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AN ASSESSMENT OF STRUCTURAL DESIGN GUIDELINES FOR OFFSHORE WIND TURBINES

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ABSTRACT

This paper addresses the need for U.S. standards to establish design requirements for offshore wind turbine support structures. There are wind power resources in U.S. waters that can be developed to generate substantial amounts of clean, renewable energy. While a number of offshore wind farms have been proposed for U.S. waters none have been built. The U.S. Minerals Management Service and the National Renewable Energy Laboratory have recently commissioned a study to compare and benchmark the International Electrotechnical Commission (IEC) design standards with the American Petroleum Institute (API) recommended practices.

Offshore wind farms that are operating in Europe have been designed using standards developed specifically for offshore wind, such as those developed by Germanischer Lloyd (GL) and Det Norske Veritas (DNV). The IEC has recently drafted design requirements specifically for offshore wind farms that provides a comprehensive definition of load conditions and references other standards, where needed, to provide a complete guidance document.

The intent of this paper is to examine the range of applicability of the various design standards and to assess how these standards apply to the design of U.S. offshore wind turbine (OWT) support structures.

INTRODUCTION

While the U.S. has a long history of on-shore wind power development, offshore wind power resources remain largely untapped. At the time of this publication, there are a few offshore wind farms proposed for U.S. waters but none has been constructed. Offshore wind represents a relatively new resource that can be developed with the use of today's very large, high efficiency, turbines (5 MW units are now in operation offshore).

The U.S. Minerals Management Service has been established as the lead regulatory authority for offshore wind power developments on the U.S. Outer Continental Shelf (OCS). This responsibility was established through the Energy Policy Act of 2005. There are currently no guidelines that have been accepted by the MMS or other U.S. agencies for the design of offshore wind power generators in U.S. waters. The codes and guidelines developed for offshore wind power development overseas have a limited history of use and have not been reviewed for their applicability to the conditions that exist on the U.S. OCS or for the levels of safety that would be required by the MMS and other U.S. agencies.

Substantial experience with land-based wind farms has provided the industry with the basis to understand complex wind loading and the associated design requirements for wind power generators, support structures, and foundations. The codes and guidelines that have been developed for the design of land-based wind turbine structures have been adapted to address issues associated with the marine environment. These additional requirements have focused primarily on the loads generated from waves and currents and the affect of these loads on the design of the support structure and its foundation.

The MMS has significant experience with the design, fabrication, and installation of offshore structures. As stated in the Code of Federal Regulations, the MMS utilizes the American Petroleum Institute (API) Recommended Practice for Planning, Designing, and Constructing Fixed Offshore Platforms (API RP-2A Working

Stress Design [1]) as the basis for regulating offshore structures in U.S. waters. This recommended practice is currently in its twenty-first edition, reflecting refinements based on the design of over 7,000 structures installed in the Gulf of Mexico, offshore Southern California, and in the Cook Inlet of Alaska. In addition to the application for oil and gas platforms located in U.S. federal waters, API RP-2A has been used for the design of numerous offshore platforms worldwide.

API RP-2A provides a basis for the design of offshore structures subject to wave, wind, current, and earthquake loading conditions; however, it does not address the scope and range of all conditions that are required for the design of wind turbine support structures. API RP-2A would have to be adapted or supplemented with other standards if it were to be used as the basis for wind turbine design.

Guidelines that have been developed for the design of offshore wind turbine generators such as IEC 61400-3 [2], have utilized offshore guidelines similar to API RP-2A as the basis for the development of their marine requirements. Guidelines such as IEC 61400-3 and API RP-2A may therefore include similar design requirements for wave and current loading conditions. However, a direct comparison of the IEC and API requirements show that there are some specific differences. The IEC uses a 50-year return period for the definition of extreme environmental design conditions. API RP-2A uses a 100-year return period for the definition of design conditions for high consequence platforms and includes three levels of design requirements based on the platform type and its failure consequence. While there are other differences in the guidelines that may offset these factors, a direct comparison of the safety levels generated with the use of these guidelines has yet to be completed.

A full comparison of the API and IEC guidelines needs to address the design methods, definition of loading, factors and safety, and so forth that set the levels of reliability inherent within each guideline. This comparison must evaluate the similarities and differences in the failure consequence for the types of facilities for which the guidelines were developed. Consequence issues should include life safety, environmental impact, reliable energy supply, and economic factors.

The IEC has established guidelines with the intent of providing levels of overall performance and safety for offshore wind farms that are equivalent to those of land-based wind farms. In establishing the requirements for the U.S., the MMS requires a level of overall performance and safety for any new offshore facility equal to or exceeding the reliability of facilities that are currently approved for service. For OWTs, the MMS must address the levels of performance and overall reliability that are consistent with current OCS facilities as well as meeting public needs.

This paper presents a framework for analysis and some initial findings from a comparison of different design guidelines' applicability to the design of offshore wind turbine support structures in U.S. waters. In this paper, we use the word guideline(s) and standard(s) interchangeably: these refer to the set of rules or recommended practices provided by the respective organizations for OWTG.

DEVELOPMENT OF GUIDELINES FOR OFFSHORE STRUCTURES

Design guidelines relevant to offshore wind turbines and other offshore structures have four main origins:

- Industry developments
- Governmental initiatives
- Classification societies
- International developments

The API series of standards and recommended practices have been developed with support from industry. The API currently maintains over 500 standards and recommended practices covering all segments of the oil and gas industry, including the design and construction of fixed base and floating offshore platforms. The U.S. Federal Government provides specific regulations for the exploration and production of oil and gas resources in US waters. The MMS as stated in the Code of Federal Regulations (CFR) refers to the API standards for the design of offshore platforms.

Government initiatives include a series of publications by the Department of Energy / Health and Safety Executive in the United Kingdom, Norwegian Petroleum Directorate (NMD) standards in Norway and the Danish Energy Authority (DEA) standards in Denmark.

Germanischer Lloyd (GL) and Det Norske Veritas (DNV) are two classification societies that have been active in developing design guidelines specifically for offshore wind turbines.

Relevant work within international standards organizations has included the development of new onshore and offshore wind turbine guidelines by the International Electrotechnical Commission (IEC) and the development and standardization of general offshore design guidance by the International Organization for Standardization (ISO).

American Petroleum Institute (API)

The API recommended practice for offshore platforms (API RP-2A Working Stress Design) was first compiled in 1969. Since its inception, RP-2A has undergone substantial expansion and refinement to meet industry's changing needs and in response to “lessons learned.” The recommended practice is in its 21st edition. The types of structures that have been designed using RP-2A range from major multi-level platforms installed in very deep water to minimal structures located in shallow water for the development of marginal fields. Structures that have been designed using API RP-2A are located in areas that are dominated by extreme storms, hurricanes, earthquakes, and ice. As such, API RP-2A provides a valuable experience base that can be used for the design of structures operating in harsh marine environments.

API RP-2A addresses all of the requirements for the design of offshore oil and gas platforms. It provides detailed guidance and design formulas for the development of forces and the calculation of individual component capacity (e.g., individual member strength in bending, tension, compression, buckling, and fatigue).

API RP-2A is specifically applicable to the design of offshore oil and gas platforms and as such, does not include provisions that have been developed specifically for offshore wind turbine support structures. RP-2A categorizes structures into three levels of exposure based on specific life safety and consequence of failure. These exposure categories may be used to define environmental design criteria.

While RP-2A does not include specific provisions for wind turbines, the guideline does include a wide array of technical information required for the design of offshore structures that are applicable to offshore wind turbine support structures. The guideline provides extensive environmental information on wind, wave, and currents on the U.S. OCS. It also provides extensive guidelines for pile, fabrication, installation, member design, and structural analysis.

International Electrotechnical Commission (IEC)

Technical Committee TC-88 of the International Electrotechnical Commission has compiled the international guidelines for wind turbines since 1988. TC-88 has a number of working groups, project teams, and maintenance teams that produce and revise the guidelines, technical reports (TR) and technical specifications (TS).

TC-88 developed IEC 61400, which is a series of guidelines specific to the design and assessment of wind turbines. IEC 61400 comprises ten guidelines, covering a range of topics from safety and design requirements to performance assessments of prototype turbines. Of these, 61400-1[3]: “Design Requirements” and 61400-3: “Design Requirements for Offshore Wind Turbines” contribute the most to the design process. It should be noted that IEC 61400-3 is under development within working group WG3 and is currently in draft form, not yet having completed all of the approval steps required to become an international guideline.

IEC 61400-3 specifies the requirements for the definition of site conditions and, together with IEC 61400-1, provides essential design requirements for offshore wind turbines. The guideline is intended to provide an appropriate level of protection against damage from all hazards during the planned lifetime of the structure. IEC 61400-3 is fully consistent with, but does not duplicate, the requirements of IEC 61400-1 (the IEC guideline for onshore wind turbine design). IEC specifies that these guidelines be used together.

IEC 61400-3 focuses on the engineering integrity of the structural components of an offshore wind turbine but also provides requirements for subsystems such as control and protection mechanisms, internal electrical systems, and mechanical systems. One of the most valuable aspects of IEC 61400-3 is the rigorous specification of design load cases that address all operating conditions in combination with applicable external loads.

IEC 61400-3 does not include component design requirements or a capacity formula. The guideline requires the use of other codes for these elements and makes specific reference to the ISO standards for component design as illustrated in Figure 1. The standard allows for the use of other industry design guidelines, such as GL, DNV, and API. Nonetheless, IEC specifies that when partial safety factors from national or international design codes are used together with partial safety factors from IEC 61400-3, the resulting safety level shall not be less than the intended safety level inherent in IEC 61400-3.

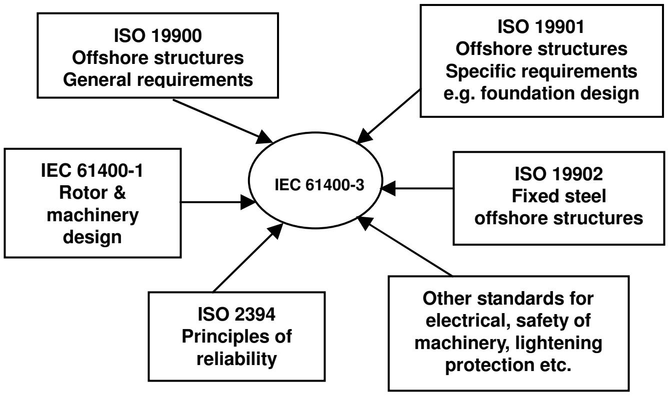

Figure 1: References to other standards in IEC 61400-3

Germanischer Lloyd (GL)

Certification of offshore wind turbines may be carried out by Germanischer Lloyd (GL) on the basis of the Guidelines for the Certification of Offshore Wind Turbines (Edition 2005) [4]. GL issued the first rules for offshore wind turbine design and certification of offshore wind turbines in 1995. The guideline was updated and republished in 1999, 2004, and 2005.

The 2005 edition of the GL guideline for the Certification of Offshore Wind Turbines provides a complete set of rules for the certification of offshore wind turbines and offshore wind farms. The guideline covers requirements for the support structure, turbine machinery, and blades.

The GL guidelines make reference to the “Guideline for the Certification of Wind Turbines” (Edition 2003 with supplement 2004) and the “Guideline for the Certification of Condition Monitoring Systems for Wind Turbines” (2003) for those topics that are not specific to offshore conditions but apply to the design of wind turbines in general. The GL includes normative references to the IEC and Deutsche Institut für Normung (DIN) guidelines. The GL references ISO standards and other Germanischer Lloyd Rules and Guidelines.

The philosophy behind the GL Wind Guideline for the Certification of Offshore Wind Turbines (COWT) is to provide a specification of requirements for the entire wind turbine design process. The COWT includes a clarification of certification extent, loads, materials, structures, machinery, rotor blades, electrical systems, safety systems, and condition monitoring systems.

The GL safety philosophy is derived from onshore turbine experience. The load factors are harmonized with IEC 61400-1/3 and the material factors are comparable but specified in greater detail than the IEC guidelines. IEC specifies material safety factors in a general manner, without consideration of the material uncertainties. The GL Wind Guideline specifies material safety factors depending on the material. For example, the material factors are higher for soil resistance than for steel as soil resistance can only be estimated with relatively high uncertainty.

Det Norske Veritas (DNV)

First published in 2004, the DNV offshore wind turbine guideline DNV-OS-J101 [5] provides principles, technical requirements, and guidance for design, construction, and in-service inspection of offshore wind turbine structures. The guideline may be used for the design of support structures and foundations of offshore wind turbines, as well as the design of support structures and foundations of other structures within an offshore wind farm, such as transformer stations and meteorological masts. Note that DNV-OS-J101 does not cover design of wind turbine components such as the nacelle, rotor, generator, and gearbox.

The DNV guideline may be used as a stand-alone document. For structural design of wind turbine components for which no DNV guidelines exists, reference is made to the IEC61400-1 guideline.

DNV-OS-J101 lists other DNV offshore structural design guidelines as normative references. Informative references are made to other DNV guidelines, i.e., American Institute of Steel Construction (AISC), API, British Standards (BS), DIN, Eurocode, IEC, ISO and Norsk Sokkels Konkuranseposisjon (NORSOK).

DNV makes the provision that when using non-DNV codes or standards; one must obtain the same safety level prescribed in DNV-OS-J101.

International Organization for Standardization (ISO)

Founded in 1947, the International Organization for Standardization (ISO) is a network of national standards organizations from 157 countries. ISO provides a worldwide framework for the development and international standardization of a wide range of standards, covering topics relevant to wide sectors of business, industry, and technology. As of August 2006, ISO had a portfolio of 16077 standards, ranging from standards for agriculture and construction, mechanical engineering, manufacturing and distribution, to transport, medical devices, information and communication technology, and services.

The ISO 19900 – 19909 series contains standards relevant to offshore technologies. While these standards do not specifically address offshore wind turbines, considerable guidance is given for the design of offshore structures [6] in general, particularly with regard to structural integrity.

Relevant ISO standards for offshore wind turbines include:

- ISO 2394: General principles on reliability of structures
- ISO 4354: Wind actions on structures
- ISO 19900: General requirements for offshore structures
- ISO 19901: Specific requirements for offshore structures
- ISO 19902: Fixed steel offshore structures
- ISO 19903: Fixed concrete offshore structures

Table 1 provides a summary of the various organizations' different guidelines for offshore wind turbine design.

Table 1: Comparison of provisions in various guidelines

Parameter	API	IEC	GL	DNV	ISO
Environmental conditions	✓				
Design load cases	✓	✓✓	✓✓	✓	✓
General guidance on offshore structural design	✓✓	✓	✓	✓	✓✓
Specific guidance on offshore wind turbine design		✓✓	✓✓	✓✓	
Ultimate limit state code checks	✓✓		✓✓	✓✓	✓✓
Fatigue limit state and serviceability limit state code checks	✓✓		✓✓	✓✓	✓✓
Project certification			✓✓	✓✓	

Key:✓ = some guidance given✓✓ = substantial guidance given

PROVISIONS FOR FATIGUE & EXTREME CONDITIONS IN GUIDELINES

An important distinction between offshore wind turbines and offshore structures used in oil and gas production is fatigue demand. Conventional oil and gas platforms are subject to cyclic loading primarily from waves; wind loads are typically ignored as a source of cyclic loading. The support structures for offshore wind turbine will experience wave-induced cyclic loads just like oil and gas structures. In addition, these structures will experience substantial cyclic loading due to wind load and rotor rotation. The relative significance of the wave and wind fatigue demand depends upon specific environmental conditions. Recent experience with European wind farms has shown that wind-induced fatigue is a primary design driver for offshore wind turbines in relatively mild ocean environments.

The design guidelines that address offshore wind turbine structures specifically (IEC, GL, and DNV) all provide detailed descriptions of the methods to calculate the fatigue loading environment. These methods address design load cases that represent normal operation and idling states of the turbine over a range of wind speeds and sea states. API provides detailed descriptions on fatigue analysis for wave environments and addresses specific provisions for the detailing of tubular connections.

API RP-2A specifies a return period of 100 years for environmental conditions such as wind, wave, and current on the design of offshore structures. Criteria are typically developed for 100-year wave heights with concurrent wind and current conditions; however, the recommended practice also includes provisions for defining the 100-year wind with concurrent wave and current. The ISO 19902 standard for fixed steel offshore structures also specifies a return period of extreme external conditions of 100 years.

Inherent in the IEC 61400-3 guideline is an assumed safety level for offshore wind turbines that is equal to the safety level for onshore wind turbines specified by IEC 61400-1. For design load cases that feature normal design situations (turbine operation or idling without faults), the extreme external conditions are specified with a return period of 50 years. In the case of an offshore wind turbine, wind and waves are important sources of loading and therefore the *combination* of extreme wind and wave conditions is specified such that the global extreme environmental action has a *combined* recurrent period of 50 years. For design situations that feature turbine faults (e.g., yaw and pitch errors), 1-year return external conditions are specified.

Both the GL and DNV guidelines adopt the basic assumption of a 50-year return period of extreme external conditions for ultimate load cases.

CASE STUDIES FOR RELIABILITY ANALYSIS

The levels of reliability resulting from the use of a particular code or standard can be compared through a side-by-side review of criteria. These comparisons may include, for example, the definition of environmental conditions (e.g., return period), factors of safety, and load and resistance factors. However, in comparing the codes in this way, one must make basic assumptions regarding both external conditions (e.g., load combinations) and internal response (e.g., modes of failure). The comparison of reliability defined by different standards for a system dominated by wave load and subject to pile axial failure will be different from that for a system dominated by wind and subject to fatigue. Also, one might conclude that two standards differ significantly in one area but then find that this difference is offset by other factors or does not affect real designs for most practical applications. An example is the comparison of two codes on the basis of extreme loading where the design of the structure is governed by dynamic response and fatigue. Therefore, a complete comparison of reliability requires realistic case studies to assess levels of reliability for a range of structure types and environmental conditions. In adopting this approach, one attempts to bound the range of reliability ratio over a broad spectrum of conditions.

COMPARISON OF INHERENT RELIABILITY

A straightforward way to compare inherent reliabilities of IEC 61400-3 and API RP-2A is to generate separate designs of a structure using each guideline and then assess and compare the respective reliabilities of the two designs. To provide a broad comparison of the two guidelines, this exercise would need to be repeated for a large number of structural types and environmental/load conditions. Therefore, a simpler approach is to compare the two guidelines without considering a specific design structure. This approach is possible by eliminating structure-dependent coefficients in the design or reliability formulations, as described below.

In general, performance criterion in design guidelines is defined in terms of load effects, e.g., stresses, internal forces, and deformations. However, statistical information is usually available in terms of load space, e.g., for wind velocity and wave height. The transformation from loads to load effects depends on the configuration and other properties of the structure. This transformation needs to be overcome in order to compare two guidelines without resorting to a specific structure.

For an elementary case where load and resistance are represented as normally distributed variables, the failure zone is shown in Figure 2. The normal inverse of the failure probability is the reliability index of the performance criterion.

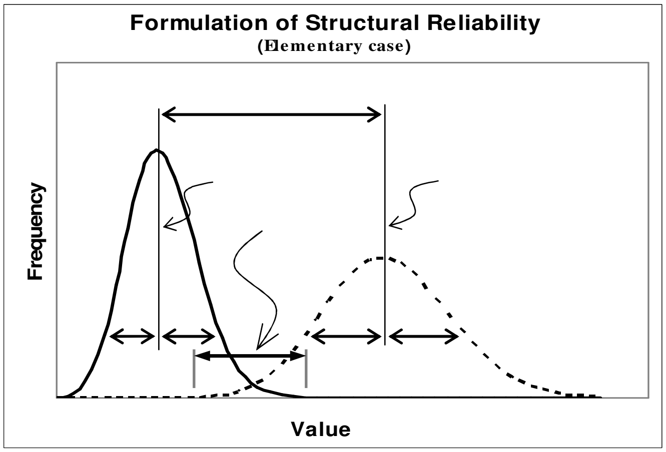

Figure 2: Representation of Load & Resistance Variables

We therefore assume the performance criterion in the guideline is specified in the form:

$$R_{code} - S_{code} = R_{code} - c\,L_{code} \geq 0 \qquad (1)$$

where R denotes capacity (or resistance), S denotes load effect, L denotes load, and c denotes an influence coefficient, which converts the load to the appropriate load effect. The subscript "code" is used to indicate that the capacity and load values are determined in accordance with the rules specified in the guideline. Assuming the performance criterion is satisfied at the limit, the inequality sign in the above expression is replaced with an equality sign, from which one can solve for the influence coefficient:

$$c = \frac{R_{code}}{L_{code}} \qquad (2)$$

For reliability analysis, a limit-state function $g(\mathbf{x})$ must be formulated so that $\{g(\mathbf{x}) \leq 0\}$ defines the failure event, with $\mathbf{x}$ denoting the random variables of the problem. In the present case, the limit state function can be written as:

$$\begin{aligned} g(R,L) &= R - cL \\ &= R_{code}\left(\frac{R}{R_{code}} - \frac{L}{L_{code}}\right) \end{aligned} \qquad (3)$$

where R and L now define the random capacity and load values. For any specifications of the distributions of R and L, and the code values R_{code} and L_{code}, the reliability of the design can be evaluated without resorting to a particular structure. Furthermore, since any positive scaling of the limit-state function does not alter the reliability, the above limit-state function can be simplified to read

$$g(R,L) = \frac{R}{R_{code}} - \frac{L}{L_{code}} \qquad (4)$$

This formulation is convenient as the random variables are normalized by their respective code values.

The API RP-2A (WSD) and IEC 61400-3 guidelines have two fundamental differences in specifying the code capacity and load values:

a) **Formats:** API specifies $R_{code} = SF \cdot R_n$ and $L_{code} = L_n$, where SF is a "allowable stress reduction factor" and R_n and L_n are nominal capacity and load values, whereas IEC specifies $R_{code} = R_c / \gamma_m$ and $L_{code} = \gamma_f L_c$, where γ_m is a "material factor," γ_f is a "partial load factor" and R_c and L_c are "characteristic" capacity and load values.

b) **Nominal and Characteristic Values:** In particular, for wind and wave loads, API specifies L_n as the 100-year value, whereas IEC specifies L_c as the 50-year value.

Using Equation (4), the limit-state functions for determining the inherent reliabilities of the two guidelines can be written as:

API: $$g(R,L) = \frac{R}{SF \cdot R_n} - \frac{L}{L_n} \qquad (5a)$$

IEC $$g(R,L) = \frac{\gamma_m R}{R_c} - \frac{L}{\gamma_f L_c} \qquad (5b)$$

The above formulation applies when a single load is acting, or when the loads have a combined effect, which is usually the case for wind and wave loads. The formulation needs to be expanded if additional loads, e.g., dead and live loads, are to be included. In the present case, these loads are expected to have negligible contributions and are not considered.

EXAMPLE APPLICATION

To illustrate the process and to provide an initial indication of the comparison of inherent reliability, this framework was applied to a simple offshore wind turbine problem. The example selected was the design of a typical monopile. It was assumed that the monopile would be controlled by bending at the mudline. Analyses were performed for wind and wave loadings as separate conditions. The turbine is assumed to be in an idle state. The detailed formulations presented by Tarp-Johansen [7, 8] were used to account for errors in modeling the capacity and load values.

Accordingly, the normalized capacity (R/R_n or R/R_c) in Equations 5(a) and (b) are replaced by $\tilde{F}_y X_m$, where $\tilde{F}_y$ is the ultimate bending capacity normalized by its nominal or characteristic value (here assumed to be identical) and X_m is a random variable representing the uncertainty in the capacity model. For extreme wind loading, the normalized load is replaced with $\tilde{P} X_a (1 + X_{dyn} T)/2$, where $\tilde{P}$ is the normalized annual maximum 10-minute mean wind pressure, X_a and X_{dyn} are model error terms and T is a random variable representing the turbulence effect. For drag-dominated wave loading, the normalized load is replaced with $\tilde{H}^2_{max} X_h$, where $\tilde{H}^2_{max}$ is the normalized annual maximum hydrodynamic load (based on a significant wave height determined for a 3-hour reference period) and X_h is a model error.

A brief description of the variables [7, 8] used in the analysis is given:

$\tilde{F}_y$ - lognormal distribution with 5% coefficient of variation (c.o.v.) and 1.13 as its 5-percentile value,
X_m - lognormal distribution with mean 1.11 and c.o.v. 8.5%.
X_a and X_{dyn} - lognormal distribution with both means equal to 1 and c.o.v.s equal to 0.10 and 0.05, respectively;
T - Gumbel distribution with mean 1 and c.o.v. equal 0.32;
$\tilde{P}$ - the Gumbel distribution with c.o.v. equal to 0.32 and a characteristic value equal to 1.
X_h - with mean equal to 1 and c.o.v. equal to 0.10,
$\tilde{H}^2_{max}$ - Gumbel distribution with a c.o.v. of 0.30 and a characteristic value equal to 1.

In this analysis, we assume the characteristic value of $\tilde{P}$ and $\tilde{H}^2_{max}$ correspond to the 99-percentile (100-year) value for the API and the 98-percentile (50-year) value for the IEC.

API specifies a variable allowable stress reduction (ASR) factor between 0.66 and 0.60 in bending for members with high D/t ratios. However, for the extreme load condition, API allows an increase of one-third in the ASR factor. Assuming an ASR of 0.66, the result is a net allowable bending stress of 0.88 x F_y. The IEC guideline specifies the partial material factor $\gamma_m = 1.05$ and, for the extreme load condition, the partial load factor $\gamma_f = 1.1$. The probability distributions for the random variables in the analysis are similar to those presented by Tarp-Johansen [7, 8]. However, there is one significant difference for the partial load factor: in our example, we use a partial load factor of 1.1 for abnormal conditions, whereas Tarp-Johansen [8] used a value of 1.35, which refers to normal conditions.

Reliability analyses were carried out with the above formulations of the limit-state function and assumed distributions. Table 2 lists the computed reliability indices for designs based on API and IEC guidelines under wind load and wave load alone, respectively. The computed reliability indices are based on the first-order reliability method (FORM) and are computed by use of the CalREL program [9]. Corresponding generalized reliability indices, computed using Monte Carlo simulation, are given in parentheses, and show that the FORM approximations are sufficiently accurate.

In the offshore wind turbine community, there has been extensive discussion on the 100-year storm condition design requirement. Table 2 shows the reliability indices for extreme wind and wave loads acting separately. From the results in the table, it can be seen that the β factors are higher for API when compared to IEC.

Table 2: Reliability indices for wind and wave loads

Code	Wind alone	Wave alone
API RP -2A (WSD)	3.35 (3.33)	3.38 (3.39)
IEC 61400-3 Ed.1	3.14 (3.10)	3.18 (3.20)

API & IEC COMPARISON FOR WIND PROFILE

The wind criteria included in API and IEC differ in terms of return period, averaging time and reference height. While the return period is typically viewed as the major source of difference in the standards, the other factors also play a significant role. As an illustrative example, we compare the wind speed profiles defined for API and IEC for a location that would experience wind speeds at the maximum levels allowed for Class 1 wind turbines (defined on the basis of the IEC standards). This 50-year wind speed is defined at an elevation of 80 m with a 50 m/s velocity averaged over a period of 10 minutes. IEC specifies an extreme wind speed used for design that is averaged over 3 seconds. This results in velocity of 65 m/s (at an elevation of 80 m). The velocity profile is defined for the 3 second average using the following formula:

$$V_{e50}\ (\text{m/s}) = 1.3 * V_{ref} * (z/z_{hub})^{0.11} \tag{6}$$

where, V_{e50} – Extreme wind speed with averaging time of 3 seconds

V_{ref} is the reference wind speed at hub height (m/s) – with averaging time of 10 minutes,

z is the height where the wind speed is being calculated, (m)

z_{hub} is the hub height (m)

The extreme wind profile in API RP-2A for a 100 year return period is given by

$$U(z,t)\ (\text{fps}) = U(z) * (1 - 0.41\ I_u(z) * \ln(t/t_0)) \tag{7}$$

where $U(z)\ (\text{fps}) = U_o * (1 + C * \ln(z/32.8))$

$I_u(z) = 0.06*(1 + 0.00131U_o * (z/32.8)^{-0.22})$

$C = 5.73 * 10^{-2} * (1+0.0457U_o)$,

U_o – reference wind speed at 10 m height (fps)

z – height (ft)

t – averaging time in seconds

t_o – 3600 seconds

The associated API values are calculated by first factoring the 50 year values to 100 year equivalents. ASCE-7 [10] suggests a factor of 1.07 to convert a 50 year to 100 year wind speed. The results of this comparison are shown in Figure 3. It can be seen that the wind profile from API 100 year is higher than IEC 50 year return period.

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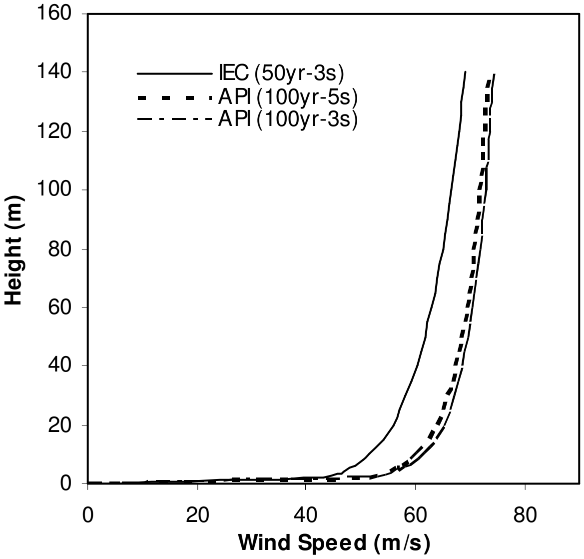

Figure 3: API and IEC comparison of wind speed

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