CHAPTER

14

Determining Structural and Hydrodynamic Loads

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14.1 INTRODUCTION

The assessment of structural loads and design of structures for wave energy converters (WECs) has primarily been driven by the expertise of the oil and gas (O&G), wind and maritime industries. This includes adapting recommended practises, standards, and guidelines from these industries. WECs, however, have different characteristics and risks, requiring careful application of existing standards as well as the requirement to develop specific approaches to properly assess the loads.

The numerical modelling techniques discussed in this chapter focus on application to the engineering design phase. The emphasis of this phase is to establish the major design considerations, technical requirements, and control of risks for a WEC. The site, type of WEC and its keys aspects drive the applicability of methodologies and modelling techniques, for example the level of sophistication on derivation of hydrodynamic loading, structural modelling and refinement of modelling of the power take-off (PTO). Design criteria for structural response are discussed as well as recommendations for evaluation of fatigue and extreme loads.

14.2 DESIGN PRINCIPLES

14.2.1 General

The design philosophy of WEC requires the understanding of control of risks that will lead to the success of technology. The success of technology is not limited to aspects related to the survivability, safety or environmental aspects but extends to the capacity to be able to compete with other technologies generating electricity. Thus reliability, power generation optimization and reduced costs are paramount and the structural definition should take these aspects into account. The structural design is also affected by the deployment requirements of WEC (temporary phases).

In order to adjust the design requirements and targets to the uncertainties related to site

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characterization and adequacy of techniques used to derive loading and the aspects threatening success, a risk-based approach is applied through "technology qualification" (DNV-RP-A203 (DNV, 2011) for example) to define the adequate safety class (see Section 14.2.3) and the actions required to reduce uncertainty during the design of WECs.

14.2.2 Design Methods

14.2.2.1 *Design by the Partial Safety Factor Method*

The partial safety factor method is a design method by which the target safety class (Section 14.2.3) is obtained as closely as possible by applying load and resistance factors (Section 14.5.4) to characteristic values of the governing variables. The governing variables consist of (1) loads acting on the structure or load effects in the structure, and (2) resistance of the structure or strength of the materials in the structure.

The characteristic values of loads and resistance, or of load effects and material strengths, are chosen as specific quantiles in their respective probability distributions. The requirements for the load and resistance factors are set such that possible unfavourable realizations of loads (eg, misalignment) and resistance, as well as their possible simultaneous occurrences, are accounted for to an extent that achieves a satisfactory safety class. Structural reliability analysis methods for direct probability-based designs are mainly considered as applicable to special case design problems, to calibrate the load and material factors to be used in the partial safety factor method, and to design for conditions where limited experience exists.

14.2.2.2 *Design by Direct Simulation of Combined Load Effect of Simultaneous Load Processes*

For design of WECs that are subjected to two or more simultaneously acting load processes, design by direct simulation of the combined load effect is an alternative to design by the linear load combination model of the partial safety factor method. This process is based on a direct simulation of the characteristic combined load effect from the simultaneously applied load processes. In particular, this should be applied when the linear combination model of the partial safety factor method may be inadequate: for example, in cases where the load effect associated with one of the applied load processes depends on structural properties that are sensitive to the characteristics of one or more of the other load processes.

14.2.2.3 *Design Assisted by Testing*

Design by testing or observation of performance is in general to be supported by analytical design methods. Load effects, structural resistance, and resistance against material degradation may be established by means of testing or observation of the actual performance of full-scale WECs. Full-scale tests or monitoring of existing WECs may be used to give information on response and load effects to be utilized in calibration and updating of the safety class of the WEC. To the extent that testing is used for design, the testing shall be verifiable.

14.2.2.4 *Probability-Based Design*

Structural design is traditionally based on deterministic analysis. However, uncertainties relating to loads, material characteristics and analysis models contribute to the small possibility of the structure not performing as intended. The probability of this situation is defined as the failure probability, and the reliability, defined as the complement of the failure probability, is regarded as a rational measure of safety (DNV, 1992).

Structural reliability analyses require knowledge of all significant modes of failure of a WEC and the probability distribution of all governing load and resistance variables. Whether or not a probabilistic reliability assessment can be accepted is based on a risk-based design approach. The risk-based design takes into consideration the consequences in case of failure and is used to define target reliability levels. For requirements for probability-based design, reference is made to DNV-OS-J101 Section 2

(DNV, 2014b) and DNV Classification Notes No. 30.6 (DNV, 1992).

14.2.3 Safety Philosophy and Safety Classes

Designs of WECs typically contain important subsystems for which there is no or limited relevant service history. These systems, loads and load–structural interaction effects may additionally not be adequately addressed by codes or standards. In order to overcome this shortcoming, a risk-based approach is generally adopted in the offshore industry with the aim of providing better safety and improved protection for the environment. The approach, first defined and adapted for marine renewables in (DNV, 2005), provides the most effective approach to dealing with the challenges in marine renewables. The risk-based approach is well suited to deal with the uncertainties and limited data/information as well as to adjust the process to include all main requirements for a successful technology.

Whilst defining the safety classes to be applied to WECs it is important to manage expectations from the stakeholders, safety of personnel and the balance between survivability, reputation, maintenance, repairs, and production costs. An overall safety philosophy should be clearly established covering all phases up to and including decommissioning. Three safety classes have been identified from experience with representative industries and activities and are defined considering the probability of failure as described below:

1. low safety class $<10^{-3}$ per annum
2. normal safety class $<10^{-4}$ per annum
3. high safety class $<10^{-5}$ per annum (DNV GL, 2015)

A low safety class is defined when failure implies negligible risk to human life, low risk for personal injuries and pollution and low risk for economic consequences.

A normal safety class is defined where failure implies some risk for personal injuries, significant pollution or high economic or political consequences. The normal safety class is aimed and it is reflected in the use of existing standards from other industries and adjusted requirements to address novelty and risks covering alignment systems, drivetrain, seals, bearings, auxiliary, electrical, and control systems. The target safety class for structural design of foundations, substructure, moorings and the reacting body to the normal safety class is a nominal annual probability of failure of 10^{-4}. This target safety is the class aimed at for structures whose failures are ductile and which have some reserve capacity.

A high safety class is defined where failure implies large possibilities for personal injuries or fatalities, significant pollution or very large economic or political consequences. Higher classes of safety may be required for critical subsystems and components depending on their consequences of failure.

14.3 SITE CHARACTERIZATION

Site conditions consist of all site-specific environmental components that may influence the design of a WEC by governing its loading, its capacity, or both. Environmental loads on a WEC are mainly due to wind, waves, and current, but loads due to soil conditions, seismicity, biology, and various human activities, etc. shall also be considered where applicable. Consideration may also be given to water and air temperature, water salinity, density and viscosity, and mechanical loads from ship or marine life impact. Characterization of site conditions is associated with the extent of data measurement and the range of parameters observed. This section introduces the three principle sources of environmental loads: waves, currents, and wind.

14.3.1 Wave

Although design methods may use concepts of long-crested regular (deterministic) waves, in reality offshore storm waves are random and short-crested. The intensity, frequency, and direction of wave fields are stochastic in nature and combined with tidal, surge, current, wind, and set-up effects. Secondary design considerations must allow for wave interactions with a structure, including shoaling, diffraction, reflection, frictional losses, and wave breaking.

A number of wave theories have been developed to describe the water particle kinematics associated with ocean waves of varying degrees of complexity. Regular wave theory encompasses Airy, Stokes second and fifth-order theories, stream-function and Cnoidal theories, amongst others. These theories generally define particle velocity very well up to the still water level for regular waves, but they can only be applied up to the still water level. Another problem with linear wave theory, Stokes and stream-function theories is that there is a systematic departure from physical modelling of steep waves. This is where physical experiments become particularly valuable since they are not limited by wave breaking. For design based on these waves, numerical theory from wave tank methods may be used.

For WECs at the free surface, waves above the still water level may have a considerable influence on structural response. Second-order and random wave theories are extensions of linear random wave theory and are aimed at improving representations of the free surface. Several modifications have been proposed, including the hybrid and stretching (Wheeler and vertical) methods.

The applicability of the discussed wave theories, however, depends on conditions at the site in question, namely the wave height, period, and water depth.

Accurate and reliable determination of the wave climate requires both measurement at the proposed deployment location, together with hindcast wave transformation modelling to provide long-term data from which 50-year or 100-year return sea-states can be obtained. A range of both measurement systems and modelling techniques are available for defining the wave climate. IEC 62600-101 (IEC, 2015) provides further guidance on the suitability of measurement instruments and associated analysis methods. Clearly, the accuracy and reliability of these systems and techniques will influence the accuracy and reliability of the estimate of the wave climate. Consequently, the characteristics of these systems and techniques should be taken into account in the definition and utilization of the wave climate. However, discussion of these topics is outside of the scope of this book, but the reader is directed to (EMEC, 2009a; EquiMar, 2010a; IEC, 2015) for further information.

14.3.2 Current and Water Level

In a similar fashion to the wave climate, the marine currents and water level are typically determined using a combination of measurement and modelling. For marine currents it is useful to recognize that they may be generated by different physical phenomena, the main ones being:

1. tidal currents generated by the effect of astronomical bodies
2. current generated by the wind stress and atmospheric pressure gradient (ie, throughout a storm)
3. large-scale ocean currents driven by latitudinal distributions of winds and thermohaline ocean circulation (ie, the Gulf Stream) and
4. the coastal currents generated as a result of waves approaching the shore, eg, longshore or rip currents

Water level consists of the astronomical tide above or below mean water level (MWL) and the storm surge component, for a given return period. MWL is defined as the arithmetic mean of all water levels measured over a long period. Storm surges are mostly wind generated and subsequently follow the wind directional and speed distribution. As a result they are randomly distributed in relation to the water level changes due to tides. In sites where the storm surge component is insignificant, or if long-term statistical data is limited, harmonic analysis for the prediction of tidal elevation may be used. If the effects of storm surge cannot be neglected, the estimation of the storm surges at a given site requires at least 10 years of measurements at the site or at nearby locations if hindcast models are used (DNV GL, 2015).

14.3.3 Wind

Wind is typically assumed not to represent a main source of loading for WECs. However, it is recommended that simultaneous observations of wave and wind data in terms of simultaneous values of H_S and U_{10} should be obtained where relevant. It is also worth noting that extreme waves may not always come from the same direction as extreme winds.

14.4 DEVICE CONSIDERATIONS

14.4.1 Numerical Modelling

To achieve a representative 'wave-to-wire' model of a WEC, numerical models should encompass all relevant system interactions, including, but not limited to, the wave-structure interactions, the PTO system and the mooring configuration (where applicable).

14.4.1.1 Frequency Versus Time Domain

If the WEC system/response is demonstrably linear, such that its behaviour is linearly related to its displacement, velocity, and acceleration, then the behaviour of the system may be studied in the frequency domain (see Chapter 2). Frequency-domain dynamic response models are often used to predict device performance and power production. These tools are, however, not well suited to analyse WEC survivability in large or breaking waves. Beyond their inability to handle realistic inputs (eg, irregular nonlinear waves), frequency-domain models are not capable of incorporating the nonlinear physical phenomena, such as large amplitude motions, wave breaking, viscous flow, and nonlinear power conversion chain (PCC) dynamics, that come to dominate WEC loading in large nonlinear waves.

Floating, moored WECs have the additional challenge of responding to wind, waves, and current with motions on three different time scales: wave frequency motions, low frequency motions, and high frequency motions (Cruz et al., 2014). While some of these scales can be linearized and included in a frequency-domain approach, others are highly nonlinear and the superposition principle—no longer applies. In this instance the equations of motion must be solved in the time domain (see Chapter 3).

14.4.1.2 Coupled Versus Uncoupled

The analysis of the system dynamics can follow a decoupled or coupled approach. In a decoupled analysis the effects of each individual subsystem (eg, the mooring system) are treated separately: that is, even if time-domain analysis is conducted, the instantaneous influence of a load source and stiffness on another load source/stiffness (and thus on the global system dynamics) is not fully accounted for. In a coupled analysis the complete system of equations accounting for the WEC structures and core subsystems is solved simultaneously using a nonlinear time-domain approach for dynamic analysis (Cruz et al., 2014).

The response of a floating WEC and its mooring is commonly calculated using uncoupled analysis techniques. However, in relatively deep water, inertia and damping effects of the mooring may require a coupled analysis, and thus solving of the analysis in the time domain for the elements simultaneously. Furthermore, the PTO may be a significant source of loading. This loading is often nonlinear and should be coupled with other sources of loading in time-domain analysis. A coupled analysis is additionally recommended to determine the horizontal motions of floating

WECs induced by slow drift wave exciting forces (ISSC Committee V. 4, 2009). Recommendations on methods for coupled analyses are described in DNV-RP-F205 (DNV, 2010).

14.4.1.3 Semiempirical and Potential Flow Methods

Semiempirical and nonlinear potential flow time-domain methods offer a robust approach for hydrodynamic analysis of WECs in large, nonbreaking waves (see Chapter 5) (Coe and Neary, 2014). Nonlinear potential flow codes have been shown to perform well compared to experimental investigations (Coe and Neary, 2014) and are thus efficient for linear and weakly nonlinear wave structure interaction problems (Greenhow et al., 1982).

Furthermore, WEC mooring systems utilising semiempirical and nonlinear potential flow models benefit from the reduced demand on predicting localised hydrodynamic loads as the focus is on loads within the mooring system. This approach is additionally suited to partial failure analyses, eg, loading after the failure of a mooring cable (Coe and Neary, 2014).

14.4.1.4 Computational Fluid Dynamics Methods

For the highly nonlinear phenomenon of wave breaking, green water and possible violent body motion computational fluid dynamics (CFD) can be used (see Chapter 6 and Westphalen et al., 2012). The advantage of CFD is that in principle it is valid for all flow regimes in offshore engineering, hence can be applied for rotational flows and where viscous effects are important (Westphalen et al., 2012). Furthermore the simulations do not need to be scaled, though they are often validated against tank tests due to a lack of full-scale data available. However, the computational effort for CFD is high and the accuracy of the prediction not assured compared to the empirical and potential flow methods (Westphalen et al., 2012).

14.4.2 Physical Modelling

At an early stage numerical modelling facilitates WEC configuration and geometry optimization. Experiments with scaled physical models are, however, essential for validation of the numerical simulations and investigations of survivability not covered by simulation tools, such as steep or breaking waves and slamming. A number of guidelines for the physical modelling of WECs have been published by various bodies (EquiMar, 2010b; EMEC, 2009b); a key theme which arises is the importance of both numerical and physical modelling at all stages of development of a WEC and the need for a staged approach to testing with varying requirements on the hydrodynamics, PTO and control subsystem depending on the objectives.

14.5 DESIGN CRITERIA

The design criteria are those that determine the suitability of the structural design. Generally, these are specified using limit states, which are conditions beyond which the design requirements are no longer satisfied. These limit states are tested against design load cases (DLCs) that are defined by the full range of operating conditions and potential combinations of different load sources. Effectively, the structural design may be considered acceptable if none of the limit states are exceeded in all of the DLCs.

14.5.1 Limit States

A limit state is a condition beyond which a structure or structural component will no longer satisfy the design requirements. The following limit states are considered in this chapter:

1. ultimate limit states (ULS): corresponding to the maximum load-carrying resistance
2. *abnormal* ultimate limit states (ULSa): as above, but for abnormal load cases. Abnormal loads are loads resulting from a number of

severe fault situations for the WEC which result in activation of system protection functions. Abnormal loads due to fault conditions for a WEC have a higher probability of occurrence than accidental loads considered for the ALS. The appropriate limit state is applied depending on the type of fault and its associated probability of occurrence; abnormal loads due to fault conditions may even have a higher probability of occurrence than typical ULS loads (DNV GL, 2015)

3. fatigue limit states (FLS): corresponding to failure due to the effect of cyclic loading
4. accidental limit states (ALS): corresponding to survival conditions in a damaged condition or in the presence of events with a remote annual probability of happening (10^{-4}) and
5. serviceability limit states (SLS): corresponding to the acceptable operation of the WEC

14.5.2 Sources of Characteristic Loads

Loads are categorized according to type. The load categorization is used as the basis for definition of characteristic loads for use in design. The following load categories are defined:

1. permanent loads: eg, mass of structure, ballast and permanent equipment, internal and external hydrostatic pressure of a permanent nature, etc.
2. variable functional loads: eg, loads from transport operations, PTO, etc.
3. environmental loads: wind, wave, current, etc. (Section 14.3)
4. abnormal WEC loads (loads associated with fault scenarios)
5. deformation loads
6. accidental loads: from collisions, mooring line failures, flooding of buoyant compartments, etc.

The magnitude and characteristics of these loads used in the analysis depends on both the WEC condition (eg, operation/installation/maintenance) and the limit state to which they are being applied. For example, different environmental loads should be used for calculation of the ULS during operation compared to those used for the ALS of a damaged structure during repair. In particular, the environmental design conditions shall be specified with due attention to the actual location, the season of the year, the weather forecast, duration of operation and the consequences of failure.

14.5.3 Design Load Cases

For the design of all components of a WEC, a number of load cases due to environmental loads on the hydrodynamic and reaction subsystems shall be considered, corresponding to different design situations for the WEC. This set of DLCs should be as exhaustive as possible. Thus, it should include situations such as power production (with and without a fault condition, eg, with partial PTO failure), start-up and shut-down (including emergency shut-down), parked (with and without a fault condition) and transport/assembly/maintenance and repair. For each of these DLCs different conditions should also be considered, such as normal operational conditions, severe operational conditions, transient conditions and a range of fault conditions. It can be recognized that this analysis will typically result in the identification of hundreds of DLCs to consider.

Following an initial review (after the selection of the site(s), the characteristics of the WEC and the collation of technical documentation by the WEC developer including the final environmental conditions report), it may be possible to exclude some conditions from the DLCs; for example:

1. wind-induced loads (should the WEC freeboard be sufficiently small)
2. tidal range, if site conditions allow enough compliance in the mooring system relative to the highest and lowest astronomical tides and

if the change in water depth is small in comparison with the overall depth
3. sea ice and icebergs, etc. (DNV GL, 2015)

This conventional approach to load case reduction can reduce the number of DLCs by up to two orders of magnitude.

Careful consideration is required to ensure that appropriate environmental conditions (sea-state/currents/wind) are derived to fulfil the targets of each limit state. This is likely to mean that for many of the DLCs a number of different instances will need to be considered. For example, for normal operation in extreme sea-states (of which there may be more than one defined, depending on the WEC control strategy and expected response), instances should also be considered for different current directions and water levels (depending on their significance to the WEC technology being investigated).

The combined load effect in the structure due to simultaneous current, wave, and wind loads may be calculated by combining the separately calculated wind load effect and the separately calculated current and wave load effect by linear superposition (DNV GL, 2015). This method may be applied to concept evaluations and in some cases also to load calculations for final design, for example in shallow water or when it can be demonstrated that there is no particular dynamic effect from waves, wind, ice, or combinations thereof. Useful information on linear combination of two load processes is given in DNV-OS-J101 Section 4 (DNV GL, 2014b).

Alternatively, the combined load effect in the structure due to concurrent wind and wave loads may be calculated by direct simulation. This approach is based on structural analyses in the time domain for simultaneously applied simulated time series of the wind load and the wave load.

For the FLS a sufficient number of reference directions and sea-states should be defined, in order to provide a good representation of the frequency and directional distribution of a long-term wave environment. Furthermore, fatigue damage prediction can be sensitive to the number of sea-states in this discretization, and sensitivity studies should be used to ensure that an adequate number of sea-states are defined, bearing in mind that the number of reference sea-states depends on the site and also the level of detail of the information.

14.5.4 Load and Resistance Factors

Load factors are multipliers that are applied to each of the sources of loads when they are combined to produce the net load to be compared to the relevant limit state. Generally, the higher the safety class the larger the load factor that needs to be applied. Typically, load factors are greater than 1.0; however, when a permanent or variable functional load is a favourable load (ie, where a reduced value of the load leads to an increased load effect in the structure), then a load factor of less than unity (eg, 0.9) should be used. Some possible values of the load factors to use for the ULS and ALS are given in DNVGL-ST-0164 Section 6 (DNV GL, 2015). However, it is important to observe that the load factors proposed in (DNV GL, 2015) have not been calibrated for the different WEC technologies and simulation techniques. Nevertheless, they are based on experience of calibration of safety factors for tidal and offshore structures; the proposed values are probably a good first approximation for prototype application. The load factors for the FLS and SLS are typically taken as unity for all load categories.

Typically, the load factors consider a level of uncertainty that is not affected by the way and duration that the data for site characterization is carried out (DNV GL, 2015). An additional factor (typically in the range 1.0–1.25) considering this additional impact may be required to represent the resultant uncertainty in the environmental conditions (DNV GL, 2015). Effectively, this means that higher design values reflecting the level of confidence in the site data may be applied.

Resistance factors are associated with uncertainty in the characteristics of the properties of the structural material and are effectively multipliers of the acceptable stress levels. Resistance factors for the ULS are well established and can be obtained from (DNV GL, 2015) to achieve resistance factors that are compatible with the load factors applied. The resistance factor for the ALS and the SLS are typically taken as unity. Design against the FLS is based on a format that makes use of an overall design fatigue factor (DFF) applied to a characteristic cumulative damage, as detailed in Section 14.6.2.

14.6 STRUCTURAL ASSESSMENT

14.6.1 Extreme Event Analysis

Wave energy converters must be designed for the full range of environmental conditions that they will experience during their design lifetime, accounting for the stochastic nature of the loading. Thus, the long-term prediction of extreme values of wave parameters is of paramount importance for WECs in order to assess structural capacity. Extreme values for structural assessment can be assessed in terms of extreme environmental conditions or directly from extreme load effects from load time series. For both cases, the same theory, discussed in the following, can be applied.

Where extensive wave datasets are available, return periods are calculated by Gumbel's approach. Where an extensive wave dataset is not available (as will often be the case) a statistical approach may be used. Statistical approaches of identifying extreme loads include Gumbel's approach, generalized extreme value and generalized Pareto, including a range of fitting methods. An alternative approach is to represent the three-dimensional sea-state (amplitude, frequency, direction) in two dimensions (amplitude, frequency), and to assume wave propagation in only one direction. This approximation serves better for computing efficiency and building towards a greater understanding of three-dimensional sea-states.

The problem of statistical combination of extreme structural loads acting on marine structures in order to determine design loads is usually solved using load combination factors (ISSC Committee V. 4, 2006) as discussed in Section 14.5.4. The choice of load and resistance factors should reflect the fact that the threat to human life and economic and environmental consequences of structural failure are much smaller for a WEC than for a conventional offshore installation. In regard to the return period for the extreme loads, current practise in the offshore industry is to use 100 years; however, for WECs a 50-year return period is also considered, as for wind structures. In this case a higher load factor is applied adjusting loading associated with the lower return period to maintain the same probability of failure.

The assessment of structural strength under extreme loading requires consideration of several failure modes, such as yield, fracture and buckling. For wave devices, failure criteria may additionally be defined by deformation leading to flooding of compartments, damage to equipment and systems or impairment of safety features. Checks of the structural capacity of all structural components shall be performed. Requirements for checking ultimate strength capacity and ALS for steel, concrete and composites are given in DNV GL or international Standards.

14.6.2 Fatigue Analysis

14.6.2.1 Methods of Analysis

Fatigue analysis of WECs should comprise all actions contributing to fatigue damage both in non-operational and operational design conditions, especially for dynamically sensitive structures. According to (Cruz et al., 2014), the predominant sources of fatigue-inducing loads comprise:

1. actions producing variable load effects (commonly waves and combinations with current or other equipment-induced variable loads)

2. wave impact, particularly slamming
3. vortex shedding

Fatigue capacity evaluation may be performed based upon methods utilising fatigue tests (S-N curves) and estimation of cumulative damage (Palmgren-Miner's rule). Stresses should be calculated in agreement with the three categories of stress: nominal, hot-spot or notch stress (DNV GL, 2014).

The long-term stress range distribution may be found by a simplified (or deterministic) or spectral analysis (where the fatigue is directly related to the waves and linearisation is sufficient to determine the structural response to the different waves). In the simplified method a Weibull distribution is assumed for the long-term stress ranges, leading to a simple formula for calculation of fatigue damage (ABS, 2014; DNV, 2014a). The load effects, in terms of motions, displacements, and internal forces and stresses in the WEC structure, should be determined with due regard to spatial and temporal variability, load nonlinearities and relevant limit states. This method is generally used for preliminary estimations of fatigue damage in simple cases of wave-induced fatigue effects. The spectral analysis method implies that the long-term stress range distribution is calculated from a given (or assumed) wave climate. This can be combined with different levels of refinement of structural analysis (DNV GL, 2014). The fatigue analysis may also be performed based on a combination of simplified and refined techniques, as indicated in (DNV GL, 2014; DNV, 2014a).

Accumulated fatigue damage can be accounted for using a variety of approaches, namely the frequency, time-domain, or a mixture of the two. For many WEC technologies, assessment techniques that are based on time-domain analysis methods are the only proper way to assess structural systems that are subjected to nonlinear structural response or nonlinear loading. In this approach, analysis is performed for each sea-state and fatigue damage is accumulated using a rain flow counting technique (DNV, 2005). It is recommended that damage equivalent loads (DELs) be used, where possible, to equate the fatigue damage represented by the rain flow counting data to that caused by a single stress range repeating at a single frequency, especially for initial assessments and concept definition (Cruz et al., 2014).

Fracture mechanics may also be used for fatigue capacity evaluation. Fracture mechanics are commonly employed for investigations of acceptable or minimum detectable flaw size and crack growth prediction (ABS, 2014), as well as defect sensitivity studies.

In addition to stress range distributions, due consideration shall also be given to the possibility of localised stress concentrations arising. In practice, the application of a geometric stress concentration factor (SCF) shall address this issue. A stress concentration factor may be defined as the ratio of hot-spot stress range over nominal stress range. The stress concentration factors may be based on tabulated values or by finite element analysis to explicitly compute the geometric SCF (DNV GL, 2014).

In addition, DFFs can be applied to reduce the acceptable probability of fatigue failures. The DFFs are dependent on the significance of the WEC components with respect to structural criticality and availability for inspection and repair and shall be based on risks to life, environment and technology success identified during the Technology Qualification stage. The DFFs (outlined in DNVGL-ST-0164 Section 8, DNV GL, 2015) typically range in values from 1 to 10, with the lowest values for low risk, easily accessible structural elements and the highest values of high risk, nonaccessible structural elements. Importantly, they should be consistent with the risk-based approach and targets of probability of failures for marine renewables.

14.7 SUMMARY

- In general structural loads should be determined using a time-domain simulation

- Semiempirical and nonlinear potential flow methods represent the most efficient modelling methods for large, nonbreaking waves
- CFD can in principle be used for any wave conditions, but without calibration the accuracy of the prediction is not assured compared to empirical and potential flow methods
- Physical modelling is generally essential for the validation of all numerical models in extreme waves
- The structural design should consider a range of limit states, including ULS, ULSa, FLS, ALS, and SLS
- The potential sources of loads should include permanent loads, variable function loads, environmental loads, abnormal loads, deformation loads, and accidental loads
- The structural loads (multiplied by load factors) for a comprehensive set of DLCs should be compared to the limit states to ensure that the design is acceptable
- The DLCs should include all potential scenarios including operation, installation, fault conditions as well as relevant combinations of environmental conditions
- A lack of data makes it difficult to specify appropriate load factors, but experience from other offshore structures can provide reasonable estimates for prototype development

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