Performance Levels and Fragility for Offshore Wind Turbine Support Structures during Extreme Events

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ABSTRACT

Successful development of the offshore wind energy resource depends upon the reliability of the structures that support the electricity-generating rotor-nacelle assemblies that form the core of a wind turbine system. The risk posed to offshore wind turbines (OWTs) by extreme environmental events such as Atlantic hurricanes requires a more detailed examination of post-elastic structural performance during events occurring at greater return periods than the design conditions. This paper focuses on the assessment of the fragility of OWTs with jacket-type support structures under extreme environmental loadings. Performance levels ranging from undamaged to near collapse of the jacket supported OWT are defined and are assessed using static pushover analysis of the support structure for given wind and wave conditions. A numerical example is presented based on an environmental hazard model for a site off the coast of the state of Massachusetts along the Atlantic coast of the U.S. Using probabilistic models for the structural demands and capacities, fragility curves are developed for two damage states. It is shown how such fragility curves can be convolved with estimates of the economic consequences associated with the various performance levels to develop a complete risk profile for the support structure.

KEYWORDS: offshore wind turbines, jacket, fragility, incremental wind-wave analysis, probabilistic models

INTRODUCTION

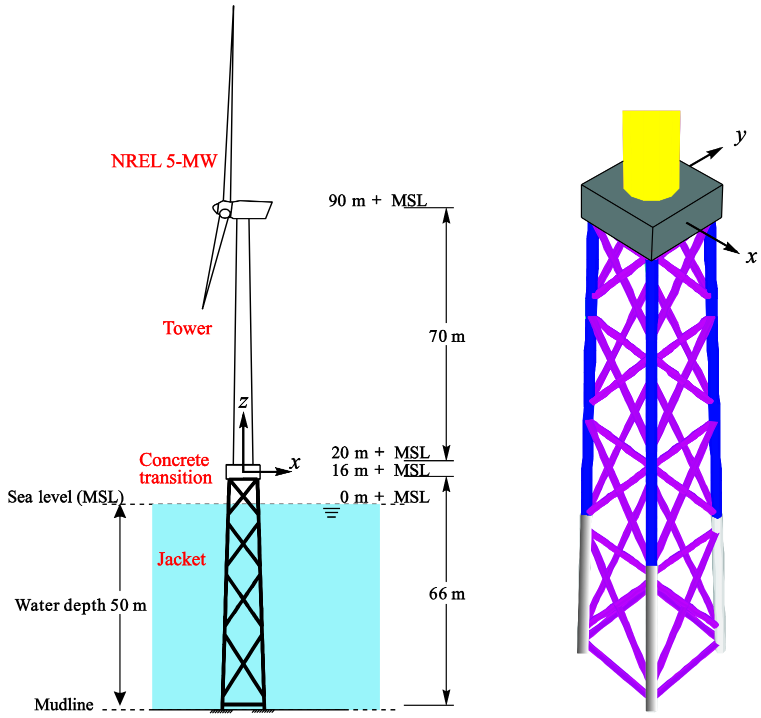
Development of offshore wind turbines (OWTs) is being aggressively pursued along the Atlantic coast of the U.S. because of the abundant wind resources, extensive available space for wind farm installation and proximity to major population centers (Manwell et al. 2002). Successful exploitation of the offshore wind energy resource depends upon the reliability of the structures that support the electricity-generating rotor-nacelle assemblies that form the core of a wind turbine system. Current design practice targets elastic response for conditions with mean return periods (MRPs) of 50 to 100 years multiplied by load factors (International Electrotechnical Commission 2009). However, the Atlantic coast provides designers of OWT support structures with additional challenges that are not commonly experienced: extreme wind and wave events induced by storms and hurricanes create significant loadings to the supporting structures at design return periods (Rose et al. 2012) and beyond. Therefore, a more detailed examination of post-elastic structural performance during events occurring at greater return periods than the design conditions is required for a full understanding of the risk posed to OWTs by extreme events. This paper presents a method for fragility analysis of OWT support structures under extreme wind and wave events. The fragility estimates are developed for two damage states that delimit three performance levels of the support structure. The obtained fragility curves present the probability of the OWT support structures reaching each of the limit states as a function of the MRP of extreme wind and wave event intensity. They provide many opportunities to bridge the gap between the risk of wind farm damage and the interests of engineers, decision makers, shareholders, etc.

Fragility analyses are commonly used in earthquake engineering as an essential tool for assessing the vulnerability of structures and offer a means of communicating the probability of damage over a range of potential loading intensities (Kafali and Grigoriu 2004; Kinali and Ellingwood 2007; Padgett and DesRoches 2008). Some research has been conducted on the assessment of the seismic fragility of wind turbines. Myers et al. (Myers et al. 2012) assessed the fragility of an 80m tall onshore wind turbine tower for the yielding damage state as a function of ground motion intensity and frequency content. Kim et al. (Kim et al. 2014) studied the seismic fragility of a 5MW monopile supported offshore wind turbine considering nonlinear soil-structure interaction. Inspired by seismic fragility analysis, Quilligan et al. (Quilligan et al. 2012) selected hub-height wind speed as the intensity measure and investigated the fragility of onshore wind towers as functions of materials, hub heights and wind speeds. Mardfekri and Gardoni (Mardfekri and Gardoni 2013) developed probabilistic demand models for the deformation, shear and moment demands on a OWT monopile subject to operational wind, wave and current loadings and assessed the fragility of OWT monopiles under these loadings as a function of wind speed or wave height. However, the fragility of jacket support structures under the combination of extreme wind and wave conditions has received less attention and yet remains important and challenging since proposed offshore installations are moving to deeper water and because jackets are more indeterminate than monopiles, and therefore have the potential for richer post-elastic performance.

To address the limitations of previous research, this paper focuses on the fragility of the jacket-type support structure of OWTs. A method for calculating fragility as a function of MRP of extreme events is proposed. In the framework, three performance levels are proposed: undamaged, damaged, and near collapse. Damage states utilized in this study include the first yielding and formation of a plastic mechanism. Probabilistic models for the wind and wave conditions are developed and response surfaces based on the authors' Incremental Wind-Wave Analysis (Wei et al. 2014) are used to define the capacity at the performance levels, with the added feature of uncertainty in structural material properties and demand at given wind speed and wave height. Monte Carlo simulation using such response surfaces is finally used to calculate the probability of damage across a range of MRPs.

OVERVIEW OF METHOD

General configurations and assumptions



(a) Dimensions of UpWind jacket (m)   (b) 3D view of jacket by colors of sections

Figure 1 Schematics of the jacket supported OWT structure

Several simplifying assumptions regarding the structural design and loading conditions are made to allow primary attention to be paid to the fragility of jacket supported OWTs to extreme loading. First, the jacket substructure is assumed to have four legs and be square in plan (Figure 1); second, the wind and wave loads are assumed to be approaching the jacket broadside without wind and wave misalignment; third, extreme wind and wave conditions are assumed to be independent and the independent wind and wave conditions at equivalent MRPs occur simultaneously, thereby condensing a vector measure of the conditions (e.g. at a minimum, wind speed and wave height) to a scalar measure (MRP); fourth, static nonlinear pushover analysis using plastic hinges with moment and axial force interaction is used to assess the nonlinear damage of the jacket neglecting dynamic effects.

Fragility analysis method

Fragility is the conditional probability of a damage measure (DM) attaining or exceeding a damage limit state for a given intensity measure (IM) of extreme environmental conditions. The conditional probability of failure can be evaluated by Eq. (1) (Mackie and Stojadinović 2007):

$$P_{f,i} = P[DM_i \mid EDP = edp]P[EDP = edp \mid IM = im] \quad (1)$$

where IM represents the intensity measure of the environmental action, DM_i refers to damage measure according to the i^{th} damage state and EDP is the engineering demand parameter. Lower case versions of these symbols represent values of the, generally random variables, IM and EDP. $P[DM_i \mid EDP = edp]$ is the probability that the structure reaches damage state i given the EDP value. The EDP value in turn comes from the IM, probabilistically, as $P[EDP = edp \mid IM = im]$. The fragility function is then obtained by calculating P_f for a convenient number of intensity values.

In this study, pushover analysis is used to map the intensity measure directly onto the damage state. Damages to all the structural members are treated equally. The base shear of jacket is the only EDP considered because it correlates well with jacket damage measures. $P[DM_i \mid EDP = edp] = P(C_i \le D \mid EDP = edp)$, where C_i is the capacity corresponding to the i^{th} damage state, D is the demand corresponding to the intensity measure. *IM* is defined as the MRP of the environmental conditions, which can be used to characterize the intensity measure of environmental wind and wave loadings simultaneously. The MRP is assumed to be uniquely and deterministically coupled to a pair of wind speed and wave height (Wei et al. 2014), simplifying the intensity measure from a vector (wind speed and wave height at least) to a scalar (MRP).

In principal, any method for estimating the wind and wave conditions at various MRPs can be used. In this paper, the independent probabilistic distribution of hub height mean wind speed W_s (MRP) and significant wave height H_s (MRP) is obtained by fitting a generalized extreme value (GEV) distribution to the annual maxima of measured wind speed and wave height (Valamanesh et al. 2013). Based on the developed model, related pair of hub height mean hourly wind speed and significant wave height are uniquely and deterministically coupled with arbitrary MRPs. The pushover analysis used here to assess damage takes as input the maximum, or extreme, 3 second wind gust at hub height and wave height that will occur during a one hour period of sustained conditions for the specified hub height mean hourly wind speed and significant wave height. The wave height and wind speed are taken as independent extremes and the independently estimated maxima are assumed to occur simultaneously. Probabilistic models for these extreme conditions are developed and used to sample random values of the extreme wind speed and wave height to be used in the pushover analysis.

Once these models have been developed, the following procedure is performed to complete the fragility analysis: (1) Select a series MRP_j; j = 1, . . . , n_{MRP} as the hazard IMs of interest; (2) For each MRP_j, the extreme wind speed, the extreme wave height and the material yield stress are treated as random variables, and n_s samples are generated by Monte Carlo simulation; (3) For each sample, the demand base shear and the base shear capacity corresponding to each damage state is computed with modifications to account for uncertainty in the material yield stress; (4) For each sample, compare the demand base shear and the damage state capacities to evaluate the damage measure for that sample; (5) Estimate the probability of attaining a given damage measure at a given intensity measure.

NUMERICAL EXAMPLE

Site description and structural model

This paper assesses the fragility of the NREL 5-MW OWT (Jonkman et al. 2009) with a jacket-type support structure installed in 50 m water depth and subject to extreme environmental loadings. The jacket design was made as part of the UpWind project of the European Union to serve as an open research and development tool (Vorpahl et al. 2011). As shown in Figure 1, the rotor-nacelle-assembly (RNA) has a total mass of 350,000 kg and the jacket consists of four legs, four levels of X-braces and cross braces. A rigid concrete block with a mass of 666,000 kg and plan dimensions of 4.0×9.6×9.6 m is positioned on top of the jacket as the transition piece or platform connecting the jacket with the tower of the turbine. The jacket is assumed to be rigidly fixed at the mudline. Fully interacting three dimensional axial force-bending moment plastic hinge models are assigned to the jacket members to simulate post-yield behavior in nonlinear pushover analyses to, in turn, estimate the damage state of the structure.

The site selected for study of the jacket supported OWT is off the coast of the state of Massachusetts, where National Oceanic and Atmospheric Administration (NOAA) data buoy 44008 is located (40.502° N 69.247° W). Water depth is 65.8 m though, in this study it is modified to 50 m to conform to the water depth for which the jacket structure was designed. Environmental conditions at the site are modeled based on 31 years of continuous wind and wave data collected hourly by the buoy. The probability models for wind and wave conditions are based on the annual maxima extracted from the historical database of the wind speed at 5m elevation and significant wave height. For both the wind speed and wave height a generalized extreme value (GEV) distribution is used and wind and wave conditions are treated as independent of one another. Hourly mean wind speed at 5 m elevation can be transferred to 10 min mean wind speed at hub height by a factor of 1.472 (Simiu 2011). Figure 2 shows the significant wave height H_s and 10 min hub height wind speed W_s obtained from the independent environmental wind and wave models for the Massachusetts site at selected MRPs. It should be noted that a greater degree of realism could be obtained in the hazard model by modeling dependent wind and wave conditions and incorporating information about hurricane effects through a stochastic catalog of hurricanes. Each of these topics is under current investigation by the authors. The approach shown here is included for illustrative purposes and because that the data used to construct the current model are readily available in the public domain.

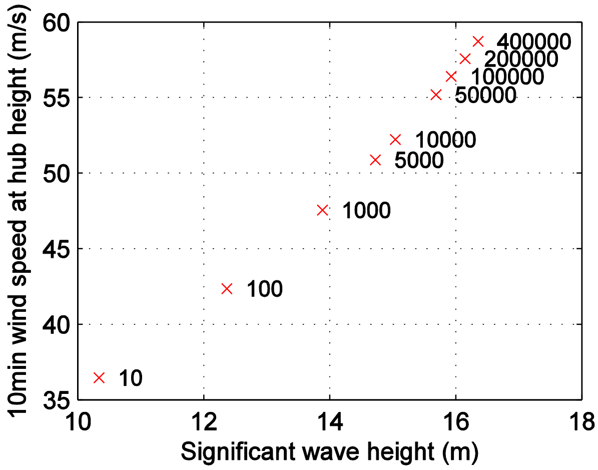


Figure 2 Significant wave height and 10min hub height wind speed for Massachusetts site at various MRPs

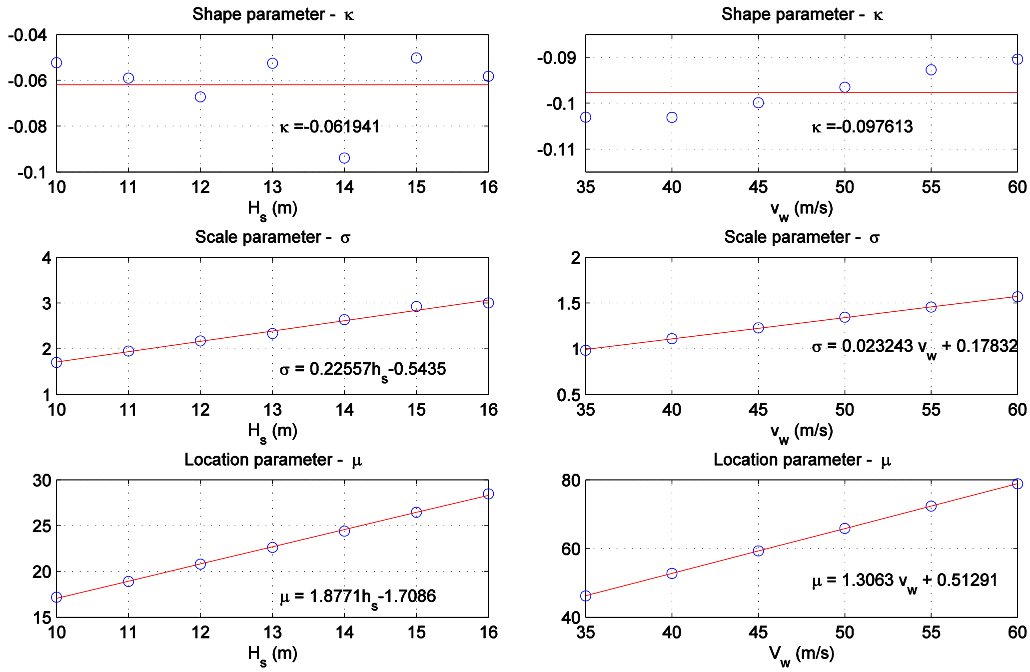
Proposed Probabilistic model of extreme wave height and extreme wind speed

In the static pushover analysis used here for damage state evaluation, the extreme wave is used to represent the maximum considerable loading that will occur at a given MRP. Since the NOAA data gives the significant wave height, and the GEV model gives a deterministic value of H_s at each MRP, a probabilistic mapping from H_s to the extreme wave H_e is required. To do so, 1000 samples of a one hour irregular wave train are generated using nonlinear-irregular wave modeling and JONSWAP spectrum for each value of H_s and the maximum wave height is extracted from each of these samples (Kim and Manuel 2012). A three-parameter GEV distribution (Martins and Stedinger 2000) is then fit to these extreme wave heights and used as the probabilistic model for the extreme wave height conditioned upon a value of the significant wave height. The wave period T for a chosen wave height in 50 m deep water can be obtained by Eq. (2), which is the lower bound of the wave period range suggested by IEC recommendation (International Electrotechnical Commission 2009):

$$T = 11.1\sqrt{H_s / g} \quad (2)$$

A similar procedure is used to model the extreme wind speed W_e, defined as the 3 second gust. 1000 samples of one hour turbulent wind histories for a range of 10 min hub height wind speeds are generated using the Kaimal spectrum (International Electrotechnical Commission 2005). The turbulence intensity for the Kaimal spectrum is set to be 10% (Lange et al. 2003), which is lower than over land according to measurements in the North Sea (Coelingh et al. 1992). Three parameters of GEV distribution for extreme wind speed are obtained by fitting the maximum wind speeds of 1000 wind histories for different 10 min wind speeds.

Figure 3 proposes the approximated estimation of three GEV parameters for extreme wave height and extreme wind speed. Figure 3(a) plots the shape parameter, scale parameter and location parameter as a function of significant wave height along with best fit linear regressions for the scale and location parameters. The shape parameter is assumed independent of significant wave height. The shape parameter, scale parameter and location parameter of GEV for extreme wind speed are presented in Figure 3(b) as a function of 10 min hub height wind speed with best fit linear regressions for the scale and location parameters. The shape parameter is constant.



(a) **GEV parameters: *κ*, *σ* and *μ* for extreme wave height**

(b) **GEV parameters: *κ*, *σ* and *μ* for extreme wind speed**

Figure 3 Proposed GEV probabilistic models for extreme wave height and extreme wind speed

Probabilistic model of structural material

The offshore jacket in this study is assumed to be made of ASTM A572 Grade 50 steel, of which the nominal yield strength is 345Mpa, with a coefficient of variation of 6% (Billingham et al. 2003). According to the DNV guideline for offshore structural reliability (Skjong et al. 1995), steel yielding strength is defined by the 5% quantile of test data and log-normal distributed. The mean of yielding strength following the assumption equals 381 MPa. Therefore, the variable of steel yielding stress F_y is modeled with a log-normal distribution with a mean of 381 MPa and a covariance of 0.06 (Skjong et al. 1995). The ultimate strength is deterministically related to the yield strength. A constant ratio of 0.67 is used as the yield to ultimate strength ratio (F_y/F_u), meaning that the material properties can be modeled with a single random variable, the yield stress F_y (API 2005). For example, when the variable of yield strength equals 380 MPa, the related tensile strength variable F_u = 380/0.67 = 570 MPa.

Definition of performance levels

Three performance levels of a jacket-type support structure are developed as illustrated in Figure 4: i) undamaged, in which all members remain elastic; ii) damaged, in which at least one member has reached its yield point through combined bending and axial effects; iii) near collapse, in which plastic mechanism has formed in the jacket. Two discrete damage states, which are used to delimit the performance levels, include damage initiation and ultimate strength in general. Damage states for this study are specified as first yield and formation of plastic mechanism. Non-structural damage states in the undamaged operational range, such as the blade failure, are not included.

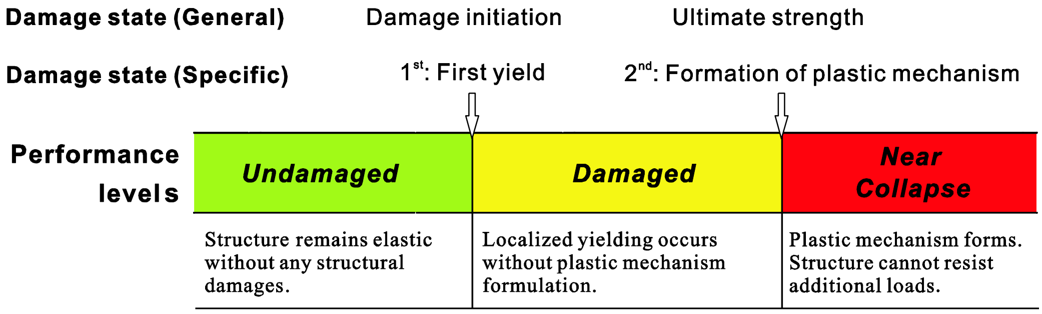


Figure 4 Proposed performance levels and corresponding damage states of an OWT jacket based on Pushover analysis

Prediction of demand

Given the values of H_e and W_e, the demand on the structure can be obtained. The aerodynamic forces on the OWT are determined with the aid of the computer-aided engineering tool FAST (Jonkman and Buhl Jr 2005). The aerodynamic loads on the rotor are calculated based on a steady wind with magnitude equal to W_e and the aerodynamic loads on the tower are calculated according to the recommendation of the DNV specification (Det Norske Veritas 2010). The wind speed is assumed to vary with height above sea level according to a power law with a wind shear exponent of 0.14. Hydrodynamic loads on the submerged part of the jacket are calculated by using a nonlinear stream function to compute water particle velocity and acceleration through the depth of the water column and Morison's equation to compute drag and inertial forces on the structural members. Wave force on the jacket is drag dominated due to the slender member dimensions, meaning that peak loads are achieved when the crest of the wave passes the structure.

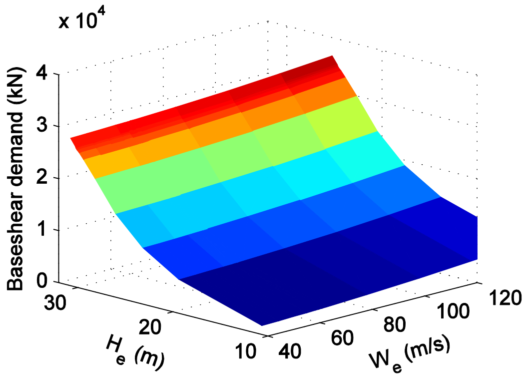
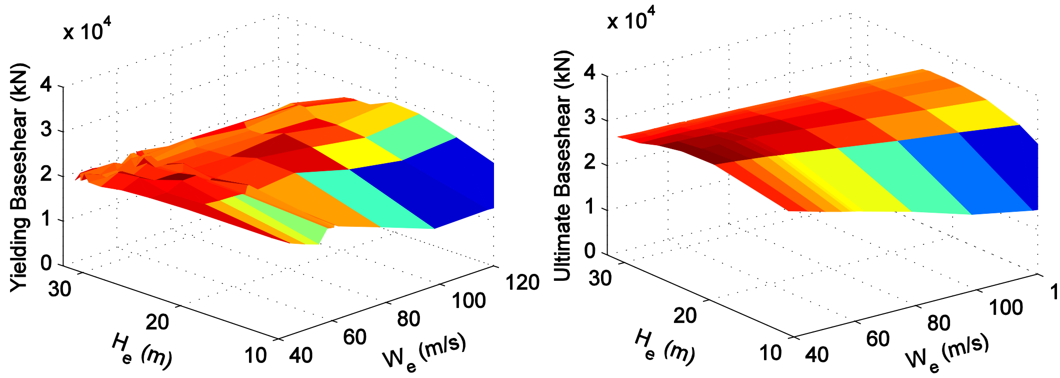


Figure 5 Demand surface for Massachusetts site as a function of W_e and H_e

For extreme environmental conditions when the wave height is such that the wave crest contacts the deck of the jacket, a Morison-type approach is used to calculate the so-called wave-in-deck force generated by this interaction (Wei et al. 2014). The summation of the lateral components of all above forces equals the demand base shear of the sample. Demand is function of H_e and W_e for a determined site and geometry of jacket supported OWT. Figure 5 plots the demand surface as a function of H_e and W_e. This demand surface is used in the following section to determine the demands for randomly samples of H_e and W_e without having to conduct a full aero- and hydrodynamic analysis.

Prediction of structural capacity

Once the yielding strength F_y, extreme wave height H_e and extreme wind speed W_e of each sample are drawn from their respective distributions, capacity of the 1st damage state C_1 (jacket base shear corresponding to the appearance of the 1st yielding hinge) and capacity of the 2nd damage state C_2 (jacket base shear corresponding to the formulation of plastic mechanism) must be determined for comparison to the demand and damage measures. This can be accomplished most directly by performing a pushover analyses for each sample. However, this approach is extremely time consuming and not economical for a Monte Carlo simulation with a large number of samples. To overcome this limitation, a simplified approach is proposed here to estimate the first yield and ultimate capacities on the basis of the IWWA2 surfaces for the jacket supported OWT using steel with the nominal yielding strength $f_{y,0}$ (Wei et al. 2014). IWWA2 surfaces give the first yield and ultimate capacity as functions of MRP(*We*) and MRP(*He*) through a series of pushover analyses. Since the IWWA2 surfaces are developed for a deterministic hazard model in which the MRP uniquely and deterministically specifies the wind speed and wave height, the IWWA2 surfaces can equally well be defined in terms of H_e and W_e directly. Capacity C_1 and C_2 as a function of H_e and W_e are given in Figure 6. However, the capacity results plotted in Figure 6 are only for yielding strength of $f_{y,0}$=345 MPa and since the fragility analysis presented here incorporates uncertainty in the material yield stress, a method is required for accounting for yield stress variation.



(a) Capacity C1: first yielding (b) Capacity C_2: plastic mechanism formation

Figure 6 Capacity surfaces as a function of We and He

The authors studied the first yield capacity C_1 and ultimate capacity C_2 as a function of material yield stress, with the material ultimate stress related deterministically to the yield stress as described previously. The linearization relationships are found over a range of yield stresses corresponding to roughly ±2 standard deviations. Moreover, the slope of the fitting line is almost independent of the load patterns, meaning that the IWWA2 surfaces can be scaled linearly with the yield stress. The formulations of these scaling relationships are:

$$C_1(f_y) = C_1(f_{y,0}) + 75(f_y - f_{y,0}) \tag{3}$$

$$C_2(f_y) = C_2(f_{y,0}) + 95(f_y - f_{y,0}) \tag{4}$$

in which $C_i(f_y)$, $i = 1, 2$, represents the yielding, ultimate capacity for a sample with arbitrary yielding strength of f_y, respectively; $C_i(f_{y,0})$, $i = 1, 2$, represents the yielding, ultimate capacity interpolated from capacity surface with nominal yielding strength of $f_{y,0}$, respectively. Note that Eq. (3) and (4) can be applied only when capacity is measured in kN and stress in MPa

RESULTS AND DISCUSSION

When demand base shear D and capacity base shear C_1 related to yielding damage states and C_2 related to plastic mechanism states are obtained for all the samples at the given MRP and corresponding values of the mean wind speed and significant wave height, the fragility with respect to the first yielding $P_{f,1}(mrp)$ and plastic mechanism $P_{f,2}(mrp)$ can be determined by Eq. (5) and (6),

$$P_{f,1}(MRP_j) = 1 - P[D < C_1 \mid IM = MRP_j] \tag{5}$$

$$P_{f,2}(MRP_j) = P[D \geq C_2 \mid IM = MRP_j] \tag{6}$$

Figure 7 shows the fragility estimates of the example jacket-supported OWT as a function of the MRP of extreme events based on n_s=1000 random samples at each of 9 discrete MRPs from 10 to 400,000 year. Two curves in Figure 7 show the fragilities associated with two damage states: first yielding and plastic mechanism. Fragilities for both states are affected by the intensity of extreme events. 40% of the jacket-type OWTs yield and 18% are near collapse during the event with a 10,000 year MRP. Under the loading of an event with a 100,000 year MRP, only 41% of the OWT jackets survive from repair.

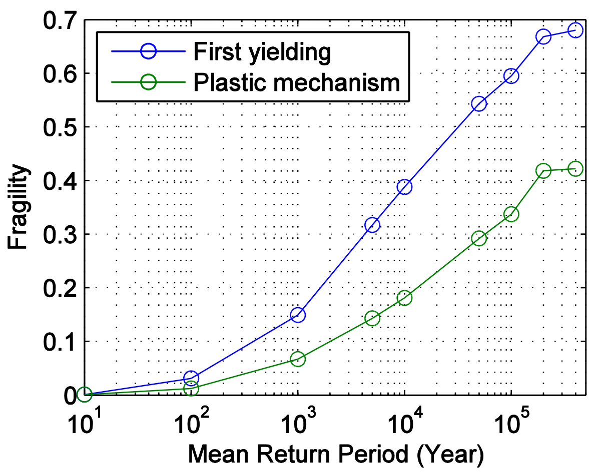


Figure 7 Fragility curves for two damage states of jacket supported OWT under extreme wind and wave loading

It is worth recalling at this point several of the assumptions and simplifications made in this analysis which act as qualification to Figure 7. (1) In attempting to estimate extreme wind speeds and wave heights from a limited duration of measurements of annual maxima, the severity of the conditions may be underestimated; (2) The independent combination of wind and wave annual maxima may overestimate the hazard; (3) Failure and damage modes other than member yielding are neglected; (4) Yield stress and ultimate stress are treated as perfectly correlated; (5) The jacket used here was designed for different conditions than prevail at the site investigated here; (6) Some modeling idealizations (fixed base, rigid joints, one-dimensional wave and regular wave kinematics, etc.) are adopted. These assumptions and simplifications affect the shape and magnitude of the fragility curves shown in Figure 7, however, they do not affect the framework by which these fragility curves were derived as a basis for risk assessment of jacket-supported OWTs. Refinements related to these assumptions and simplifications constitute the core of an ongoing research program to develop a total risk assessment strategy relevant to the financing and insuring of offshore wind farms. Future work will be determined based on the potential of specific refinements to affect fragility assessments like the example provided above.

CONCLUSION

In this study, a methodology for fragility analysis of offshore jacket structures intended to support wind turbines under extreme wind and wave loading events is presented for a Massachusetts site. The fragility curves for two damage states corresponding to three pre-defined performance levels were obtained from Monte Carlo simulations using response surfaces for the structural capacity subject to random wind and wave conditions and random material properties. The approach presented here can be used as part of a complete risk analysis of the offshore structure if models for the financial consequences of reaching various damage states are developed.

ACKNOWLEDGEMENT

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