regional load factors (LRFD) or factors of safety (WSD) to appropriate levels requires a significant amount of research to address the effect of the variation in regional environmental conditions, configurations of wind turbine support structure and foundation properties.

- The load factors in IEC 61400-3 are specified for the ‘normal’, ‘abnormal’ and ‘transportation/installation’ conditions, which are defined using the combination of turbine operational modes and external conditions. This adds another level of complexity to the exercise of defining and applying the adjusted safety factors.
- Applying a single safety factor for the entire US OCS would result in an over-stringent requirement to areas with less hurricane risk.

An alternative approach is to increase the return period of extreme design storm condition. Practically, this is a more straightforward approach to account for hurricane effects, which lead to high uncertainties in environmental loads. The calibration study performed during the development of the ABS *Guide for Building and Classing Offshore Wind Turbine Installations* shows that:

- The same IEC load factors in combination with the 100-year storm condition in the US GoM and East Coast areas can result in a design with the approximately same safety level as that of offshore wind turbine support structures designed to IEC61400-3 and the North Sea metocean conditions.
- Site variation of the probability of hurricane occurrence can be taken into account by requiring the site-specific 100-year return environmental conditions in the design such that there is no need to calibrate the regional safety factors.
- One disadvantage of this approach could be the fact that designing to 100-year storm condition is currently not considered as a common practice of turbine manufacturers. There is a possibility, however, that the existing IEC61400-1 Class S could be refined to cover the change of return period. Note further that the increase of load factor or safety factor as discussed above will also lead to the change of the turbine design requirements and, therefore, the definition of standard turbine classes in IEC 61400-1 even if the 50-year return period is retained.

Site-Specific Design

The definitions of environmental conditions and design load case for extreme storm conditions in IEC 61400-3 are associated with turbine’s Reference Wind Speed, V_{ref}. This appears to be a practice inherited from the land-based turbine tower design, where the tower is designed for a given turbine. By definition [11], V_{ref} is not necessary a site-specific design parameter unless the wind turbine belongs to a special site-specific class (Class S). The developer can select a serial manufactured turbine as long as it can meet the requirement of site conditions. An offshore wind turbine support structure (tripod, jacket, etc.) is therefore required to be designed to environmental conditions that likely exceed the actual site-specific conditions of a given return period. Using V_{ref} as a basis for the design of an offshore wind turbine support structure is to some extent equivalent to requiring the offshore support structure be designed for a serial manufactured wind turbine, which may result in an over-conservative design.

Instead of the turbine-specific design approach as implied in IEC 61400-1 [11] for land-based wind turbines and adopted in IEC 61400-3 [12] for offshore wind turbines, the design load cases (DLCs) specified in the ABS *Guide for Building and Classing Offshore Wind Turbine Installations* follow the site-specific design approach so as to allow for a more optimized design. V_{ref} is replaced by a site-specific mean wind speed at turbine’s hub height with 10-minute averaging time duration.

Design Load Cases (DLCs)

The DLCs required in the ABS *Guide for Building and Classing Offshore Wind Turbine Installations* are generally in agreement with those defined in “Table 1 – Design load cases” of IEC 61400-3 [12], while a number of modifications are made to account for such changes as the return period of extreme storm, site-specific design approach, yaw misalignment, etc. As a minimum design requirement, there are a total of seven DLCs specified for the fatigue design and 26 DLCs for the strength design. The DLCs for strength design of an offshore wind turbine are further divided into three categories

- N - Normal design conditions are expected to occur frequently during the lifetime of an offshore wind turbine. The corresponding operational mode of the turbine is in a normal state or with minor faults or abnormalities.
- A - Abnormal design conditions are less likely to occur than normal design conditions. They usually correspond to design conditions with severe faults that result in activation of system protection functions.
- T - Transport, assembly onsite, maintenance and repair conditions that are to be defined by the manufacturer or operator.

The type of design conditions, N, A or T, determines the safety factor to be applied in the structural strength design.

As an example, Table 1 is adapted from the ABS *Guide for Building and Classing Offshore Wind Turbine Installations* for the strength design under the extreme storm (DLC 6.2a, b).

Table 1: ABS Design Load Cases for the Strength Design under Extreme Storm Conditions (Turbine is in Abnormal Condition)

Wind Condition	Waves	Wind & Wave Directionality	Sea Currents	Water Level	Yaw Control	Safety Factor
Extreme turbulent wind model $V_{hub} = V_{10min,100\text{-}yr}$	100-year return significant wave height	1. Colinear 2. Wind/Wave misalignment	100-year Currents	100-year Water Level	Yaw misalignment $-180^0 \leq \varphi < 180^0$	Abnormal Condition
Extreme steady wind model $V(z_{hub}) = V_{3sec,100\text{-}yr}$	Reduced 100-year return maximum wave height	1. Colinear 2. Wind/Wave misalignment	100-year Currents	100-year Water Level	Yaw misalignment $-180^0 \leq \varphi < 180^0$	Abnormal Condition

Notes:

1. V_{hub} and $V(z_{hub})$ are the mean wind speed and steady wind speed at hub height, respectively.
2. $V_{10min,100\text{-}yr}$ is the 100-year return 10-minute average wind speed at hub height.
3. $V_{3sec,100\text{-}yr}$ is the 100-year return 3-second average wind speed at hub height.

As indicated in the calibration study, yaw misalignment could lead to significant overload in the turbine support structure. The DLCs specified in the ABS *Guide for Building and Classing Offshore Wind Turbine Installations* for the extreme storm conditions expanded the requirement of considering the effects of yaw misalignment, which may occur on various occasions such as:

- Fault in yaw control system
- Loss of grid connection and lack of sufficient back-up battery power supply
- Rapid change of wind direction

An offshore wind turbine typically has two or three pitch-controlled blades that can be feathered during storm conditions to minimize the aerodynamic loads. Since the pitch control for each blade operates independently, the possibility of having failure in all pitch controllers is very low. The direct consequence of malfunction of pitch angle control is over-speeding of rotor under strong wind that can cause damage to the turbine blades and power drive train before leading to overload in the turbine support structure. As a result, failure of blade pitch control is normally not considered for the design of turbine support structure and thus not included in the DLCs.

Strength and Fatigue Design Criteria

A WSD-based design approach is provided in the ABS *Guide for Building and Classing Offshore Wind Turbine Installations* for the bottom-founded support structure of an offshore wind turbine. The factors of safety in strength design criteria are applied in conjunction with the type of turbine operational conditions, N, A and T, as described above. In summary, the computed stresses in steel structures are not to exceed the allowable stress as obtained from the following equation:

$$F_{alloable} = F_{cr} / F.S. \qquad (1)$$

where

$F_{allowable}$ = allowable stress

F_{cr} = strength capacity

- specified minimum yield strength for a structural member subject to axial tension
- critical buckling strength of a structural member subject to axial compression
- critical bending strength of a structural member subject to bending moment

$F.S.$ = factor of safety

- $1.5/\psi$ for the Normal (N) conditions
- $1.25/\psi$ for the Abnormal (A) conditions
- $1.67/\psi$ for the design load conditions (T) involving transport, assembly on site, maintenance and repair

ψ = adjustment factor (see Section 1 of the ABS *Guide for Buckling and Ultimate Strength Assessment for Offshore Structures* [2] for more details)

- 1.0 for axial tension or bending
- $0.87 \leq \psi \leq 1.0$ for axial compression (column buckling or torsional buckling)
- $0.833 \leq \psi \leq 1.0$ for compression (local buckling of tubular members)

The design of structural members subject to combined axial tension/compression and bending should use the strength capacity model specified in the ABS *Guide for Buckling and Ultimate Strength Assessment for Offshore Structures* [2] in conjunction with the safety factors as defined above.

For the fatigue design criteria for steel structures, the Fatigue Design Factors (FDFs) shown in Table 2 are specified in the ABS *Guide for Building and Classing Offshore Wind Turbine Installations.* The fatigue design requirement is approximately in agreement with that in API RP 2A-WSD for the L-2 medium consequence fixed offshore platforms.

Table 2: Safety Factors for Fatigue Life of Structures (Fatigue Design Factors)

Importance	Inspectable and Repairable	
	Yes	*No*
Non-Critical	1	3
Critical	3	5

Notes:
1. "Critical" indicates that failure of these structural items would result in the rapid loss of structural integrity and produce an event of unacceptable consequence.
2. A Fatigue Design Factor of 1.0 is applicable to inspectable and repairable non-critical structural members above the splash zone and diver or ROV inspectable and repairable redundant framing
3. For the turbine tower structure installed above the splash zone, a Fatigue Design Factor of 2 may be applied provided that the tower structure is inspected at times of anticipated scheduled survey or when structural damage is suspected such that critical crack development can be detected and repaired.

Comparison of IEC and ABS Design Criteria Using Nominal Reliability Analyses

Nominal reliability analyses were performed to evaluate the level of safety of the WSD-based design criteria specified in the ABS *Guide for Building and Classing Offshore Wind Turbine Installations*. The results presented in this paper are for the extreme storm design load case with the turbine under normal and abnormal conditions.

The limit state equations shown in Eq.(2)-(5) are derived based on Tarp-Johansen's model [17], which has been used in a number of comparative studies of different design standards [4][5][15][18]. These limit state equations are developed for the action of a global load (base shear or bending of turbine support structure) generated by a single source (wind or wave). It is further assumed that uncertainties from aerodynamic and hydrodynamic loads are predominant.

For wind loads:

ABS: $$g(x) = F.S.\,\tilde{F}_y X_m - \left(\tilde{V}_{ABS}\right)^2 X_v \frac{1 + X_{dyn} T}{2} \tag{2}$$

IEC: $$g(x) = \gamma_m \tilde{F}_y X_m - \frac{\left(\tilde{V}_{IEC}\right)^2}{\gamma_f} X_v \frac{1 + X_{dyn} T}{2} \tag{3}$$

For wave loads:

ABS: $$g(x) = F.S.\,\tilde{F}_y X_m - \left(\tilde{H}_{ABS}\right)^2 X_h \tag{4}$$

IEC: $$g(x) = \gamma_m \tilde{F}_y X_m - \frac{\left(\tilde{H}_{IEC}\right)^2}{\gamma_f} X_h \tag{5}$$

The ABS and IEC safety factors in the above limit state functions are defined in Table 3, where the material factors are obtained from ISO 19902 [13] as recommended by IEC 61400-3. Definitions of the random variables in the above limit state functions are provided in Table 4, which is adapted from the previous studies [5][17][18].

Table 5 lists the distributions of metocean parameters used in the reliability analyses. The regional metocean data for the North Sea, US GoM and East Coast as well as the site-specific conditions in Massachusetts and Texas offshore were applied. Coefficients of variation (COVs) for the North Sea and US GoM are defined according to [5] and [15]. For the US East Coast, ABS acquired a gridded wind map derived using the National Oceanic and Atmospheric Administration (NOAA) historical hurricane database covering about 30 miles offshore. The exceedance probability curves for wind, wave, current and surge occurrence were calculated for four regions along the entire US East Coastal areas, divided based on the similarity of hurricane risk (see Figure 1 for an example). Those empirical regional exceedance probability curves were used to determine the distributions of metocean parameters for Atlantic 1-4 regions as summarized in Table 5. The site-specific metocean conditions in Massachusetts and Texas offshore are based on the site assessment results presented in [15]

The reliability index β for each limit state equation was calculated using the FORM analysis and verified by the SORM analysis and Monte Carlo simulation. The results for extreme storm conditions are summarized in Figure 2 for the wind turbine under the normal design condition and Figure 3 for the wind turbine under the abnormal design condition.

Table 3: Safety Factors for ABS and IEC/ISO Design Criteria

Load Type	ABS		IEC 61400-3 / ISO 19902			
	Normal	Abnormal	Normal		Abnormal	
	F.S.	*F.S.*	γ_m	γ_f	γ_m	γ_f
Bending	1.50	1.25	1.05	1.35	1.05	1.10

Notes:

1. As recommended by IEC 61400-3, the partial safety factors γ_m are obtained from ISO 19902 [13]. The dependence of γ_m on D/t is not taken into account.

Table 4: Definitions of Random Variables

Variable	Definition	Distribution	COV	Characteristic Value
$\widetilde{F}_y$	Normalized critical bending strength	Lognormal	5%	5-percentile value 1.13
X_m	Model uncertainty of material strength (resistance)	Lognormal	8.5%	Mean value 1.11
$\widetilde{V}_{ABS}$	Normalized Annual maximum wind speed (100-year return)	Gumbel	See Table 5	99-percentile value 1.0
$\widetilde{V}_{IEC}$	Normalized Annual maximum wind speed (50-year return)	Gumbel	See Table 5	98-percentile value 1.0
X_v	Model uncertainty of aerodynamic load	Lognormal	10%	Mean value 1.0
X_{dyn}	Model uncertainty for dynamic response to turbulent wind	Lognormal	5%	Mean value 1.0
T	Normalized response to turbulent wind	Gumbel	10%	Mean value 1.0
$\widetilde{H}_{ABS}$	Normalized Annual maximum wave height (100-year return)	Gumbel	See Table 5	99-percentile value 1.0
$\widetilde{H}_{IEC}$	Normalized Annual maximum wave height (50-year return)	Gumbel	See Table 5	98-percentile value 1.0
X_h	Model uncertainty of hydrodynamic load	Lognormal	10%	Mean value 1.0

Table 5: Coefficients of Variation (COVs) for Wind and Wave Parameters

Location	COV of Normalized Annual Maximum Wind Speed	COV of Normalized Annual Maximum Wave Height
North Sea	0.12	0.12
GoM	0.25	0.25
Atlantic 1	0.40	0.50
Atlantic 2	0.31	0.23
Atlantic 3	0.22	0.29
Atlantic 4	0.28	0.35
MA site-specific	0.40	0.45
TX site-specific	0.53	0.47

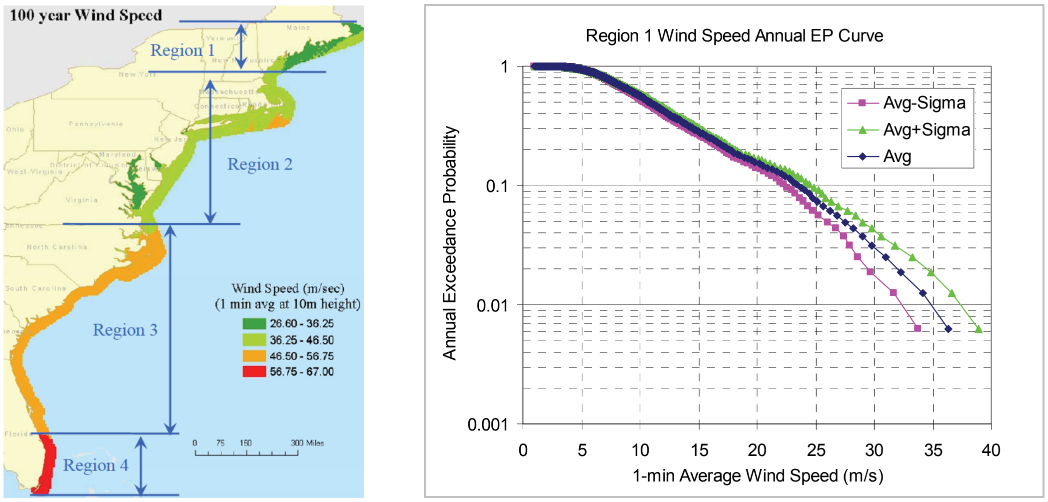


Figure 1: Regional Wind Conditions in the US Atlantic Coast

The results in Figure 2 and Figure 3 show that:

1. An offshore wind turbine support structure designed to the ABS WSD-based design criteria and the US metocean conditions can approximately reach the similar reliability level of the design based on IEC 61400-3 in the North Sea.
2. Applying IEC 61400-3 strength design criteria in combination with the US metocean conditions could result in a design with much lower reliability than what is anticipated from a design in European waters.
3. The conclusions drawn above assume that the design of turbine support structure is governed by the strength criteria. It is likely that other design considerations such as resonance avoidance and fatigue resistance may dominate and thus determine the actual structural reliability level.

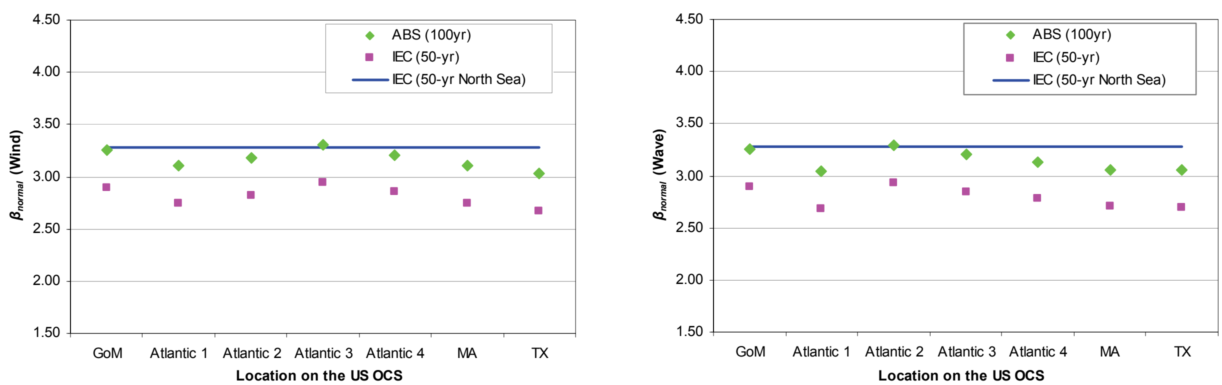


Figure 2: Reliability Index for Normal Conditions under Wind or Wave Loads

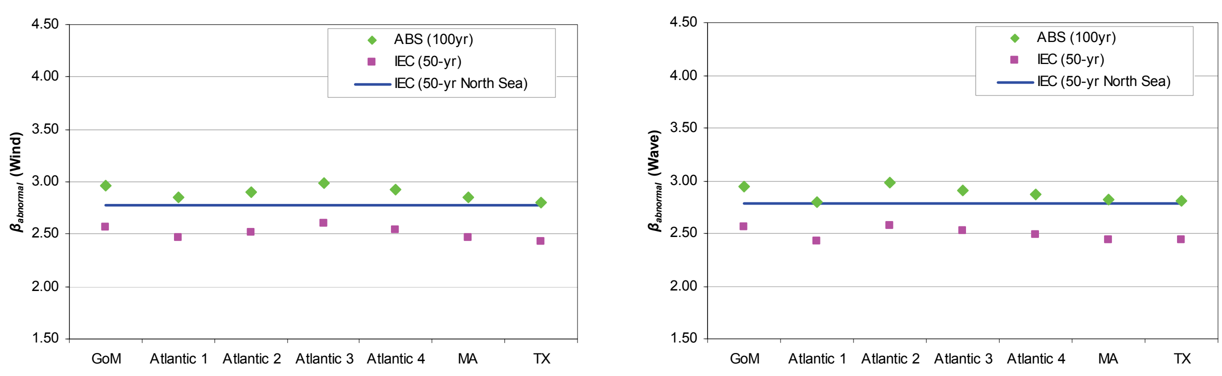


Figure 3: Reliability Index for Abnormal Conditions under Wind or Wave Loads

Calibration Results of Case Study Based on the Unity Check of Structural Members

The objective of this case study is to evaluate the adequacy of the overall ABS WSD-based design approach at the level of individual structural members. Twenty-two DLCs defined in the ABS *Guide for Building and Classing Offshore Wind Turbine Installations* for the strength design were evaluated. The results presented in this paper are a summary of the structural responses to the governing load case for the normal and abnormal design conditions. The analysis method used and major assumptions made in the case study are summarized as follows:

- Coupled aerodynamic and hydrodynamic load analyses were carried out using the FAST program developed by the National Renewable Energy Laboratory (NREL) [9]. As the modeling capability in the FAST program is currently limited to the monopile type of turbine support structure, an equivalent monopile emulating the first few natural frequencies and mode shapes as well as the wave drag and inertial loads of the actual tripod structure was derived for the load analysis using the FAST program. The schematic plot of the tripod and the main particulars of the equivalent monopile are shown in Figure 4.

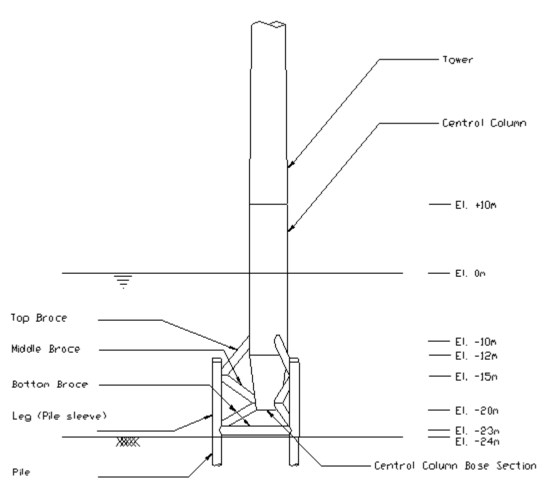
- The site-specific metocean conditions used in the case study are obtained through the site assessment at a Texas offshore site. The metocean data for the extreme storm conditions are obtained from [15] and listed in Table 6.

- The wind turbine selected for the case study is the NREL 5-MW baseline offshore wind turbine [10], which is a three-blade horizontal axis wind turbine. Note that both ABS *Guide for Building and Classing Offshore Wind Turbine Installations* and IEC 61400-3 are developed for horizontal axis wind turbines and may not be applicable to other turbine configurations.

- A conceptual design of tripod support structure originally developed in [15] was adapted with some modifications for the present case study. Since the two highest natural periods of the NREL 5-MW baseline offshore wind turbine are 5 and 3 seconds, respectively, the tripod support structure was designed to achieve the first natural period of 3.79 seconds in order to avoid the resonant response.

- Ten realizations were calculated in the load analysis for each DLC involving turbulent wind and stochastic wave conditions. The maximum base shear and overturning moment of the equivalent monopile were obtained from their time histories for each realization. The mean of these maxima were calculated over the 10 realizations and used in the subsequent structural finite element analysis of the tripod. For the DLCs defined by steady-state wind and regular wave conditions, only one simulation was performed as all the loads were deterministic.

- The structural analysis results were processed and presented in terms of unity check results. For the ABS WSD-based criteria, the unity check result is defined as the ratio of structural response times the factor of safety to the strength capacity. For the IEC LRFD-based criteria, the unity check result is defined as the ratio of the factored structural response to the factored strength capacity.



Equivalent monopile thickness (m)	0.06
Tower base outer diameter (m)	6
Tower base wall thickness (m)	0.03
Tower top outer diameter (m)	3.87
Tower top wall thickness (m)	0.02
Steel density (effective) (kg/m^3)	8500
Steel Young's modules (E) (MPa)	1.834×10^5
Steel shear modulus (G) (MPa)	7.055×10^4
Water Depth (m)	24
Height monopile extends above MSL (m)	10
Length of Tower+Monopile (m)	111.6
C_d	0.98
C_m	1.18
Structural fore-aft period (s)	3.79

Figure 4: Tripod Support Structure for the 5MW NREL Baseline Turbine and Its Equivalent FAST Input Data

Table 6: Site-Specific Metocean Conditions at a Texas Offshore Site (Water Depth = 24m)

Return Period	Ws (10m,1hr) (m/s)	Hs (m)	Tz (s)	Hmax (m)	Tmax (s)	Surge (m)	Current (m/s)
50-year	38.96	8.68	8.81	14.39	10.57	1.27	0.88
100-year	43.99	9.74	9.11	15.88	10.94	1.53	0.98

Figure 5 shows the comparison of unity check results for the DLC 6.1 (extreme storm conditions in combination with the normal design condition) and DLC 6.2 (extreme storm conditions in combination with the abnormal design condition). For the DLC 6.1, ±15 degrees of yaw misalignment was considered for the steady-state wind model and ±8 degrees for the turbulent wind model, as required by both ABS *Guide for Building and Classing Offshore Wind Turbine Installations* and IEC 61400-3. For the DLC 6.2, ±180 degrees of yaw misalignment was assumed. Figure 6 depicts the effect of yaw misalignment on the base overturning moment when the tripod support structure and wind turbine are subject to the 100-year return storm condition defined in Table 6. The following observations can be made from the analysis results:

1. When the difference in the return period of storm condition is removed, the unity check results obtained using ABS WSD-based design criteria ('ABS_50yr') are comparable to those obtained using IEC 61400-3 design criteria ('IEC_50yr'). This observation appears valid for both normal and abnormal design conditions. Note that the ABS *Guide for Building and Classing Offshore Wind Turbine Installations* requires using the 100-year return storm conditions. The reduced return period will be subject to special considerations. It can also be expected that for the regions with small statistical variations, i.e., small COVs, of metocean conditions, the effective difference between ABS and IEC design criteria becomes insignificant.

2. For the normal conditions (DLC 6.1), the unity check results obtained using the ABS 100-year WSD-based design criteria ('ABS_100yr') are higher than those based on IEC 61400-3. The level of difference, approximately 27% on average, is relatively higher than that observed in the previous JIP study [15], where the yaw misalignment, i.e., ±15 degrees for the steady-state wind model and ±8 degrees for the turbulent wind model, was not considered. Another source of difference may come from the strength capacity models defined in the ABS *Guide for Building and Classing Offshore Wind Turbine Installations* and API RP 2A-WSD, although the effect of this difference is considered insignificant. The observed load increase is roughly in agreement with the conclusion from Clausen, et al. [6], who suggested to increase the load factors for the normal condition from 1.35 to 1.7~2.0 for the regions subject to typhoons in the Philippines, assuming the return period is still 50 years for the design storm condition and the turbine is designed to the same safety level as in Europe.

3. For the abnormal conditions (DLC 6.2), the unity check results obtained using the ABS WSD-based 100-year design criteria ('ABS_100yr') are significantly higher than those based on IEC 61400-3. The magnitude of this relative increase in structural response due to the change of return period from 50-year to 10-year is approximately 60% as shown in Figure 5, which is in contrast to a typical 20%~30% increase for a hydrocarbon-related offshore structure designed to API RP 2A-WSD in the GoM. It appears the combined effect of strong hurricane wind and most unfavorable yaw misalignment could amplify the level of load increase. This observation can also be found from Figure 6, where the base overturning moment is increased by approximately 100% when the yaw misalignment is shifted from 0 degree to 40 degrees and the turbine is subject to the 100-year return conditions at a GoM offshore site. Such relative magnitude of load increase becomes less significant when the wind condition turns weaker.

4. For an optimized design based on the strength check results using IEC 50-year return conditions, the unity check results could be much closer to 1.0 than those (around 0.5) shown in Figure 5 for the abnormal condition (DLC 6.2). Since the aggregated safety margin for the abnormal condition is approximately 25% according to IEC 61400-3, a member of optimized support structure designed to 50-year return conditions as required by IEC 61400-3 may exceed the strength capacity after 60% of load increase under the 100-year return conditions, assuming the turbine blades are still intact during a 100-year storm. However, it is also likely that other considerations, such as resonance avoidance and fatigue resistance, may dominate the design such that the strength unity check result may be much lower than 1.0.

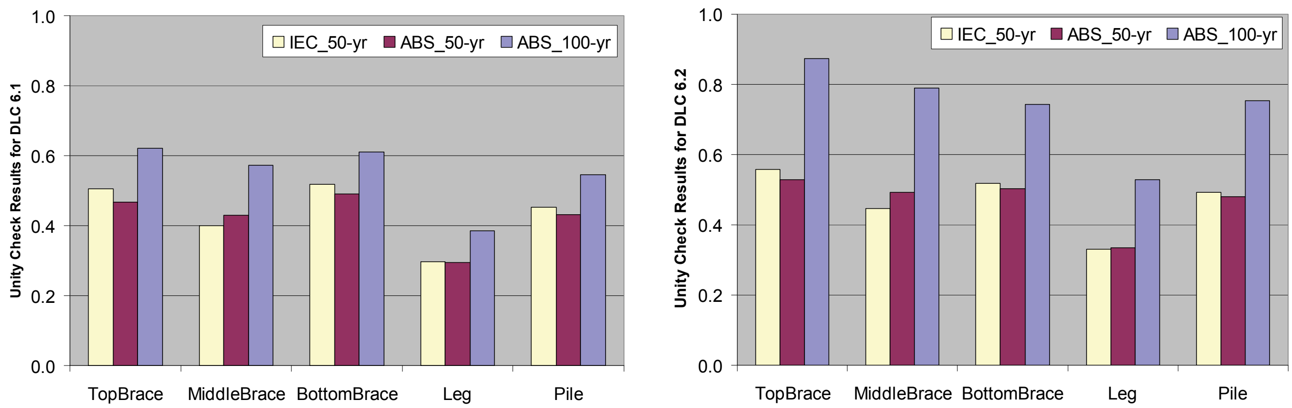


Figure 5: Strength Unity Check for the Extreme Storm DLCs with Normal (DLC 6.1) and Abnormal (DLC 6.2) Turbine Conditions

Figure 6: Effect of Yaw Misalignment under the 100-year Storm Conditions at a TX Offshore Site

Conclusions

To adequately design an offshore wind turbine support structure for the US OCS, the unique environmental conditions for the area have to be considered. The design criteria specified in IEC 61400-3 are not directly applicable to areas having tropical storms and the effects of the unique hurricane conditions in US waters require special considerations. A new set of design criteria has therefore been developed in the latest ABS *Guide for Building and Classing Offshore Wind Turbine Installations*. The experience from IEC 61400-3, which was calibrated to European offshore conditions, and the experience of designing hydrocarbon-related offshore structures in the US served as a starting point for this new development. One of the objectives of the ABS *Guide for Building and Classing Offshore Wind Turbine Installations* was to develop a design guideline that can result in a robust offshore wind turbine support structure in US waters that is at least as safe as those designed to IEC 61400-3 under European offshore conditions.

Extensive calibration studies, including reliability analyses and more detailed case studies, for the new design criteria have been carried out to verify the adequacy of the proposed design load cases and strength design criteria. Regional and site-specific metocean conditions in the US GoM and East Coast were applied in the calibration. Some unique responses of an offshore wind turbine to the strong hurricane wind conditions were observed. The results of calibration studies show that the new ABS design criteria can capture those unique responses and take them into account in the design.

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