Structural Forces and Stresses for Wave Energy Devices

Final Report

WES_LS02_ER_Forces and Stresses

Job number 247772-00

Ove Arup & Partners Ltd
13 Fitzroy Street
London
W1T 4BQ
United Kingdom
www.arup.com

Cruz Atcheson Consulting Engineers, Lda.
Rua do Montepio Geral, N° 4-A
1500-465 Lisboa
Portugal
www.cruzatcheson.com

Document Verification

ARUP

Job title	Structural Forces and Stresses for Wave Energy Devices - Landscaping Study	**Job number** 247772-00
Document title		**File reference**
Document ref	ARP LS2	

Contents

Glossary

ALS	Accidental Limit State
BEM	Boundary Element Method
CFD	Computational Fluid Dynamics
DEL	Damage Equivalent Loads
DLC	Design Load Case
DFF	Design Fatigue Factor
DNV	Det Norske Veritas
EMEC	European Marine Energy Centre
FLS	Fatigue Limit State
FEA	Finite Element Analysis
FMEA	Failure Modes and Effects Analysis
FMECA	Failure Modes, Effects and Criticality Analysis
IEC	International Electrotechnical Commission
JONSWAP	Joint North Sea Wave Project
LCoE	Levelised Cost of Energy
OWC	Oscillating Water Column
OWSC	Oscillating Wave Surge Converter
PTO	Power Take-Off
RANSE	Reynolds Averaged Navier-Stokes Equations
RFCC	Rain Flow Cycle Counting
SCF	Stress Concentration Factor
SLS	Serviceability Limit State
SWL	Sea Water Line
TRL	Technology Readiness Level
ULS	Ultimate Limit State
WEC	Wave Energy Converter
WEC-Sim	Wave Energy Converter Simulator
WES	Wave Energy Scotland

Executive Summary

This report has been prepared by Arup and Cruz Atcheson on behalf of Wave Energy Scotland (WES) as part of a landscaping study of structural forces and stresses for wave energy converters (WECs). It is aimed at developers of WEC devices, and others in the supply chain who have a stake in the design, fabrication, operation and certification of wave energy converters.

The objective of this report is to provide guidance on the application of relevant methods and standards to the design and analysis of WEC devices. The report is not intended to be a definitive nor an exhaustive list of design requirements, rather an interpretation of existing methods and standards in the context of WECs.

The report is broadly presented in two Sections with distinct objectives. Section 1 aims to highlight existing standards and practices that are relevant to WECs; Section 2 aims to propose suitable methodologies for the load assessment and structural analysis of WECs through interpretation of these standards and practices. In this respect, this report builds on previous studies which have provided more practical guidance but may have focused on a single software or device, rather than providing an independent overview of alternative techniques.

The report also includes the results of a survey of active WEC developers. The findings of this survey show that the developer community is making use of a range of tools and techniques. However, these are not always deployed at the right stages of design development, and not necessarily to the level of detail appropriate for the maturity of the technology being pursued. These survey findings suggest that the industry is not operating as effectively as it could and that the industry would benefit if robust methodologies were in place.

A representative example is also presented to demonstrate certain methodologies described in this report. This example highlights some of the challenges that the industry faces which could be addressed through the provision of further guidance beyond this report. Derivation of loads can be an extremely onerous, computationally-intensive exercise beyond the means of some developers. Fabrication details can be complex and non-standard, requiring detailed stress analysis. In particular, methods of improving the efficiency of time history techniques, or improving access to relevant software would be of great benefit.

Finally, the wider community must be acknowledged too. It is not just the design engineers who pursue these issues – there are financiers, insurers, certification bodies and others in the supply chain who need to understand and agree on the process. More established offshore industries are highly regulated and standards and techniques have been calibrated to an internationally accepted safety level, well recognised by investors. A wider understanding, even at a high level, of a more standardised WEC design process would surely improve the industry's route to commercialisation.

Introduction

The industry's technical challenge

There are several answers to the question, "Why have wave energy conversion technologies not been implemented on a large scale?"

From a technical perspective, even the failure in creating a solid design basis at the concept design stage can be a key issue. The structural assessment of WECs and assimilation of clear, standard guidance for such assessment is particularly challenging in comparison to other offshore industries, and the absence of comprehensive methodologies that cover both performance and non-performance design situations from an early design stage directly contribute to poor specification of the vital sub-systems that make up a WEC.

The fact that the design of WECs has not converged presents another significant challenge. The loads expected can vary significantly not only with the design of the device, but also with short term operational considerations such as faults and installation configurations. This creates a complex array of design situations, from which it is challenging to apply uniform approaches.

As with all offshore structural design, the analysis of WECs involves the intersection of hydrodynamic and structural analysis. However, unlike fixed offshore structures which aim to minimise drag and inertial wave forces, WECs rely on the interaction with the waves often within the splash zones where unsteady loading is significant. The device therefore has to be designed to harness as much energy from the waves as possible during operating conditions, without causing excessive loads during the survivability state.

Existing offshore design approaches therefore are not readily transferable to much of the analysis necessary for WEC design and a detailed understanding of the interaction between hydrodynamic and structural disciplines is required. New techniques and guidance are required in order to provide the necessary toolset to analyse WECs in a more standard manner.

The industry's financial challenge

Generation of electricity from WECs, although in its infancy, is well-established as a concept and is supported by the need to move away from carbon-intensive energy sources. Development to date supports a market opportunity which, by some estimates, could be of the order of hundreds of gigawatts installed, with an industry worth £20bn per annum by 2050[1]. Currently, a great number of developers are active globally, all pursuing a range of concepts, at various stages of development. This volume of developers demonstrates the level of R&D activity and supports the view that the market opportunity is considerable.

[1] Carbon Trust, Marine Renewables Green Growth Paper, 2011

Despite this progress, the marine energy sector is at a critical juncture; having demonstrated a number of technologies at full-scale, the next step is deployment of early commercial arrays.

One of the key challenges to demonstrating at full-scale and enable funding of R&D, and to deploy in arrays, is the significant investment required. That can only be made possible if the cost of energy from projects, even with revenue-support schemes, is low enough to offer a commercial return to investors. Hence near-term cost reduction, as well as being able to forecast an attractive longer-term trajectory, is of paramount importance.

Key Metrics

These technical and financial challenges are reflected in key industry metrics proposed by Wave Energy Scotland and described below.

The financial challenge is reflected in one of Wave Energy Scotland's key industry metrics: affordability. Wave Energy Scotland have identified a further three key metrics by which to measure progress in the industry. These are:

- Reliability
- Survivability
- Performance

Each one of the key metrics reflect the Levelised Cost of Energy (LCoE), and a thorough appreciation of structural loads and integrity has an impact, in varying degrees, on all four metrics. A balance must be found between conservative over-engineering and ambitious, but necessary, cost-reduction. This balance can – to a significant extent – be facilitated through the development of a formal design methodology.

Affordability

We know from experience, and from a number of industry studies, that the affordability of WECs is strongly influenced by the capital cost of the device structure. This share of cost can be up to 50% of total device cost[2]. Hence optimising the structural design in order to reduce the tonnage of structural material is an important design decision to be addressed in pursuit of reducing the LCoE. A robust understanding of loads and structural integrity of a WEC, and appropriate use of relevant tools and techniques is crucial in this respect.

Survivability

As referred to later in this report, significant structural failures can be catastrophic and lead to complete loss of a WEC. The optimisation of the structure of WECs, in pursuit of greater material efficiency and lower LCoE must be robustly guided with well-informed design decisions. In addition, any safety or environmental

[2] Carbon Trust, Capital, operating and maintenance costs, 2006

consequences of structural failures can have a negative impact on perceptions and potential investment, irrespective of the direct impact on LCoE.

Reliability

Reliability tends to be discussed in the context of systems (e.g. power take-off) but structural design has a part to play here too. Many WECs rely on the relative movement of large buoyant bodies and the PTO systems can contain significant load-bearing structural elements themselves. If the integrity of these becomes compromised, then the overall system reliability will suffer as a result. Hence, the structural integrity of these components should be evaluated to the same level of rigour as the main structure of the WEC.

Performance

As is the case with reliability, performance tends to be discussed in the context of systems. However there is a clear relationship between WEC size and power capture. As concepts progress from experimental models to larger-scale real-sea devices, the tools and techniques used for assessing loads and structural integrity must follow suit.

It is clear from the metrics above that there is a balance to be struck between conservative over-engineering and ambitious, but necessary, cost-reduction. This balance can – to a significant extent – be facilitated through the development of a robust structural design methodology.

Report Objectives and Overview

This study aims to provide guidance on the application of existing methods and standards to the design and analysis of WEC devices. It provides an independent overview of a range of structural analysis techniques and standards, from wider engineering and industrial sectors, in the context of WECs.

The report is presented in three Sections:

1. Design Process: Key Principles
2. Load and Structural Analysis
3. Summary of Key Findings

Section 1 provides a description of existing practices and standards for undertaking WEC design. This includes a list and description of key design basis requirements, an outline of the overall design process, a review of applicable offshore guidelines and standards, and finally the results of a survey of 24 WEC developers to identify the design and analysis methodologies they currently employ.

Section 2 contains guidance for load and structural analysis of WECs based on our interpretation of the existing methods identified in Section 1. This includes a brief overview of various types of WECs along with an approach for deriving loads and suitable approaches for assessing the structural integrity of WECs. The conclusions are summarised using rating matrices which rank load and structural analysis methodologies in terms of their applicability to design situations and to different WECs. Section 2 concludes with a representative example of how some of the methods described might be implemented in order to estimate loads and to demonstrate the structural integrity of a WEC.

Section 3 presents the key findings of this study, by summarising the guidance for load and structural analysis described in Sections 1 and 2.

1 Design Process and Current Practice

At a high level, the WEC design process comprises of three stages; design basis definition, concept design and detailed design. A brief outline of the key objectives and tasks associated with the WEC design process is provided in Figure 1. Following the completion of the design basis definition, an initial selection of design load cases (DLCs) can be made, informing the concept and detailed design efforts. Typically, load and structural integrity assessment is then conducted, initially for preliminary design conditions and subsequently for a complete set of DLCs.

Guidelines and standards that may inform the WEC design process are reviewed in Section 1.2.

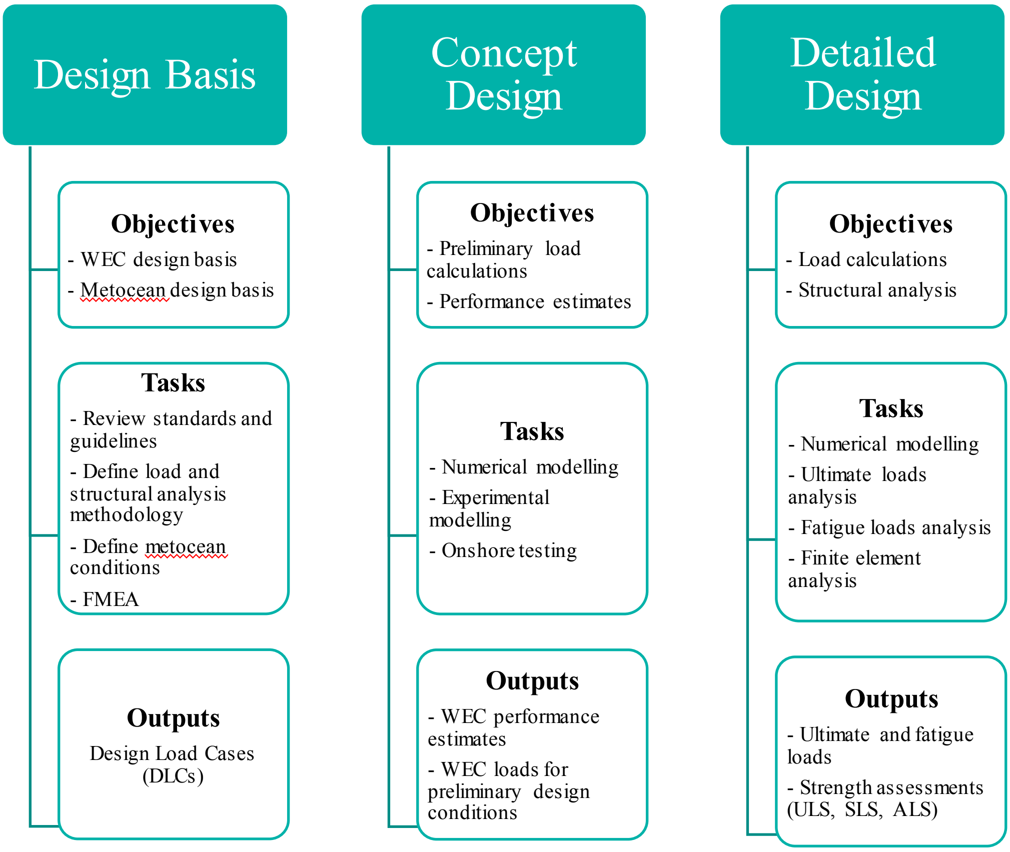


Figure 1 Key objectives and tasks: WEC design process

1.1 Design Basis

The design basis definition is typically captured in a document, defined by DNV to be, "A document defining owner's requirements and conditions to be taken into account for design and in which any requirements in excess of this standard should be given." A design basis for a WEC should, at a minimum, define the following:

- Principal design objectives
- Device fabrication, installation and maintenance criteria

- Device decommissioning criteria
- Review of design codes, standards and guidelines
- General description of the device:
  - Main structural components
  - Array layout, mooring cable systems, grid connections, pipework and any other peripheral functional components
- Environmental conditions of target site (further information contained in Section 2.2):
  - Metocean data
  - Marine operations
  - Marine growth and activity
- Design load cases and applicable partial factors
- Material properties and applicable partial factors
- Load and structural analysis methodologies
- Corrosion protection systems
- Safety and hazard assessments
- Failure modes, effects and criticality analysis (FMEA)

1.2 Review of Guidelines and Standards

At present there are no dedicated standards for the design of WECs. In addition, there is limited experience in defining DLCs for any type of WEC. Notable exceptions include e.g.[1], [2]. A small number of documents that specifically cover WEC design and certification have been published however. These include:

Det Norske Veritas AS (DNV) Offshore Service Specification (OSS) 312 (DNV-OSS-312, October 2008). This document overviews the principles and procedures associated with the certification of WECs, including an overview of relevant documentation. It does not, however, include technical provisions.

DNV's 'Guidelines on Design and Operation of Wave Energy Converters', May 2005, The Carbon Trust. In the absence of a specific standard for WEC design, this document compiles a long list of related standards and outlines methodologies for fatigue analysis and wave load modelling.

The European Marine Energy Centre (EMEC) 'Guidelines for Design Basis of Marine Energy Conversion Systems', 2009. This report overviews general aspects behind design basis documentation, covering both wave and tidal energy converters.

In addition to the above documents, relevant standards from the maritime, oil & gas and offshore wind sectors have been reviewed. There are considerable similarities between the design of WECs and such structures / installations, allowing these documents to be used as a starting point when defining load and integrity assessment methods for WECs.

It is recommended that the key documentation listed in Table 1 is consulted, which is adapted from [1], for WEC design. It is also recommended that technology developers use Table 1 as a shortlist of representative guidelines when investigating suitable documentation for concept and detailed design.

It should be noted that an IEC technical committee (IEC TC114/PT 62600-2) is currently deriving the technical specification / design requirements for marine energy systems. It is hoped that this specification will provide further guidance for WEC design, for example the definition of the applicable safety factors.

Table 1 Core documentation: WEC load and structural analysis (adapted from [1])

Doc. Reference	Application / Relevance	Supporting / Additional Documents
DNV-OSS-312 (2008) Certification of Tidal and Wave Energy Converters	Guidance on overall procedures	DNV-OSS-304 (2006) Risk Based Verification of Offshore Structures DNVGL-RU-OU-0102 (2015) (replaced DNV-OSS-102) Rules for Classification of Floating Production, Storage, and Loading Units DNV-RP-A201 (2012) Plan Approval Document Types – Definitions
GL Rules and Guidelines IV-6-4 (2007) Offshore Technology - Structural Design	Overall description of environmental conditions and design loads (environmental, permanent, functional and accidental), including principles for structural design	DNV-RP-C205 (2014) Environmental Conditions and Environmental Loads GL Rules and Guidelines IV-6-3 (2007) Fixed Offshore Installations (Section 4 – TLPs) DNVGL-OS-C103 (2015) (replaced DNV-OS-C103) Structural Design of Column Stabilised Units (LRFD Method) DNV-RP-C204 (2010) Design against Accidental Loads API RP 2FPS (2011) Recommended Practice for Planning, Designing, and Constructing Floating Production Systems

Doc. Reference	Application / Relevance	Supporting / Additional Documents
GL Rules and Guidelines IV-2-5 (2012) Guideline for the Certification of Offshore Wind Turbines - Strength Analyses	Structural design and analysis	GL Rules and Guidelines II-2-1: Materials and Welding - Non-metallic Materials (2006) Fibre Reinforced Plastics and Bonding DNV-OS-C205 (2014) Environmental Conditions and Environmental Loads DNV-RP-C501 (2013) Composite Components ISO 10092 Petroleum and natural gas industries: Fixed Steel Offshore Structures DNV-RP-C208 Determination of Structural Capacity by Non-linear FE analysis Methods DNV-RP-C301 Design, Fabrication, Operation and Qualification of Bonded Repair of Steel Structures DNV-RP-C204 Design Against Accidental Loads DNV-OS-J101 Design of Offshore Wind Turbine Structures DNV-OS-C102 Structural Design of Offshore Ships
DNVGL-OS-E301 (2015) Position Mooring	Mooring specification / load assessment	GL Noble Denton 0032/ND (2015) Guidelines for Moorings API RP 2SK (2005) Design and Analysis of Stationkeeping Systems for Floating Structures, 3rd ed., (with 2008 addendum)
DNV-RP-A201 (2012) Plan Approval Document Types – Definitions	Quantitative reliability assessment	API RP 17N (2009), Recommended Practice for Subsea Production System reliability and Technical Risk Management BS 5760 (2014) Reliability of systems, equipment and components ISO 14224 (2014) Petroleum and Gas Industries - Collection and Exchange of Reliability and Maintenance Data for Equipment. ISO 2394 (2015) General Principles on Reliability for Structures

Doc. Reference	Application / Relevance	Supporting / Additional Documents
ABS Pub# 115 (2003) Guide for Fatigue Assessment of Offshore Structures	Overview of fatigue assessment methods in offshore installations (inc. safety factors)	DNVGL-RP-C203 Fatigue Design of Offshore Steel Structures DNVGL-RP-C206 (2015) (replaced DNV-RP-C206) Fatigue Methodology of Offshore Ships BS 7608 Guide to fatigue design and assessment of steel products ISO 10092 Petroleum and natural gas industries: Fixed Steel Offshore Structures API-RP-2A Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms: Working Stress Design
DNV-RP-F205 (2010) Global Performance Analysis of Deepwater Floating Structures	Floater load models, de-coupled and coupled response analysis	GL Rules and Guidelines IV-6-4 (2007) Offshore Structures: Structural Design (Section 4.6)
IEC/TS 61400-3-2 Ed. 1.0 Wind turbines - Part 3-2: Design requirements for floating offshore wind turbines Standard for Floating Offshore Wind Turbines (FOWT) (final publication forecast 07/2016) DNV-OS-J103 (2013) Design of Floating Wind Turbine Structures	Design Load Cases (DLCs) Strength analysis in FEM Floating support structures (at least partially)	DNV-OS-J101 (2014) Design of Offshore Wind Turbine Structures IEC 61400-3 (2009) Wind Turbines–Part 3: Design requirements for offshore turbines Lloyd's Register (2012) Guidance on offshore wind farm certification. Section 4.2–Loading on floating structures. Section 6.2–Floating structures GL Rules and Guidelines IV-2 (2012) Guideline for the Certification of Offshore Wind Turbines (Chapter 4–Load Assumptions; and Chapter 5–Strength Analyses) ABS (2014) Guide for building and classing floating offshore wind turbine installations

Information on where to source documents cited in Table 1 is included below.

GL Rules and Guidelines IV-2 (2012): A pdf-version of the GL Renewable Certification Guideline for the Certification of Offshore Wind Turbines, Edition 2012 (pdf-version) may be ordered via this link to the DNV GL website.

API RP 2FPS (2011) Recommended Practice for Planning, Designing, and Constructing Floating Production Systems, 2nd Edition: This documents may

be purchased from the American Petroleum Institute publications store online via this link.

API RP 2SK (R2015) (2005) Design and Analysis of Stationkeeping Systems for Floating Structures, 3rd Edition (Includes 2008 Addendum): This documents may be purchased from the American Petroleum Institute publications store online via this link.

Lloyd's Register (2012) Guidance on offshore wind farm certification: This document should be sought directly from Lloyds Register.

IEC 88/379/NP (PEL/88_10_0084): This is a working draft document from the IEC/TS 61400-3-2 Ed. 1.0 Wind turbines - Part 3-2: Design requirements for floating offshore wind turbines project. The forecast publication date for the title is 07/2016.

IEC 61400-3 (2009): This document may be purchased online; one source is the British Standards Institution (BSI) shop via this link.

1.3 Current Practices: How do WEC Developers Estimate Loads and Stresses?

A WEC developer survey was conducted between the 17th and 24th of February 2016. Over forty WEC developers from across the globe were invited to complete the survey. A personal e-mail invitation was sent directly to key contacts from each developer, and the surveys were completed electronically via an online survey tool.

Twenty-four survey responses were received, which equates to approximately 60% of the developers surveyed.

The survey was composed of twenty carefully selected questions to assess the design methodologies for estimating loads and stresses currently applied by WEC developers.

This Section provides an overview of the key results and a more detailed analysis of the responses with the aim of mapping the design methodologies currently being followed by the surveyed WEC developers.

It should be noted that the survey responses are subject to the developers' opinions and in some cases these may represent an overly optimistic perspective. In particular, this was observed in the TRL estimations presented by some developers (see Section 1.3.7).

1.3.1 WEC device types

Developers were asked to identify their technology from one of seven different generic WEC device types (specified by WES). The WEC developer responses can be summarised as follows (see also Figure 2):

- 11 point absorbers
- 3 oscillating wave surge converters
- 3 oscillating water columns
- 1 overtopping device
- 1 attenuator
- 1 pressure differential device
- 4 'other' WEC types

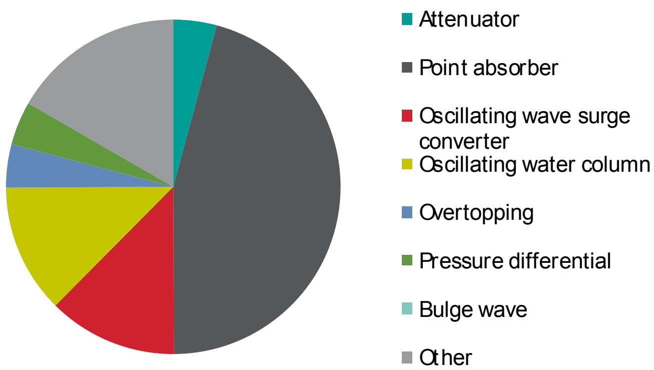


Figure 2 WEC device types

In summary, the majority of WEC device types under development by the WEC developers who responded to the survey were point absorbers. Oscillating wave surge converters and oscillating water columns were also common, with 3 respondents for each device type. The least common device types were overtopping, pressure differential and attenuator devices, with only a single developer for each device type. No bulge wave device types were identified by the survey respondents. Four respondents selected the 'other' WEC type category; based on an assessment of the individual responses and an understanding of more unique WEC device types under development, this may correspond to (e.g.) small arrays of point absorbers combined in a single system.

1.3.2 WEC development progress

There are multiple approaches to classifying the status of innovative technologies and identifying the stage of development. The US Department of Energy (DOE) Technology Readiness Assessment (TRA) Guide[3] follows a tailored version of a proven National Aeronautics and Space Administration (NASA) and Department of Defence (DoD) technology assessment model. A TRA evaluates technology maturity using the Technology Readiness Level (TRL) scale which was established by NASA in the 1980s. The TRL scale ranges from 1 (basic principles observed) through to 9 (total system used successfully in project operations). The definitions of each TRL classification are provided in the aforementioned DOE report.

A summary of the TRL breakdown for the WEC technologies under development by survey respondents is presented below (see also Figure 3).

- 8% TRL 7
- 46% TRL 6
- 33% TRL 4-5
- 13% TRL 1-3

[3] https://www.directives.doe.gov/directives-documents/400-series/0413.3-EGuide-04-admchg1

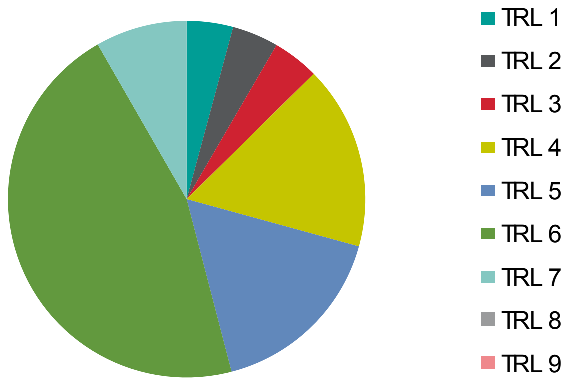


Figure 3 WEC technology readiness levels (TRL)

The most common TRL selected for devices under development was TRL 6. This corresponds to a development stage of engineering-scale models or prototypes being tested in a relevant environment. At this TRL prototypes should be capable of performing all the functions that will be required of the operational system. The highest TRL selected by respondents was TRL 7. This represents a significant step up from TRL 6, representing the demonstration of a full-scale prototype system in a relevant environment.

The surveyed WEC developers were also asked to specify the amount of funding spent to date and given five different options to select from. The responses obtained indicate that the respondents have varying levels of resources committed to the development of their technologies to date. The breakdown for the funding spent to date was (see also Figure 4):

- < £1m 25%
- < £5m 21%
- < £10m 25%
- < £50m 21%
- > £50m 8%

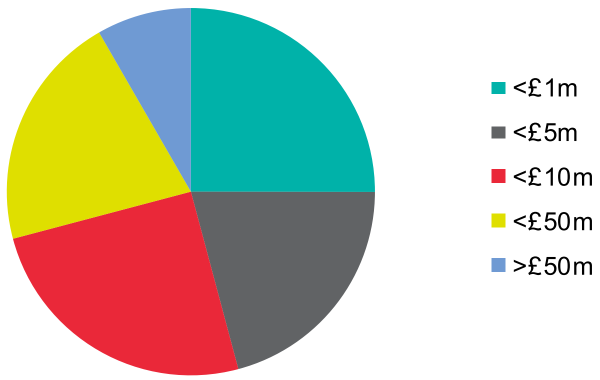


Figure 4 Amount of funding (£m) spent to date by respondents

1.3.3 Modelling activities to date

The significant majority of WEC developers who responded to the survey have conducted both numerical (92%) and experimental (96%) modelling. Developers who completed experimental modelling activities were asked to specify the scale(s) at which the WEC was tested. Three different test scale options were provided for developers to choose from, with a request to select all suitable options. The responses received from the survey were as follows:

- Proof-of-concept (1:100 – 1:20) 61%
- Functional testing (1:20 – 1:5) 57%
- Large scale testing (>1:5) 52%

In addition, 54% of the WEC developers surveyed have also conducted open ocean trials to date, with 29% of those trials involving the testing of WECs connected to the grid.

In short, and although virtually all the respondents have done some numerical and experimental modelling to date, with over half of them testing a functional prototype and conducted some large scale testing, only a small group have proceeded to grid-connected trials. This is consistent with the findings outlined in Section 1.2.2 for both the TRLs and the funding spent to date.

1.3.4 Baseline formulations and methodologies

WEC developers were asked to identify their current baseline load calculation formulations and structural assessment methods. Furthermore, WEC developers were also asked to identify the design situations that, in their perspective, have been assessed to date, and how the load data has been obtained. Respondents were allowed to select all applicable answers, in an effort to provide a comprehensive overview of all of the methods currently being used by WEC developers.

Figure 5 illustrates the breakdown of the responses received to the question that aimed to identify the baseline formulation used in load calculations. The three most popular answers – first-principles (68.4%), linear Boundary Element Methods (BEM) (57.9%) and Morison's equation (52.6%) – demonstrate, at least partially, the infancy of the wave energy industry. Such conclusion can be justified with the fact that any of these formulations provide the means of simulating an accurate representation of all the load sources, thus leading to early-stage numerical models that are likely to be uncoupled, i.e. methods that do not simultaneously account for all the load types identified in Section 2.2 of this report. However, it is encouraging that a large proportion of the survey respondents have identified the use of fully coupled load models in the assessment of critical design situations, although the least detailed option (point load, frequency-domain approach) was, within the fully coupled option, the most popular response (47.4%). More detailed models in the time-domain (either point or distributed loads) were selected by a minority of the respondents (42.1% and 36.8%, respectively), with even fewer developers selecting the most advanced options possible (including fully nonlinear methods). A detailed description of each baseline formulation and an overview of the design situations that may be tackled using the different methods is presented in Section 2.2.6.

Figure 6 illustrates the design situations that respondents have addressed to date. In close alignment with the findings highlighted in the previous paragraph, the overwhelming majority of the respondents have identified ‘power production’ as a design situation already analysed (94.7%). This is consistent with the fact that the majority of WEC developers that responded to the survey identified simpler, potentially uncoupled load calculation formulations as those currently in use (it should be noted that the accuracy of any load estimate, including those that are related to power production conditions, is likely to improve if a suitable fully coupled model is used). The second most popular answer (survival events, 84.2%) can be associated with the use of Morison equation based models. On the other side of the response spectrum, design situations associated with fault scenarios and damage stability are those least addressed to date, with the latter being analysed by only 36.8% of the respondents. Detailed definition of the DLCs associated with each design situation are proposed in Section 2.2.4.

Finally, in Figure 7 a trend that indicates an appetite for experimental modelling as the main source of WEC load data can be identified (see also Section 1.3.8). However, it should be noted that this is closely followed by numerical modelling results. Both findings stress the importance of ensuring that the derived models (numerical and / or experimental) are accurate representations of its full-scale equivalent. Load data from onshore trials and offshore tests are, according to the survey responses, much rarer, with approximately half of the responses when compared to numerical and experimental modelling. Again, the relative infancy of the wave energy industry can be associated with this findings – as e.g. onshore trials for reliability testing are standard practice in more mature industries.

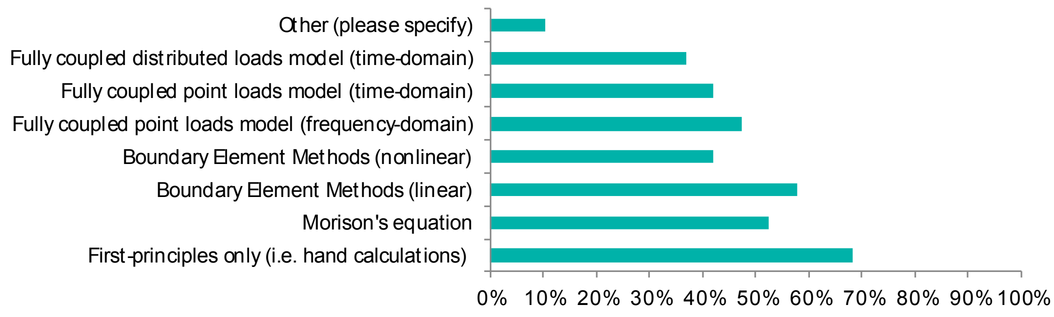


Figure 5 Baseline formulations used in load calculation exercises by respondents

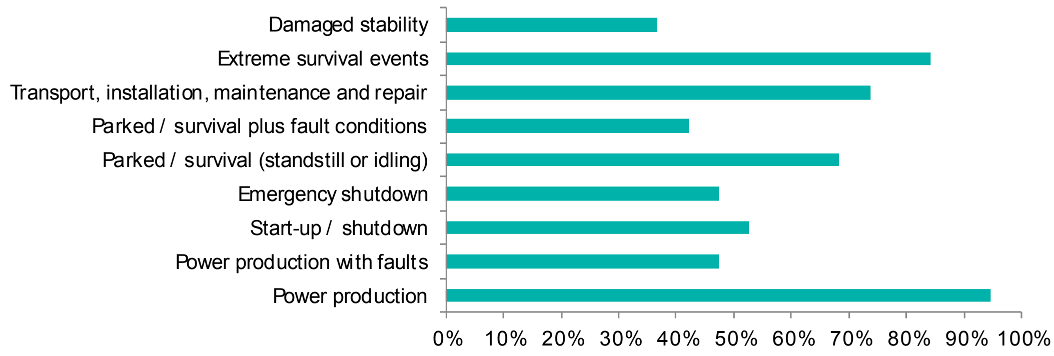


Figure 6 Design situations addressed to date by respondents

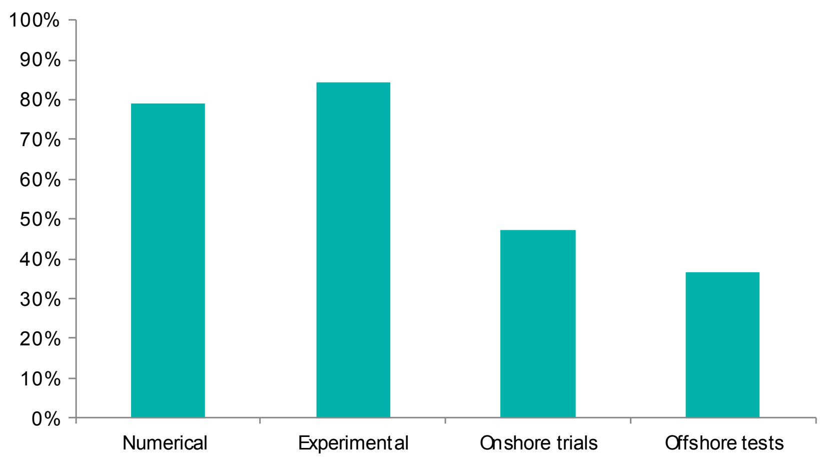


Figure 7 Data used by respondents in load calculation exercises

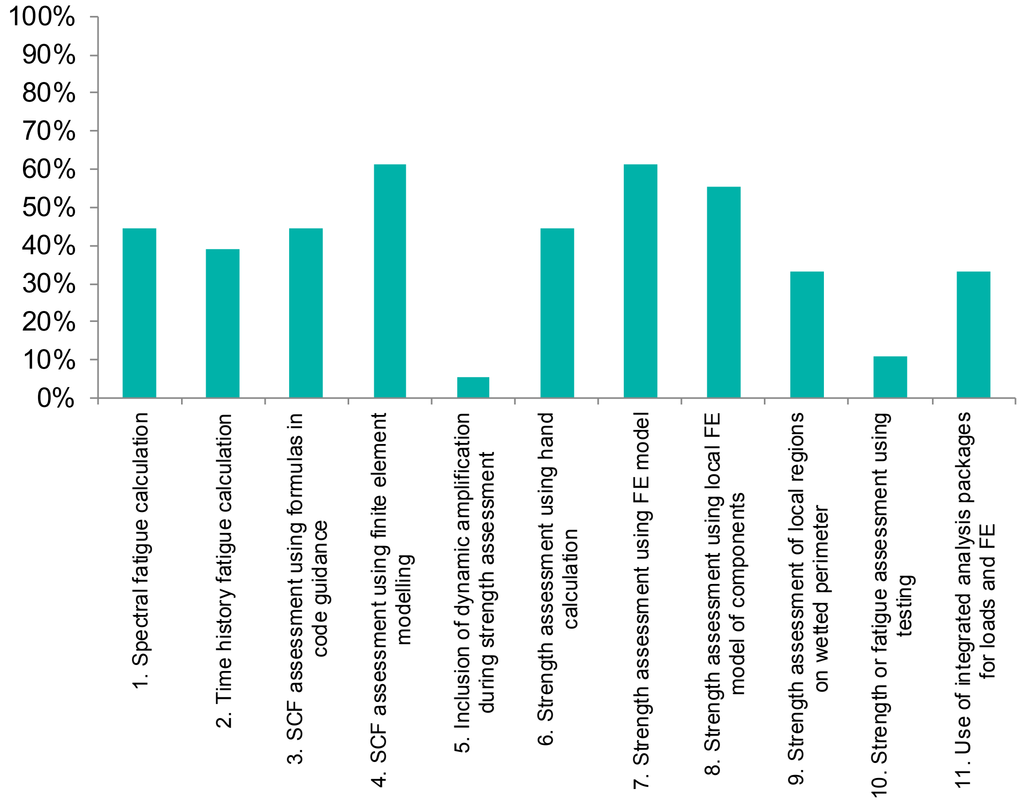


Figure 8 Methods used by respondents in the assessment of structural integrity

Figure 8 illustrates a range of methods which are typically used for the assessment of structural integrity for offshore structures.

Methods associated with fatigue and strength analysis have been grouped separately with options 1-4 relevant to fatigue analysis and options 5-9 relevant to strength assessment. Options 10 and 11 are relevant to both.

It should be noted that entries 1, 2 and 5 overlap with loads assessment methods but are not captured within the load analysis formulations contained in Figure 5.

Fatigue

Offshore fatigue assessment is typically conducted using a time domain simulation or a spectral fatigue calculation. A further breakdown of load assessment methods is contained in Figure 5.

More than 45% of respondents used a spectral fatigue calculation. This technique is widely used in fixed offshore structures and is normally advantageous due to the reduced computational effort compared to time domain simulations. Spectral fatigue relies on a satisfactory representation of the device being provided by a linear system which is unlikely to be the case for the majority of WEC devices. A larger proportion of developers using time domain simulation would therefore be expected.

The dominant methods for the calculation of Stress Concentration Factors (SCFs) were also included as options in the survey (options 3 and 4). The responses show that assessment using Final Element Analysis (FEA or FE) is more prevalent than following code guidance and that some respondents use a combination of the approaches.

These results suggest some consideration of stress concentrations as part of fatigue assessment of WECs. It was expected that a larger proportion of respondents would use FEA for SCF assessment due to the use of novel components with complex geometry that are not covered by code guidance. The results suggest that standard details present in code guidance are still relevant in some instances however.

It should be noted that respondents may not have considered SCFs if detailed global FE models were used. SCF derivation involves a standard process which is applicable to WECs however, and it was therefore expected that the method would be used by a wide range of WEC developers.

Fatigue assessment methods are described further in Section 2.3.4.

<u>Strength</u>

It is likely that a global finite element model is required for detailed design of WECs, supplemented with local models to assess areas with complex geometry. Sixty-two percent of respondents indicated that finite element modelling had been used during design. A large proportion of those using FE modelling conducted detailed local models of components and 45% of respondents used hand calculations. Hand calculations are useful for preliminary design and certain specific calculations but are likely to be insufficient for detailed design of WECs.

Six percent of respondents considered dynamic amplification of the structure during their strength assessment. Dynamic amplification of loads is the term used to define cases where inertial loads associated with resonant response contribute appreciably to the total loads. Inertial forces in fixed structures are often dominated by resonance, but in WECs quasi-static response to hydrodynamic loads can also be significant. Inertial loads due to resonant response may not be considerable in comparison to other loads for WECs, as reflected in the survey response.

Strength assessment methods are described further in Section 2.3.4.

<u>Other</u>

Eleven percent of respondents used testing of individual components as part of their design process. It is standard practice to undertake structural testing for the detailed design of synthetic materials which are used widely in moorings and may be present in several WEC designs.

Thirty-three percent of respondents used integrated analysis packages for the assessment of structural loads and FE analysis. This type of software is widely available for the assessment of fixed offshore structures (e.g. DNV Sesam) and this result suggests that similar analysis packages suitable for WEC design are also available.

1.3.5 Design procedure overview

Survey questions were posed to assess the familiarity or application of different design procedures by WEC developers. The following responses were obtained to the questions posed:

- 90% of respondents are familiar with design load cases (DLCs).
- 79% of respondents completed a failure mode and effects analysis (FMEA).
- 45% of respondents conducted limit state design in line with code guidance.
- 78% of respondents have developed a basis of design document.
- 77% of respondents follow design standards or guidelines from a range of industries. Table 2 presents the crossover between guidelines used by WEC developers and other industries.

Table 2 Design standards/guidelines used by survey respondents from other industries

Industry	% Respondents
Wave and tidal	85%
Offshore engineering	69%
Oil and gas	46%
Offshore wind	39%
Other (i.e. pressure vessel standards)	23%

1.3.6 Assessing the need for clearer design methodologies

WEC developers were asked to provide their opinion on whether clearer load and structural design methodologies were required. The responses received from developers who participated in the survey was a resounding yes, with 94% of respondents agreeing that clearer methodologies are required.

Developers were subsequently asked; if this landscaping study provides detailed design guidance, how likely are they to use the study findings? Figure 9 illustrates the survey responses obtained, which indicate that 76% of the respondents are likely (i.e. response ≥4) to use detailed design guidance informed by this landscaping study.

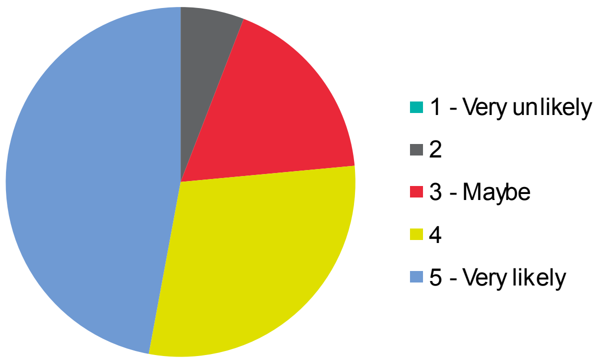


Figure 9 Likelihood of survey respondents to use detailed design guidance informed by this study

1.3.7 Detailed comparisons

In an effort to map the methodologies for loads and structural integrity assessment currently applied by WEC developers, individual survey responses were examined and compared. The process chosen to map design procedures applied by developers was to compare methodologies based on the TRL of the WEC technology.

In some cases, these comparisons produced findings in line with the initial expectations. For example, Table 3 compares survey responses from WEC developers at relatively high (7) and low (4) TRLs. The responses illustrate that a WEC with a higher TRL followed a more comprehensive design process, which implemented more sophisticated load estimation formulations and considered the majority (7 of 9) of design situations listed, compared to the device at a lower TRL where only the first-principles formulation was applied and three design situations were assessed.

Table 3 Comparison between responses for WECs at a relatively high and low TRL

	Respondent # 24	Respondent # 23
Device type	Attenuator	Oscillating water column
TRL	4	7
Numerical modelling	No	Yes
Experimental testing	Proof-of-concept (1:100-1:20); functional testing (1:20-1:5)	Large scale testing (>1:5); ocean trials - grid connected
Baseline formulation for loads	First-principles	First-principles; BEM (linear); fully coupled point loads model (freq.-domain); fully coupled distributed loads model (time-domain)
Design situations	3 design situation considered	7 design situations considered
Data used in load analysis methods	Experimental	Numerical, experimental, onshore trials and offshore tests
Familiar with DLCs	Yes	Yes
Conducted a FMEA	No	Yes

However, the design methodologies implemented for WEC technologies at mid-level TRLs (5-6) were more difficult to characterise, with a wide range of responses received from developers. For example, Table 5 presents the survey responses for two WEC developers that identified themselves at the same TRL, but with quite distinct design approaches. One developer has undergone a series of experimental tests at different scales, while the other has directly progressed to large-scale testing. Both developers have implemented relatively basic formulations for loads and have a varied knowledge of design procedures used in other industries (i.e. DLCs and FMEA). Respondent # 5 only considered performance design situations, whilst respondent # 2 claims to have considered all of the nine design situations listed in the survey despite not being familiar with DLCs (although it is noted that a very basic baseline formulation for load analysis is listed by the same developer). This broad range in the respondents' answers highlights the difficultly of creating a design procedure that can be adopted by WEC developers with varying levels of familiarity with standard design practices, a fact that has been taken into account when deriving the methodologies proposed in this report (see Section 2).

Table 4 Comparison between survey responses for WECs at a TRL of 5

	Respondent # 5	Respondent # 2
Device type	Point absorber	Oscillating wave surge converter
TRL	5	5
Numerical modelling	Yes	Yes
Experimental testing	Proof-of-concept (1:100-1:20); functional testing (1:20-1:5); ocean trials–not grid connected	Large scale testing (>1:5)
Baseline formulation for loads	Morison's equation	First-principles
Design situations	1 design situation considered	9 design situations considered
Data used in load analysis methods	Experimental	Experimental, onshore trials and offshore tests
Familiar with DLCs	Yes	No
Conducted a FMEA	Yes	No

Finally, Table 5 compares responses from point absorber device developers at a similar TRL of 6. Both respondents have implemented detailed baseline load formulation methods and considered a wide range of design situations. These results show a general progression towards more detailed load analysis procedures for devices with a higher TRL, when comparing Table 5 to the survey responses presented for WECs at TRL 5 presented in Table 4.

Table 5 Comparison between survey responses for WECs at a TRL of 6

	Respondent # 12	Respondent # 7
Device type	Point absorber	Point absorber
TRL	6	6
Numerical modelling	Yes	Yes
Experimental testing	Proof-of-concept (1:100-1:20); functional testing (1:20-1:5); large scale testing (>1:5); ocean trials - grid connected	Large scale testing (>1:5); ocean trials - grid connected
Baseline formulation for loads	First principles; Morison's equation; BEM (linear &non-linear); fully coupled point loads model (freq. and time-domain); fully coupled distributed loads model (time-domain)	Fully coupled point loads model (freq. and time-domain); fully coupled distributed loads model (time-domain)
Design situations	5 design situation considered	8 design situations considered
Data used in load analysis methods	Numerical, experimental, onshore	Numerical, experimental, onshore trials & offshore tests
Familiar with DLCs	Yes	No
Conducted a FMEA	Yes	Yes

1.3.8 Overview of WEC developer survey findings

Based on the survey responses, two WEC developer groups are identifiable for devices assigned a mid-level TRL. These are briefly introduced in Figure 10.

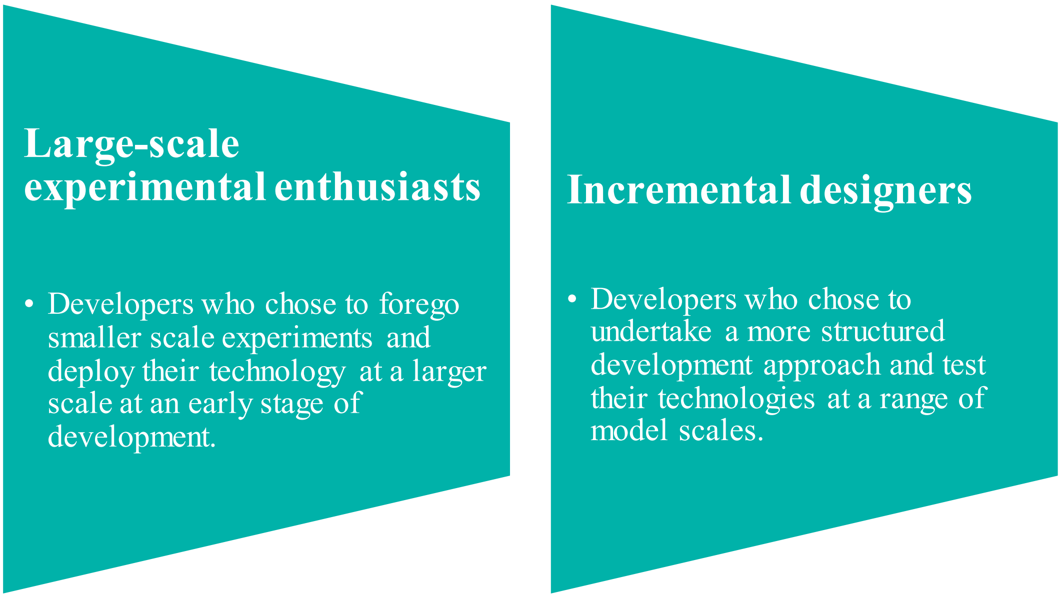


Figure 10 WEC developer groups (based on the survey responses)

In an effort to map the load methodologies currently applied by these groups of WEC developers, some key characteristics have been extracted from the survey results and are summarised in Table 6. It should be noted that a high degree of variability can be associated with the answers, thus the Table 6 summary simply presents a snapshot of the most notable patterns visible in the survey responses.

Table 6 Methodologies currently used by different classifications of WEC developers

Large-scale experimental enthusiasts	Incremental designers
• Test at large scale or open ocean trials. **No small scale tests.** • **Basic load formulations** used (i.e. first principles and Morison's equation). • Load methodologies informed by experimental results. • Mainly **performance** design situations considered.	• **Test conducted at a range of scales**. (Proof-of-concept; functional tests; large scale test and open ocean trials). • **Range of load formulations considered.** • Load methodologies informed by experiment, numerical and open ocean results. • Both **performance and non-performance** design situations considered.

Another group of WEC developers identifiable from the survey responses can be associated with early-stage, new-generation WEC developers. These developers appear to implement more detailed baseline load formulation methodologies, using numerical models, at a lower TRL. Some consideration is also give to non-performance design situations, in addition to power production. Table 7 presents a list of characteristics broadly identifiable from the survey results for the respondents (low to mid TRL) that fall under the classification of early stage, new generation WEC developers.

Table 7 Key characteristics of the early stage, new generation WEC developers

Early stage, new generation WEC developers
• **Numerical modelling focused**. Smaller scale model tests in functional environments (i.e. proof-of-concept and functional tests). • **Range of load formulations** considered from an early stage. • Load methodologies mainly informed by numerical results. • Smaller sub-set of **performance and non-performance design situations considered.**

It should be noted that the classifications outlined in Table 6 and Table 7 were also informed by phone interviews with selected respondents. In general, the contacted developers acknowledged that further guidance was required and that more detailed methods at an earlier stage could help to prevent the use of unsuitable design methodologies, which in turn could lead, at a later and potentially irreversible detailed design stage, to an under- or over-conservative design of specific aspects of a WEC. The results of the survey highlighted a clear need for usable design guidance for the development of WECs.

2 Load and Structural Analysis

This Section contains guidance for load and structural analysis, building on the information that was presented in Section 1.

It contains a brief overview of the 7 types of WECs that are considered in this study, followed by an interpretation of suitable methods for load and structural analysis in the context of these WEC types. This is summarised in rating matrices which rank the applicability of load and structural analysis methodologies to design situations and WEC device types. The Section concludes with an example load and structural integrity calculation for a generic point absorber device.

2.1 WEC Types

The following 7 WEC types were considered in this report. A brief description of each, accompanied by a generic sketch, is provided below.

1. Point absorber
2. Oscillating wave surge converter
3. Oscillating water column
4. Bulge wave
5. Attenuator
6. Overtopping
7. Pressure differential

2.1.1 Point Absorber

This is a floating device that is small in comparison to the incident wavelength. The heaving motion drives the PTO (power take-off) system. The device may be fixed to the seabed or be suspended mid-water. A schematic of an example point absorber is shown in Figure 11.

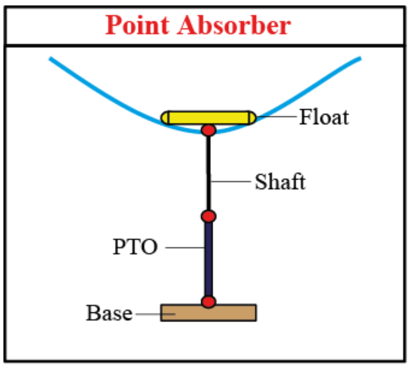


Figure 11 Schematic of an example point absorber converter

2.1.2 Oscillating Wave Surge Converter (OWSC)

In this device a partially or fully submerged flap rotates about a fixed or sliding hinge. The motion of the flap or hinge drives the PTO. The hinge may be fixed to the seabed (bottom hinged) or fixed to an overhang structure (top hinged). A schematic of an example OWSC is shown in Figure 12.

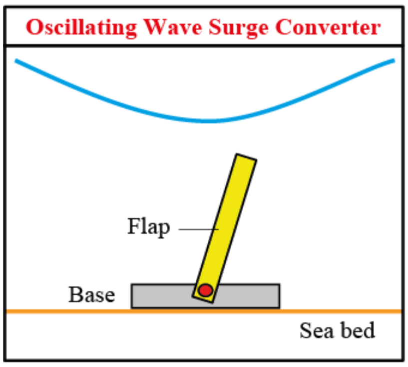


Figure 12 Schematic of an example oscillating wave surge converter

2.1.3 Oscillating Water Column

This device may be offshore or onshore. It has a partially submerged hollow chamber. The oscillating water height inside the chamber compresses/ decompresses the air above it and drives an air turbine. A schematic of an example oscillating water column device is shown in Figure 13.

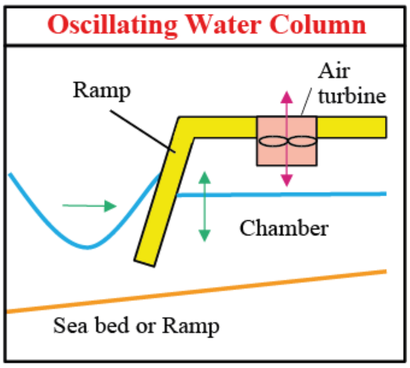


Figure 13 Schematic of example oscillating water column converter

2.1.4 Bulge Wave

This device includes a submerged rubber tube acting parallel with the direction of wave travel. The water enters through the bow which generates a “bulge” pressure wave that travels along the tube and drives a hydraulic turbine located at the stern. A schematic of an example bulge wave device is shown in Figure 14.

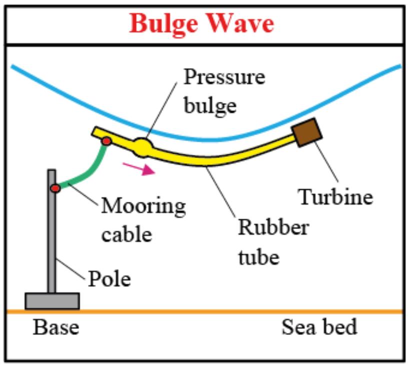


Figure 14 Schematic of example bulge wave converter

2.1.5 Attenuator

This is a floating device which generally acts parallel with the direction of wave travel; sometimes referred to as a line absorber. The relative motion between the Sections drives an internal PTO. A schematic of an example attenuator device is shown in Figure 15.

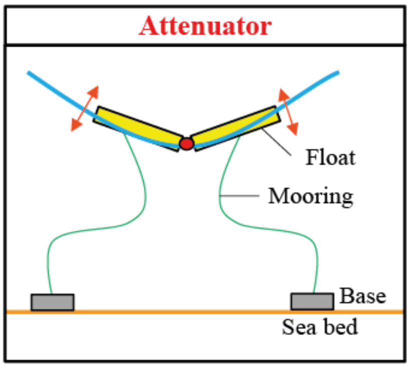


Figure 15 Schematic of example attenuator converter

2.1.6 Overtopping

This may be an offshore or onshore device which includes an open reservoir. The oscillating water height in the reservoir drives a hydraulic turbine. A schematic of an example overtopping device is shown in Figure 16.

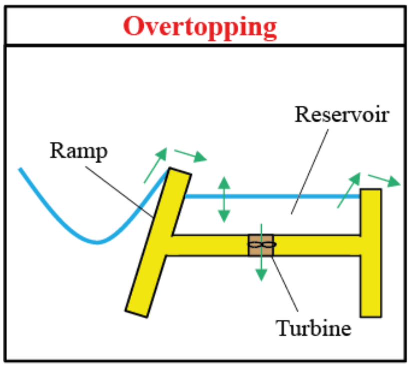


Figure 16 Schematic of example overtopping converter

2.1.7 Submerged Pressure Differential

This is a submerged device with a base fixed to the sea bed. The buoy heaves in response to varying water draft above it as the wave passes. The heaving motion drives the PTO. A schematic of an example submerged pressure differential device is shown in Figure 17.

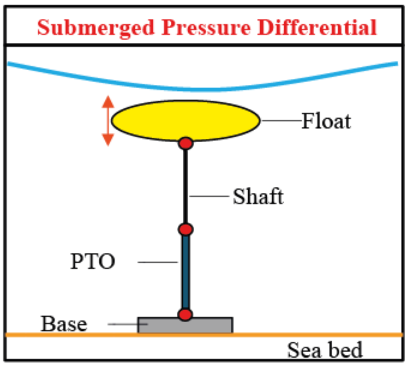


Figure 17 Schematic of example submerged pressure differential converter

2.2 Load Calculations

2.2.1 Types of Loads

Following Section 2 of the GL Rules and Guidelines IV-6-4 (2007) *Offshore Structures: Structural Design*, design loads for marine structures include:

- Environmental loads (e.g. wind, current and wave loads, marine growth, etc.);
- Permanent loads (e.g. weight of structures, permanent ballast, buoyancy, etc.);
- Functional loads (loads from transport and installation operations, power take-off (PTO), varying ballast, etc.);
- Accidental loads (e.g. collisions, flooding of buoyant compartments, mooring line failures, inadequate lifting operations, explosions, etc.).

The GL Rules and Guidelines IV-6-4 (2007) document specifies which design loads are to be used in structural analysis of offshore structures. Other documents, such as GL Rules and Guidelines IV-2 (2012) *Guideline for the Certification of Offshore Wind Turbines (Chapter 4 – Load Assumptions)*, apply similar methods to derive DLCs for fatigue and ultimate strength scenarios. Additional types of loads, such as deformation loads, are introduced in e.g. DNV-OS-J103 (2013) *Design of Floating Wind Turbine Structures*.

In the absence of offshore standards specifically related to WEC design, a methodology is proposed to derive design load cases (DLCs) which can be used to assess fatigue (F) and ultimate strength (U). The proposed methodology should be complemented by an FMEA for all critical sub-systems. A preliminary failure analysis by WEC type is presented in Section 2.3.2.

Following [1] and based on the documentation suggested in Table 1, preliminary load cases can be defined (see also Section 2.2.4). For WEC design, and similarly to the design procedures outlined in GL Rules and Guidelines IV-2 (2012) *Guideline for the Certification of Offshore Wind Turbines, Chapter 4 – Load Assumptions*, the DLCs may be further grouped within the ultimate strength (U) category and split into the design categories:

- Normal (N);
- Extreme (E);
- Abnormal (A);
- Transport and installation (T).

It is recommended that the calculation of design loads is primarily conducted computationally via fully coupled time-domain numerical simulations that accounts for all load contributions simultaneously. Such procedure is consistent with method II.2 of GL Rules and Guidelines IV-6-4 (2007) *Offshore Structures: Structural Design (Section 4.6)*, which applies to the majority of the WEC types outlined in Section 2.1. Further guidance, including the main source of wave loads to be considered pending on the type of offshore structure, is given in e.g. DNV-

RP-F205 (2010) *Global Performance Analysis of Deepwater Floating Structures* (see Table 3-1, page 12).

It should be noted that in both GL Rules and Guidelines IV-6-4 (2007) and DNV-RP-F205 (2010), fully coupled rigid body models that take into account all relevant load sources are mentioned as suitable for analysis. For certain WEC types (e.g. bulge wave), numerical solutions using deformable bodies may be required prior to structural assessments, however this may not be achieved in practice if all load sources are accounted for simultaneously (which should be seen as a priority). Numerical simulation which includes deformable bodies is computationally very expensive and there are limited software solutions available for this purpose.

All relevant nonlinearities, including those induced by the main sub-systems such as the PTO and the moorings, are to be considered. At least some of these nonlinearities (e.g. those related to hydrodynamics or mooring forces) may also be evaluated experimentally. Where possible, comparisons between numerical and experimental estimates are recommended.

For WECs, coupled analysis of all major loads should be carried out in the time-domain. Simulation periods should be increased from the standard wind industry default of 10 minutes in order to adequately capture effects associated with the natural frequencies of support structures. A minimum simulation length of 30 minutes is recommended when investigating the WEC response. Furthermore, it is recommended that the variability of parameters derived from 30 minute simulations is checked under simulations with the same spectral density and different sets of random phases and directions (if applicable). This is particularly relevant should phase control techniques be implemented by the WEC.

For estimating the maxima and minima of a WEC response variable (e.g. motion response) in a given sea state, a longer simulation time is recommended (~3hrs). Where applicable, a minimum simulation length of 1 hour is recommended to adequately model second-order effects and slow varying responses. These recommendations are aligned with those proposed in DNV-OS-J103 (2013).

The calculated loads may be used in further structural design assessments similar to those outlined in GL Rules and Guidelines IV-2 (2012) *Guideline for the Certification of Offshore Wind Turbines (Chapter 5 – Strength Analyses)*. Initial guidance on the methodology suggested for strength assessment is given in Section 2.3.

The concept of limit states should also be considered when defining types of loads and DLCs. This concept is briefly described in Section 2.3.

2.2.1.1 Ultimate Loads

As outlined at the start of Section 2.2.1, the design load categories to be considered in the overall load and strength analysis calculations include permanent loads, variable function loads, environmental loads, and accidental loads. For all of these categories, the maximum loads to be expected in service are usually classified as ultimate loads when considering WECs.

The dynamic loads acting on a WEC will, in general, be driven by its response to the environment (waves, currents, etc.). The design environment must be carefully selected to ensure that it covers the sea states which lead to the maximum loading on the WEC during its design lifetime. In this regard, it is important to acknowledge that the loads will, in addition to wave height, be primarily sensitive to wave period and directionality, and potentially the phasing of wave groups. Preliminary guidance on how to define the relevant environmental conditions is provided in Section 2.2.2.

The GL Rules and Guidelines IV-2 (2012) state that generally DLCs used to determine structural integrity of offshore wind turbines can be calculated from the following combinations:

- Normal design situations and normal external conditions;
- Normal design situations and extreme external conditions;
- Fault design situations and related external conditions;
- Design situations for transportation, installation and maintenance, and the appropriate external conditions.

The principles overviewed in GL Rules and Guidelines IV-2 (2012) can be applied to determine the structural integrity of WECs. Additionally, if any correlation exists between an extreme external condition and a fault design situation, a realistic combination of the two should be considered for a DLC.

The following are considered to be of key importance for the analysis of ultimate loads on WECs:

- Hydrostatic loads;
- Hydrodynamic loads;
- Inertial forces, both rotational and translational, arising due to acceleration of part or all of the device;
- Abrupt forces from support nonlinearities (e.g. mooring line maximum extensions or failure, end-stop activation, etc.);
- Marine growth loading (e.g. weight and drag);
- Wave run-up and overtopping (“green water”) loading;
- Power take-off (PTO) loads and effects from the control system;
- Mooring loads (including loads induced at the mooring attachment points), if applicable;
- Point loads at critical mechanical systems (e.g. end-stops, mechanical fail-safe, seabed attachments, bearings, etc.);
- Accidental loads (collisions, impacts, etc.).

It should be noted that some of the items listed above may be excluded depending on the type of WEC, its characteristics and the target site conditions.

For the hydrodynamic loads, DNV-RP-F205 (2010) *Global Performance Analysis of Deepwater Floating Structures* provides recommended practices regarding global performance analysis of deep-water floating structures and lists hydrodynamic effects of importance for each class of floater found in the oil & gas industry. Following this reference, it is recommended that the following hydrodynamic load sources are considered to assess whether they have a material effect on the global motions or loading of the WEC:

- Wave frequency loads;
- Low frequency loads (i.e. wave drift forces);
- Air-water interface loading (i.e. wave slamming loads).

The four load design categories outlined at the start of Section 2.2.1 can also be defined based on the recurrence period of external conditions. In turn, and to assist with the definition of the type of load and partial safety factor to apply, the design categories can be related to design situations. This relationship is illustrated in Table 8.

When assessing ultimate loads, and to ensure that reliable design values are obtained, the loads shall be multiplied by a partial safety factor, γ_F (as per the formula below). This safety factor shall cover the uncertainties of the procedure, the probability of the load occurring, possible deviation of the loads from the characteristic values, and the accuracy of the load model.

$$F_d = \gamma_F \cdot F_k$$

where:

F_d - Design value of the load

γ_F - Partial safety factor for the load

F_k - Characteristic value of the load.

Table 8 Design categories: recurrence period and design situation (based on [3])

Design category	Recurrence period	Design situations
Normal (N)	≤ 1 year	Normal operation Normal operation plus fault Parked / idling Parked / idling plus fault Parked / idling after fault "Survival" configuration
Extreme (E)	≤ 50 years	Parked / idling Parked / idling plus fault "Survival" configuration
Abnormal (A)	≤ 500 years	Hurricane Earthquake / tsunami Accidents
Transport and installation (T)	≤ 1 year	Installation Maintenance

The value(s) of load partial safety factor(s) to be used depend(s) on the various design categories defined in Table 8 and the source of loading (environmental, operational, permanent, accidental). At subsequent design stages, the load factors to apply for all WEC components may be initially adapted from related standards, following e.g. Table 1. The initial selection may also benefit from initial high-level discussions with a certification body.

In many cases, especially when unsteady loads lead to dynamic effects, the load components cannot be determined independently of each other. In these cases, the highest partial safety factor, γ_F, of the corresponding design category shall be applied to the loads.

For the assessment of mooring loads, including mooring line tensions, specific guidance can be found in e.g. DNVGL-OS-E301 (2015) (see also Table 1).

Loads defined in these standards shall apply to the design of the mooring lines as well as the design of the anchor that transfers the loads to the seabed.

It should also be noted that DNVGL-OS-E301 (2015) defines characteristic environmental loads based on a 100-year recurrence period, compared to the 50-year period suggested in DNV-OS-J103 (2013).

In the transition to the detailed design stage, it is recommended that ultimate load DLCs specifically address structural vulnerabilities where failure can be expected to occur more easily (e.g. mooring line connection points, bearings, end-stops, etc.). These areas can be identified following an FMEA exercise (see Section 2.3.3) and are also likely to be critical in fatigue load strength assessments.

2.2.1.2 Fatigue Loads

In DNVGL-OS-C103 (2015) *Structural Design of Column Stabilised Units (LRFD[4] Method) Chapter 2, Section 2 – Design Loads*, fatigue loads are classified as repetitive loads which could lead to significant fatigue damage. The following load sources are identified:

- Waves (including those loads caused by slamming and variable pressures);
- Wind;
- Currents (especially when vortex induced vibrations may occur);
- Equipment induced, mechanical loading and unloading (e.g. PTO, moorings, etc.).

General guidelines on fatigue loading and analysis can be found for floating offshore vessels in DNVGL-RP-C206 (2015) *Fatigue Methodology of Offshore Ships* and in ABS Pub #115 (2003) for offshore structures. In the absence of WEC specific recommendations, these can be used as representative examples.

Furthermore, GL Rules and Guidelines IV-6-4 (2007) also prescribes that fatigue strength analysis should be performed for all structures which are exposed to cyclic loading, with wave loading as the main source of potential fatigue cracking. Specific guidance is given in e.g. DNV-RP-C205 (2014) *Environmental Conditions and Environmental Loads* for particular loading sources. For example, the contributions to fatigue damage due to wave slamming loads can be assessed in Section 8.9 of DNV-RP-C205 (2014).

ABS Pub #115 (2003) *Guide for the Fatigue Assessment of Offshore Structures* highlights that some of the loads may excite dynamic response, which can in turn amplify the acting fatigue inducing stresses. Such motion stresses highlight the importance of using fully coupled models when estimating fatigue loads. Other methods for including these dynamic loads are described in Section 2.3.4.

It is recommended that the following distributions are used for the calculation of fatigue loads (including lifetime weighted equivalents):

- A range of directionally spread sea states (in combination with unidirectional current and wind effects, if applicable);
- If available, site specific metocean data should be used. In the absence of directional information, a parametric distribution for the directional spread may be considered.

Damage Equivalent Loads (DELs) can be calculated to relate the fatigue damage represented by Rain Flow Cycle Counting (RFCC) data to that caused by a single stress range repeating at a single frequency. Damage equivalent loads provide a suitable high level metric for assessing fatigue damage for a given WEC

[4] Load and Resistance Factor Design.

geometry. The method is based on Miner's rule and the damage equivalent stress is given by the formula:

$$L_N = \sqrt[m]{\frac{\sum L_i^m n_i}{N}}$$

where:

L_N is the equivalent stress for N cycles

L_i is the stress range bin i

n_i is the number of rain flow cycles at stress range bin i

m is the negative inverse of the slope on the material's Wöhler curve (m is also referred to as the S-N curve slope)

N is the number of cycle repetitions in the WEC lifetime.

The stress L_i is dependent on the geometry of the structure under consideration. It is assumed that stress is proportional to load, and therefore it is acceptable to use load instead of stress in the above equation. For simplicity, L_i and n_i may be derived from the one-dimensional table of stress ranges vs. number of cycles with no correction to account for the fatigue damage due to mean stresses.

There is limited experience in WEC design to allow the specification of a reference frequency for lifetime integrated DELs. As an example, Table 9 illustrates the reference frequency for a common value of number of cycles and different device lifetime. Should the lifetime of the prototype be reduced, the resulting reference frequency will be considerably higher. Rain flow cycle exceedences and Markov matrices of the main load components may also be presented in the loads calculations report.

Table 9 Examples of reference frequencies for lifetime integrated DELs

Number of cycles	**WEC lifetime (years)**	**Reference frequency (Hz)**
1.E+07	1	0.3171
1.E+07	5	0.0634
1.E+07	20	0.0159

2.2.2 Defining the Environmental Conditions

As outlined in Section 1, a metocean design basis report should be provided at the design basis stage to define the representative conditions at an installation site. Several documents that define the information required to describe the environmental conditions are also introduced in Table 1. Overall, the following key documents can be followed:

Section 3 (B) of the DNV-OSS-312 (2008) *Certification of Tidal and Wave Energy Converters* for an overview of the environmental data used as a basis for the design;

Section 1 of the GL Rules and Guidelines IV-6-4 (2007) *Offshore Structures: Structural Design* for technical definitions specifically related to the environmental conditions (wind, wave, currents, tides, etc.);

Section 7 of the DNV-RP-C205 (2014) *Environmental Conditions and Environmental Loads* for an overview of appropriate theory for wave and current induced loads on large volume structures.

It is recommended that the definitions associated with the above listed documents are followed and, where relevant, adapted to wave energy conversion. For example:

- The description of the site conditions must be made in sufficient detail so that the DLCs cover all representative operational conditions at the site;
- If measured site specific spectral shapes are not available, IEC 61400-3 (2009) recommends using JONSWAP spectra for representing developing wind seas and Pierson-Moskowitz (PM) spectra for fully developed seas. Should double-peaked spectra be considered, DNV-RP-C205 (2014) recommends the use of the Torsethaugen spectrum. This may be relevant as single peak spectra based on a single wave period parameter can significantly underestimate the amount of energy at low frequencies, which may affect e.g. fatigue loading calculations.

It may be possible to exclude some conditions from the DLCs based on the WEC design and consideration of the environmental conditions at a planned installation site. Examples of these exclusions may involve:

- Wind induced loads (should the WEC freeboard be sufficiently small);
- 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);
- Tsunamis (if a site is not in a high risk region);
- Sea ice and icebergs (if the probability of occurrence of seasonal or permanent sea ice is reduced at a site);
- Seismic effects / seabed stability (if seismic activity and seabed movements are not expected at a site);
- Sea temperature / thermal effects (to be considered only if the site specific thermal range will affect structural design).

2.2.3 Defining Relevant Design Situations

The loads analysis methodology described in this report may be illustrated in a set of DLCs, designed to be representative of all significant loading scenarios experienced during the lifetime of a WEC device. The DLCs detailed in Section 2.2.4 and summarised in Section 2.2.5 are provided as an illustrative set for initial consideration. The following design situations are addressed (see also Section 2.2.4 for a detailed description of each situation):

- Power Production;
- Power Production Plus Occurrence of a Fault;
- Start-up;
- Normal Shutdown;
- Emergency Shutdown;
- Parked / Survival (standstill or idling);
- Parked / Survival Plus Fault Conditions;
- Transport, Installation, Maintenance and Repair;
- Accidental / Abnormal Events (if not covered in any of the other load cases);
- Damaged Stability.

Some cases may be excluded on a WEC or site specific basis, and a final DLC selection should be preceded by a WEC specific risk analysis and/or Failure Mode and Effects Analysis (FMEA) study to identify the design situations that may apply to the design process. The PTO and other machine settings that apply to each design situation should be defined. If multiple PTO conditions or machine operational states apply for a design situation, then those leading to the highest loads should be selected.

The analysis of the FMEA and the adoption of the methodologies provided in Section 2.2 will directly contribute to the creation of load case descriptions from which a series of simulations associated with the final DLCs can be defined. As a first step, the definitions of the environmental conditions and of each load case descriptions are presented in Section 2.2.4.

2.2.4 Design Load Cases (DLCs)

2.2.4.1 DLC Environmental Conditions

As described in Section 2.2.2, environmental conditions can vary significantly across WEC deployment sites. The environmental conditions used in the DLCs summarised in Section 2.2.5 attempt to capture the most significant environmental effects that may drive ultimate and fatigue loading. A combination of irregular wave sea states, synthesised regular waves and wave groups are proposed as a potential means of characterising critical loading situations. The terminology used to describe these environmental conditions, together with some additional notes for tidal conditions, are outlined below.

Normal Operational Sea States: These correspond to irregular wave sea states covering the standard operational scatter diagram for the WEC (binned by significant wave height, H_s and energy period, T_e). The range of H_s, T_e combinations is restricted by the wave breaking criteria (steepness and depth limitations, where relevant). If the WEC is axisymmetric, a single mean wave direction may be considered. For each H_s, T_e pair, a single unimodal spectral shape is assumed. The effect of the spectral shape on the ultimate loading is considered separately under a reduced subset.

Reduced Range Normal Operational Sea States: For some DLCs, where ultimate loading is of particular importance, a reduced range of normal operational conditions may be specified. Conditions are synthesised for a subset of the normal operational case H_s, T_e combinations, allowing additional machine or environmental conditions to be imposed on the machine, or for the effects of different unimodal and bimodal spectral shapes to be analysed. The sea states leading to the highest loading under the full range of normal operational conditions will be selected for this reduced set. The reduced range will cover the complete operational range, albeit at a coarser resolution.

In the case of bimodal sea states, simulations will be completed with a range of divisions of energy between the low frequency swell and high frequency wind sea components of the spectrum and a range of separations between the periods of the swell and wind sea peaks.

The effect of differing wind sea and swell directions may also be considered.

Regular Waves: Regular wave sets can be specified for DLCs where the WEC is required to settle into a steady-state response prior to a loading or fault event in the simulation. The regular waves will be ramped up, starting from calm water, in order to mitigate the risk posed by transient effects at the start of simulations.

Focused Wave Group: The machine response and potential damage associated with an instantaneous loading event or fault is dependent on the sea state in which the loading event occurs. Focused wave groups are suggested as a means of ensuring that the machine experiences significant wave loading during the fault or high loading event. The ability of the machine to respond to the event despite wave loading represents an important part of the analysis. The effect of the timing of the loading event with respect to the wave group will be investigated.

For the simulations outlined in DLC 1.4 (see 'DLC Descriptions') where the effect of larger waves within operational sea states is examined, the focused wave group will be defined to have a height corresponding to the most probable maximum value for each sea state bin, based on the expected number of hours per year associated with each bin.

Simulations in focused wave groups should not replace longer simulations in random irregular waves to establish the ultimate loading resulting from continuous operation.

Extreme operational sea state: Following DNV-OS-J103, extreme sea states beyond the limits of the operational range can be modelled using irregular, directionally spread waves with the 1-year and 50-year return values of H_s.

Normal current model: The wave conditions above may be supplemented by varying sub-surface current conditions. The normal current model accounts for the current velocity profile as a function of water depth and also the wave-current interaction effects.

Tide levels: Tidal range effects may have an impact on the WEC response and loading. The range of operational water depths throughout the machine lifetime will be considered in the DLCs. For ultimate load cases, the most conservative water depth for machine loading will be assessed on a case by case basis.

2.2.4.2 DLC Descriptions

Design Load Cases are described in detail below, and tabulated against environmental conditions and relevant design situations in Table 10.

Power Production (DLC 1.1 to 1.6)

In this design situation, the WEC is in operation and is connected to the electrical grid. The control system is set to normal power production.

In DLC 1.1, a normal operational sea state is assumed, with a directional spread that is representative of the site (or range of sites) where the WEC will be deployed. The effect of currents may be considered if these are judged to be significant at the site or range of sites under assessment.

In DLC 1.2 the effects of tidal currents are considered in greater detail and multiple current directions are considered. Simulations are conducted for a subset of the sea states defined for DLC 1.1, including the most severe cases.

In DLC 1.3, loading combinations resulting from a range of spectral shapes, including bimodal spectra with two widely spaced frequency and/or directional components are considered.

DLC 1.4 covers large wave groups that may occur during operational sea states (using focused wave groups). The random phasing assigned to the DLC 1.1 sea states may not lead to the generation of these as part of the normal operational time series and so loading effects are accounted for using focused wave groups. This approach reduces the need to run lengthy sea state simulations with multiple random wave phases.

In DLC 1.5 transient switching operations of the WEC triggered by grid failure (rather than machine fault as addressed under design situation 2) is considered with regard to the analysis of fatigue loads.

Finally, in DLC 1.6 the operation of the machine with substantial marine growth and/or freeboard icing is considered for a subset of DLC 1.1 operations. The level of marine growth will depend on the frequency of maintenance operations and the water conditions in the proposed deployment sites.

Power Production Plus Occurrence of a Fault (DLC 2.1 to 2.3)

Any fault in the control or safety system or any internal fault in the PTO system that is significant for WEC loading (such as a generator short circuit) is assumed to occur during power production in this category of load cases. It will be assumed that independent faults do not occur simultaneously.

Control system faults that can be considered a normal event are covered in DLC 2.1, whilst safety system fault events considered abnormal or rare are considered in DLC 2.2.

DLC 2.3 covers faults that cause an immediate shutdown or any other faults for which the consequent loading can lead to significant fatigue damage.

The following fault cases may be common enough to be considered as part of the DLCs (for loads which may feasibly occur during the lifetime of the machine).

- Transducer failure – control system demands incorrect PTO restraint forces.
- Joint seizure in an articulated part of the WEC structure.
- Complete seizure.
- Stroke length limitation.
- Loss of grid power due to internal WEC fault.
- Hydraulic or pneumatic PTO depressurisation.
- Operation following mooring line failure for floating WECs, resulting in WEC reorientation and repositioning, is considered in DLC 10.

Start-up (DLC 3.1)

This design situation includes all the events resulting in loads on the WEC during the transitions from any standstill or idling situation to power production.

DLC 3.1 considers start-up of the machine during a sub set of operational sea states deemed to meet the environmental start-up criteria specified by the manufacturer.

Normal Shutdown (DLC 4.1 to 4.2)

This design situation includes all the events resulting in loads on the WEC during normal transitions from power production to a standby condition (standstill or idling).

DLC 4.1 represents cases where the device operator shuts down the WEC. Shutdown times at a range of different instants during a focused wave group may be considered.

DLC 4.2 represents cases where the WEC shuts down due to the sea state (control system induced normal shutdown). DLC 4.2 may be expected to occur at a different frequency for fatigue calculations compared to DLC 4.1. For a prototype design, DLC 4.1 may be expected to have a high probability of occurrence.

Emergency Shutdown (DLC 5.1)

This load case corresponds to the manual actuation of the emergency stop push button. The WEC will be set to a parked / standby condition in which some internal moving PTO components may be locked or disconnected.

Parked / Survival (Standstill or Idling) (DLC 6.1 to 6.4)

For this design situation, the WEC is in standby mode and may be locked or idling.

In DLC 6.1 and DLC 6.2, the WEC is assumed to be experiencing severe sea states associated with different recurrence period (1y and 50y, respectively) which prevents operation in power production mode.

In DLC 6.3, grid loss is added to DLC 6.2.

In DLC 6.4, the expected number of hours of non-power production time at a fluctuating load appropriate for each sea state will be considered (to investigate if significant fatigue damage can occur).

Parked / Survival Plus Fault Conditions (DLC 7.1 to 7.3)

This design situation considers the parked state resulting from the occurrence of a WEC fault.

The fault cases are combined with extreme wave sea states with a recurrence period of up to 50 years in DLC 7.1 and DLC 7.2, although a shorter recurrence period, or a reduced sea state, may be appropriate for prototype assessment.

In DLC 7.3, the expected number of hours of non-power production time due to faults will be considered for each sea state where significant fatigue damage can occur in any component.

Transport, Installation, Maintenance and Repair (DLC 8.1 to 8.6)

This design situation covers the installation period as well as transport, maintenance and repair operations on the WEC.

The load cases include any additional loading resulting from the weight of tools, cranes, machinery or any additional mooring / fendering configurations or mobile equipment, as specified by the WEC manufacturer.

DLC 8.1 covers the situation where the WEC is being transported to the installation site.

DLC 8.2 includes all critical loading arrangements present during installation.

DLC 8.3 includes loading applied to the WEC during routine maintenance operations.

In DLC 8.4 the expected number of hours of non-power production time whilst the PTO is in a maintenance state shall be considered for all routine maintenance operations where significant fatigue damage can occur to any component.

DLC 8.5 addresses the impact of a collision between the WEC and an installation or maintenance vessel. For this load case, the size of the intended installation vessel will be considered, potentially requiring the load case to be run on a site specific basis unless a standardised size, or a conservative, maximum vessel size, can be guaranteed.

Finally, DLC 8.6 considers the case where the WEC has to be abandoned for a period of time part way through a maintenance operation as a result of a storm event. An extreme sea state is assumed with the PTO and/or control system locked in a range of maintenance states.

Accidental / Abnormal Events (DLC 9.1 to 9.3)

This design situation covers extreme loading situations which may occur in the maritime environment and are not otherwise covered in the preceding load cases.

DLC 9.1 considers ship impacts beyond those considered as part of the maintenance operations outlined in DLC 8.5. DLC 9.2 considers severe ice impacts. The likelihood of ship or ice impact and the maximum impact energy will be determined based on information regarding the proposed deployment site(s).

DLC 9.3 addresses loading from Tsunami, caused by either an earthquake or tropical cyclone. Waves generated by these events normally come with some warning allowing the machine to be put in to the survival state. The load case is only relevant for WECs being developed for deployment in risk regions.

DLC 9.4 considers loading associated with varying ground conditions (not related to earthquakes) under normal sea states. Several scenarios (e.g. coastal erosion, scouring, mismatch between surveyed data and actual installation conditions, etc.) can be considered.

Damaged Stability (DLC 10.1 to 10.6)

The survival of damaged floating WECs is covered in this design situation. The aim is to ensure that the WEC is recoverable after sustaining damage and so the WEC must be shown to float in a stable condition without sustaining significant further damage in each case.

DLC 10.1 and 10.2 address the failure of a single mooring line or station keeping component.

In DLC 10.1, the WEC may not have reached a new, stable position and will be in transition following a failure.

In DLC 10.2, stable conditions have been reached following a mooring line failure.

DLC 10.3 addresses stability following a hull leak and partial flooding of the WEC. Flooding of individual hull volumes will be considered separately.

DLC 10.4 to 10.6 cover station keeping and flooding failures when the WEC is parked in severe sea states rather than during power production. These cases may potentially be excluded or relaxed for prototype assessment if a 50 year return sea state is overly conservative for a WEC with a short design lifetime.

2.2.5 Design Load Case Summary Table

Table 10 summarises the proposed design situations covered in Section 2.2, the environmental conditions defined in Section 2.2.2 and the load case descriptions described in Section 2.2.4. Following the review of the WEC specific FMEA, and the selection of the final deployment site, Table 10 can be adapted to provide specific load case descriptions that associate each DLC with specific simulations and their related inputs.

The following abbreviations are used in Table 10:

NSS	Normal Operational Sea States
RNSS	Reduced Range Normal Operational Sea States
RW	Regular Waves
FWG	Focused Wave Group
ESS	Extreme Operational Sea States
H_{s1}	Significant wave height with a recurrence period of 1 y
H_{s50}	Significant wave height with a recurrence period of 50 y
H_{s_T}	Significant wave height for transport
NCM	Normal Current Model
MCD	Multiple Current Directions
U	Ultimate strength analysis
F	Fatigue strength analysis
*	Fatigue partial safety factor
N	Normal partial safety factor
E	Extreme partial safety factor
A	Abnormal partial safety factor

Table 10 Summary of suggested design load cases (DLCs)

Design situation	DLC	Wave conditions	PTO conditions	Other conditions	Type of analysis	Partial safety factors
1. Power Production	1.1	*NSS*	*Power Production*	NCM	F U	* N
	1.2	*RNSS*	*Power Production*	NCM MCD	U	N
	1.3	*RNSS*	*Power Production*	Range of spectral shapes, including bimodal seas	U	N
	1.4	*FWG*	*Power Production*		U	E
	1.5	*FWG*	*Power Production*	Grid Loss	F U	* E
	1.6	*RNSS*	*Power Production*	Marine growth or freeboard ice accumulation	U	N
2. Power production plus occurrence of fault	2.1	*RW* *FWG*	*Power Production*	Fault in control system(s)	U	N
	2.2	*RW* *FWG*	*Power Production*	Fault in safety system or preceding internal electrical fault	U	A
	2.3	*RW* *FWG*	*Power Production*	Fault in the control or safety system(s)	F	*
3. Start-up	3.1	*RNSS*	*Start-up Procedure*		F U	* N
4. Normal shut-down	4.1	*FWG*	*Normal Shutdown Procedure*	Vary shut-down time to different points during the wave group	F	*
	4.2	H_{s1}	*Normal Shutdown Procedure*		F U	* N
5. Emergency shut-down	5.1	*FWG*	*Power Production*		U	N
6. Parked (standstill or idling)	6.1	*ESS* - H_{s1}	*Parked*	NCM	U	N
	6.2	*ESS* - H_{s50}	*Parked*	Tide height/current due to storm surge	U	A
	6.3	*ESS* - H_{s50}	*Parked*	Grid loss	U	A
	6.4	*NSS*	*Parked*		F	*
7. Parked plus fault conditions	7.1	*ESS* - H_{s1}	*Parked*	Fault condition	U	A
	7.2	*ESS* - H_{s50}	*Parked*		U	A
	7.3	*NSS*	*Parked*		F	*

Design situation	DLC	Wave conditions	PTO conditions	Other conditions	Type of analysis	Partial safety factors
8. Transport, installation, maintenance and repair	8.1	*NSS - H_{s_T}*	*Transportation configuration*	To be specified by manufacturer (transport / tow)	U	N
	8.2	*RNSS*	*Installation configuration*	To be specified by manufacturer (installation / removal)	U	A
	8.3	*RNSS*	*Maintenance configuration*	To be specified by manufacturer (including tidal currents where applicable)	U	A
	8.4	*RNSS*	*Maintenance configuration*	Absence of grid for long period	F U	* A
	8.5	*NSS - H_{s_T}*	*Maintenance configuration*	Collision with transport or installation vessels	U	A
	8.6	*ESS - H_{s1}*	*Locked in maintenance configuration*		U	A
9. Accidental / Abnormal Events	9.1	*RW*	*Power Production*	Ship impact Instantaneous load applied to each of the largest bodies in the system	U	A
	9.2	*RW*	*Power Production*	Ice impact Instantaneous load applied to each of the largest bodies in the system	F U	* A
	9.3	*Tsunami due to earthquake/cyclone*	*Controller in survival mode (if this can be done remotely) Otherwise: Power Production*	None	U	A
	9.4	*NSS*	*Power Production*	Varying ground conditions	F U	* A

Design situation	DLC	Wave conditions	PTO conditions	Other conditions	Type of analysis	Partial safety factors
10. Damaged stability	10.1	*NSS*	*Power Production*	Transient condition between intact and redundancy check condition	U	A
	10.2	*NSS*	*Power Production*	Single mooring line failure, redundancy check.	U	A
	10.3	*NSS*	*Power Production*	Leakage (damaged stability)	U	A
	10.4	*ESS* - H_{s50}	*Parked*	Transient condition between intact and redundancy check condition	U	A
	10.5	*ESS* - H_{s50}	*Parked*	Single mooring line break, redundancy check	U	A
	10.6	*ESS* - H_{s50}	*Parked*	Leakage (damage stability)	U	A

2.2.6 Overview of Suitable Formulations

A range of load analysis methodologies are available for the assessment of WECs taken from a range of applications in the offshore industry. This Section provides a high level description of a range of baseline load calculation formulations and highlights their applicability to the WEC design process.

Formulation	Notes	Example application to WEC design process
First-principles (e.g. hand calculations)	As illustrated in Section 1.3, first-principle calculations have been identified as the most popular baseline load calculation formulation currently used by WEC developers (over 68% of the survey respondents selected it). This result can be seen as a symptom of the early stage of the wave energy industry, as although the method carries some clear advantages (e.g. the ability to very quickly cover a wide design space by assessing the technical viability of using certain components), it also carries some significant disadvantages. Among the latter, the risk of using very simplistic representations of the wave environment is particularly high, which in turn can compromise the accuracy of the numerical estimates and often leads to any wave-structure interaction effects being neglected. Therefore, this formulation is only recommended for very early stage investigations, not aimed at deriving any load data for concept or detailed design activities (see also Section 2.4.2).	• Parametric investigations at embryonic stage • 'Goal posting' for initial component investigation / specification • Not recommended for the calculation of any WEC load metrics (irrespective of the design situation)

<table>
<tr><th>Formulation</th><th>Notes</th><th>Example application to WEC design process</th></tr>
<tr><td>Boundary element methods (linear)</td><td>
Linear boundary element methods (BEM) offer the capability of addressing key wave-structure interactions problems (namely diffraction and radiation) while performing calculations for many load cases at an acceptable computational time, which can be particularly crucial for initial investigations. Depending on their accuracy, such methods may be more or less utilised at a detailed design stage. Linear BEM methods also carry the fundamental assumptions associated with linear wave theory, in particular:

The fluid is assumed incompressible and the flow is irrotational (potential flow);
Viscous effects like shear stresses are not considered.

For general offshore engineering problems, linear BEM methods are one of the most widely used explicit formulations to estimate wave loading (first-order). In wave energy, and using the survey results documented in Section 1.2, linear BEM was identified as the second most popular baseline load calculation formulation currently used by WEC developers, with nearly 58% of the survey respondents selecting it. Although the key outputs obtained from linear BEM solvers are fundamentally related to linear (regular) waves, irregular wave results can be derived under linearised assumptions following the superposition principle.
The main limitation associated with the direct use of linear BEM methods in WEC modelling is that the formulation is, when used in isolation, uncoupled. However, if additional load sources (PTO, moorings, etc.) are considered in add-on tools associated with a linear BEM solver, then the formulation is in essence equivalent to a frequency-domain, fully coupled point loads model. Also, outputs from linear BEM solvers may be used as inputs to other, more advanced fully-coupled models based e.g. in time-domain formulations (and thus suitable for the inclusion of relevant nonlinearities).
Following e.g. Sarpkaya and Isaacson (1981) [11], a suitable threshold over which diffraction effects can be considered relevant can be set at $kD > 1.3$, where k is the wavenumber and D the characteristic dimension of the body. Knowing that the wavelength λ is equal to $2\pi/k$, this relation can be converted in $D/\lambda > 0.2$. Such threshold may be useful when assessing if an explicit flow solver is required, or if an empirical solution like Morison's equation may be more directly applicable.
</td><td>

Parametric investigations
Potential flow, inviscid fluid
First pass at key wave-structure interaction metrics (e.g. quantification of the first order wave excitation force)
Uncoupled (unless all load sources are considered (which would make the method equivalent to a frequency-domain fully coupled point loads model))
Potential to use selected outputs in more advanced, fully coupled models (the range of DLCs that it is applicable to will depend on the frequency or time-domain nature of the model)

</td></tr>
</table>

Formulation	Notes	Example application to WEC design process
Boundary element methods (nonlinear)	Unlike the linear BEM formulation where a mean wetted surface is used, nonlinear BEM formulations rely, in the majority of cases, on the pressure integration over the instantaneous wetted surface at every instant in time. As a result, the nonlinear formulation is based in the time-domain, whereas the linear equivalent is based in the frequency-domain. However, nonlinear BEM solutions of the wave-structure interaction problem still carry significant assumptions (e.g. potential flow, inviscid fluid). Even if used in isolation, nonlinear BEM formulations may therefore provide some insight into loading conditions that are mostly associated with non-power production design situations, often in ULS, scenarios associated with high energy environmental conditions. However, it should be noted that if other relevant load sources such as those induced by the PTO system are neglected when modelling the WEC, the validity of the load estimates may be compromised. One disadvantage of using a nonlinear BEM formulation is the computational effort required to conduct the simulations. This limitation may be even further exacerbated if a fully nonlinear potential flow solver is included as part of a fully coupled model, in an attempt to simultaneously account for all relevant load sources. To address these concerns, variations to fully nonlinear BEM formulations may include partially nonlinear solutions that address e.g. nonlinear components of the radiation and hydrostatic forces. At present, the application of fully nonlinear BEM solvers in WEC modelling is still rare, with some notable exceptions. An overview of studies that aim to address nonlinear hydrodynamic and real fluid effects on WECs can be found in Wolgamot and Fitzgerald (2015) [12].	• Detailed investigations • Potential flow, inviscid fluid • Potential to address non-power production design situations (namely ULS related scenarios) • Particularly relevant for DLCs 4.x, 5.x, 6.x, 7.x, 8.6, 9.3, 10.4, 10.5, 10.6

Formulation	Notes	Example application to WEC design process
Morison's equation	The formulations used to estimate the loading on a WEC may be explicit, i.e. they may address the physics of the problem and explicitly solve the equations that dominate the WEC response; or empirical, i.e. based on experimental evidence, a parametric set of equations is devised and used to estimate the relevant forces in similar conditions. The most commonly used empirical method is Morison's equation, first conceptualised in Morison et al. (1950) and now extensively used in offshore engineering. As illustrated in Section 1.3, it has been identified as the third most popular baseline load calculation formulation currently used by WEC developers (with nearly 53% of the survey respondents selecting it). It was originally derived to estimate the wave loading on circular cylinders / piles. However, it has since been applied in a wide range of offshore problems. Unlike BEM, it aims to address viscous effects in addition to inertial loads. When Morison's equation is used to calculate the hydrodynamic forces acting on a WEC, the variation of the hydrodynamic coefficients (C_A and C_D for mass and drag, respectively) as a function of the Reynolds number, Keulegen-Carpenter number and the surface roughness, needs to be considered. Detailed guidance is provided in [11]. Being empirical by nature, model validation may prove more challenging as the resulting solution is not directly dependent on the physical problem being solved. However, Morison's equation offers a straightforward formulation to address viscous phenomena, which may prove relevant for a wide range of design situations. It is also typically applied when conducting a dynamic analysis of a mooring system.	• Parametric and detailed investigations • Possibility to address viscous effects • Relevant for the majority of DLCs but particularly relevant for design situations that may lead to large body velocities • At a sub-system level: may be used for the assessment of mooring dynamics • Potential to use similar formulation as extension to fully coupled models (add-on to fully coupled models) • When used in addition to a point loads model (hybrid model): same range of applicable DLCs as fully coupled models

Formulation	Notes	Example application to WEC design process
Fully coupled point loads model (frequency-domain)	Fundamentally, frequency-domain solvers assume that the solution of the equation of motion can be obtained via the superposition of results related to the WEC response in regular (linear) waves. This steady-state approximation effectively limits the application of frequency-domain formulation to linear (or linearised) problems, including not only the hydrodynamics but all relevant load sources. However, and within the above described limitations, the frequency-domain formulation still allows for fully coupled models to be derived, which may be more relevant for reliable loading and / or performance estimate than a nonlinear (yet uncoupled) method. Together with the low computational effort and the ease to implement a frequency-domain based solver, these advantages have contributed to the formulation becoming one of the most widely used in WEC research to date. Based on the WEC developer survey results presented in Section 1.3, this baseline load calculation formulation is currently used by 47% of survey respondents. Fully coupled, frequency-domain point loads models may be considered as entry models for wide range parametric investigations, which may include alternative WEC geometries, mass matrices, PTO options, etc. They are mostly suited for early stage, concept design activities with a particular focus on power production.	• Parametric investigations • Early stage, concept design activities • Initial power production estimates ('goal posts') • Primarily applicable for DLC 1.1 (within the limitation of the linear assumptions)

Formulation	Notes	Example application to WEC design process
Fully coupled point loads model (time-domain)	When nonlinear effects are significant, time-domain solutions are required. Building on the frequency-domain formulation, time-domain models typically use inputs from linear BEM solvers, namely the exciting force and the radiation damping coefficients. These fundamental properties recognise and incorporate the frequency dependence of the hydrodynamic forces, in addition to memory effects (i.e. effects that persist after the motion of the WEC ceases), and can be used to characterise the hydrodynamic loading. Specific modules can then be constructed to provide a nonlinear description of all relevant load sources. Recent developments in WEC modelling software include the partially nonlinear characterisation of the hydrodynamic loads and, more rarely, direct coupling with nonlinear BEM solvers. Fully coupled, time-domain point load models are currently available for WEC modelling, and can be applied to a wide range of design situations for extensive load calculation exercises due to their ability to accurately model nonlinear effects (in particular those related to critical machine conditions such as fault scenarios). However, and although the use of time-domain formulations is well aligned with the guidelines and standards recommendations listed in Section 1.1, widely applicable WEC time-domain formulations are relatively recent and only 42.1% of the survey respondents have confirmed that they are currently using such method (the third lowest score). Commercial and open source solution have been recently proposed, including e.g. WEC-Sim, which was used in this study to estimate the loading on a multi-body point absorber (see Section 2.5.1). Further developments may focus on hybrid models that have both explicit and empirical elements, to address e.g. viscous effects in less computationally intense yet accurate formulations, assisting in the transition from concept to detail design.	• Parametric and detailed investigations • Detailed assessment of performance and loading related WEC metrics • Potential to cover wide range of design situations (including fault related scenarios) • Suitable for the transition from concept to detailed design • Mostly suitable for DLCs 1.x, 2.x, 3.x, 4.x, 5.x, .4, 7.3, 8.x, 9.1, 9.2, 10.1, 10.2, 10.3

Formulation	Notes	Example application to WEC design process
Fully coupled distributed loads model (time-domain)	The extension of fully coupled, time-domain loads model from point to distributed loads is (to date) rare in WEC research. Essentially, and in addition to rigid bodies, the distributed load formulation offers the possibility to model flexible bodies, which may be particular relevant for certain WEC types. The ability to model flexibility in the main structural components of the WEC makes the distributed loads formulation more directly suitable for the estimation of structural stresses, as the load outputs may be directly input to finite element analysis (FEA) software packages (see Section 2.3). However, and assuming that the use of rigid bodies is acceptable, suitable variations using point loads models can also be used to estimate the distributed pressures that impact the main structural components, often following linear assumptions and creating a direct interface with an FEA package.	• Detailed investigations • Suitable for extension of load assessment to the detail design stage • Directly suitable for the transition from loads to stresses • Mostly suitable for DLCs 1.x, 2.x, 3.x, 4.x, 5.x, 6.4, 7.3, 8.x, 9.1, 9.2, 10.1, 10.2, 10.3 (as per point load equivalent model)

Formulation	Notes	Example application to WEC design process
Others (advanced methods)	For highly nonlinear scenarios, both hydrodynamic nonlinearities, machine related nonlinearities (e.g. nonlinear PTO force profiles) and viscous effects are likely to be relevant. In WEC modelling, baseline time-domain approaches have recently been extended to explicitly incorporate viscous load sources, mostly using Reynolds Averaged Navier-Stokes Equations (RANSE) solvers. Studies comparing wave loads obtained via linear BEM methods, hybrid solvers that include Morison corrections and RANSE solvers can be found in the literature. For example, Bhinder et al. (2015) [14] compared loading and performance estimates obtained via an inviscid BEM solver, a hybrid BEM + Morison formulation and a RANSE solver for a single degree-of-freedom floating WEC. Regular and irregular waves of varying steepness / energy content were tested. The results flagged the significant influence that the inclusion of viscous effects may have on loading and performance estimates, in particular for more energetic environmental conditions. However, the similarity between the hybrid BEM + Morison formulation and the RANSE solver results emphasise the potential merits of hybrid solutions. In addition to verification studies, validation of the more advanced load calculation formulation is required and is currently an ongoing topic of research. Initial validation studies involving RANSE solvers for WEC modelling include e.g. Schmitt and Elsaesser (2015) [15], where the response of a bottom mounted OWSC was estimated in OpenFOAM and compared to small scale experimental results.	• Detailed investigations • Detailed design stage • Potential for advanced methods to inform hybrid methods (e.g. RANSE derived C_d for Morison corrections) • Particularly relevant for DLCs 4.x, 5.x, 6.x, 7.x, 8.6, 9.3, 10.4, 10.5, 10.6

2.3 Structural Analysis

2.3.1 Structural Analysis Process

A range of established methods and design guidance exists for the assessment of structural integrity for offshore structures. This Section provides an interpretation of these existing methods in the context of WECs.

2.3.1.1 Limit States

Limit state design is an important concept in offshore structural analysis as it defines acceptable limits for safety and serviceability requirements of a structure. Four reference limit states are typically defined, with different allowable limits suitable to satisfy the performance of the structure (ISO 19900 [22]):

1. Ultimate Limit State (ULS): resistance to ultimate loads[5], described in Section 2.2.1.1.
2. Serviceability Limit State (SLS): criteria governing normal functional use.
3. Fatigue Limit State (FLS): resistance to the accumulated effect of repetitive action, described in Section 2.2.1.2.
4. Accidental Limit State (ALS): resistance to loads during abnormal or accidental events.

Partial factors and their combinations form an important consideration within limit state design. Partial factors are used to allow for uncertainties and variability originating from materials and combinations of loads in order to gain sufficient reliability. Partial factors applied to loads (typically referred to as action or load factors) are dependent on the limit state and the source of loading. Partial factors applied to materials (resistance or material factors) are dependent on the limit state and the material classification. Different action factors are typically applied to each of the loads that form the combinations defined in each SLC. Further information on partial factors is described in Section 2.2.1.

Definition of a Design Fatigue Factor (DFF) as a factor applied to the cumulative fatigue is also required. While the DFF is the approach most commonly used for offshore design, an alternate is to apply a partial factor to the loads. The latter approach is generally less favoured as it may change the effective stress/cycle gradient under which the detail is operating and thus the influence on the total fatigue damage is less predictable.

The DFF value is a function of accessibility for inspection of the region of interest and the consequence of failure. It should be noted that the DFFs used for offshore wind (e.g. see DNVGL-OS-J101 [19]) are lower than offshore oil and gas applications (e.g. see ISO-19902 [16]). This is because of the perceived lower

[5] The use of abnormal ultimate limit state loads is also relevant in the context of WECs as described in Section 2.3.1.1.

consequence of failure as the turbines are unmanned and present a low risk of significant pollution of the environment, guidance which will also apply to WECs.

In the absence of formal guidance, determining suitable partial factors for WECs is challenging. As discussed in Section 2.2.1, only ultimate and fatigue limit states are typically considered for WEC design. Existing offshore guidance provides factors for ULS and FLS conditions for oil and gas and offshore wind applications (e.g. ISO 19902 [16] and DNVGL-OS-J101 [19]). It may be appropriate to apply higher action factors for WECs due to uncertainties in their loading regimes, although it is increasingly difficult to design in a cost-effective manner when higher action factors are used.

Resistance factors reflect the probability of deviation of materials from characteristic properties and are directly relevant to WECs where standard material specifications are used. Reference is made to ISO 19902 [16] and ISO 19903 [23] for steel and concrete components respectively.

As identified in the survey results (Section 1.3), a range of structural analysis methods are currently employed by WEC developers. It should be noted that consideration of limit states and partial factors is required independent of the sophistication of the chosen analysis technique.

The definition of limit states fits into the design process as part of the definition of DLCs and development of the FMEA. Limit states can be defined for each DLC, as explained in Section 2.2.4 in the context of WECs. Some DLCs cover more than one limit state, for example a range of ultimate DLCs may contribute significantly to the FLS. Applicable limit states can also be defined with the FMEA, which highlights the applicable limit state(s) for which a vulnerable part of the structure should be checked.

A general overview of limit state design and associated partial factors is provided in ISO 19900: General Requirements for Offshore Structures [16]. An example of the application of limit states to design load cases is contained in DNVGL-OS-J101: Design of Offshore Wind Turbine Structures [19]. As discussed in Section 1.2, the process of deriving limit states for WECs is yet to be formally considered.

2.3.1.2 Fatigue Analysis

Fatigue refers to the cumulative damage incurred by repeated application of time-varying stresses at a specific location in the structure. A spectrum of fatigue loads for fatigue analysis are typically assessed either using a time history method or a spectral method. The output of a fatigue loads assessment is a description of the cyclic forces at fatigue sensitive areas on the structure with an associated number of cycles. These loads are converted into stresses with consideration of local concentrations at fatigue sensitive details. The cumulative damage is then calculated by summing the relative contributions for different stress ranges. The process by which a fatigue load spectrum should be converted into cumulative fatigue is well understood in structural steel and reinforced concrete with extensive code guidance available (e.g. DNV-RP-C203 [17] and DNV-OS-C502 [29]).

A detailed description of the fatigue analysis process for fixed offshore steel structures, much of which is relevant to WECs, is contained in ISO 19902 [16]. Guidance for individual methods referred to in this Section are provided in Section 2.3.4. Key considerations for the fatigue analysis of WECs include:

- Although the design of WECs is yet to converge the structural integrity assessment from a given set of cyclic loads is standardised and applicable to the analysis of WECs. Exceptions to this will exist, for example S-N data for novel materials.

- As described in Section 2.2.1, fully coupled time domain simulations are recommended for the analysis of the majority of DLCs for WECs. Although this provides a complete load time history, from which stress cycles and accumulated fatigue damage can be calculated, a time-history stress analysis sufficient to calculate the required range of sea-states could be computationally extremely expensive. Overcoming this challenge in the fatigue analysis of WECs may require: appropriate reductions in the range of operating conditions considered, use of simplifications for processing cyclic data and/or appropriate setup of FE models for time-history analysis.

- Unlike the majority of fixed offshore structures that are assessed for high cycle fatigue (i.e. high numbers of cycles, low stress-range), WECs are typically exposed to significant low cycle fatigue with large stress ranges as part of their operational cycle and low cycle fatigue has been a large contributor to WEC failure to date.

- Much of the current offshore guidance for fatigue focuses on tubular connections and it is anticipated that generation of detailed linear models for the assessment of Stress Concentration Factors (SCFs) will often be required for assessment of WEC designs.

- Although all components subject to cyclic loads are sensitive to fatigue damage, it is usually connections and structural discontinuities which require particular focus for fatigue assessment. A detailed FMEA provides indication of parts of the structure most susceptible to fatigue to enable focus of the analysis, as highlighted in Section 2.3.3.

2.3.1.3 Strength Analysis

Strength analysis refers to the structural check that a component doesn't exceed its allowable capacity when exposed to the expected loads during its design life. The process broadly involves calculating the extreme stresses for the critical loading and assessing these against allowable values, including consideration of all relevant failure mechanisms (e.g. yielding, buckling). The details of methods for strength assessment and their applicability to WECs are described in Section 2.3.4

A detailed description of the strength analysis process is contained in the DNVGL Guidance for Offshore Wind Certification [20]. Key considerations for the strength analysis of WECs include:

- In contrast to the loads derivation of offshore devices there is a limited range of methods for assessing the structural integrity for a given set of loads. It is therefore expected that the majority of methods described in Section 2.3.4 will be applicable for the strength analysis of a given WEC.
- The dynamic nature of WECs makes selection of the governing DLC for a given component difficult. Although fully coupled time-domain simulations are recommended for the analysis a range of DLCs for WECs (Section 2.2.1), limitations within the hydrodynamic modelling may mean more sophisticated analyses (e.g. CFD) may be required to capture governing load cases. Even if more standard hydrodynamic models are appropriate it can be challenging to ensure the simulation is run for an appropriate duration to get the governing loads given the interaction of the device with the wave conditions.
- As WECs are dynamic machines, inertial loading is an important component and the effect of accelerations (including the contribution from hydrodynamic mass) on the structure must be included in any structural analysis model as well as application of hydrodynamic and restraint loads.
- Corrosion allowance is an important consideration for design of offshore structures, usually considered by reduction in the thickness of material. The splash zone, in which many WECs operate, has a particularly aggressive corrosion regime and corrosion allowance is likely to be an important consideration for strength analysis of WECs.
- Completion of an FMEA forms an important step in ensuring that the most damaging load cases are captured. The FMEA is also important for the identification of structural vulnerabilities and single points of failure of a WEC device so that areas requiring redundancy are highlighted.

2.3.2 Failure Analysis by WEC Type

As part of the structural analysis process, it is necessary to identify the risks associated with the design of the device.

The safety critical risks, both in terms of danger to humans and the surrounding environment, or to the business, such as loss of income or power production facility, that are conceivable during the design life of a device may be identified effectively by means of an FMEA. The FMEA can also be extended to a FMECA (failure modes, effects and criticality analysis).

FMEA is a method of qualitatively and systematically assessing possible failure modes. It also offers a quantitative procedure, which enables ranking of the failure modes according to likelihood and consequence. The FMEA method was originally developed by NASA as a means of ensuring desirable reliability characteristics in system design. It has remained a powerful technique that allows vulnerabilities in the design to be highlighted and, adequately accounted for in the design process.

In this report an example FMEA is presented for each of the 7 WEC types described in Section 2.1. The full list of FMEAs may be found in the Appendix of this report, A1. Whilst there are many variations of FMEAs that may be applicable to the design of WECs, here the analysis has been limited to identifying possible structural failure modes. It should be noted that the design of WECs considered are generic. Therefore only the structural failure modes of principal components or connections, which are considered as particularly vulnerable, have been considered. Failure modes are strictly limited to those associated with a single WEC, therefore any failures related to array behaviour or failure of other peripheral systems, such as subsea piping or grid connections, have not been considered.

These FMEAs are presented as a demonstration of how the principles of an FMEA analysis may be applied by a WEC developer in order to identify governing failure modes and thus failure locations where design redundancies may be required.

Table 11 shows the FMEA column headings, followed by a brief description of the content.

Table 11 FMEA column headings

WEC	Failure Location	Schematic of Selected Failure Modes	Possible Structural Failure Modes	Cause	Governing Failure Mode?	Consequence	Relevant DLCs

- **WEC**: Type of wave energy converter device
- **Failure Location**: Principal components or connections of a generic WEC design that were identified to be structurally vulnerable. This is accompanied by a small schematic, which marks out salient components of the device.

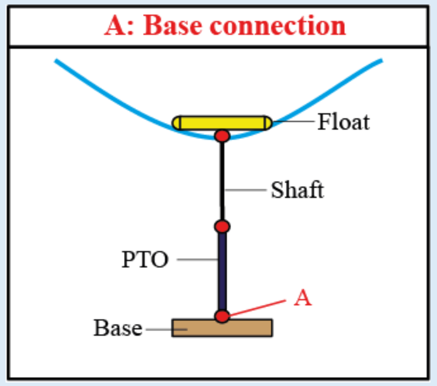
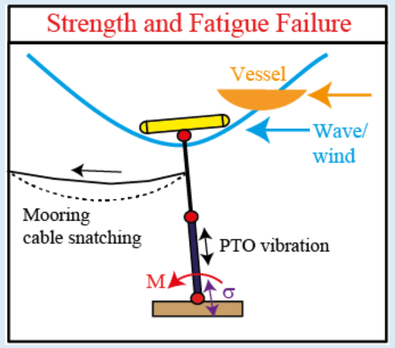
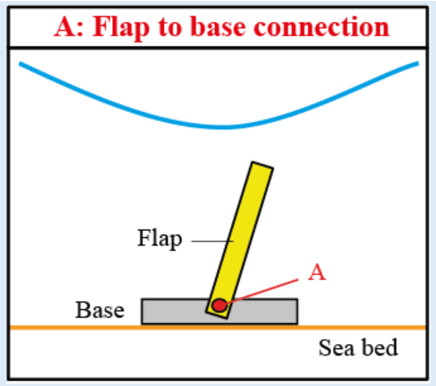
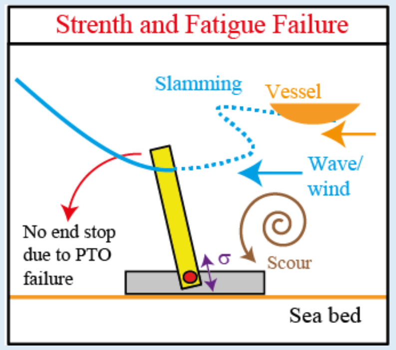
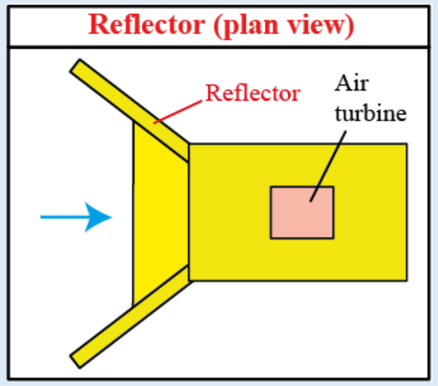
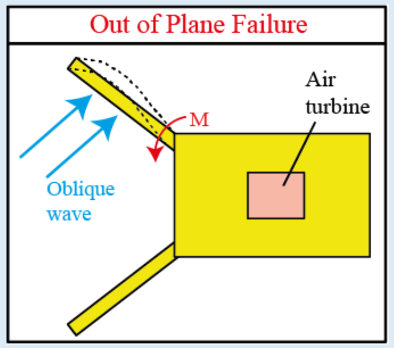
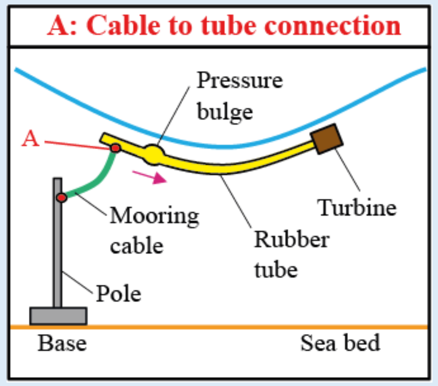
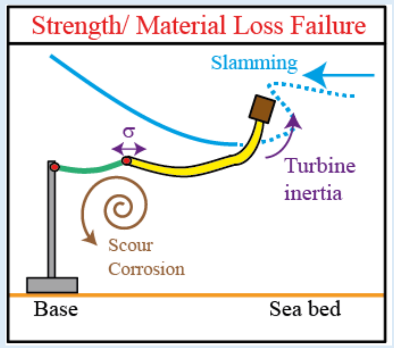
- **Schematic of Selected Failure Modes**: Schematics that illustrate the cause and effects of selected failure modes are presented.
- **Structural Failure Modes**: The possible structural failure modes identified for each WEC and each failure location are listed. All possible modes of failure have been broadly categorised into the following:
    - Strength
    - Fatigue – high cycle
    - Fatigue – low cycle
    - Material Loss
    - Stability
- **Cause**: For each structural failure mode identified, the possible causes/loads/design situations are listed.
- **Governing Failure Mode**: Here the likelihood of whether the failure mode identified could be governing, is identified. The likelihood has been classified into 3 levels:
    - **1.** Possibly
    - **2.** Likely
    - **3.** Definitely
- **Consequence:** Here the severity for the consequence of structural failure, is identified. The consequence has been classified into 3 levels:
    - **1.** Minor Maintenance
    - **2.** Component Failure
    - **3.** Machine Failure
- **Relevant DLCs (Design Load Cases):** DLCs (defined in **Table 10** in Section 2.2.5), which may be relevant to the listed cause for structural failure are referenced.

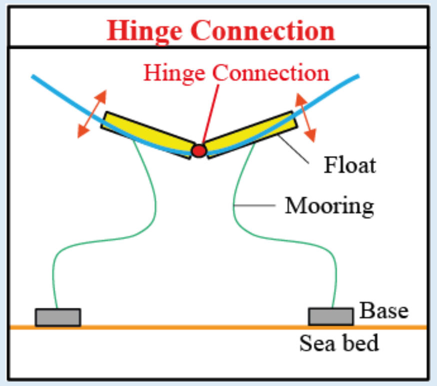
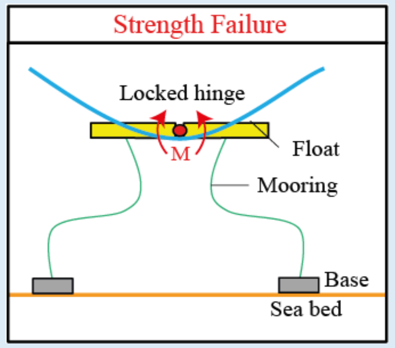
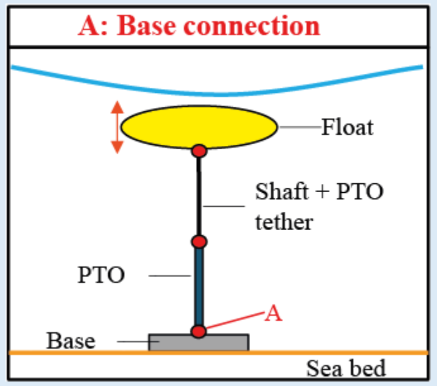
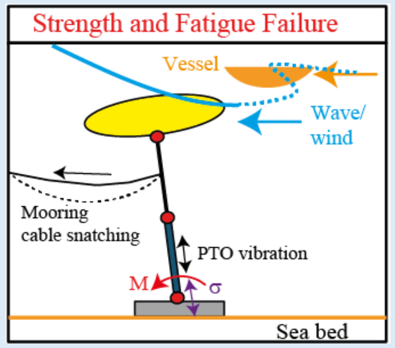
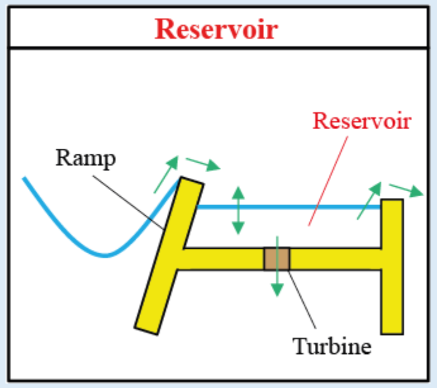
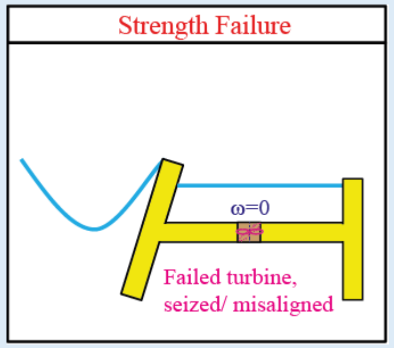
The value of the FMEAs in design are determined by the failure modes identified and the detail into which it discusses the risks associated with them that may feed then into iterative design or mitigation strategies. Thus it is of utmost importance, for any given design, for every design load case, all significant failure modes are captured in the FMEA.

In Section 2.3.3, a high level, summary FMEA table is presented. This contains one or two governing failure modes for each of the 7 WEC types considered in this report. The full list of FMEA for each device has been allocated to Appendix A1.

2.3.3 Summary FMEA

A high level summary FMEA table is presented below covering the 7 WEC types considered in the report. The table contains one or two failure modes considered most likely to govern with the most severe consequence of failure. For the full list of FMEA for each device, see Appendix A1.

WEC	Failure Location	Schematic of Selected Failure Modes	Possible Structural Failure Modes	Cause	Governing Failure Mode?	Consequence	Relevant DLCs
Point Absorber			Strength	ULS environmental loads (wave slamming, wind, currents, tidal effects)	3: Definitely	3: Machine Failure	1.x, 2.x, 3.x, 4.x, 5.x 6.x, 7.x, 9.x, 10.x
				ALS loads (vessel/ice impact, tsunami, seismic effects)			9.1, 9.2, 9.3 10.3, 10.6
				Transportation and installation loads			8.x
				Transient snatch loads in cable systems			2.x, 5.x, 9.x, 10.x
				Joint seizure leading to machine parking			6.1, 6.2, 6.3 7.1, 7.2
				Material and Section discontinuity at composite joints			6.1, 6.2, 6.3 7.1, 7.2
				Marine growth			1.6
				PTO/ controller failure			2.1, 2.2, 2.3
				Mooring connection failure (if relevant)			
				Seabed anchor failure			10.1, 10.4
			Fatigue - high cycle	FLS environment loads (wave, wind, currents)	3: Definitely	3: Machine Failure	1.1, 1.5, 2.3, 9.2
				Stress concentration around geometric discontinuity			6.4, 7.3
				PTO induced excitation			1.1, 1.5, 2.3, 9.2
				Mooring load induced excitation			1.1, 1.5, 2.3, 9.2
				Any other excitation of global resonance modes			8.4
Oscillating Wave Surge Converter			Strength	ULS environmental loads (wave slamming, oblique waves/ wind, currents, tidal effects)	3: Definitely	3: Machine Failure	1.x, 2.x, 3.x, 4.x, 5.x 6.x, 7.x, 9.x, 10.x
				ALS loads (vessel/ice impact, tsunami, seismic effects)			9.1, 9.2, 9.3 10.3, 10.6
				Transportation and installation loads			8.x
				Joint seizure leading to machine parking			6.1, 6.2, 6.3 7.1, 7.2
				Material and Section discontinuity at composite joints			6.1, 6.2, 6.3 7.1, 7.2
				Marine growth			1.6
				PTO/ controller failure			2.1, 2.2, 2.3
			Fatigue - high cycle	FLS environment loads (wave, wind, currents)	3: Definitely	3: Machine Failure	1.1, 1.5, 2.3, 9.2
				Stress concentration around geometric discontinuity			6.4, 7.3
				PTO induced excitation			1.1, 1.5, 2.3, 9.2
				Any other excitation of global resonance modes			8.4
Oscillating Water Column			Strength	ULS environmental loads (wave slamming, oblique waves/ wind, currents, tidal effects)	3: Definitely	2: Component Failure	1.x, 2.x, 3.x, 4.x, 5.x 6.x, 7.x, 9.x, 10.x
				ALS loads (vessel/ice impact, tsunami, seismic effects, seabed instability)			9.1, 9.2, 9.3 10.3, 10.6
				Transportation and installation loads			8.x
				Material and Section discontinuity at composite joints			6.1, 6.2, 6.3 7.1, 7.2
				Marine growth			1.6
				Mooring connection failure			10.2, 10.5
			Fatigue - high cycle	FLS environmental loads (wave, wind, currents)	3: Definitely	2: Component Failure	1.1, 1.5, 2.3, 9.2
				Stress concentration around geometric discontinuity			6.4, 7.3
				Turbine/ controller induced excitation			1.1, 1.5, 2.3, 9.2
				Mooring load induced excitation			1.1, 1.5, 2.3, 9.2
				Sudden change in temperature			2.x, 5.x, 9.x, 10.x
			Stability	Buoyancy system failure	3: Definitely	2: Component Failure	10.x
Bulge Wave			Strength	ULS environmental loads (wave slamming, wind, currents, tidal effects)	3: Definitely	3: Machine Failure	1.x, 2.x, 3.x, 4.x, 5.x 6.x, 7.x, 9.x, 10.x
				ALS loads (vessel/ice impact, tsunami, seismic effects)			9.1, 9.2, 9.3 10.3, 10.6
				Transportation and installation loads			8.x
				Material and Section discontinuity at composite joints			6.1, 6.2, 6.3 7.1, 7.2
				Marine growth			1.6
				Survivability mode failure			6.2, 7.2
				Inertial loading from hydrodynamic loading on turbine			2.x, 4.x, 5.1
			Fatigue - high cycle	FLS environment loads (wave, wind, currents)	3: Definitely	3: Machine Failure	1.1, 1.5, 2.3, 9.2
				Stress concentration around geometric discontinuity			6.4, 7.3
				PTO induced excitation			1.1, 1.5, 2.3, 9.2
				Mooring load induced excitation			1.1, 1.5, 2.3, 9.2
				Any other excitation of global resonance modes			8.4

WEC	Failure Location	Schematic of Selected Failure Modes	Possible Structural Failure Modes	Cause	Governing Failure Mode?	Consequence	Relevant DLCs
Attenuator			Strength	ULS environmental loads (wave slamming, oblique waves/ wind, currents, tidal effects)	3: Definitely	3: Machine Failure	1.x, 2.x, 3.x, 4.x, 5.x 6.x, 7.x, 9.x, 10.x
				ALS loads (vessel/ice impact, tsunami, seismic effects)			9.1, 9.2, 9.3 10.3, 10.6
				Transportation and installation loads			8.x
				Transient snatch loads in cable systems			2.x, 5.x, 9.x, 10.x
				Joint seizure leading to machine parking			6.1, 6.2, 6.3 7.1, 7.2
				Material and Section discontinuity at composite joints			6.1, 6.2, 6.3 7.1, 7.2
				Marine growth			1.6
				PTO/ controller failure			2.1, 2.2, 2.3
				Mooring connection failure			10.2, 10.5
				Seabed anchor failure			10.1, 10.4
			Fatigue - high cycle	FLS environment loads (wave, wind, currents)	3: Definitely	3: Machine Failure	1.1, 1.5, 2.3, 9.2
				Stress concentration around geometric discontinuity			6.4, 7.3
				PTO induced excitation			1.1, 1.5, 2.3, 9.2
				Mooring load induced excitation			1.1, 1.5, 2.3, 9.2
				Any other excitation of global resonance modes			8.4
Submerged Pressure Differential			Strength	ULS environmental loads (wave slamming, wind, currents, tidal effects)	3: Definitely	3: Machine Failure	1.x, 2.x, 3.x, 4.x, 5.x 6.x, 7.x, 9.x, 10.x
				ALS loads (vessel/ice impact, tsunami, seismic effects)			9.1, 9.2, 9.3 10.3, 10.6
				Transportation and installation loads			8.x
				Transient snatch loads in cable systems			2.x, 5.x, 9.x, 10.x
				Joint seizure leading to machine parking			6.1, 6.2, 6.3 7.1, 7.2
				Material and Section discontinuity at composite joints			6.1, 6.2, 6.3 7.1, 7.2
				Marine growth			1.6
				PTO/ controller failure			2.1, 2.2, 2.3
				Mooring connection failure			10.2, 10.5
				Seabed anchor failure			10.1, 10.4
			Fatigue - high cycle	FLS environment loads (wave, wind, currents)	3: Definitely	3: Machine Failure	1.1, 1.5, 2.3, 9.2
				Stress concentration around geometric discontinuity			6.4, 7.3
				PTO induced excitation			1.1, 1.5, 2.3, 9.2
				Mooring load induced excitation			1.1, 1.5, 2.3, 9.2
				Any other excitation of global resonance modes			8.4
Overtopping			Strength	ULS environmental loads (wave slamming, wind, currents, tidal effects)	3: Definitely	3: Machine Failure	1.x, 2.x, 3.x, 4.x, 5.x 6.x, 7.x, 9.x, 10.x
				ALS loads (vessel/ice impact, tsunami, seismic effects)			9.1, 9.2, 9.3 10.3, 10.6
				Transportation and installation loads			8.x
				Marine growth			1.6
				Turbine failure			2.1, 2.2, 2.3
			Fatigue - high cycle	FLS environment loads (wave, wind, currents)	1: Possibly	3: Machine Failure	1.1, 1.5, 2.3, 9.2
				Stress concentration around geometric discontinuity			6.4, 7.3
				Turbine induced excitation			1.1, 1.5, 2.3, 9.2
			Material Loss	Corrosion	1: Possibly	3: Machine Failure	1.6, 6.x, 7.x, 9.x, 10.x
				Scouring			1.6, 6.x, 7.x, 9.x, 10.x
				Marine activity			8.x, 9.x
				Interface between dissimilar materials			2.x, 5.x, 9.x, 10.x
				Sudden change in temperature			2.x, 5.x, 9.x, 10.x
			Stability	Buoyancy system failure	2: Likely	3: Machine Failure	10.3, 10.6
				Mooring connection failure			10.2, 10.5

2.3.4 Overview of Suitable Methods

A number of existing structural analysis methodologies are relevant for the assessment of WECs. This Section provides a high level description of a relevant structural analysis methods and highlights their applicability to WEC analysis and design.

2.3.4.1 Fatigue Analysis

Structural analysis method	Notes	Applications to WECs
Spectral Fatigue Analysis	The spectral analysis technique is a method for calculating the cyclic loading spectrum on a structure in the frequency domain. The method involves representing the sea state as a spectrum with a function of frequency for each sea state and calculating a transfer function to relate these spectra to forces or moments in the components of interest. The main advantage of this technique is that it provides a comprehensive representation of waves across an entire sea-state without having to run a significant number of time histories, which is computationally expensive. Its limitation is that it requires linearization of the hydrodynamic loading and WEC dynamics, for example, variations in the water level around the still water line and other nonlinearities present in the system such as power take-off need to be satisfactorily represented in a linear manner. Spectral analysis is typically used in design of offshore steel structures where linearization of drag components is appropriate and the heights of waves that cause the majority of fatigue damage (i.e. those with small periods) is relatively small. Spectral analysis has proven applications in the design of WECs however, (for example in [10]) and it is recommended that it is used where the device operation and dynamics allow it. ISO 19902 [16] and API-RP-2A [18] (including the commentary on fatigue) provide comprehensive description of the application of spectral fatigue analysis. Several textbooks also cover the theory of the technique (e.g. [8]).	Connections and operational modes where the response can be well represented by a linear system e.g. connections to shallow catenary cables which are not subject to frequent snatch loads.

Structural analysis method	Notes	Applications to WECs
Time-History Fatigue (Deterministic Fatigue Analysis, Stress Calculation and Rain-Flow Counting)	Deterministic fatigue analysis is an alternative to the spectral method. It involves building up the cyclic loading on a structure from its response to a series of individual waves. For a deterministic analysis it is important that an appropriate number of sea-states are chosen to cover those that will occur over the lifetime of the structure. The appropriate selection of sea-states is listed in Table 10. As deterministic analysis generally relates to the individual waves it is not usually used where dynamic amplification of hydrodynamic loads is likely to be significant, which will often be the case in WEC devices. Time history analysis is an extension to standard deterministic technique commonly applied to WECs where the wave climate is represented by a realistic wave train for each sea state and contributing operational state. The main advantage of this method is that if the WEC device is satisfactorily represented then the method can fully capture the dynamics and nonlinearities of the system. For example, behaviour of the optimal power take-off system is unlikely to be linear. The main disadvantage of the method is that it can be complex and computationally expensive to produce time histories for the required range of sea-states. The output of a time history analysis are forces and moments for a given location on the structure as a function of time. Once converted to stresses, a rainflow analysis (e.g. as described in BS 7608 [30]) can be performed to calculate the number of cycles and stress ranges from a generic time history profile and a damage calculation performed. An example of the application of this method in the context of WECs can be found in the Structural Design of Wave Energy Devices publication [10]. A simplified approach is to convert time history damage equivalent stress as explained in Section 2.2.1. Conversion into a damage equivalent stress requires some assumptions (most commonly that stress amplitudes in the spectrum conform to a Rayleigh distribution and that the S-N gradient in the fatigue design curve is constant) which may result in over-conservative results. It can however be a useful tool during initial design. As a general modelling aspiration, FE models representing the WECs should be as simple as allows while capturing the relevant stiffness and dynamic behaviour in order to minimise computational expense. It may often be attractive to use a relative simple global model of the WEC device with more detailed models of specific components to understand their behaviour under specific extreme loads or to obtain stress concentration factors. This approach may allow the analyses of the more detailed models to be conducted statically.	• For WEC devices a time-history analysis is required for all situations where nonlinear effects significantly affect the response. • If the dynamic response of the WEC device is captured in the analysis, there is no obvious deficiency relative to spectral analysis i.e. all devices which could be analysed satisfactorily using a spectral method could also be analysed using a time-history method, though in all likelihood at greater computational expense. • This will include a large range of WEC geometries and design situations.

Structural analysis method	Notes	Applications to WECs
Stress Concentration (and Allowable Cycle Calculation)	For offshore structures, connections are one of the most fatigue sensitive areas due to high local peak stresses. The peak stress at these connections is typically quantified by multiplying nominal stress values on parent plates by stress concentration factors (SCFs) to capture the concentrations associated with the connection geometry. The peak stress values used for calculation of life are defined as the hot spot stress. SCF values may be derived from finite element analysis, model tests or empirical equations based on these methods which are provided in standards. This allows simplification of global FE models. There is a large array of guidance for the calculation of SCFs in relation to steel structures. Parametric equations and methods for combining stresses at joints are provided for standard joint details in API-RP-2A [18], ISO 19902 [16] and DNV-RP-C203 [17]. Where parametric equations of other suitable guidance is not available, it is recommended that DNV-RP-C203 [17] is used as guidance for calculation of hot spot stresses using finite element analysis. This contains a recipe for understanding an appropriate position to extract and extrapolate hot spot stress values at connections from detailed local linear FE models such that they are compatible with S-N curves provided in the code. This guidance also provides information on best practice for setting up detailed FE models for SCF assessment. Calculation of nominal stresses is typically taken from a global linear FE model for a given loading. S-N curves represent empirically determined relationships between stress range and the number of cycles to failure including the effects of weld profile and discontinuities at the weld toe. S-N curves vary based on a range of factors including material, weld type and corrosion protection. S-N curves for standard weld details in steel are contained in DNV-RP-C203 [17]. The standard also includes estimation of the efficacy of post-weld treatments to improve weld life (e.g. hammer peening, grinding, heat treatment).	• This describes a standard process for the calculation of fatigue stresses for a given input load. • It is therefore expected that this method is applicable to fatigue assessment of all WEC devices. • It is expected that local FE models will be required in some cases to assess SCFs of novel connections found in WECs. • Equations for standard details can be found in design standards.
Damage Calculation and Recommended Life	The damage associated with a fatigue loading is calculated using the Palmgren-Miner damage accumulation rule as shown below (DNV-RP-C203 [17]). $D = \sum_{i=1}^{k} \frac{n_i}{N_i} = \frac{1}{\bar{a}} \sum_{i=1}^{k} n_i \cdot (\Delta\sigma_i)^m \leq \eta$ It is recommended that the life is a multiple of the design life of the structure (i.e. D<1) due to the uncertain nature of the analysis and environmental loading. Appropriate multipliers are discussed in Section 2.3.1.	• This describes a standard process for the calculation of damage and is expected to apply to the majority of steel fatigue calculations for WECs.

2.3.4.2 Strength Analysis

Structural analysis method	Notes	Applications to WECs
Hand calculations and code guidance	Preliminary sizing of structural members is typically done using hand/spreadsheet calculations with structural members initially sized using a nominal design stress excluding load factors and SCFs e.g. 150 MPa for steel. Preliminary loads would often be provided by analytical methods for hydrodynamic actions e.g. Morison's equation, examples and guidance on which can be found in DNV-RP-C205 [25], Baltrop [8] and Section 2.2.6. of this report.	Hand/spreadsheet calculations to determine initial loads and structural element sizes would be the starting point for virtually all WEC devices.
Linear global model combined with design code checks and/or local models	This process involves assessing stresses and structural behaviour resulting from the critical load cases using a global finite element model. Capacity checks of the structural members and connections are then performed. The global finite element model comprises of the main structural elements with appropriate detail for modelling a good representation of the expected structural behaviour and the nominal stresses. The use of section capacity checks in accordance with design standards form an efficient and conservative approach where possible. A range of code guidance for the assessment of strength capacity is available for structures of typical offshore design (for example, steel tubular structures). Whether code guidance is applicable or not depends on the geometry and material of the structure. Where guidance provided in standards is not applicable to the structural geometry the effects represented in code guidance need to be considered in some way (e.g. second order geometrical effects, tolerances, punching shear at connections). This is likely to involve linear buckling analysis of individual members and local finite element models of components/connections with complex geometry. It is important that appropriate boundary conditions are applied to local models to adequately capture their behaviour in the global structure. This may involve prescription of displacement or force conditions at boundaries, or stitching detailed local models into a less refined global model. *(continued on next page)*	**Global linear FE model:** • All WEC design will require a global FE model to assess the global capacity. **Local FE model:** • Individual components with complex geometry on the main load path may also require a detailed local model. • Examples: attenuator connections, mooring and foundation connections, connections with PTO for OWSC and point actuator device. **Design code checks:** • Current design standards cover tubular structures, concrete foundations, grouted connections, threaded connections, flanged connections. • Tubular components with OSWC, point actuators, attenuators and OWC. Concrete standards are to be relevant to near-shore based overtopping devices.

<table>
<tr><th>Structural analysis method</th><th>Notes</th><th>Applications to WECs</th></tr>
<tr><td>Linear global model combined with design code checks and/or local models</td><td>(continued from previous page)

This method is closely aligned with code guidance and is adopted for the majority of existing offshore structures, this provides the approach with credibility and, in all likelihood, an easier path through certification. The limitation of this technique is that generalised methods will have a tendency to conservatism, when applied as intended, and that the design codes cater only for specific geometries and scenarios.

Applicable standards:
• General guidance on the applicability and limitations of global finite element modelling is provided in ISO 19902 [16] and API RP-2A [18].
• Detailed guidance for FE model setup, including local models, is provided in DNVGL guidelines [17] Appendix 5.
Standards for member and joint checking include ISO 19902 [16] (steel), ISO 19903 [23] (concrete).</td><td></td></tr>
<tr><td>Nonlinear simulation using global and local models</td><td>This is the same as the method described above, except that non-linear behaviour such as post-yield response of the material and non-viscous power take-off are considered. As nonlinear behaviour is often considered beyond code capacity, the applicability of code based checks may no longer be applicable.

These types of methods can remove conservatism from the design and so are particularly suited to extreme load cases, such as the accidental limit state. However, it is not a universal rule that non-linear simulation will result in a leaner design as linear analysis may not be sufficient to capture all the important responses of the devices e.g. new load paths may be identified in a post-yield condition. As with the linear equivalent, the difficulty of this method is that other areas that are codified need to be considered from first principles and modelled explicitly. A limitation of this method is the computational effort involved with nonlinear material models. For critical components with complex geometries undergoing extreme loads (as identified in the FMEA) this can be a valuable technique however.

Guidance for the determination of structural capacity by non-linear FE analysis methods, including examples, is provided in DNV-RP-C208 [24].</td><td>• Elements in the device which are intended to behave in a non-linear manner in operational conditions e.g. power take-off.
• Accidental limit state analysis (e.g. boat impact) for the majority of WEC devices (see FMEA).
• Abnormal ULS environmental assessment on structural components (see definition in Section 2.2.1).
• Composite connections where linear methods are inappropriate (e.g. grouted connections, interface between steel and concrete foundations).
• Pushover analysis to assess overall structural capacity in locked conditions.</td></tr>
</table>

Structural analysis method	Notes	Applications to WECs
Inclusion of dynamic amplification	Dynamic amplification of loads is the term used to define cases where inertial loads associated with resonant response contribute appreciably to the total loads. Inertial loadings in WECs may be generated through rigid body accelerations of the device and also through dynamic deformations of the structure. Inertial forces in fixed structures are often dominated by resonance i.e. vibration of the natural modes of vibration, but in WECs, quasi-static response to hydrodynamic loads e.g. waves, can also be significant. Capturing these effects within the loads analysis will typically require spectral or time-history analysis. As for fatigue, spectral analysis is limited to cases where the device behaviour can be adequately represented by a linear model while time history analysis has the potential to capture non-linear effects. After completion of an analysis, determining which load cases provide the governing strength load cases can be non-trivial. It should be noted that inertial forces due to resonant deformations are implicitly captured by applying time-history loads to an FE model (see description of Deterministic Fatigue Analysis). It must be ensured that such models include suitable hydrodynamic added mass.	• The requirement for the inclusion of dynamic amplification of loads is dependent on the propensity of the device to exhibit resonant excitation under harmonic loading or 'over-shoot' following application of an impulsive load. • An assessment of whether resonant response is significant can often be conducted by comparing the structure's natural frequencies to the wave periods that occur at the site. Modes with natural frequencies in excess of 0.5 Hz are, generally speaking, unlikely to exhibit significant resonant behaviour under wave loading.
Component testing	Structural testing to determine fatigue and ultimate strength is an option where standard guidance doesn't exist. One example where this can be of particular importance is in the design of mooring connections and tethers where novel materials (which do not have standard strength or development of empirical S-N fatigue curves) are required. DNV-OS-C301 [26] provides a description of where structural testing is most applicable and detailed guidance on how best to perform tests. Clearly, an essential pre-cursor to component testing where code guidance is unavailable is a literature survey of existing research.	

2.4 Method Assessment

This Section contains a critical evaluation of the applicability to WEC analysis of the load and structural analysis techniques previously discussed.

A matrix technique was developed to systematically assess options in terms of their relative transferability to the analysis of WECs. The assessment has been conducted differently for methods associated with loads analysis and those associated with structural analysis. The loads analysis methods are, in general, applicable to all WEC types, and hence are assessed against design situation. The structural analysis methods are, in general, applicable to all design situations and hence are assessed against WEC type.

The developed matrices follow the review of guidelines and standards presented in Section 1.2. Where applicable, the identification of alternative methods through the possible generation of hybrid formulations is also proposed (e.g. combining simple analysis methods with more advanced techniques).

2.4.1 Load Calculations

Table 12 illustrates a critical assessment of the baseline load calculation formulations as a function of the design situation under consideration. The rating system developed and applied to Table 12 aims to assess both the suitability of the baseline formulation(s) to each design situation and, when applicable, the level of effort required to further develop the method(s) in order to apply the technique to WECs. As a result, the rating is well aligned with the effort required to develop solutions to address all the DLCs suggested in Table 10 (see Section 2.2.5).

In order to calculate the loads on a WEC, all the loading sources must be accounted for. Broadly, these involve environmental considerations and machine operating conditions (see Section 2.2.1). The baseline formulations presented in 1.3.4 are considered in terms of their applicability to estimate the design loads affecting a WEC and, when applicable, the development effort required to fulfil this objective. Some of the baseline formulations considered (e.g. BEM methods) are primarily used to assess the hydrodynamic loads on a WEC structure, and may therefore require developments to incorporate additional load sources (PTO, moorings, etc.) in order to consider all of the relevant loads affecting a WEC system (in some cases, the fully coupled models have in summary followed a similar development path).

The following points provide a detailed commentary that summarises the critical assessment presented in 2.2.6 and the key findings that may be extracted from its analysis.

- A formulation based on first principles is only applicable for high level, ‘goal posting’ power production (and potential transport / installation) considerations.
- Linear BEM solvers are capable of addressing key wave-structure interactions problems (namely diffraction and radiation), while performing calculations for many load cases at an acceptable computational time. The primary limitation associated with the direct use of linear BEM methods in WEC modelling is that when the formulation is used in isolation, it is uncoupled and requires the incorporation of additional load sources (PTO, moorings, etc.) to consider loading on a WEC system. If such developments are incorporated, the formulation in essence becomes equivalent to a fully coupled point loads, frequency-domain model.

- Nonlinear BEM formulations have the potential to address a wider range of non-power production design situations, as they consider the pressure integration over the instantaneous wetted surface at every instant in time. Similar to linear BEM formulations, nonlinear BEM solvers focus on the wave-structure interaction problem, with a need to incorporate other relevant load sources to estimate WEC loading for different design situations. Therefore, significant to major development efforts are required to adapt the baseline nonlinear BEM formulation for different design situations.
- Morison's equation is a common empirical method for estimating the loads impacting offshore structures. Being empirical, it is by definition based on a parametric equation derived from experimental evidence, and as such may lead to erroneous estimates when applied in dissimilar conditions. Morison's equation is particularly useful as a means of addressing viscous effects in addition to inertial loads, thus relevant for design situations that may be associated with large body velocities. With suitable adaptations, the formulation is transferable to the majority of design situations with minor to significant development efforts.
- All frequency-domain based formulations are fundamentally unsuitable for DLCs that involve highly transient effects, which may be induced by e.g. energetic environmental conditions, fault conditions and / or a combination of both external and internal WEC conditions.
- All coupled methods are well suited for DLC 1.x (power production), with the more advanced time-domain methods being particularly well suited as they allow for nonlinearities to be included in the simulations.
- Varying levels of effort are required to develop suitable formulations to model all relevant design situations. For example, there are at present no readily available software tools to conduct batch load calculations for power production design situations involving faults (DLC 2.x).
- When comparing Morison formulations and nonlinear BEM solvers, software based on the former is more widely available that software based on the latter. Furthermore, a Morison based formulation is more easily adapted and more modular, which facilities its inclusion with other formulations in a hybrid approach (see also Section 2.2.6). As a result, it may be more practical to adapt such formulation for a wide range of design situations, within the limitation that an empirical method carries.
- A fully coupled, point loads (time-domain) load calculation method is the most directly suitable formulation for the widest range of design situations that is readily applicable at present. Time-domain solutions are capable of dealing with nonlinear effects and typically use data from linear BEM solvers as inputs (e.g. exciting force and radiation damping). A range of fully coupled, time-domain point load models are currently available for WEC modelling. For example, the baseline formulation used to estimate the loads in the example presented in Section 2.5.1 is based on a point loads (time-domain) model, with the hydrodynamic loading input data derived from a BEM (linear) solver.
- A fully coupled, time-domain distributed loads formulation may have particular challenges in terms of e.g. the computational effort required to perform batch load calculations. This is particular true for a flexible body formulation, which may be required for certain WEC types (e.g. bulge wave WECs). A distributed load technique based on rigid bodies may partially alleviate such concerns.

- Advanced methods may be applied for highly nonlinear loading scenarios, when hydrodynamic nonlinearities, machine related nonlinearities (e.g. nonlinear PTO force profiles) and viscous effects are likely to be relevant. However, one of the drawbacks of applying these formulations is the computation effort required. In order to reduce this effort, some hybrid advanced methods are currently under investigation to examine the merits of this approach (see Section 2.2.6). There is a substantial amount of ongoing research regarding the suitability of these methods in marine renewable energy, which going forward can benefit WEC developments.
- Finally, nonlinear formulations offer a possibility to address accidental / abnormal events (DLC 9.x) and damaged stability (DLC 10.x) with additional confidence. The development effort for both nonlinear BEM and advanced methods (e.g. RANSE) formulation is still significant, in particular if it is recognised that to incorporate all machine related load sources (e.g. PTO, moorings, etc.) substantial software developments changes may need to be conducted.

Table 12 Critical assessment of the baseline load calculation formulations

	Baseline Formulations: Load Calculation							
Design Situation	First-Principles	BEM (linear)	BEM (nonlinear)	Morison's Equation	Point loads (freq.-domain)	Point loads (time-domain)	Distributed loads (time-domain)	Others (advanced methods)
1. Power production								
2. Power production plus faults								
3. Start-up								
4. Normal shut-down								
5. Emergency shut-down								
6. Parked (standstill or idling)								
7. Parked plus fault conditions								
8. Transport, installation, maintenance and repair								
9. Accidental / abnormal events								
10. Damaged stability								

Rating System Key

1	2	3	4	5
Formulation fundamentally suitable	Formulation suitable with minor development efforts	Formulation suitable with significant development efforts	Formulation suitable with major development efforts	Formulation fundamentally unsuitable

2.4.2 Structural Analysis

Table 13 contains a critical assessment of the structural analysis approaches as a function of device type. The rating system developed aims to assess both the suitability of the analysis approach to each device and, when applicable, the level of effort required to further develop the method(s) in order to apply the technique to WECs.

The following points provide a commentary to support the ratings in Table 13:

- There are some techniques which have been identified as having direct applicability to all devices, specifically: hand calculations, non-linear simulation and component testing. Clearly it is still essential that the designers have a thorough understanding of the design objectives and underlying physical processes when specifying and implementing these approaches. E.g. the correct scenarios need to be addressed by hand calculations and the limitations of any such results understood, similarly component tests are only valuable if the tests satisfactorily capture the relevant loads and conditions which are anticipated to affect the component's function. The other technique seen to be of universal relevance is non-linear simulation as virtually all WEC devices will have a design scenario, often relating to extreme environmental conditions or vessel impact, where some permanent structural deformation will be defined as acceptable in the design basis.

- Spectral fatigue analysis is an efficient technique when it can be implemented but it relies on a satisfactory representation of the device being provided by a linear system. For WEC devices it is often the case that slam and slap impulsive loads will be fundamental in determining the structural fatigue response. This being the case it makes derivation of a linear representation challenging. A likely exception to this are Submerged Pressure Differential devices where a good linear representation of the fatigue loading regime looks feasible; nonetheless, application to this device would take some development from the prescribed approaches available in code guidance.

- Deterministic fatigue analysis is seen as a valuable technique where structural dynamics are not key to the device's structural response. This is likely to be the case in some aspects of the design of the Oscillating Water Column and the Overtopping devices as a waves are generally incident on a rigid breakwater type structure. Time history analysis is an extension to standard deterministic technique commonly applied to WECs where the wave climate is represented by a realistic wave train for each sea state and contributing operational state. Time history analysis is expected to be applicable to a large range of WEC geometries and design situations.

- SCF calculation, generally supported with FE, is a very flexible technique as, in principle, any practical geometry can be represented in the model hence there are few restrictions in its use. For the case of the Bulge Wave device, the influence of geometric stiffness and implementation of transitions between 'rigid' and fabric structures would require specific consideration during model development. Furthermore, the availability of information describing the degradation of the fabric material under cyclic loading will often be constrained by the data available from the supplier.

- The ease of development of SCFs from code guidance is dependent on the similarity of the proposed structural connection details on the WEC device with existing standard connection details on offshore structures. The ratings for this technique are derived on this basis.

- Similarly, the ease with which code capacity checks can be used on WEC devices is dependent on the similarity of geometry and materials with those conventionally used on offshore structures. The ratings for this technique are derived on this basis.
- The remarks with respect to SCF calculation through FE are equally applicable to the use of local detailed FE models to do capacity checks. In principle, any practical geometry can be assessed but greater development will be required in cases where geometric stiffness and transitions to fabric structures need to be considered.

Table 13 Critical assessment of the structural analysis approaches

WEC type	Spectral fatigue	Deterministic fatigue	SCF calculation with FE modelling	SCF calculation with code equations	Hand calculations with code guidance	FE + code capacity checks	FE + local models	Nonlinear simulation using global and local models	Component testing
Point absorber									
Oscillating Wave Surge									
Oscillating Water Column									
Bulge Wave									
Attenuator									
Overtopping Device									
Submerged Pressure Differential									

Rating System Key

1	2	3	4	5
Existing method suitable	Method suitable with minor development efforts	Method suitable with significant development efforts	Method suitable with major development efforts	Method fundamentally unsuitable

2.5 Representative Example

Following the results presented in Section 1.2, a point absorber WEC geometry was selected to provide representative load and structural analysis results for a range of environmental and machine specific conditions.

This Section provides a description of the numerical model setup, the load calculation methodology and the characteristic loads output for a two-body point absorber WEC. The loads derived were then used in a spectral fatigue analysis of the assumed mooring connection and a strength analysis of the assumed base plate connection.

It should be noted that the results from the example calculations are highly dependent on the assumed geometry and local design details. They therefore provide insight into the methods rather than generate absolute values of demand. The stress derivation methodology presented for spectral fatigue and strength analysis represents a single set of simplified calculations. For a detailed design exercise, a large number of design iterations would be required, involving a number of more detailed calculation approaches. The proposed best practice approach for structural analysis is summarised in Section 3.

2.5.1 Overview

The Reference Model 3 (RM3) two-body point absorber WEC, defined in the Department of Energy (DOE) funded Reference Model Project, was used as the example design. The point absorber was modelled in WEC-Sim [6]. WEC-Sim has the ability to model devices that involve rigid bodies, PTO systems and moorings. The input files to the RM3 are available online (see additional links available in [6]) and can be used by the interested reader to replicate the analysis.

Simulations are performed in the time-domain by solving the governing WEC equations of motion in all relevant degrees-of-freedom, in a fully coupled format (i.e. simultaneously accounting for all relevant load sources). In alignment with the definitions presented in Section 1.3.4, WEC-Sim's baseline formulation can be described as a fully coupled, time-domain point loads model. Further details regarding WEC-Sim can be found at http://wec-sim.github.io/WEC-Sim/.

2.5.2 Structural Model

WEC-Sim models are constructed on a multi-body basis, as a collection of linked components with specific physical properties. These components include wave-activated rigid bodies, joints at which PTO forces may be applied and mooring lines that can be attached to the WEC structure and to which anchor points may be assigned.

The RM3 is a two-body point absorber WEC, consisting of a float and a spar with a reaction plate. The WEC structural properties are represented in WEC-Sim as rigid bodies with mass, inertia, PTO and hydrodynamic properties. The full-scale dimensions of the RM3 WEC and its mass properties are shown in Figure 18 and

Table 14. A Simulink chart representing the multi-body structure implemented in WEC-Sim is illustrated in Figure 19.

The relative movement between the spar/plate and the float is restricted by a heave constraint at the location of the PTO. In this representative example, no active control strategy was used; PTO settings in terms of damping coefficients remain constant.

Table 14 Geometry and mass properties of the RM3

Body name	Mass (tonne)	Centre of gravity (m)	Moments of inertia about CG (kgm²)		
		x y z	Ixx Iyx Izx	Ixx Iyx Izx	Ixx Iyx Izx
Float	727.01	0.0 0.0 -0.72	20.9E6 0 0	0 21.3E6 4305	0 4305 37.1E6
Spar / Plate	878.30	0.0 0.0 -21.29	94.4E6 0 0	0 94.4E6 218E3	0 218E3 28.5E6

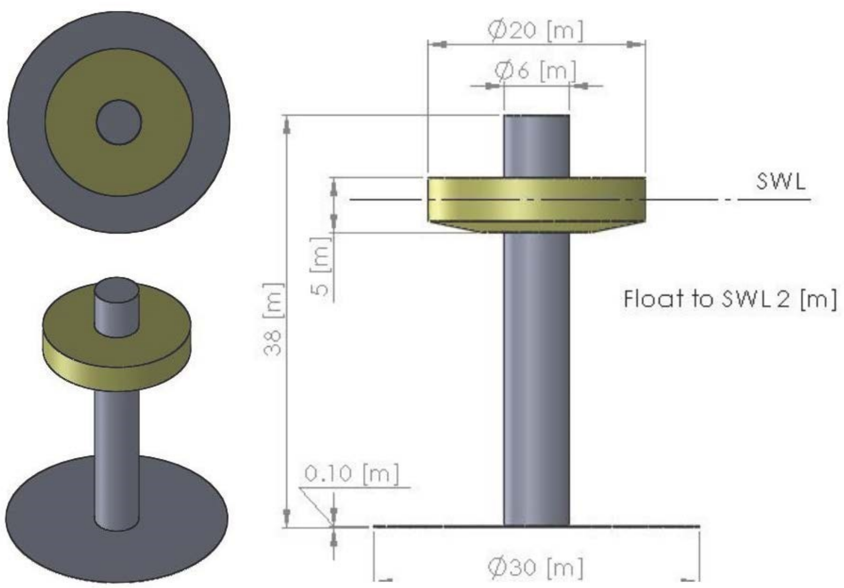


Figure 18 Dimensions of the RM3 WEC-Sim

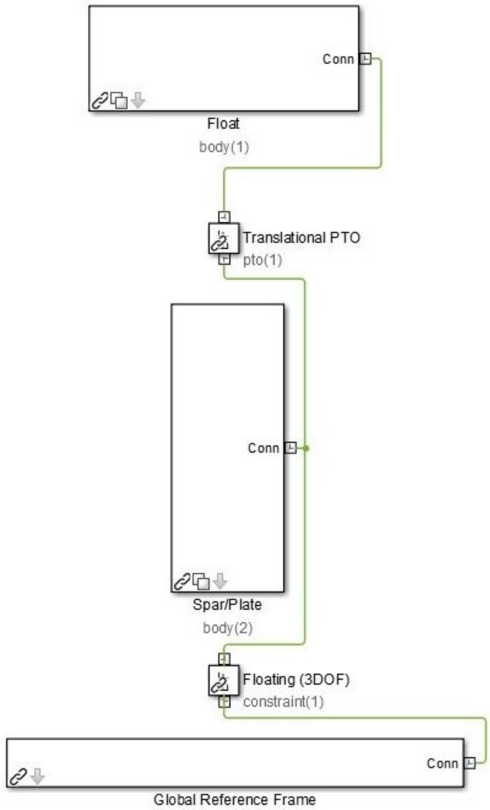


Figure 19 WEC-Sim model schematic – Baseline model

The mooring arrangement was represented using the mooring forces calculated using MoorDyn [7]. The mooring system consists of three mooring lines (see Figure 20), discretised into 20 evenly-sized line segments connected by node points. The linear mass of each line was set to 126kg/m, with an unstretched length of 280m. The mass is lumped at the node points, along with gravitational and buoyancy forces, hydrodynamic loads, and reactions from contact with the seabed. Hydrodynamic drag and added mass are calculated based on Morison's equation. The point masses are connected by spring-damper elements. The springs represent the axial stiffness of the line, defined via the product of elasticity modulus and cross-sectional area, here set at 583.4MN. Divided by the segment length, this gives an axial stiffness of 41.7MN/m to each line segment, in tension only. The dampers represent a small internal damping force that, while not corresponding to a physical characteristic, is necessary to dampen non-physical resonances caused by the lumped-mass discretisation. Bending and torsional stiffness's are neglected. Bottom contact is represented by vertical stiffness and damping forces when nodes pass below the seabed. The mooring lines are attached to the spar, 10m below the undisturbed sea water line (referred to as SWL in Figure 18).

Table 15 summarises the mooring line properties, including the coordinates of the attachment points and anchor points, mass and stiffness coefficients. The positions of the attachment and anchor points have been provided relative to a reference frame such as the horizontal (x-y) plane is aligned with the sea water line, and the z-axis is aligned with the vertical spar axis, pointing upwards. It should be noted that although the mooring system defined in MoorDyn would allow motions in six degrees-of-freedom, the floating constraints connecting the spar to the seabed in WEC-Sim restrains the motions to 3 degrees-of-freedom only (see Figure 19), namely surge, heave and pitch.

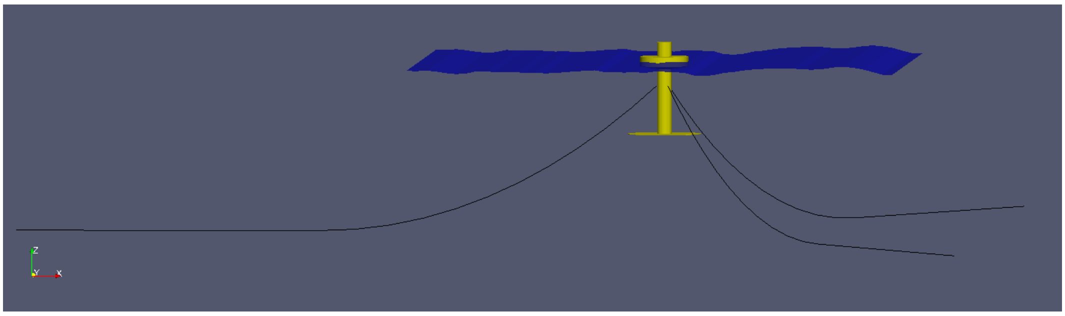


Figure 20 Mooring line arrangement schematic

Table 15 Mooring line properties

	Attachment point (m)	Anchor point (m)	Mass (tonne)	Axial stiffness (Young modulus x cross-sectional area) (MN)
Line 1	-3.0 0.0 -10.0	-267.0 0.0 -70.0		
Line 2	1.5 2.598 -10	133.5 231.23 -70.0	35.28	583.4
Line 3	1.5 -2.598 -10	133.5 -231.23 -70.0		

2.5.3 Load Calculation Methodology in WEC-Sim

The dynamic response of the system is calculated by solving the equation of motion for the WEC, including all relevant sub-systems. The equation of motion for the WEC can be given as:

$$m\ddot{X} = F_{ext} + F_{rad} + F_{PTO} + F_v + F_{ME} + F_B + F_m$$

where $\ddot{X}$ is the (translational and rotational) acceleration vector of the device, m is the mass matrix, F_{ext} is the wave excitation force vector, F_{rad} is the force vector resulting from wave radiation, F_{PTO} is the PTO force vector, F_v is the damping force vector, F_{ME} is the Morison element force vector, F_B is the net buoyancy restoring force vector, and F_m is the force vector resulting from the mooring connections.

The hydrodynamic forces were obtained via the linear boundary element method (BEM) potential flow solver WAMIT. The BEM solutions were derived by solving the Laplace equation for the velocity potential, which assumes the flow is inviscid, incompressible, and irrotational.

Both F_{ext} and F_{rad} were calculated using outputs from the BEM solver. The radiation term includes an added-mass and radiation damping term associated with the acceleration and velocity of the floating bodies, respectively. The wave excitation term includes a Froude-Krylov force component generated by the undisturbed incident waves and a diffraction component that results from the presence of the floating bodies.

In a linear approximation of the hydrodynamics, both F_{ext} and F_{rad} are calculated using integral equations, with the latter based on the Cummins equation [5]. This method is recommended to represent the fluid memory effects acting on the floating body. The excitation and radiation forces can then be given as follows, where S is the input wave spectrum and ϕ is a random phase angle:

$$F_{rad}(t) = -A(\infty)\ddot{X}(t) - \int_0^t K_r(t-\tau)\dot{X}(\tau)d\tau$$

$$F_{ext}(t) = \Re\left(R_f \int_0^\infty F_X(\omega_r)e^{i(\omega_r t+\phi)}\sqrt{2S(\omega_r)d\omega_r}\right)$$

However, not all devices and operating conditions can be accurately simulated using linear hydrodynamics approximations. When large body motions are exhibited, the wetted area can change dramatically, and a model based on linear hydrodynamic coefficients may become inaccurate. Previous studies [9] have assessed the potential differences between linear and nonlinear formulations. In this example, a nonlinear approximation was considered. In this approximation, the buoyancy force F_B and the Froude-Krylov component of the excitation force were calculated from the instantaneous position of the bodies. Instantaneous buoyancy and Froude–Krylov forces and moments were obtained by integrating the hydrostatic and hydrodynamic pressures (p_{hs} and p_{hd}, respectively) at each simulation time step over the wetted surface of the body, using the formulae given in [9].

$$p_{hs} = \rho g z$$

$$p_{hd} = \frac{1}{2}\rho g a \frac{\cosh\left(k(z+d)\right)}{\cosh(kd)}\cos(\theta)$$

where ρ is the fluid density, g is acceleration resulting from gravity, a is the wave amplitude, k is the wave number, z is the distance to the mean waterline, d is the water depth and θ is wave phase angle.

Forces and moments were calculated by discretising body geometries into triangular elements, tracking their displacement and then summing the resulting forces and moments on each element about the centre of mass of the body.

2.5.4 Load Simulation Set-Up

For normal operation conditions, simulations for eight irregular waves were completed. The significant wave height and peak period parameters defining the JONSWAP wave spectrum were selected based on a scatter diagram representing the wave climate at the European Marine Energy Centre (EMEC) [4] using refraction point RP50N. The information is summarised in Table 16. The eight most occurring sea states were selected, as highlighted in bold in Table 16, covering c.50% of the events in the scatter diagram.

When assessing the WEC response to an extreme event, different machine conditions were tested. In particular, a normal PTO setting (damping coefficient identical to operational conditions) and a PTO under fault conditions were simulated. For the latter, the loss of PTO (zero damping) and a locked PTO (infinite damping) were tested. In [4], the offshore extreme wave conditions corresponding to return periods of 1, 10, 50 and 100 years were estimated. For this study, the 50-year wave was selected, following DNV-OS-J103 as recommended in Section 2.2.4.1. A JONSWAP spectrum with 14.7m significant wave height and 18.2s peak period was using in the simulations, following the extreme wave conditions presented in [4] (see Table 17). It can be noted that although the wave conditions provided in [4] make use of the zero-crossing period T_z, WEC-Sim requires the use of the peak period T_p. These can be related for a JONSWAP spectrum by a proportionality factor of 1.285. Moreover, the energy period T_e described in Section 2.2.4.1 is also proportional to the peak period T_p for a JONSWAP spectrum using a proportionality factor of 1.107.

Nonlinear Froude-Krylov hydrodynamics and hydrostatics were used in the simulations. This is particularly relevant for situations where large body motions, such as those related to extreme wave inputs, lead to nonlinearities in the hydrodynamic loading. One fully-linear simulation under the 50-year return wave and with a faulty PTO (locked) was run to evidence the effect of taking into account nonlinearities.

A simulation length of 1850 seconds was used for all the simulations, including a ramp-up time of 50s to allow a steady state response to be reached.

Table 16 Inshore combined wave climate (significant wave height against zero crossing period) at refraction point RP50N (50m water depth) [4]

% of occ.	Mean wave period Tz (s) – centre of bin															
Significant wave height Hs (m) – centre of bin		0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5
	0.25	0.0	0.0	0.0	2.6	3.8	1.8	0.7	0.3	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0
	0.75	0.0	0.0	0.0	2.6	**9.2**	**5.9**	2.0	0.7	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0
	1.25	0.0	0.0	0.0	0.8	**6.0**	7.3	3.0	1.1	0.4	0.1	0.0	0.0	0.0	0.0	0.0	0.0
	1.75	0.0	0.0	0.0	0.2	3.0	**6.6**	3.2	1.0	0.4	0.1	0.0	0.0	0.0	0.0	0.0	0.0
	2.25	0.0	0.0	0.0	0.1	1.0	**4.4**	**4.2**	1.1	0.3	0.2	0.1	0.0	0.0	0.0	0.0	0.0
	2.75	0.0	0.0	0.0	0.0	0.1	2.2	**3.9**	1.5	0.2	0.1	0.1	0.0	0.0	0.0	0.0	0.0
	3.25	0.0	0.0	0.0	0.0	0.0	0.8	2.5	2.0	0.3	0.1	0.0	0.0	0.0	0.0	0.0	0.0
	3.75	0.0	0.0	0.0	0.0	0.0	0.1	1.5	1.9	0.6	0.1	0.0	0.0	0.0	0.0	0.0	0.0
	4.25	0.0	0.0	0.0	0.0	0.0	0.0	0.6	1.1	0.7	0.1	0.0	0.0	0.0	0.0	0.0	0.0
	4.75	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.7	0.7	0.2	0.0	0.0	0.0	0.0	0.0	0.0
	5.25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.4	0.2	0.0	0.0	0.0	0.0	0.0	0.0
	5.75	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.3	0.2	0.0	0.0	0.0	0.0	0.0	0.0
	6.25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0
	6.75	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0
	7.25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0
	7.75	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0
	8.25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	8.75	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	9.25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	9.75	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	10.25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	10.75	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	11.25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	11.75	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	12.25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	12.75	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 17 Extreme wave conditions ([4])

Return period (years)	Significant wave height H_s (m)	Zero crossing period T_z (s)	Peak period T_p (s)
1	10	11.7	15.0
10	12.7	13.2	17.0
50	14.7	14.2	18.2
100	15.4	14.6	18.8

2.5.5 Loads and Distributed Pressures Output

WEC-Sim outputs structural loads for all the bodies in the model. These are the resultant forces and moments acting on a particular element. By default, WEC-Sim outputs these structural forces at the centre of gravity of each body, and the output coordinate system is orientated with the global axis defined in WEC-Sim. The global WEC-Sim coordinate system is located at mean water level, with the z-axis pointing up-wards and the x-aligned with the incoming wave direction.

For the structural analysis, representative loads were selected to carry out to the next stage. A brief description of the variables involved are presented in Table 18.

Table 18 Description of WEC-Sim output carried out to structural analysis stage

Body	Description of the Loads
Float Spar/Plate	Forces in the body-fixed coordinate system located at the centre of mass of the structures. The output loads at these locations include: • Hydrodynamic loads • Gravity loads • Inertia loads
Mooring lines 1,2,3	The tension on the mooring lines (F_{Line}) is calculated in MoorDyn as the magnitude of the resultant force of the three components of the mooring force. Each tension is taken from the last segment (attached to the spar) of the respective mooring line.
Distributed pressures	The distributed loads on the main components of the structure can be assessed via the pressure distribution. These are derived for all the panels from the discretisation used in the hydrodynamic code and broken down into hydrostatic, linear Froude-Krylov and nonlinear Froude-Krylov pressure components.

Figure 21 shows the time series of wave surface elevations for the most frequently occurring sea state (H_s= 0.75m and T_p= 5.8s (i.e. T_z= 4.5s)) and the 50-year return period wave (H_s= 14.7m and T_p= 18.2s). Note that all repetitions of a simulation use the same seed for the phase, and the generated time series of sea states are thus identical. This is relevant for the comparison of WEC responses under the same sea state but different machine conditions (e.g. PTO conditions).

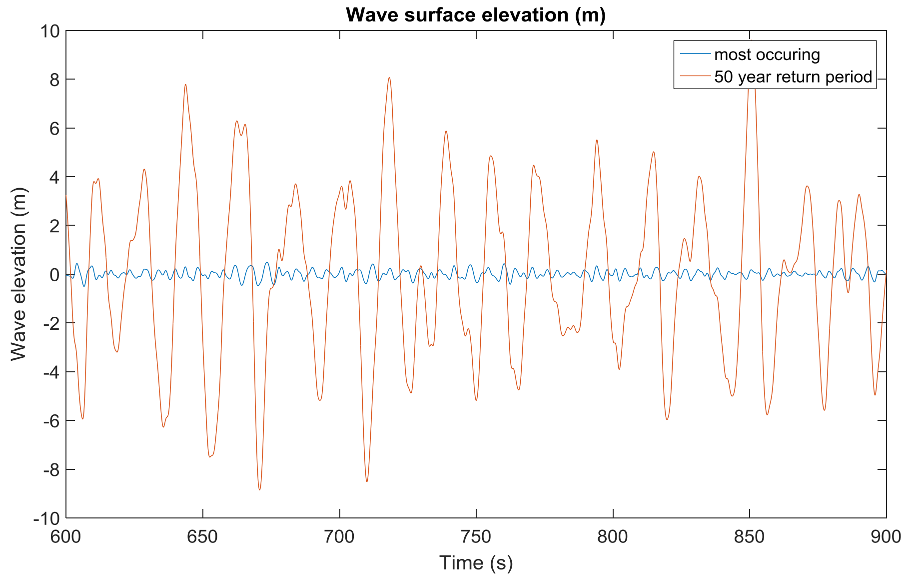
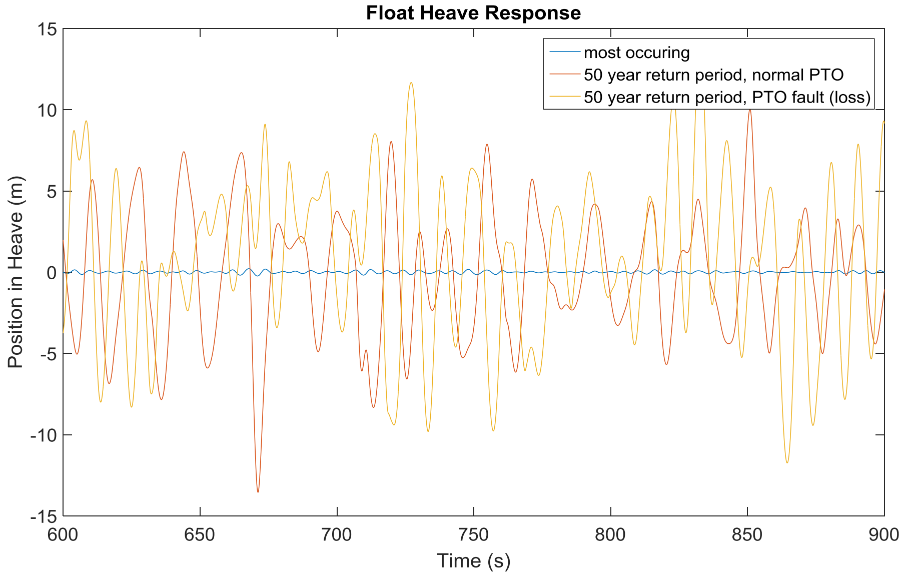


Figure 21 Extract of the wave surface elevation time-series for the most occurring sea state (blue) and the 50-year return period wave (red)

Figure 22, Figure 23 and Figure 24 illustrate the time series output of the heave (absolute and relative) and pitch body motions (respectively). Under the operational sea state, the spar/plate body remains relatively stable throughout the simulation, with less than 0.5m amplitude of motion. Its position oscillates around a point about 1.7m below the initial position due to the influence of the moorings. Under an extreme sea state, and as expected, the resulting motions are significantly larger, both in heave and in pitch. The fault case illustrated in Figure 24 exhibits a pitch oscillating around c.90°, i.e. a spar close to the horizontal. In this case, the float is pulled away from the spar and the WEC loses its structural integrity (see Figure 25). Note that the structural model does not include any auxiliary systems such as mechanical end-stops or a PTO controller that could assist in mitigating this end result. For the detailed assessment of more complex load cases, often not related to performance conditions, consideration should be given to the inclusion of end-stops and a more detailed description of the PTO. For certain load cases, e.g. PTO with fault, other, more advanced baseline formulations may also be more appropriate (see Section 2.2.6).

The total force output, that includes excitation, radiation damping, added-mass and restoring forces, is displayed in Figure 26. It can be seen that the stability and the response in general is significantly affected not only by the environmental conditions (i.e. the sea state) but also by the machine conditions (e.g. in this case the PTO settings: normal or faulty). This emphasises the importance of considering more than just environmental conditions when defining relevant DLCs (see also Table 10).



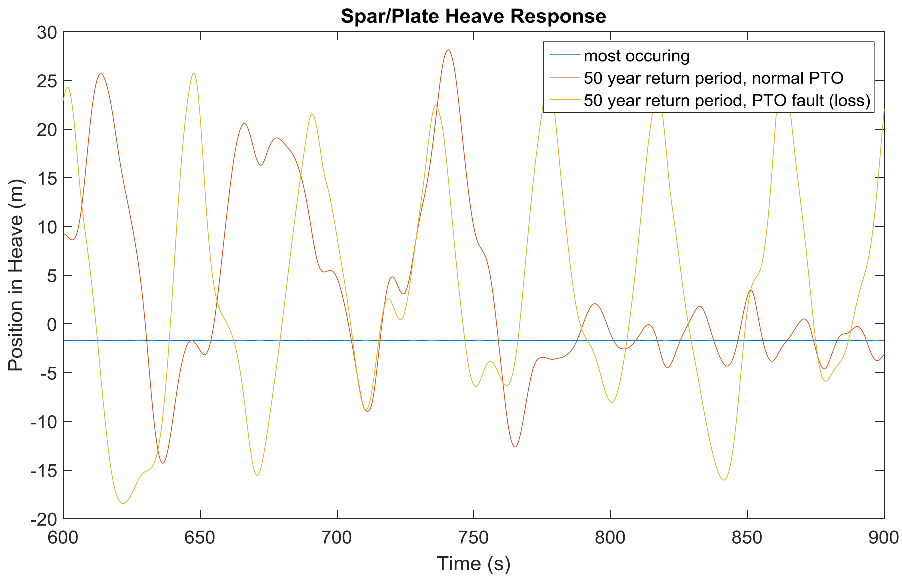


Figure 22 Extract of the float (top) and spar/plate (bottom) heave motion responses for the most occurring sea state (blue) and the 50-year return period wave under normal and loss of PTO conditions (red and orange respectively)

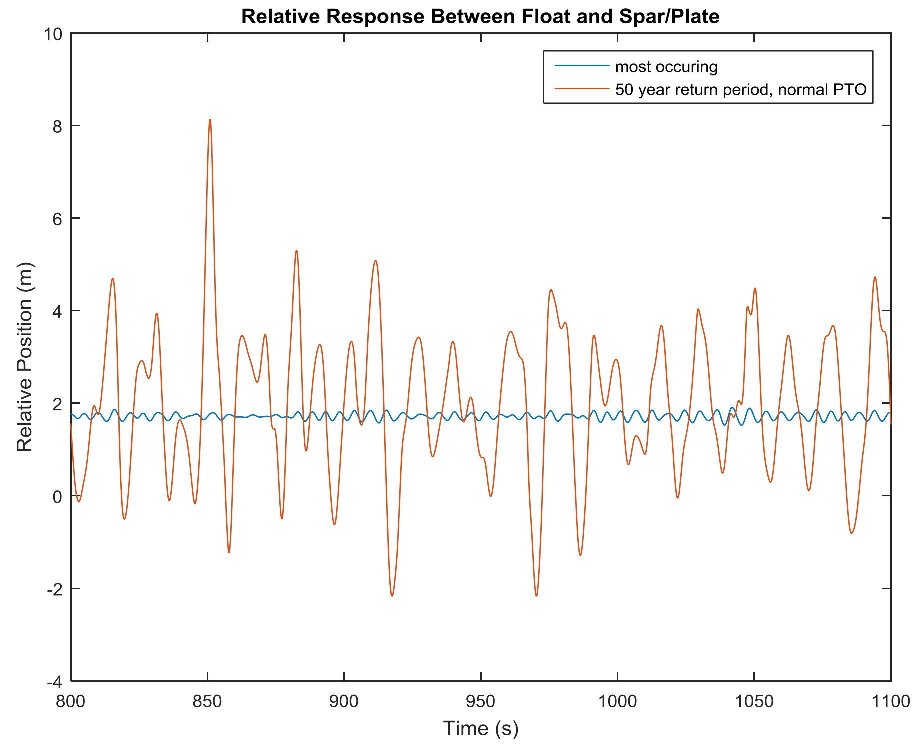


Figure 23 Extract of the relative heave motion responses between the two bodies (float and spar/plate) for the most occurring sea state (blue) and the 50-year return period wave under normal PTO conditions (red)

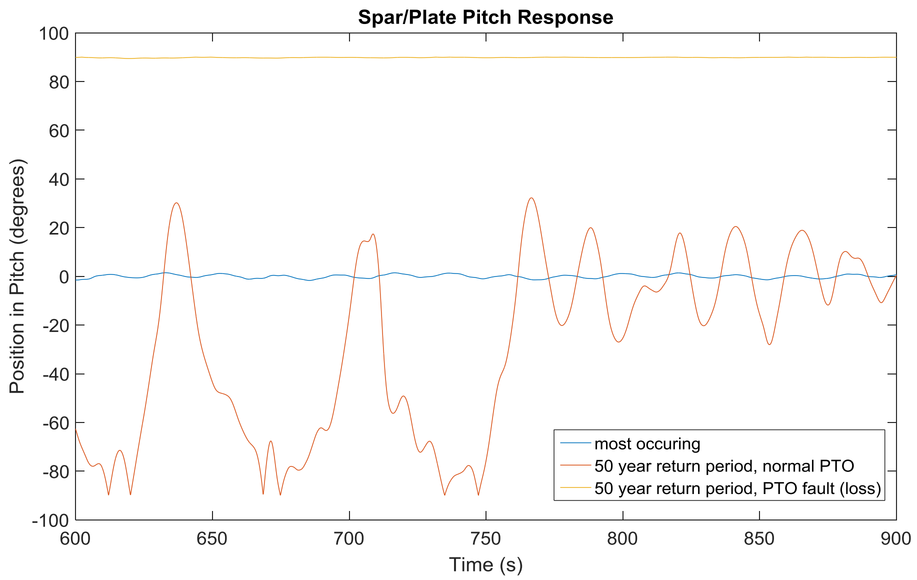


Figure 24 Extract of the spar/plate pitch motion responses for the most occurring sea state (blue) and the 50-year return period wave under normal and loss of PTO conditions (red and orange respectively)

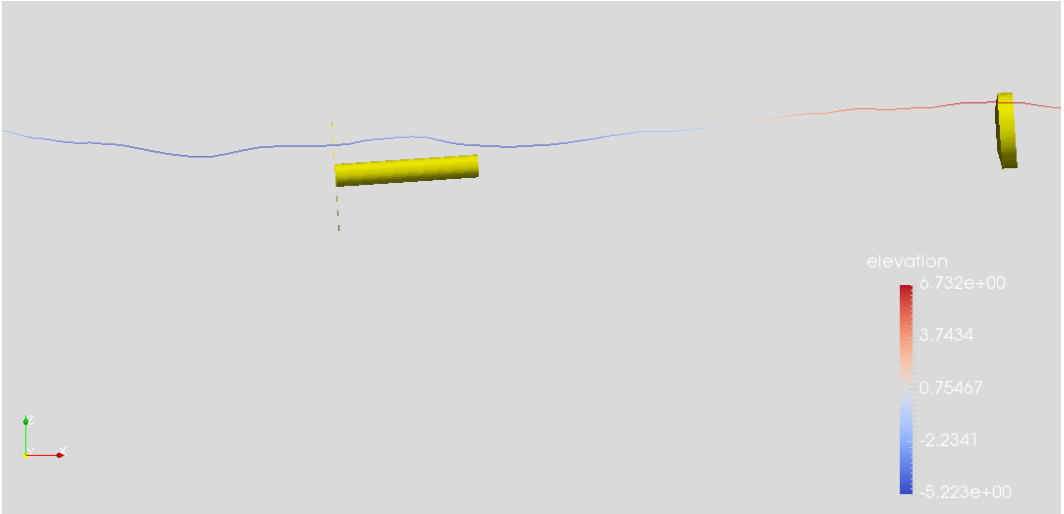


Figure 25 Snapshot of the spar/plate and float positions at t=380s under the 50-year return period wave with loss of PTO (loss of structural integrity).

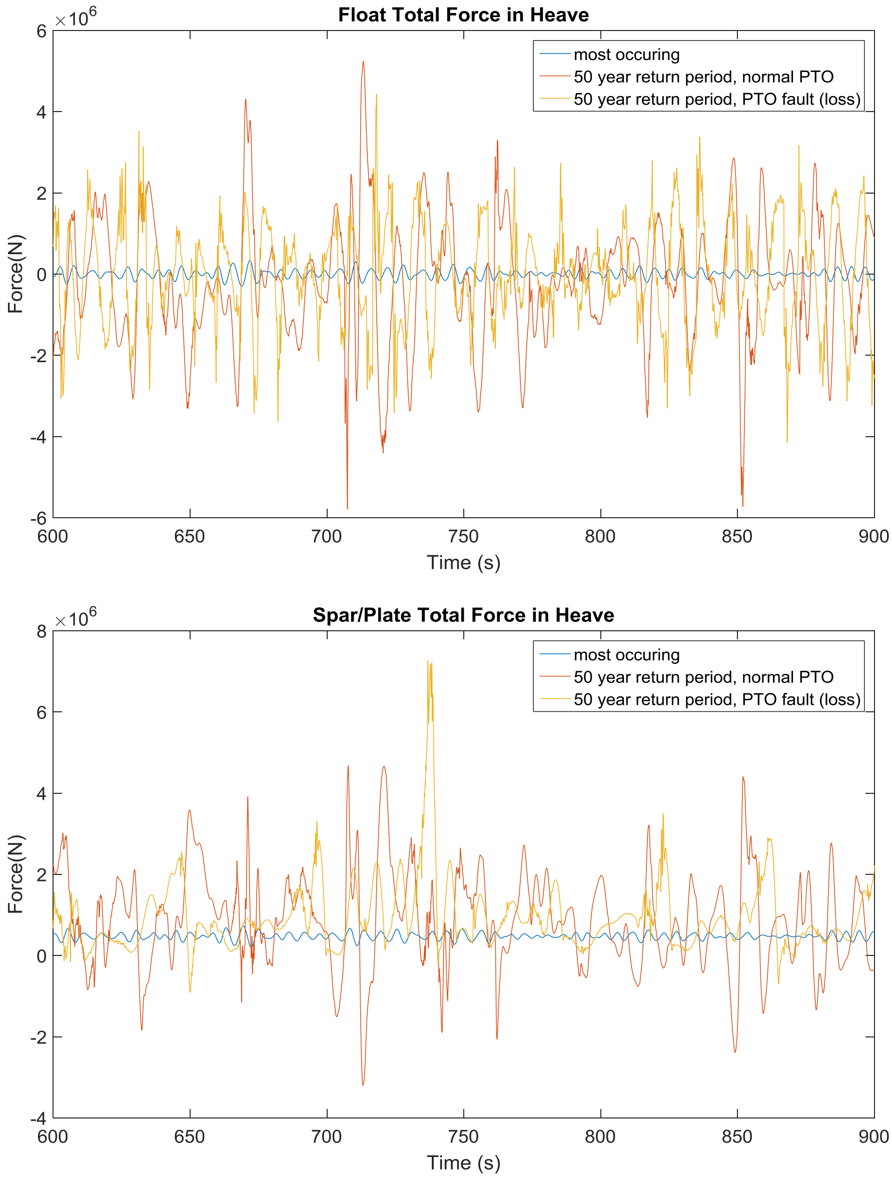


Figure 26 Extract of the float (top) and spar/plate (bottom) total heave force responses for the most occurring sea state (blue) and the 50-year return period wave under normal and loss of PTO conditions (red and orange respectively)

Figure 27 and Figure 28 show the tension in the mooring lines, in two environmental conditions (operational and 50-year return wave) and for different PTO conditions (normal, loss and locked) respectively. Tensions measured for Lines 2 and 3 are identical, as the mooring setting is symmetrical with regards to the incident wave direction.

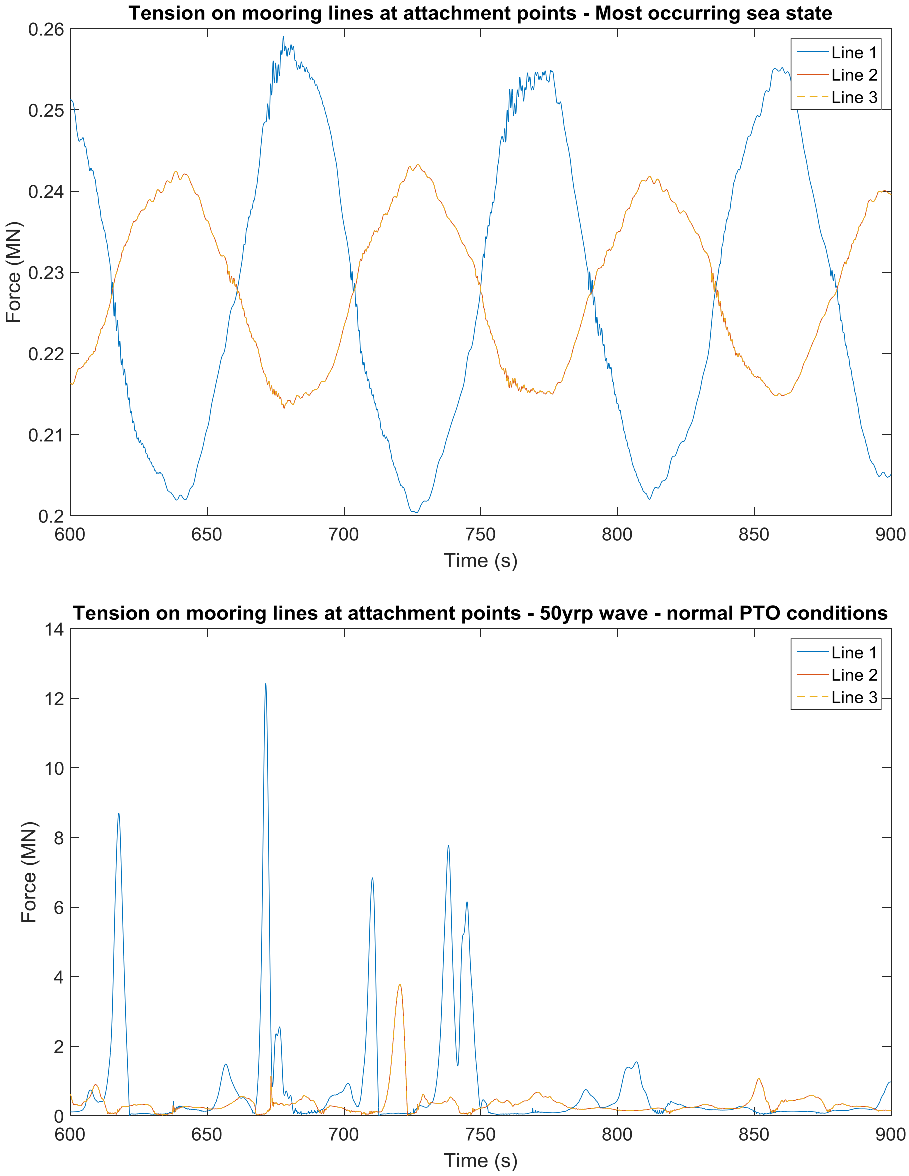


Figure 27 Extract of the tensions (in MN) on the mooring lines for the most occurring sea state (top,) and the 50-year return period wave under normal PTO conditions (bottom)

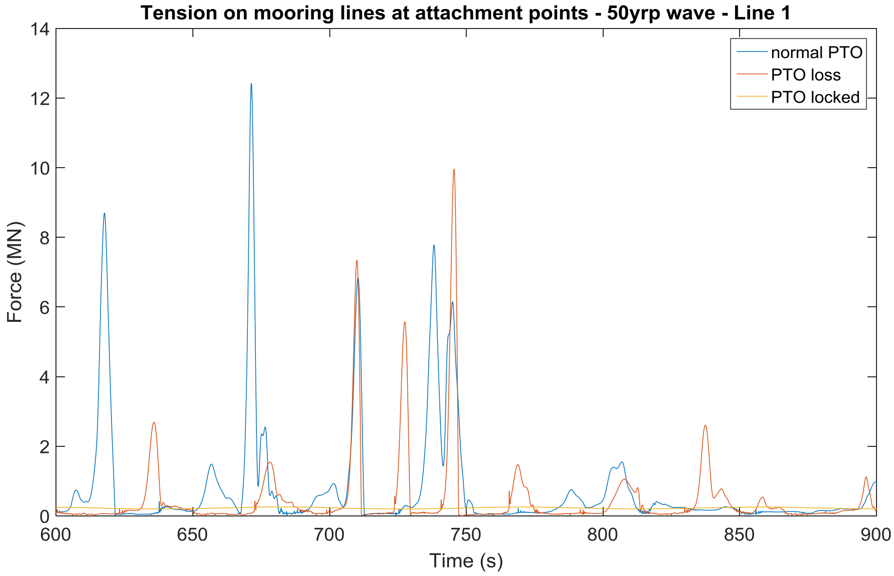


Figure 28 Extract of the tensions (in MN) on the mooring lines for the 50-year return period wave under normal PTO conditions (blue), loss of PTO (red) and lock PTO (orange)

Figure 29 illustrates the PTO absorbed power in an operational sea state with normal PTO conditions. The average power over the duration of the simulation (30min) can be derived from the entire time-series data: for a sea state of H_s=0.75m and T_p= 5.8s (i.e. the most frequently occurring sea state), the averaged absorbed power is of 8.6kW.

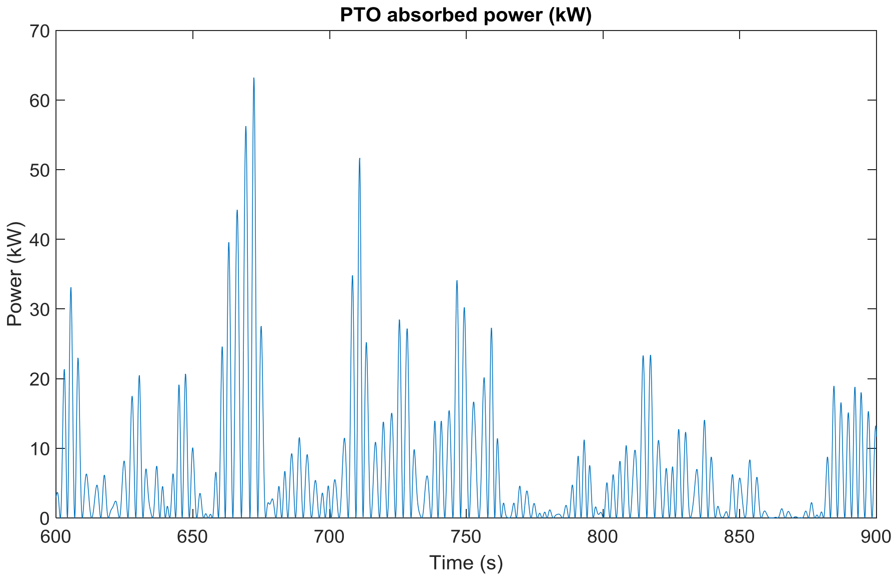


Figure 29 Extract of the absorbed power time series (kW) in the most frequently occurring sea state – 30min averaged absorbed power: 8.6kW

To conclude, an example of the instantaneous pressure distribution for a 50-year return wave with H_s= 14.7m, T_p= 18.2s is shown in Figure 30. The incident wave is approaching the WEC from the positive x direction (i.e. from the right-hand side of the figures below). The hydrostatic pressure increases significantly with the distance from the free surface. Although it can be the main contributor to the total pressure, for fatigue analysis the variation in pressure over time is also relevant, and the nonlinear Froude-Krylov pressures are of the same order of magnitude as the static counterpart.

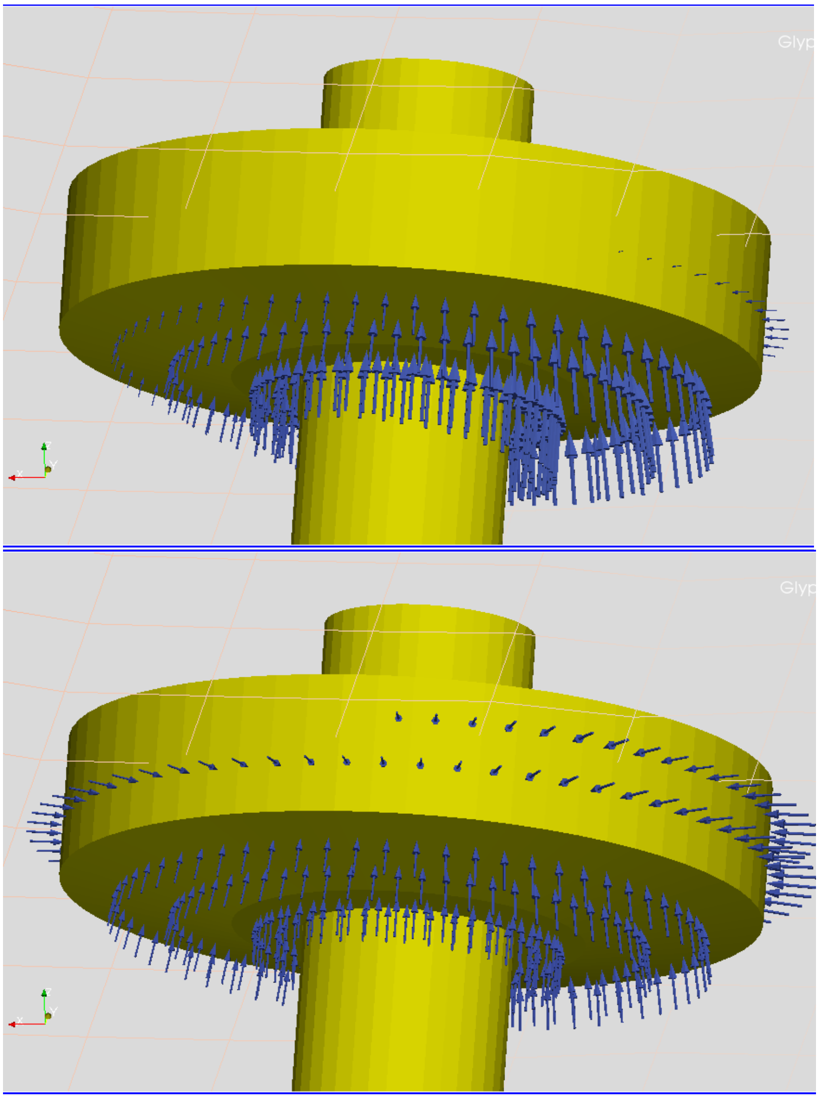


Figure 30 Distribution of pressure on the float for hydrostatic (top) and nonlinear Froude-Krylov (bottom) at t=811s (Hs=14.7m and Tp=18.2s) – normal PTO settings.

2.5.6 Mooring Connection - Spectral Fatigue Analysis

Spectral fatigue analysis is applicable to structures which are excited in their linear range by dynamic loading which can be characterised with a spectrum. Depending on the nature of the device and the environmental conditions it is possible to make a number of assumptions regarding the statistical nature of the wave loading, see Section 2.4.2 and [8] for further details.

A simplified spectral fatigue analysis was conducted in order to estimate the fatigue life of the mooring cable connections to the spar.

A number of assumptions were made regarding the geometric detail of the connection between the mooring cable and the spar, see sketch in Figure 31. A fillet weld, with a throat length of 10mm, around the perimeter of an approximately square plate (250 mm x 250 mm) was assumed. This is an assumed, simplified geometry for the mooring connection, used in order to demonstrate the process and principles of conducting a spectral fatigue analysis. Note that in practice, a number of design iterations and refinement will be required in order to determine the detailed connection geometry.

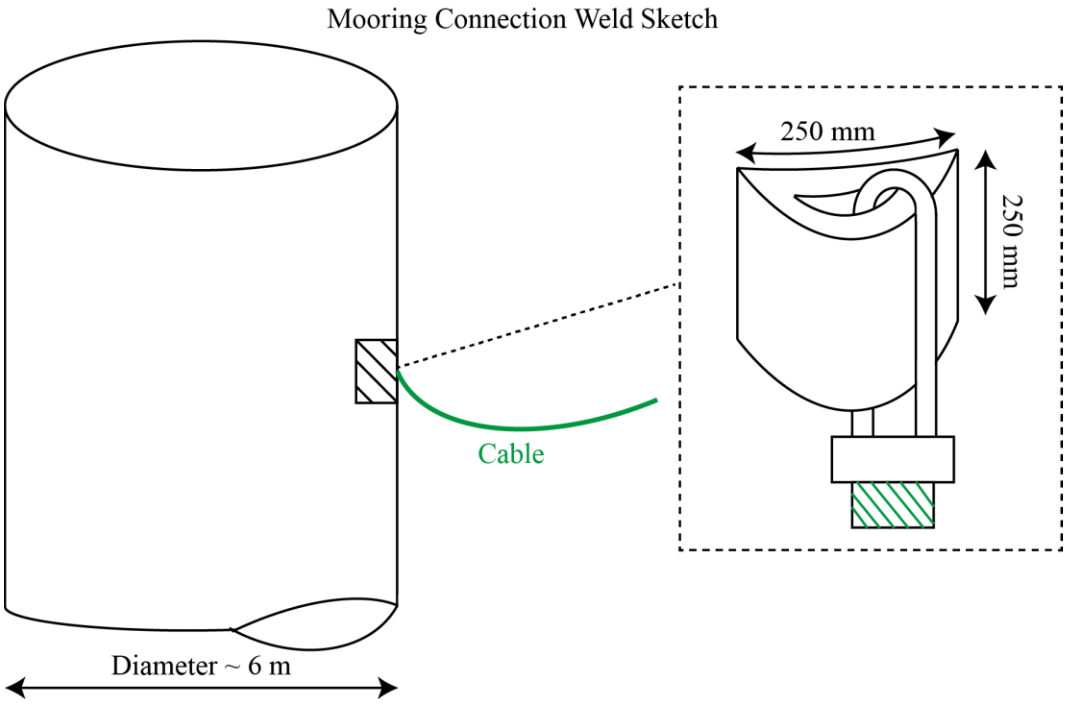


Figure 31 Assumed geometry of mooring cable to spar connection

Therefore the total assumed throat area of weld was:

A_{weld} ~ 4 x 250 mm x 10 mm ~ 0.010 m^2

The tension load was assumed to be applied and evenly distributed across the full weld area. A stress time history was therefore obtained by dividing the tension time histories, an example of which was shown in Figure 27, by the assumed weld area.

Figure 32 shows the calculated stress time history for mooring line 1, for an operational sea state characterised by a JONSWAP spectrum with H_s= 0.75m and

T_p= 5.8s. This sea state falls in the most frequently occurring bin of the EMEC inshore wave climate, see Table 16. Line 1 was chosen as it experiences the highest stress ranges out of the 3 mooring lines.

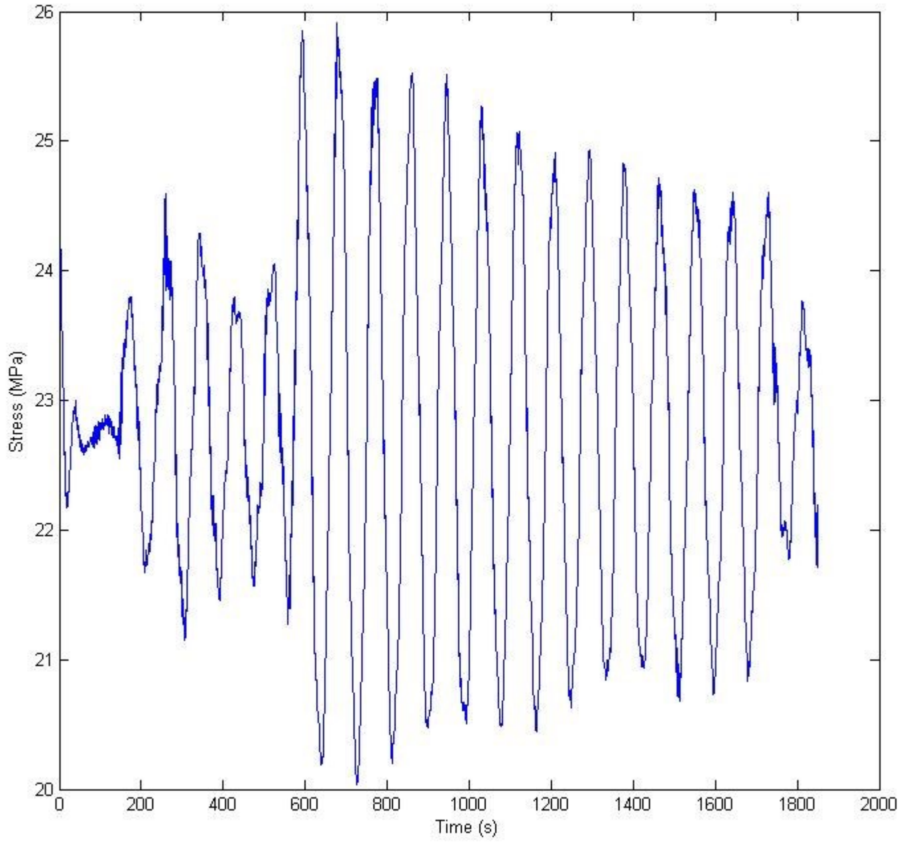


Figure 32 Stress time history for mooring line 1 for operational sea state (H_s = 0.75m and T_p = 5.8s)

The first observation to note regarding the stress time history is that it is dominated by a particular frequency. It is also evident by inspection that the stress response of the cable is characterised by the rigid body motion of the device moving fore and aft on the mooring cable system, which is dependent on the global cable system stiffness, rather than the wave period.

This stress time history can then be converted into the frequency domain by conducting a discrete Fourier transform and scaling and squaring to obtain a power spectral density function of stress. The fast Fourier transform function available in Matlab was utilized to obtain the frequency spectrum in Figure 33. This shows that there is a dominant frequency present in the stress response of the mooring cable at around 0.012 Hz (equivalent to a time period of approximately 83 seconds), which is also evident from the periodic stress time history.

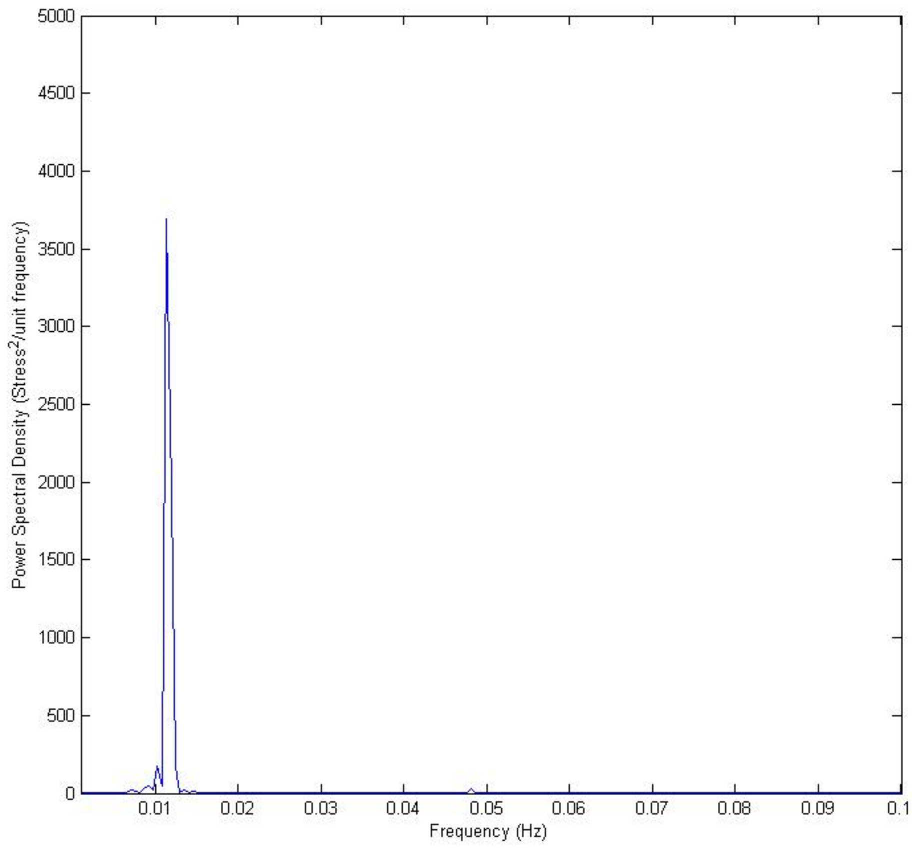


Figure 33 Power spectral density plot (frequency domain) for mooring line 1 for an operational sea state with 0.75m significant wave height and 5.8s peak period

Numerical integration was then performed to obtain the area (or the zeroth moment) under the curve about the y axis of Figure 33.

$$m_0 = 1.85 \text{ MPa}$$

For a narrow band spectrum (where there is a dominant frequency response) such as the one shown above, the effective constant amplitude stress (i.e. that which would provide the same fatigue damage as the variable spectrum) may be approximated using the following expression [8]:

$$\sigma_{efr} = (8m_0)^{1/2}(\Gamma((2+m)/2)^{1/m} = 2\sqrt{2}\times\sqrt{m_0}\times1.099$$

Where m_0 is the area under power spectral density function (i.e. the variance) and Γ is Euler's gamma function, which for $m = 3$, $\Gamma((2+m)/2)^{1/m} = 1.099$. The exponent m is dependent on the precise connection detail, further details are available in DNV-RP-C203 [17]. For the purpose of this example we assume $m = 3$ and that this remains constant irrespective of the magnitude of stress. This is a conservative assumption to make. This enables the curve of stress range versus number of cycles to failure, or S-N curve, to be characterised by the following equation:

$$N = AS^{-m}$$

Where N is the number of cycles to failure, A is a constant and S is the stress range. This is a generic equation used to describe the fatigue performance of a component, and values for reference fatigue curves (derived from fatigue tests) are tabulated in DNV-RP-C203 [17].

Multiplying the constant amplitude stress value, $\sigma_{efr,}$ by a stress concentration factor (SCF), gives the peak constant amplitude stress range which in this example works out to be 10.5 MPa. In the absence of a detailed connection geometry in this example, a value of 2.5, was assumed for the SCF.

A reference stress, for a fatigue life of 10^7 cycles is obtained from DNV-RP-C203 [17]. This reference stress or limit is obtained from a reference S-N curve, and the selection of the appropriate curve depends on the nature of the loading and type of joint. This example connection between the mooring cable and the spar was assumed to be a category W3 welded joint that carries load perpendicular to the weld line:

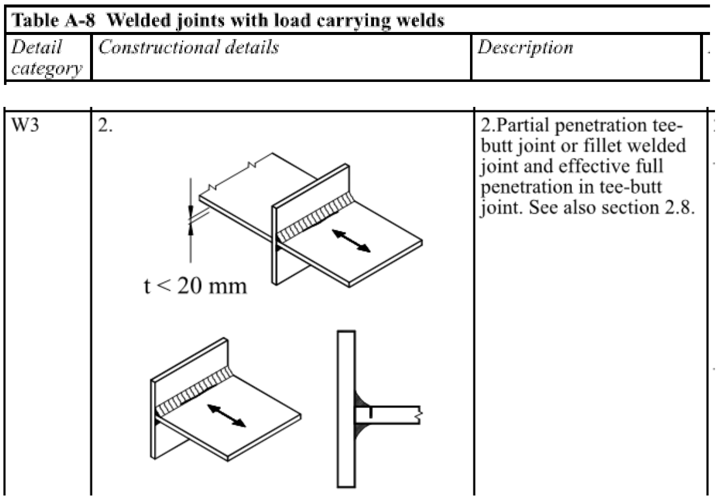


Table A-8 Welded joints with load carrying welds

Detail category	Constructional details	Description
W3	2. t < 20 mm	2.Partial penetration tee-butt joint or fillet welded joint and effective full penetration in tee-butt joint. See also section 2.8.

Figure 34 Category W3 welded joint taken from [17], Table A-8, pg 86.

A corresponding S-N curve for a component that is able to freely corrode (see Section 2.4.5 in [17]) was selected. The reference fatigue limit stress for a freely corroding W3 joint is 10.493 MPa.

Based on the above calculations a fatigue life of 29 years would be predicted if the structure were to experience a sea state of H_s = 0.75 m and Tp = 5.8 s for 100% of its life.

To account for the full wave climate it would be necessary to sum the predicted fatigue lives from all possible sea states, scaled by the corresponding occurrence rates. For this example, time history data for 7 other operational sea states was obtained, in total accounting for 50% of the yearly occurrence. In order to calculate the cumulative damage per year, it was assumed that the other 50% of the time the structure also experiences an equivalent set of sea states.

Thus by summing the contribution of 8 total sea states, the overall fatigue life for the joint works out to be 446 years. However it is accepted practice for a design fatigue factor (DFF) to be applied, refer to Section 2.3.1.1 for further details. In this case a conservative value of 3 was assumed (which corresponds to a DFF for a connection in a submerged zone in the structure with little accessibility for inspection, see [19]). Dividing the calculated fatigue life by the DFF, gives an overall fatigue life estimate of 149 years.

As a sensitivity study, the overall fatigue life was also calculated using the S-N curve for a welded connection that is exposed to seawater but with cathodic protection in place. For a joint category of W3, this gives a fatigue limit stress of 21.05 MPa [17]. If this S-N curve is assumed the overall fatigue life calculated increases to 1200 years. This demonstrates the sensitivity of the analysis to the assumptions made, and therefore care is required to avoid under conservatism in design.

2.5.7 Float to Spar Connection - Slam Load Analysis

Slam loading is a type of inertial loading which is experienced by a structural member when it comes into contact with the water surface i.e. when a member is suddenly immersed in water. Therefore the highest slam loading would be expected for components that are closest to the mean water level.

There is code guidance on an analytical method of estimating slam loads, provided in Section 8 “Airgap and Wave Slamming” in DNV-RP-C205 [25]. This would certainly be a viable method so long as the loads derived appropriately accounts for the fluid-structure interaction and the resulting water particle velocity.

Whilst it is possible to derive an estimate for the slam load, the physics that needs to be captured is complex. For a particular WEC design, the most reliable method for estimating slam loading would be to conduct a detailed CFD analysis, verified by wave tank testing of a scale model.

2.5.8 Base Plate – Strength Analysis due to Inertial Loading

<u>Model Set up</u>

A shell model of the point absorber was analysed with finite element analysis using the software LS-DYNA v 971 7.1.1, see Figure 35. The geometry as shown in Figure 18 was used, except for the base plate thickness, which was increased in the model from 0.1 m to 0.3 m. This was done in order to increase the Section modulus of the plate to a practical level in the absence of detailed geometric data e.g. stiffeners. It was also necessary to estimate plate thicknesses for the spar and the float, 0.3 m and 0.05 m were used respectively. The following linear elastic material properties for steel were assumed for all components:

Table 19 Steel material properties assumed for base plate strength analysis FE model

Density (kgm^{-3})	Elastic Modulus (GPa)	Poisson’s Ratio
7850	200	0.3

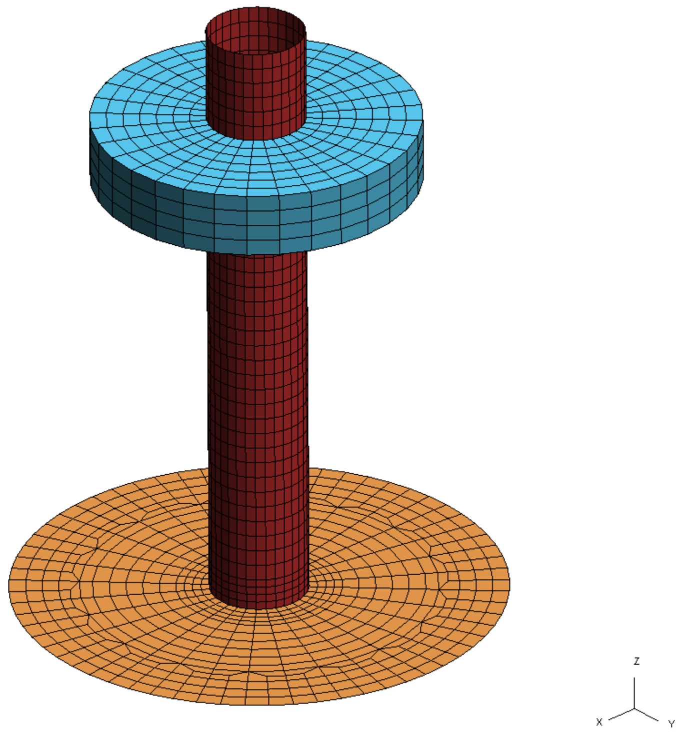


Figure 35 Shell model of point absorber analysed in LS-DYNA, consisting of 3 main components, float (blue), spar (red) and base plate (orange).

Inertial Loading

Added (hydrodynamic) mass is a type of inertial loading that is caused by the local interaction of an immersed structure with the surrounding fluid that is accelerating. It predominantly acts perpendicular to the axis of the structural member. For the current point absorber geometry, it is therefore expected to be the dominant force acting on the base plate during its operation. There will be some inertial force acting on the spar, but its effective area perpendicular to the heaving motion of the machine is relatively small. The main force acting on the float would be the uplift due to buoyancy as it is only partly submerged during normal operation.

In order to estimate the magnitude of the peak inertial loading on the base plate for the extreme sea state with a 50 year return period (H_s = 14.7m, T_p = 18.2s), the acceleration time history loading for the combined rigid body of the plate and spar was extracted (Figure 36). 4 load cases were considered where the following operational status of the PTO were assumed:

- Normal PTO operation
- No PTO
- Locked PTO (linear)
- Locked PTO (nonlinear)

The "no PTO load" case assumes zero damping, hence representing a fault situation. The locked PTO condition represents a survival strategy for some devices and the corresponding loads were derived assuming infinite PTO damping and just accounting for linear hydrodynamics. A set of "nonlinear" locked PTO loads were also derived, where buoyancy and Froude-Krylov forces were calculated based on the instantaneous position of the rigid body. However it should be noted that radiation damping and diffraction forces are still calculated using linear hydrodynamic coefficients. Further information on the derivation of these loads may be found in [9].

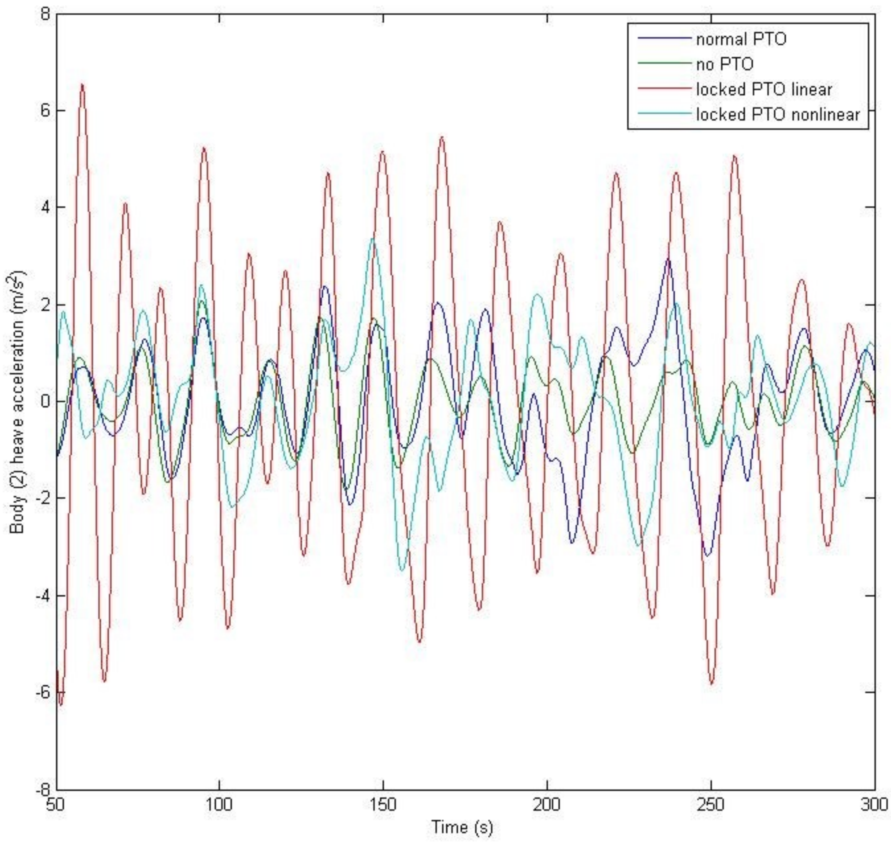


Figure 36 Acceleration time history for combined rigid body of plate and spar

The added mass, m_a, of the base plate was calculated using the equation [8]:

$$m_a = 0.63\pi\rho D^3/6$$

Where D is the diameter of the plate (30 m) and ρ is the sea water density (1029 kgm^{-3}), which results in an added mass value of ~9165 tonnes. A conservative approximation for the force time history for the inertial loading was calculated by multiplying the acceleration time history by (m_a + m), where m is physical mass of the plate.

For each load case, the peak force experienced was extracted and this load was applied as an equivalent, uniformly distributed pressure acting vertically upwards on the base plate. In the analysis the pressure was linearly ramped up from zero in a quasi-static manner.

It was assumed that in this instant in time, the buoyancy force will be acting against the inertial loading. In order to reflect this, conservatively, the top row of nodes in the spar of the model was constrained to not translate in the vertical z direction.

Results

Results are presented here for the normal PTO operation case and the locked PTO (linear) case. The normal PTO operation case resulted in the lowest stress in the base plate and the locked PTO (linear) case the highest of the 4 load cases investigated. Hence these results were compared in some detail below.

Figure 37 shows a cut section of the model after the load on the base plate has been applied and static equilibrium has been reached. Deformation shown has been magnified by 5 times. The horizontal line represents the undeformed section of the base plate. The two images represent the load cases for normal PTO operation and locked PTO (linear). This shows that hydrodynamic added mass loading causes the base plate to cantilever from the plate to spar connection.

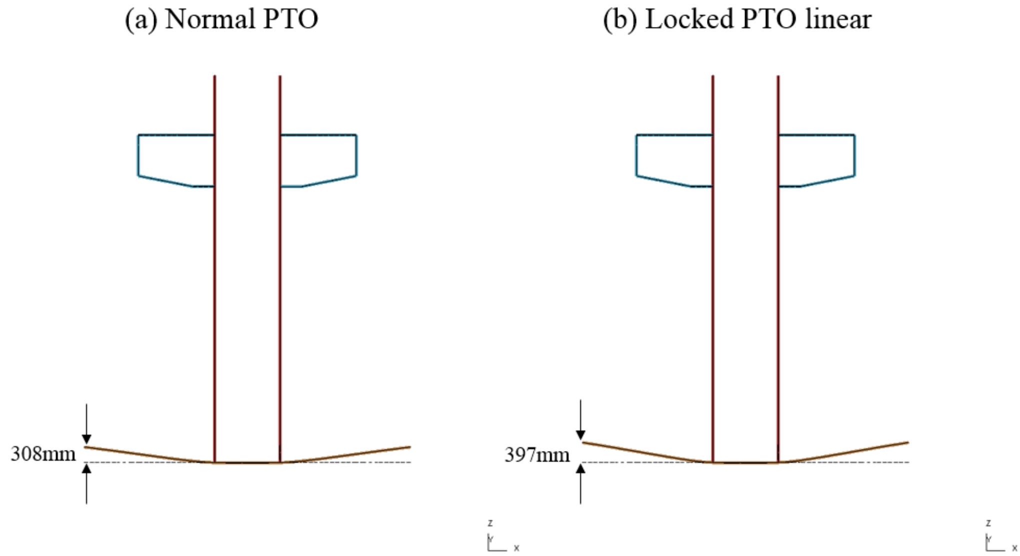


Figure 37 Cut Section of model showing base plate deformation (magnified by 5 times) after load application assuming (a) normal PTO and (b) locked PTO (linear) operation

Figure 38 shows the peak maximum principal stress (maximum of all integration points). A peak maximum principal stress of 268 MPa and 367 MPa in tension were observed for normal PTO and locked PTO respectively, in the base plate elements closest to the plate to spar connection, and they were output from the lower most integration points, on the lower side of the plate.

Figure 39 shows the peak minimum principal stress (minimum of all integration points). A peak minimum principal stress of 222 MPa and 284 MPa in compression were observed for normal PTO and locked PTO respectively, in base plate the elements closest to the plate to spar connection, and they were output from the upper most integration points on the upper side of the plate.

These results illustrate the sensitivity of the results to the PTO condition assumed in the loading simulation. It also confirms the FMEA finding (see Section 2.3.3) which identified that the structure failure of the connection between the base plate and spar is likely to govern.

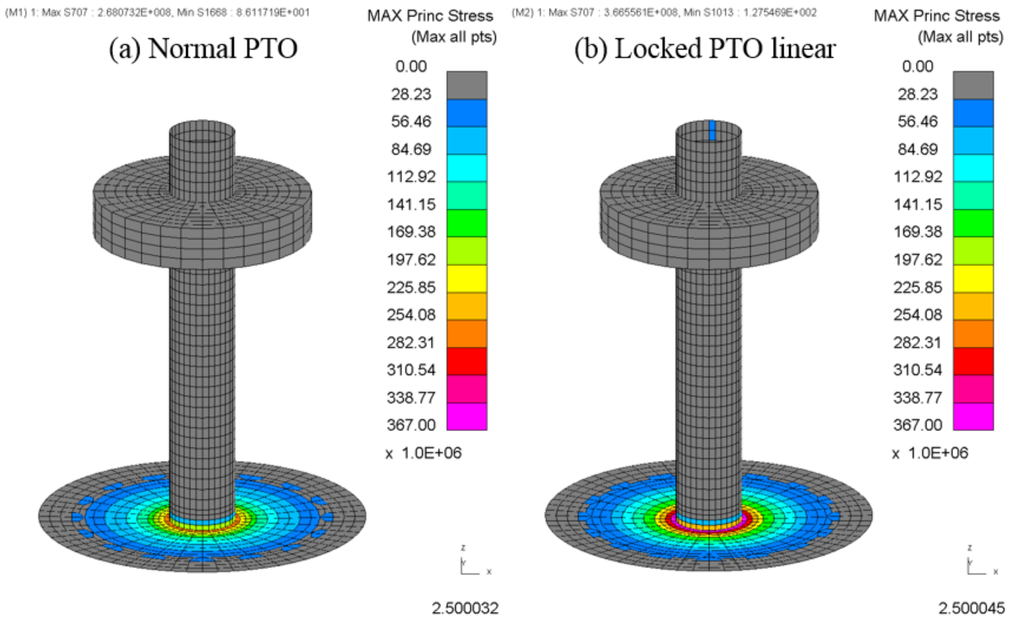


Figure 38 FEA results, maximum principal stress (max of all integration points) for (a) Normal PTO operation in extreme sea state and (b) locked PTO with loads based on linear hydrodynamics in extreme sea state

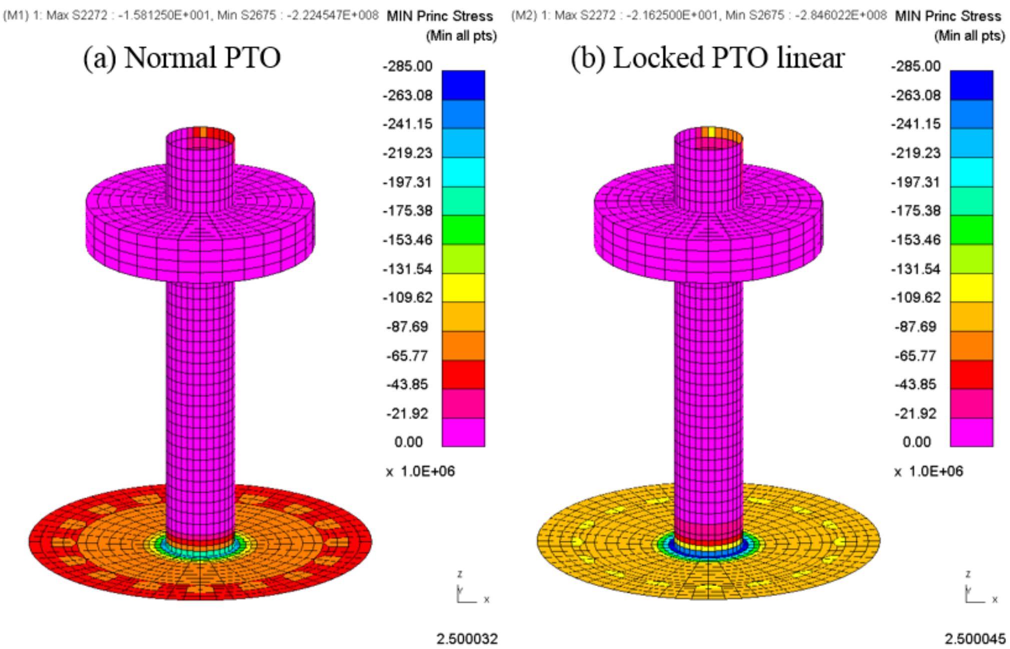


Figure 39 FEA results, minimum principal stress (minimum of all integration points) for (a) Normal PTO operation in extreme sea state and (b) locked PTO with loads based on linear hydrodynamics in extreme sea state

Figure 40 shows the maximum principal stress shown as a vector plot. This shows that the near the plate to spar connection the max principal stress is predicted to be aligned with the element local radial axis, whereas further away the max principal stress is aligned with the element local circumferential axis.

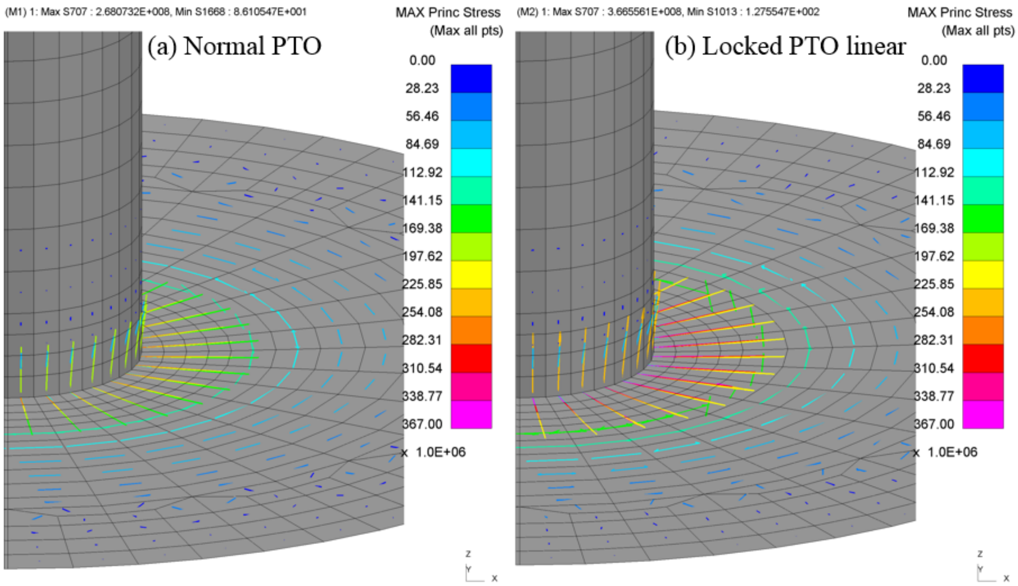


Figure 40 FEA results, maximum principal stress shown as a vector plot (max of all integration points) for (a) Normal PTO operation in extreme sea state and (b) locked PTO with loads based on linear hydrodynamics in extreme sea state

2.5.9 Calculation Summary

Hydrodynamic loads for an example geometry of a 2-body point absorber WEC were derived using WEC-Sim, a fully coupled point loads time-domain model. Loads were derived using the 8 most frequent sea states, covering 50% of occurrence at the example target site, and a 50-year return period wave to represent an extreme loading condition.

Table 20 summarises the main outputs of the load analysis under the normal and extreme wave conditions (most frequent sea states and 50-year return period wave respectively). As a first approximation, these outputs are based on the maximum values for each representative load time-series.

Table 20 Summary table of load analysis results – point absorber

Body	Type of Loads	Goal posts	
		Normal conditions	50yr wave conditions
Float	Excitation force	3.6MN	24.1MN
	Radiation damping force	0.9MN	4.1MN
	Added mass force	2.2MN	12.8MN
	Restoring force	5.1MN	24.9MN
Spar/Plate	Excitation force	1.5MN	12.1MN
	Radiation damping force	0.03MN	0.2MN
	Added mass force	1.9MN	11.6MN
	Restoring force	0.8MN	14.7MN
Mooring lines	Tension line 1	576kN	13266kN
	Tension line 2	362kN	8172kN
	Tension line 3	362kN	8172kN

The loads derived were used as an input to conduct the following structural analyses, the results for which are summarised in Table 21:

- Spectral fatigue analysis of a single mooring cable connection to the spar
- Strength analysis of the base plate due to inertial added mass loading

Table 21 Summary of structural analysis results - point absorber

Failure location	Load Calculation Methodology	Sea States Considered	Structural Analysis Methodology	Structural Analysis Results
Mooring cable to spar connection	Fully coupled point loads model (time-domain)	Normal condition. 8 operational sea states covering 50% of the most frequently occurring waves.	Spectral fatigue analysis	Effective stress range of 10.6 MPa. Assuming the connection experiences corrosion, results in a fatigue life of 149 years.
Base plate to spar connection	Fully coupled point loads model (time-domain)	Extreme condition with 50 year return period.	Quasi- static FEA strength analysis	Maximum principal stress of 367 MPa and peak shell resultant moment of 8.5 MNm/m.

It should be noted that the results from the example calculations are highly dependent on the assumed geometry and local design details. They therefore provide insight into the methods rather than generate absolute values of demand.

3 Summary of Key Findings

This Section summarises the suggested guidance for load and structural analysis of WECs described in Sections 1 and 2. The key recommended steps emanating from this study are as follows:

1. Develop a design basis

The first stage of a WEC design process should be the development of a design basis. The main objectives are to define the design methodology, specifying key components, environmental conditions and analysis methodologies, along with identifying critical aspects that should be assessed to facilitate the transition from concept to detailed design. As defined in Section 1.1, a design basis for a WEC should, at a minimum, define the following:

- Principle design objectives
- Device fabrication, installation and maintenance criteria
- Device decommissioning criteria
- Review of design codes, standards and guidelines
- General description of the device:
    - Main structural components
    - Array layout, mooring cable systems, grid connections, pipework and any other peripheral functional components
- Environmental conditions of target site:
    - Metocean data
    - Marine operations
    - Marine growth and activity
- Design load cases and applicable partial factors
- Material properties and applicable partial factors
- Load and structural analysis methodologies
- Corrosion protection systems
- Safety and hazard assessments
- Failure modes, effects and criticality analysis (FMEA)

2. Review of appropriate design guidelines

A review of existing applicable guidelines should be conducted to define and prioritise the necessary methods for the calculations that must be performed during the design process. Following existing (relevant) guidelines as closely as possible and obeying codes of best practice will support the creation of a thorough design basis and lend to de-risking the design process. Furthermore, in the later stages of the design process, certification of the WEC may be required by a range of stakeholders, thus an early adherence to the codes of best practice may prove beneficial.

At present there are no dedicated standard for the design of WECs. In Section 1.2 standards from the maritime, oil & gas and offshore wind sectors were reviewed and those most relevant to WEC design are summarised in Table 1. It should be noted that the draft technical specification / design requirements for marine energy systems is currently under development by an IEC technical committee (IEC TC114/PT 62600-2).

3. Define critical design load cases (DLCs)

A methodology to derive DLCs which can be used to assess fatigue (F) and ultimate strength (U) has been presented in Section 2.2. The DLC descriptions combine the environmental conditions at a site and relevant design situations for a WEC, leading to the definition of a range of load cases for consideration in the design process.

A summary of suggested DLCs is presented in Table 10. It is recommended that developers determine and prioritise the list of DLCs to be considered during their design process based on a review of the WEC specific FMECA and the selections of the final deployment site for a device.

4. Assess the baseline load formulation to be used

A critical evaluation of the applicability of baseline formulations for WEC load analysis is presented in Section 2.4.1. At present, a fully coupled, point loads (time-domain) load calculation method is the most readily applicable and directly suitable formulation for the widest range of design situations. For the analysis of specific design situations (e.g. accidental/abnormal events (DLC 9.x) and damaged stability (DLC 10.x)) nonlinear formulations may be most suited, but the development efforts are significant.

5. Estimate the relevant design loads

It is recommended that the calculation of WEC design loads is conducted primarily computationally, using fully coupled time-domain numerical simulations that account for all load contributions simultaneously. All relevant nonlinearities, including those induced by the main sub-systems such as the PTO and the moorings, should be considered. At least some of these nonlinearities (e.g. those related to hydrodynamics or mooring forces) may also be evaluated experimentally. Where possible, comparisons between numerical and experimental estimates are recommended. Further development may focus on advanced formulations that address the more complex design situations and / or in creating clear, practical interfaces between load and stress analysis model.

6. Apply appropriate structural analysis techniques

A range of relevant structural analysis techniques are described in Section 2.3 and the applicability of these techniques to a range of WEC designs is evaluated in Section 2.4.

In general, it is recommended that time history analysis is conducted and FE models representing the WECs should be generated. These should be kept as simple as allows while capturing the relevant stiffness and dynamic behaviour in order to minimise computational expense.

It may often be attractive to use a relatively simple global FE model of the WEC device with more detailed models of specific components to understand their behaviour under specific extreme loads. This approach may allow the analyses of the more detailed models to be conducted statically. The use of SCFs can further simplify global FE models. SCF values may be derived from finite element analysis, model tests or empirical equations based on these methods which are provided in standards.

A range of code guidance for the assessment of structural capacity is available for structures of typical offshore design (for example, steel tubular structures) and it is recommended that these are adhered to wherever possible. Whether code guidance is applicable or not depends on the geometry and material of the structure. It should be noted that where guidance provided in standards is not applicable to the structural geometry in question, all of the effects covered by the code need to be considered in some way during the structural analysis (e.g. second order geometrical effects).

References

Technical Reports

[1] Cruz J, Livingstone, M, Lee, A, Alexandre, A (2014). Design Load Cases for Wave Energy Converters: Power Production. *Proc. of the 2nd Asian Wave & Tidal Energy Conference Series*, Tokyo (Japan), July 2014.

[2] Hamedni, B and Bittencourt Ferreira, C (2014). Generic WEC Risk Ranking and Failure Mode Analysis. SDWED Deliverable D5.2.

[3] Proceeding of the 19th International Ship and Offshore Structures Congress, Volume 1, 2015. Edited by C Guedes Soares and Y Garbatov. CRC Press

[4] HR Wallingford, "Marine Energy Test Centre Stromness, Orkney", Report EX 4471, November 2001

[5] WE Cummins. The Impulse Response Function and Ship Motions. Technical Report, David Taylor Model Dasin-DTNSRDC, 1962.

[6] Wave Energy Converter SIMulator, an open-source WEC simulation tool developed in MATLAB / Simulink using the multi-body dynamics solver SimMechanics. http://wec-sim.github.io/WEC-Sim/.

[7] An open-source lumped-mass mooring dynamics model developed at the University of Maine and recently integrated in WEC-Sim. https://nwtc.nrel.gov/MoorDyn.

[8] Barltrop N.D.P, and Adams A.J, Dynamics of Fixed Marine Structures (Third Edition)

[9] Yu Y-H., Lawson M., Nelessen A., Ruehl K. and Michelen C., Implementing Nonlinear Buoyancy and Excitation Forces in the WEC-Sim Wave Energy Converter Modeling Tool

[10] Andrew S. Zurkinden and Zhen Gao, Torgeir Moan, Søren Lambertsen, Lars Damkilde, Spectral based fatigue analysis of the Wavestar-arm taking into account different control strategies, SDWED, 201

[11] Sarpkaya, T. and Isaacson, M. (1981). "Mechanics of wave forces on offshore structures". Van Nostrand Reinhold Company

[12] H Wolgamot and C Fitzgerald. Nonlinear hydrodynamic and real fluid effects on wave energy converters. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy November 2015 vol. 229 no. 7 772-7941

[13] JR Morison, MP O'Brien, JW Johnson, and SA Schaaf, "The force exerted by surface waves on piles," Petroleum Transactions, no. 189, pp. 149–154, 1950

[14] Majid A. Bhinder, Aurélien Babarit, Lionel Gentaz, Pierre Ferrant, Potential time domain model with viscous correction and CFD analysis of a generic surging floating wave energy converter, International Journal of Marine Energy, Volume 10, June 2015, Pages 70-96

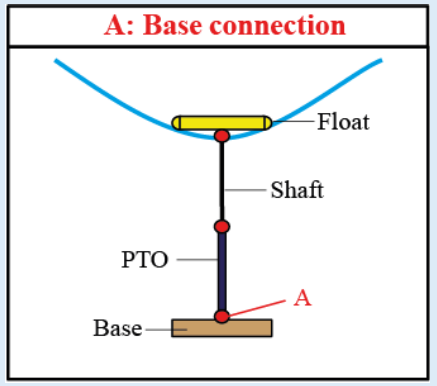
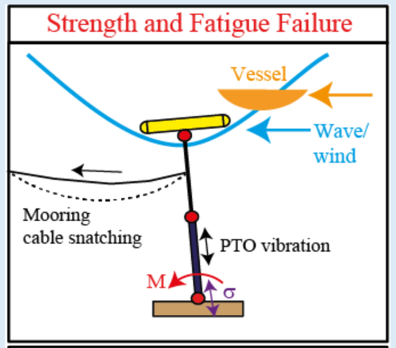
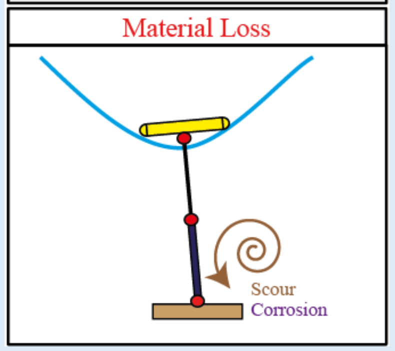
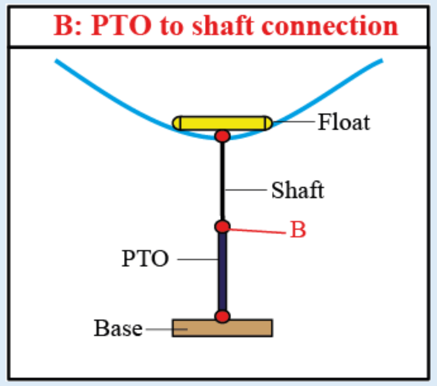
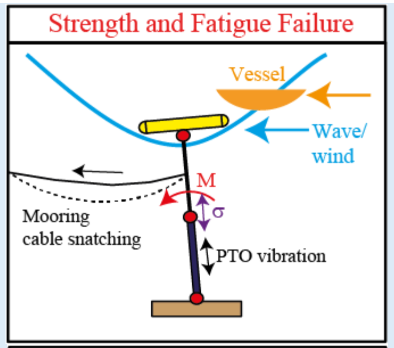
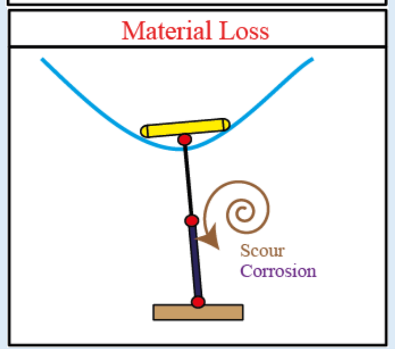
[15] Pál Schmitt, Björn Elsaesser, On the use of OpenFOAM to model oscillating wave surge converters, Ocean Engineering, Volume 108, 1 November 2015, Pages 98-104

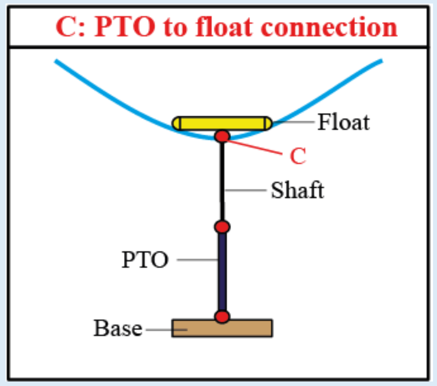
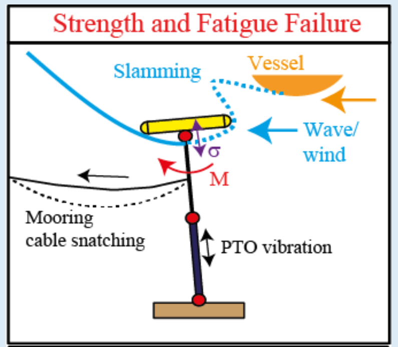
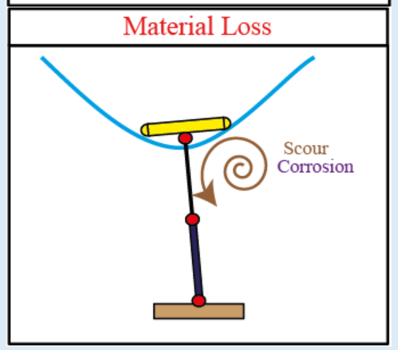
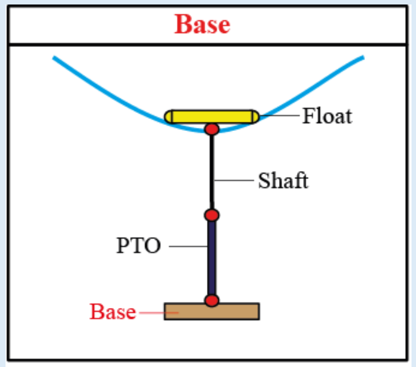
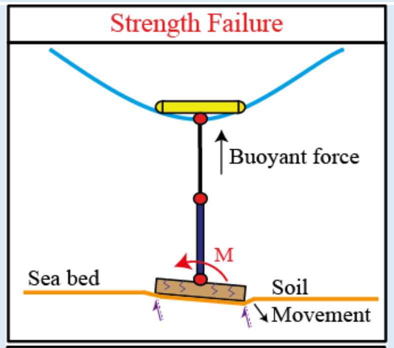
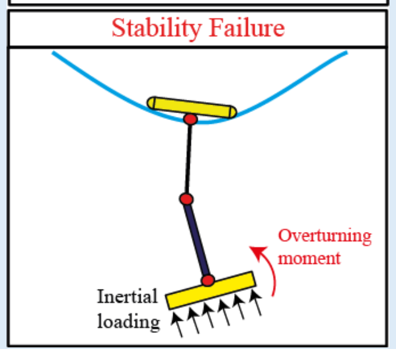
Design Standards

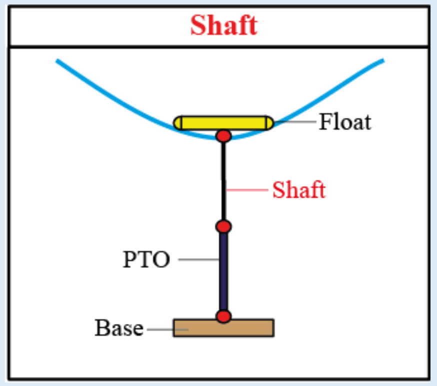
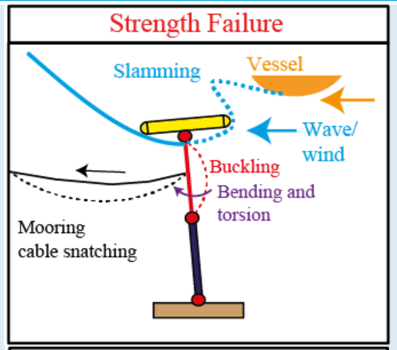
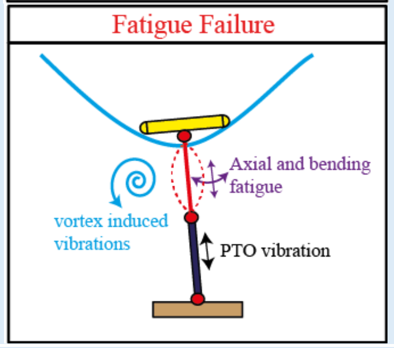
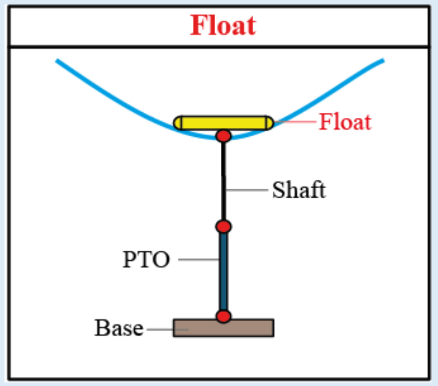
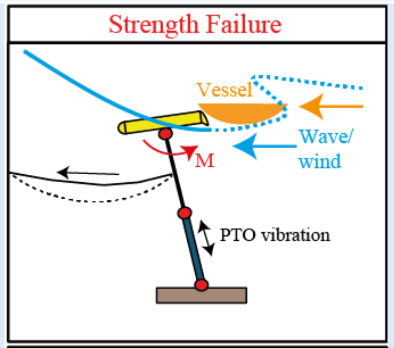
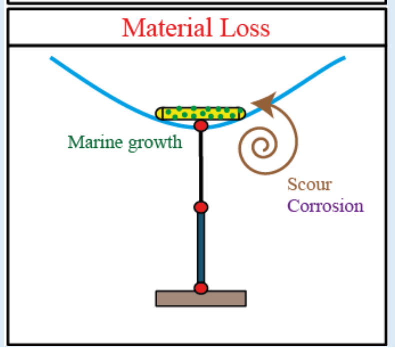
Ref	Document Number	Title
[16]	BS EN ISO 19902:2007 + A1:2013	Petroleum and natural gas industries: Fixed Steel Offshore Structures
[17]	DNV-RP-C203: 2011	Fatigue Design of Offshore Steel Structures
[18]	API-RP-2A: 2005	Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms: Working Stress Design
[19]	DNV-OS-J101: 2014	Design of Offshore Wind Turbine Structures
[20]	GL Rules and Guidelines IV-2-5 (2012)	Guideline for the Certification of Offshore Wind Turbines: Chapter 5: Strength Analysis
[21]	DNVGL-OS-E301:2015	Offshore Standard: Position Mooring
[22]	BS EN ISO 19900:2013	Petroleum and natural gas industries — General requirements for offshore structures
[23]	BS EN ISO 19903: 2006	Petroleum and natural gas industries — Fixed concrete offshore structures
[24]	DNV-RP-C208: 2013	Determination of Structural Capacity by Non-linear FE analysis Methods
[25]	DNV-RP-C205: 2014	Environmental Conditions and Environmental Loads
[26]	DNV-RP-C301: 2012	Design, Fabrication, Operation and Qualification of Bonded Repair of Steel Structures
[27]	DNV-RP-C204	Design Against Accidental Loads
[28]	DNV-OS-C102	Structural Design of Offshore Ships
[29]	DNV-OS-C502	Offshore Concrete Structures
[30]	BS 7608	Guide to fatigue design and assessment of steel products

A1 FMEA tables for 7 WEC types

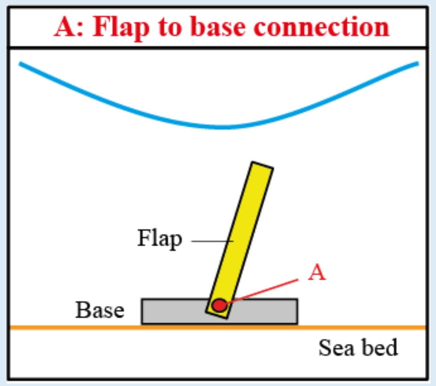
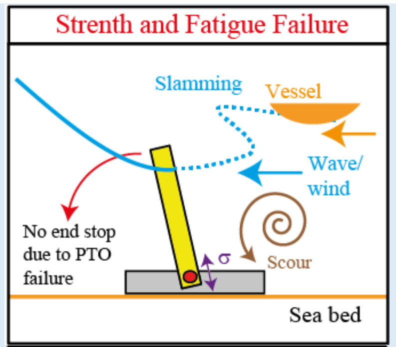
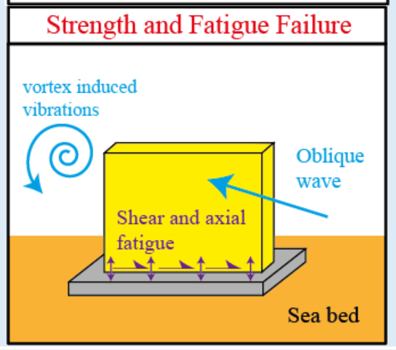
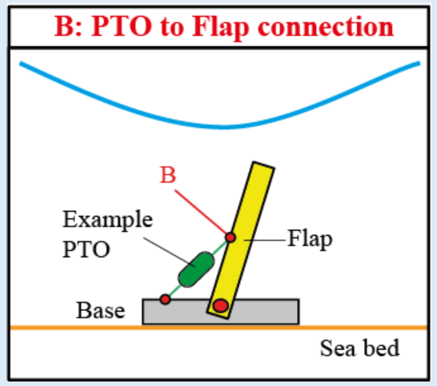
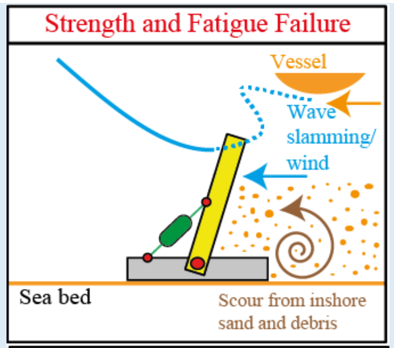
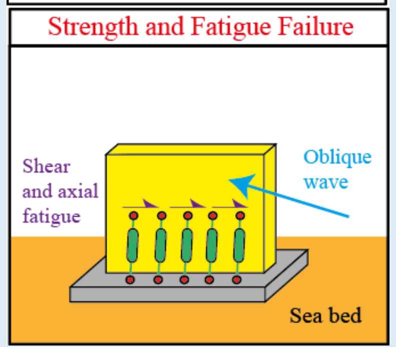
A1.1 Point Absorber

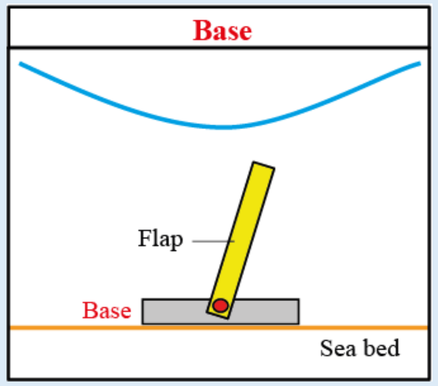
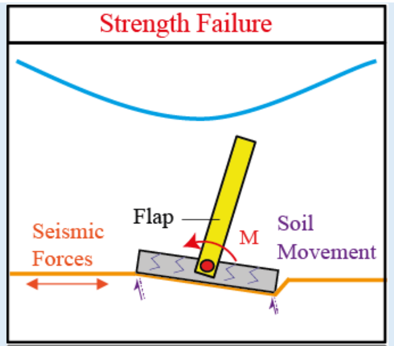
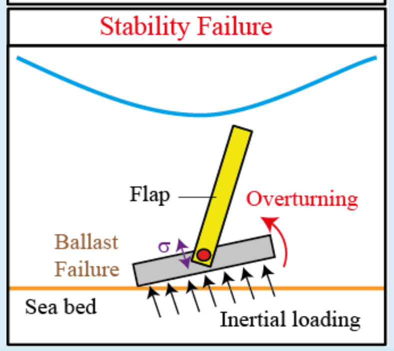
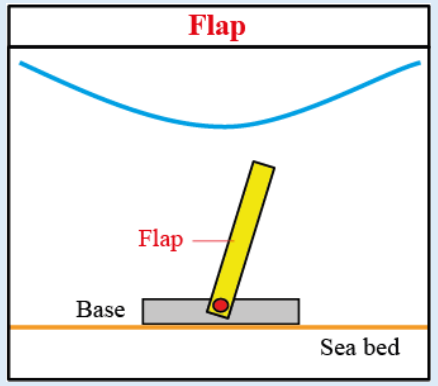
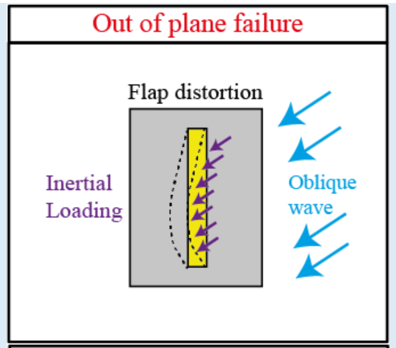
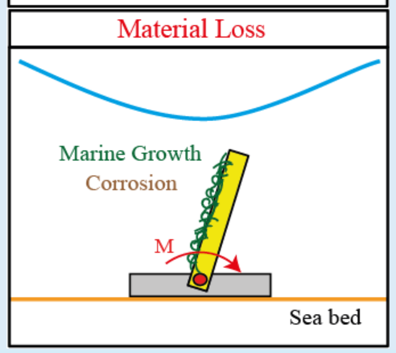
Failure Location	Schematic of Selected Failure Modes	Possible Structural Failure Modes	Cause	Governing Failure Mode?	Consequence	Relevant DLCs
		Strength	ULS environmental loads (wave slamming, wind, currents, tidal effects)	3: Definitely	3: Machine Failure	1.x, 2.x, 3.x, 4.x, 5.x 6.x, 7.x, 9.x, 10.x
			ALS loads (vessel/ice impact, tsunami, seismic effects)			9.1, 9.2, 9.3 10.3, 10.6
			Transportation and installation loads			8.x
			Transient snatch loads in cable systems			2.x, 5.x, 9.x, 10.x
			Joint seizure leading to machine parking			6.1, 6.2, 6.3 7.1, 7.2
			Material and section discontinuity at composite joints			6.1, 6.2, 6.3 7.1, 7.2
			Marine growth			1.6
			PTO/controller failure			2.1, 2.2, 2.3
			Mooring connection failure (if relevant)			10.2, 10.5
			Seabed anchor failure			10.1, 10.4
		Fatigue - high cycle	FLS environment loads (wave, wind, currents)	3: Definitely	3: Machine Failure	1.1, 1.5, 2.3, 9.2
			Stress concentration around geometric discontinuity			6.4, 7.3
			PTO induced excitation			1.1, 1.5, 2.3, 9.2
			Mooring load induced excitation			1.1, 1.5, 2.3, 9.2
			Any other excitation of global resonance modes			8.4
		Fatigue - low cycle	Extreme loads for all causes listed under high cycle fatigue that may lead to plastic response	1: Possibly	3: Machine Failure	3.1, 4.1, 4.2, 9.2
			Transportation and installation loads			8.x
			Vortex induced vibrations			10.1, 10.4
		Material Loss	Corrosion	2: Likely	3: Machine Failure	1.6, 6.x, 7.x, 9.x, 10.x
			Scouring			1.6, 6.x, 7.x, 9.x, 10.x
			Marine activity			8.x, 9.x
			Interface between dissimilar materials			2.x, 5.x, 9.x, 10.x
			Sudden change in temperature			2.x, 5.x, 9.x, 10.x
		Strength	ULS environmental loads (wave slamming, wind, currents, tidal effects)	3: Definitely	2: Component Failure	1.x, 2.x, 3.x, 4.x, 5.x 6.x, 7.x, 9.x, 10.x
			ALS loads (vessel/ice impact, tsunami, seismic effects)			9.1, 9.2, 9.3 10.3, 10.6
			Transportation and installation loads			8.x
			Joint seizure leading to machine parking			6.1, 6.2, 6.3 7.1, 7.2
			Material and section discontinuity at composite joints			6.1, 6.2, 6.3 7.1, 7.2
			Marine growth			1.6
			PTO/controller failure			2.1, 2.2, 2.3
			Mooring connection failure			10.2, 10.5
			Seabed anchor failure			10.1, 10.4
		Fatigue - high cycle	FLS environment loads (wave, wind, currents)	3: Definitely	2: Component Failure	1.1, 1.5, 2.3, 9.2
			Stress concentration around geometric discontinuity			6.4, 7.3
			PTO induced excitation			1.1, 1.5, 2.3, 9.2
			Mooring load induced excitation			1.1, 1.5, 2.3, 9.2
			Any other excitation of global resonance modes			8.4
		Fatigue - low cycle	Extreme loads for all causes listed under high cycle fatigue that may lead to plastic response	1: Possibly	2: Component Failure	3.1, 4.1, 4.2, 9.2
			Transportation and installation loads			8.x
			Vortex induced vibrations			10.1, 10.4
		Material Loss	Corrosion	2: Likely	2: Component Failure	1.6, 6.x, 7.x, 9.x, 10.x
			Scouring			1.6, 6.x, 7.x, 9.x, 10.x
			Marine activity			8.x, 9.x
			Interface between dissimilar materials			2.x, 5.x, 9.x, 10.x
			Sudden change in temperature			2.x, 5.x, 9.x, 10.x

Failure Location	Schematic of Selected Failure Modes	Possible Structural Failure Modes	Cause	Governing Failure Mode?	Consequence	Relevant DLCs
		Strength	ULS environmental loads (wave slamming, wind, currents, tidal effects)	3: Definitely	2: Component Failure	1.x, 2.x, 3.x, 4.x, 5.x 6.x, 7.x, 9.x, 10.x
			ALS loads (vessel/ice impact, tsunami, seismic effects)			9.1, 9.2, 9.3 10.3, 10.6
			Transportation and installation loads			8.x
			Transient snatch loads in cable systems			2.x, 5.x, 9.x, 10.x
			Joint seizure leading to machine parking			6.1, 6.2, 6.3 7.1, 7.2
			Material and section discontinuity at composite joints			6.1, 6.2, 6.3 7.1, 7.2
			Marine growth			1.6
			PTO/ controller failure			2.1, 2.2, 2.3
			Mooring connection failure			10.2, 10.5
			Seabed anchor failure			10.1, 10.4
		Fatigue - high cycle	FLS environment loads (wave, wind, currents)	3: Definitely	2: Component Failure	1.1, 1.5, 2.3, 9.2
			Stress concentration around geometric discontinuity			6.4, 7.3
			PTO induced excitation			1.1, 1.5, 2.3, 9.2
			Mooring load induced excitation			1.1, 1.5, 2.3, 9.2
			Any other excitation of global resonance modes			8.4
		Fatigue - low cycle	Extreme loads for all causes listed under high cycle fatigue that may lead to plastic response	1: Possibly	2: Component Failure	3.1, 4.1, 4.2, 9.2
			Transportation and installation loads			8.x
			Vortex induced vibrations			10.1, 10.4
		Material Loss	Corrosion	2: Likely	2: Component Failure	1.6, 6.x, 7.x, 9.x, 10.x
			Scouring			1.6, 6.x, 7.x, 9.x, 10.x
			Marine activity			8.x, 9.x
			Interface between dissimilar materials			2.x, 5.x, 9.x, 10.x
			Sudden change in temperature			2.x, 5.x, 9.x, 10.x
 Base can be suspended or secured to sea bed		Strength	ULS environmental loads (wave slamming, wind, currents, tidal effects)	3: Definitely	3: Machine Failure	1.x, 2.x, 3.x, 4.x, 5.x 6.x, 7.x, 9.x, 10.x
			ALS loads (vessel/ice impact, tsunami, seismic effects, seabed instability)			9.1, 9.2, 9.3 10.3, 10.6
			Transportation and installation loads			8.x
			Incorrect assessment of mechanical properties of soil			9.4
			Marine growth			1.6
			Ballast failure			10.3, 10.6
			Mooring connection failure			10.2, 10.5
			Seabed anchor failure			10.1, 10.4
			PTO/ controller failure			2.1, 2.2, 2.3
		Fatigue - high cycle	FLS environmental loads (wave, wind, currents)	1: Possibly	3: Machine Failure	1.1, 1.5, 2.3, 9.2
			Stress concentration around geometric discontinuity			6.4, 7.3
			PTO induced excitation			1.1, 1.5, 2.3, 9.2
			Mooring load induced excitation			1.1, 1.5, 2.3, 9.2
			Any other excitation of global resonance modes			8.4
		Material Loss	Corrosion	1: Possibly	3: Machine Failure	1.6, 6.x, 7.x, 9.x, 10.x
			Scouring			1.6, 6.x, 7.x, 9.x, 10.x
			Marine activity			8.x, 9.x
			Interface between dissimilar materials			2.x, 5.x, 9.x, 10.x
			Sudden change in temperature			2.x, 5.x, 9.x, 10.x
		Stability	Ballast failure	2: Likely	3: Machine Failure	10.3, 10.6
			Mooring connection/seabed anchor failure			10.2, 10.5

Failure Location	Schematic of Selected Failure Modes	Possible Structural Failure Modes	Cause	Governing Failure Mode?	Consequence	Relevant DLCs
		Strength	ULS environmental loads (waveslamming, wind, currents, tidal effects)	3: Definitely	2: Component Failure	1.x, 2.x, 3.x, 4.x, 5.x 6.x, 7.x, 9.x, 10.x
			ALS loads (vessel/ice impact, tsunami, seismic effects)			9.1, 9.2, 9.3 10.3, 10.6
			Transportation and installation loads			8.x
			Transient snatch loads in cable systems			2.x, 5.x, 9.x, 10.x
			Marine growth			1.6
			PTO/ controller failure			2.1, 2.2, 2.3
			Mooring connection failure			10.2, 10.5
			Seabed anchor failure			10.1, 10.4
		Fatigue - high cycle	FLS environmental loads (wave, wind, currents)	3: Definitely	2: Component Failure	1.1, 1.5, 2.3, 9.2
			Stress concentration around geometric discontinuity			6.4, 7.3
			PTO induced excitation			1.1, 1.5, 2.3, 9.2
			Mooring load induced excitation			1.1, 1.5, 2.3, 9.2
			Any other excitation of global resonance modes			8.4
		Fatigue - low cycle	Extreme loads for all causes listed under high cycle fatigue that may lead to plastic response	1: Possibly	2: Component Failure	3.1, 4.1, 4.2, 9.2
			Transportation and installation loads			8.x
			Vortex induced vibrations			10.1, 10.4
		Material Loss	Corrosion	2: Likely	2: Component Failure	1.6, 6.x, 7.x, 9.x, 10.x
			Scouring			1.6, 6.x, 7.x, 9.x, 10.x
			Marine activity			8.x, 9.x
			Sudden change in temperature			2.x, 5.x, 9.x, 10.x
		Strength	ULS environmental loads (waveslamming, wind, currents, tidal effects)	3: Definitely	2: Component Failure	1.x, 2.x, 3.x, 4.x, 5.x 6.x, 7.x, 9.x, 10.x
			ALS loads (vessel/ice impact, tsunami, seismic effects, seabed instability)			9.1, 9.2, 9.3 10.3, 10.6
			Transportation and installation loads			8.x
			Transient snatch loads in cable systems			2.x, 5.x, 9.x, 10.x
			PTO/ controller failure			2.1, 2.2, 2.3
			Mooring connection failure			10.2, 10.5
			Survivability mode failure			6.2, 7.2
		Fatigue - high cycle	FLS environmental loads (wave, wind, currents)	1: Possibly	2: Component Failure	1.1, 1.5, 2.3, 9.2
			Stress concentration around geometric discontinuity			6.4, 7.3
			PTO induced excitation			1.1, 1.5, 2.3, 9.2
			Mooring load induced excitation			1.1, 1.5, 2.3, 9.2
		Material Loss	Corrosion	3: Definitely	2: Component Failure	1.6, 6.x, 7.x, 9.x, 10.x
			Scouring			1.6, 6.x, 7.x, 9.x, 10.x
			Marine activity			8.x, 9.x
			Interface between dissimilar materials			2.x, 5.x, 9.x, 10.x
			Sudden change in temperature			2.x, 5.x, 9.x, 10.x

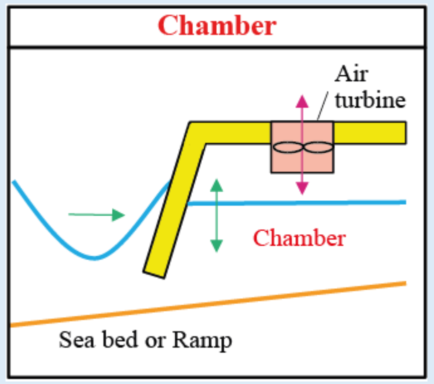
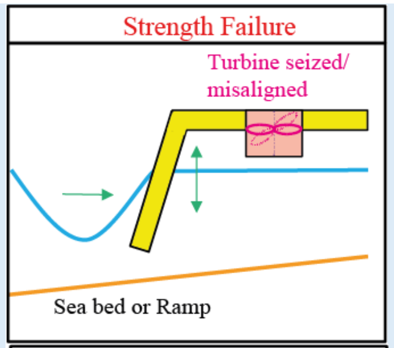
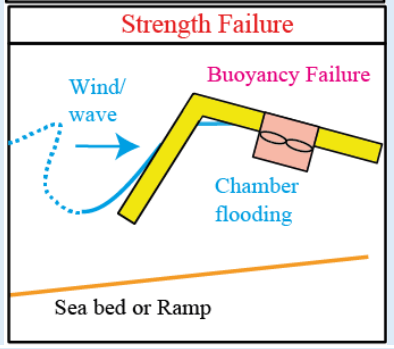
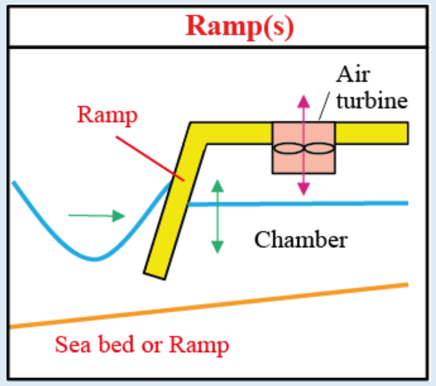
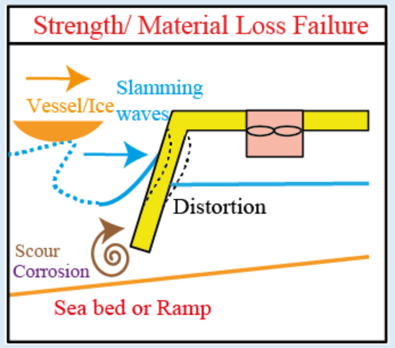
A1.2 Oscillating Wave Surge Converter

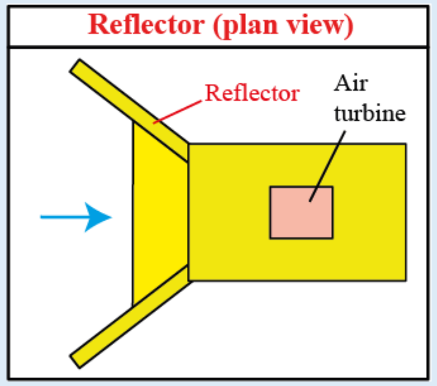
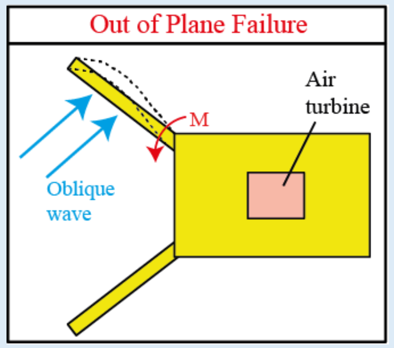
Failure Location	Schematic of Selected Failure Modes	Possible Structural Failure Modes	Cause	Governing Failure Mode?	Consequence	Relevant DLCs
	 	Strength	ULS environmental loads (wave slamming, oblique waves/ wind, currents, tidal effects)	3: Definitely	3: Machine Failure	1.x, 2.x, 3.x, 4.x, 5.x 6.x, 7.x, 9.x, 10.x
			ALS loads (vessel/ice impact, tsunami, seismic effects)			9.1, 9.2, 9.3 10.3, 10.6
			Transportation and installation loads			8.x
			Joint seizure leading to machine parking			6.1, 6.2, 6.3 7.1, 7.2
			Material and section discontinuity at composite joints			6.1, 6.2, 6.3 7.1, 7.2
			Marine growth			1.6
			PTO/ controller failure			2.1, 2.2, 2.3
		Fatigue - high cycle	FLS environment loads (wave, wind, currents)	3: Definitely	3: Machine Failure	1.1, 1.5, 2.3, 9.2
			Stress concentration around geometric discontinuity			6.4, 7.3
			PTO induced excitation			1.1, 1.5, 2.3, 9.2
			Any other excitation of global resonance modes			8.4
		Fatigue - low cycle	Extreme loads for all causes listed under high cycle fatigue that may lead to plastic response	1: Possibly	3: Machine Failure	3.1, 4.1, 4.2, 9.2
			Transportation and installation loads			8.x
			Vortex induced vibrations			10.1, 10.4
		Material Loss	Corrosion	2: Likely	3: Machine Failure	1.6, 6.x, 7.x, 9.x, 10.x
			Scouring			1.6, 6.x, 7.x, 9.x, 10.x
			Marine activity			8.x, 9.x
			Interface between dissimilar materials			2.x, 5.x, 9.x, 10.x
			Sudden change in temperature			2.x, 5.x, 9.x, 10.x
	 	Strength	ULS environmental loads (wave slamming/slapping/snatching, oblique waves/ wind, currents, tidal effects)	3: Definitely	2: Component Failure	1.x, 2.x, 3.x, 4.x, 5.x 6.x, 7.x, 9.x, 10.x
			ALS loads (vessel/ice impact, tsunami, seismic effects)			9.1, 9.2, 9.3 10.3, 10.6
			Transportation and installation loads			8.x
			Joint seizure leading to machine parking			6.1, 6.2, 6.3 7.1, 7.2
			Material and section discontinuity at composite joints			6.1, 6.2, 6.3 7.1, 7.2
			Marine growth			1.6
			PTO/ controller failure			2.1, 2.2, 2.3
		Fatigue - high cycle	FLS environment loads (wave, wind, currents)	3: Definitely	2: Component Failure	1.1, 1.5, 2.3, 9.2
			Stress concentration around geometric discontinuity			6.4, 7.3
			PTO induced excitation			1.1, 1.5, 2.3, 9.2
			Any other excitation of global resonance modes			8.4
		Fatigue - low cycle	Extreme loads for all causes listed under high cycle fatigue that may lead to plastic response	1: Possibly	2: Component Failure	3.1, 4.1, 4.2, 9.2
			Transportation and installation loads			8.x
			Vortex induced vibrations			10.1, 10.4
		Material Loss	Corrosion	2: Likely	2: Component Failure	1.6, 6.x, 7.x, 9.x, 10.x
			Scouring			1.6, 6.x, 7.x, 9.x, 10.x
			Marine activity			8.x, 9.x
			Interface between dissimilar materials			2.x, 5.x, 9.x, 10.x
			Sudden change in temperature			2.x, 5.x, 9.x, 10.x

Failure Location	Schematic of Selected Failure Modes	Possible Structural Failure Modes	Cause	Governing Failure Mode?	Consequence	Relevant DLCs
		Strength	ULS environmental loads (wave slamming/slapping/snatching, oblique waves/ wind, currents, tidal effects)	3: Definitely	3: Machine Failure	1.x, 2.x, 3.x, 4.x, 5.x 6.x, 7.x, 9.x, 10.x
			ALS loads (vessel/ice impact, tsunami, seismic effects, seabed instability)			9.1, 9.2, 9.3 10.3, 10.6
			Transportation and installation loads			8.x
			Incorrect assessment of mechanical properties of soil			9.4
			Marine growth			1.6
			Ballast failure			10.3, 10.6
			Seabed anchor failure			10.1, 10.4
		Fatigue - high cycle	FLS environmental loads (wave, wind, currents)	1: Possibly	3: Machine Failure	1.1, 1.5, 2.3, 9.2
			Stress concentration around geometric discontinuity			6.4, 7.3
			PTO induced excitation			1.1, 1.5, 2.3, 9.2
			Any other excitation of global resonance modes			8.4
		Material Loss	Corrosion	2: Likely	3: Machine Failure	1.6, 6.x, 7.x, 9.x, 10.x
			Scouring			1.6, 6.x, 7.x, 9.x, 10.x
			Marine activity			8.x, 9.x
			Interface between dissimilar materials			2.x, 5.x, 9.x, 10.x
			Sudden change in temperature			2.x, 5.x, 9.x, 10.x
		Stability	Ballast failure	2: Likely	3: Machine Failure	10.3, 10.6
			Sea bed anchor failure			10.2, 10.5
		Strength	ULS environmental loads (wave slamming, oblique waves/ wind, currents, tidal effects)	3: Definitely	2: Component Failure	1.x, 2.x, 3.x, 4.x, 5.x 6.x, 7.x, 9.x, 10.x
			ALS loads (vessel/ice impact, tsunami, seismic effects, seabed instability)			9.1, 9.2, 9.3 10.3, 10.6
			Transportation and installation loads			8.x
			Buoyancy system failure			1.x, 2.x, 3.x, 4.x, 5.x 6.x, 7.x, 9.x, 10.x

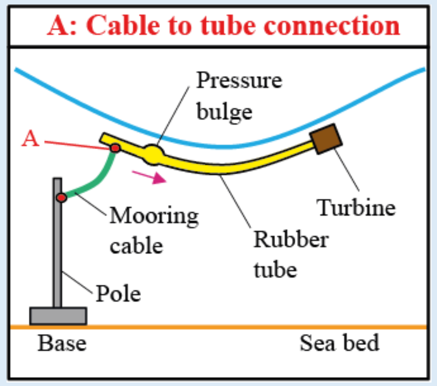
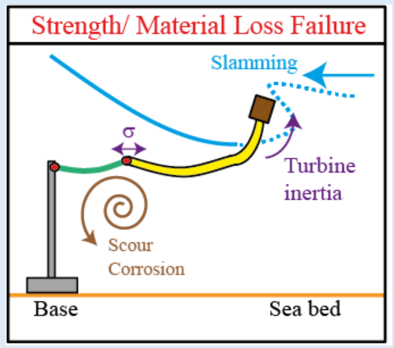
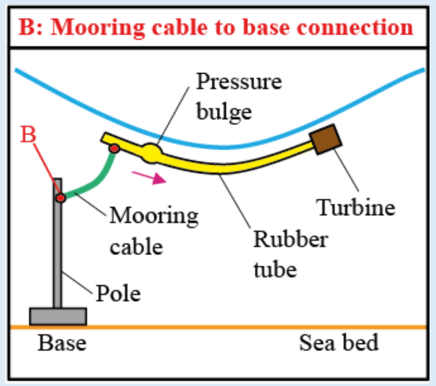
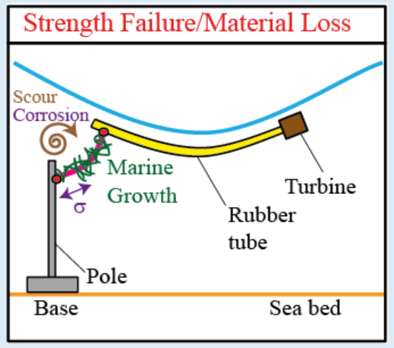
Failure Location	Schematic of Selected Failure Modes	Possible Structural Failure Modes	Cause	Governing Failure Mode?	Consequence	Relevant DLCs
			PTO/ controller failure			
			Survivability mode failure			6.2, 7.2
		Fatigue - high cycle	FLS environmental loads (wave, wind, currents)	3: Definitely	2: Component Failure	1.1, 1.5, 2.3, 9.2
			Stress concentration around geometric discontinuity			6.4, 7.3
			PTO induced excitation			1.1, 1.5, 2.3, 9.2
		Fatigue - low cycle	Extreme loads for all causes listed under high cycle fatigue that may lead to plastic response	1: Possibly	2: Component Failure	3.1, 4.1, 4.2, 9.2
			Transportation and installation loads			8.x
			Vortex induced vibrations			10.1, 10.4
		Material Loss	Corrosion	2: Likely	2: Component Failure	1.6, 6.x, 7.x, 9.x, 10.x
			Scouring			1.6, 6.x, 7.x, 9.x, 10.x
			Marine activity			8.x, 9.x
			Interface between dissimilar materials			2.x, 5.x, 9.x, 10.x
			Sudden change in temperature			2.x, 5.x, 9.x, 10.x

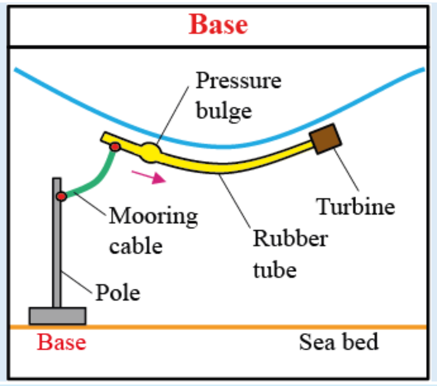
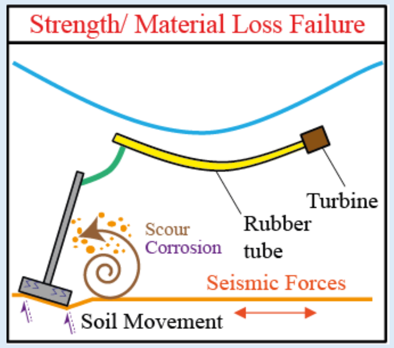
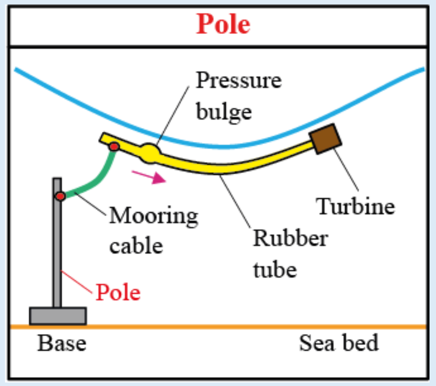
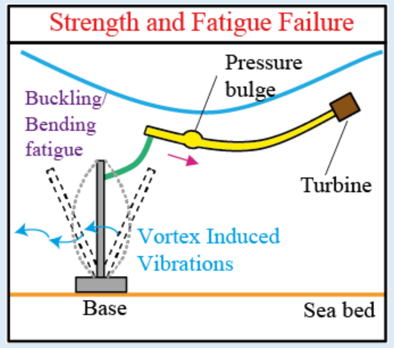
A1.3 Oscillating Water Column

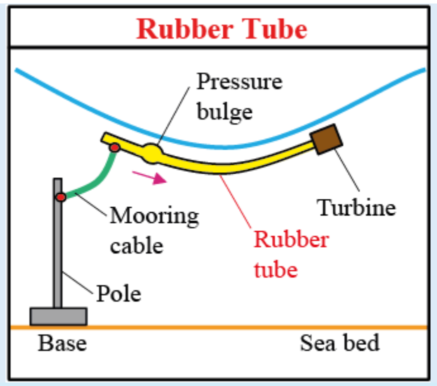
Failure Location	Schematic of Selected Failure Modes	Possible Structural Failure Modes	Cause	Governing Failure Mode?	Consequence	Relevant DLCs
	 	Strength	ULS environmental loads (wave slamming, wind, currents, tidal effects)	2: Likely	3: Machine Failure	1.x, 2.x, 3.x, 4.x, 5.x 6.x, 7.x, 9.x, 10.x
			ALS loads (vessel/ice impact, tsunami, seismic effects)			9.1, 9.2, 9.3 10.3, 10.6
			Transportation (if relevant) and installation loads			8.x
			Marine growth			1.6
			Flooding			10.3, 10.6
			Turbine/ controller failure			2.1, 2.2, 2.3
		Fatigue - high cycle	FLS environment loads (wave, wind, currents)	3: Definitely	3: Machine Failure	1.1, 1.5, 2.3, 9.2
			Stress concentration around geometric discontinuity			6.4, 7.3
			Turbine/ controller induced excitation			1.1, 1.5, 2.3, 9.2
		Material Loss	Corrosion	1: Possibly	3: Machine Failure	1.6, 6.x, 7.x, 9.x, 10.x
			Scouring			1.6, 6.x, 7.x, 9.x, 10.x
			Marine activity			8.x, 9.x
			Interface between dissimilar materials			2.x, 5.x, 9.x, 10.x
			Sudden change in temperature			2.x, 5.x, 9.x, 10.x
		Stability	Buoyancy system failure (if relevant)	2: Likely	3: Machine Failure	10.x
		Strength	ULS environmental loads (wave slamming/slapping/snatching, oblique waves/ wind, currents, tidal effects)	1: Possibly	2: Component Failure	1.x, 2.x, 3.x, 4.x, 5.x 6.x, 7.x, 9.x, 10.x
			ALS loads (vessel/ice impact, tsunami, seismic effects)			9.1, 9.2, 9.3 10.3, 10.6
			Transportation (if relevant) and installation loads			8.x
			Material and Section discontinuity at composite joints			6.1, 6.2, 6.3 7.1, 7.2
			Marine growth			1.6
		Fatigue - high cycle	FLS environment loads (wave, wind, currents)	3: Definitely	2: Component Failure	1.1, 1.5, 2.3, 9.2
			Stress concentration around geometric discontinuity			6.4, 7.3
			Turbine/ controller induced excitation			1.1, 1.5, 2.3, 9.2
			Any other excitation of global resonance modes			8.4
		Material Loss	Corrosion	2: Likely	2: Component Failure	1.6, 6.x, 7.x, 9.x, 10.x
			Scouring			1.6, 6.x, 7.x, 9.x, 10.x
			Marine activity			8.x, 9.x
			Interface between dissimilar materials			2.x, 5.x, 9.x, 10.x
			Sudden change in temperature			2.x, 5.x, 9.x, 10.x
		Stability	Buoyancy system failure	2: Likely	2: Component Failure	10.x

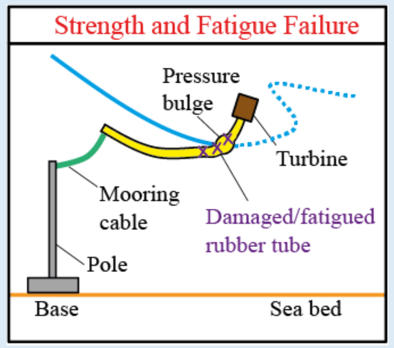
Failure Location	Schematic of Selected Failure Modes	Possible Structural Failure Modes	Cause	Governing Failure Mode?	Consequence	Relevant DLCs
		Strength	ULS environmental loads (wave slamming, oblique waves/ wind, currents, tidal effects)	3: Definitely	2: Component Failure	1.x, 2.x, 3.x, 4.x, 5.x 6.x, 7.x, 9.x, 10.x
			ALS loads (vessel/ice impact, tsunami, seismic effects, seabed instability)			9.1, 9.2, 9.3 10.3, 10.6
			Transportation and installation loads			8.x
			Material and Section discontinuity at composite joints			6.1, 6.2, 6.3 7.1, 7.2
			Marine growth			1.6
			Mooring connection failure			10.2, 10.5
		Fatigue - high cycle	FLS environmental loads (wave, wind, currents)	3: Definitely	2: Component Failure	1.1, 1.5, 2.3, 9.2
			Stress concentration around geometric discontinuity			6.4, 7.3
			Turbine/ controller induced excitation			1.1, 1.5, 2.3, 9.2
			Mooring load induced excitation			1.1, 1.5, 2.3, 9.2
		Fatigue - low cycle	Extreme loads for all causes listed under high cycle fatigue that may lead to plastic response	1: Possibly	2: Component Failure	3.1, 4.1, 4.2, 9.2
			Transportation and installation loads			8.x
			Vortex induced vibrations			10.1, 10.4
		Material Loss	Corrosion	2: Likely	2: Component Failure	1.6, 6.x, 7.x, 9.x, 10.x
			Scouring			1.6, 6.x, 7.x, 9.x, 10.x
			Marine activity			8.x, 9.x
			Interface between dissimilar materials			2.x, 5.x, 9.x, 10.x
			Sudden change in temperature			2.x, 5.x, 9.x, 10.x
		Stability	Buoyancy system failure	3: Definitely	2: Component Failure	10.x

A1.4 Bulge Wave

Failure Location	Schematic of Selected Failure Modes	Possible Structural Failure Modes	Cause	Governing Failure Mode?	Consequence	Relevant DLCs
		Strength	ULS environmental loads (wave slamming, wind, currents, tidal effects)	3: Definitely	3: Machine Failure	1.x, 2.x, 3.x, 4.x, 5.x 6.x, 7.x, 9.x, 10.x
			ALS loads (vessel/ice impact, tsunami, seismic effects)			9.1, 9.2, 9.3 10.3, 10.6
			Transportation and installation loads			8.x
			Material and Section discontinuity at composite joints			6.1, 6.2, 6.3 7.1, 7.2
			Marine growth			1.6
			Survivability mode failure			6.2, 7.2
			Inertial loading from hydrodynamic loading on turbine			2.x, 4.x, 5.1
		Fatigue - high cycle	FLS environment loads (wave, wind, currents)	3: Definitely	3: Machine Failure	1.1, 1.5, 2.3, 9.2
			Stress concentration around geometric discontinuity			6.4, 7.3
			PTO induced excitation			1.1, 1.5, 2.3, 9.2
			Mooring load induced excitation			1.1, 1.5, 2.3, 9.2
			Any other excitation of global resonance modes			8.4
		Material Loss	Corrosion	2: Likely	3: Machine Failure	1.6, 6.x, 7.x, 9.x, 10.x
			Scouring			1.6, 6.x, 7.x, 9.x, 10.x
			Marine activity			8.x, 9.x
			Interface between dissimilar materials			2.x, 5.x, 9.x, 10.x
			Sudden change in temperature			2.x, 5.x, 9.x, 10.x
		Strength	ULS environmental loads (wave slamming, wind, currents, tidal effects)	3: Definitely	3: Machine Failure	1.x, 2.x, 3.x, 4.x, 5.x 6.x, 7.x, 9.x, 10.x
			ALS loads (vessel/ice impact, tsunami, seismic effects)			9.1, 9.2, 9.3 10.3, 10.6
			Transportation and installation loads			8.x
			Transient snatch loads in cable systems			2.x, 5.x, 9.x, 10.x
			Material and Section discontinuity at composite joints			6.1, 6.2, 6.3 7.1, 7.2
			Survivability mode failure			6.2, 7.2
			Marine growth			1.6
		Fatigue - high cycle	FLS environment loads (wave, wind, currents)	3: Definitely	3: Machine Failure	1.1, 1.5, 2.3, 9.2
			Stress concentration around geometric discontinuity			6.4, 7.3
			Turbine induced excitation			1.1, 1.5, 2.3, 9.2
			Mooring load induced excitation			1.1, 1.5, 2.3, 9.2
			Any other excitation of global resonance modes			8.4
		Fatigue - low cycle	Extreme loads for all causes listed under high cycle fatigue that may lead to plastic response	1: Possibly	3: Machine Failure	3.1, 4.1, 4.2, 9.2
			Transportation and installation loads			8.x
			Vortex induced vibrations			10.1, 10.4
		Material Loss	Corrosion	2: Likely	3: Machine Failure	1.6, 6.x, 7.x, 9.x, 10.x
			Scouring			1.6, 6.x, 7.x, 9.x, 10.x
			Marine activity			8.x, 9.x
			Interface between dissimilar materials			2.x, 5.x, 9.x, 10.x
			Sudden change in temperature			2.x, 5.x, 9.x, 10.x

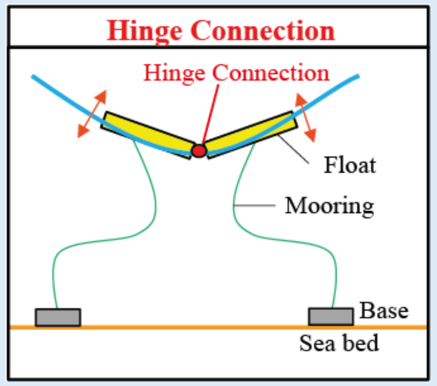
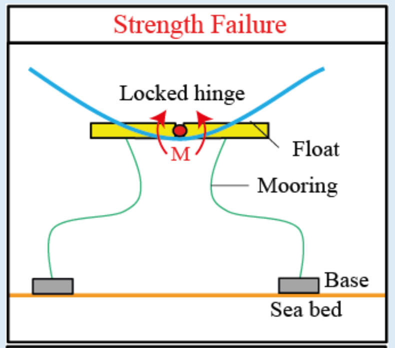
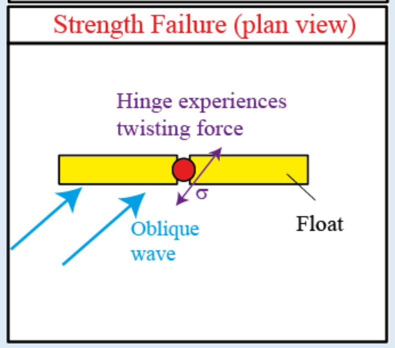
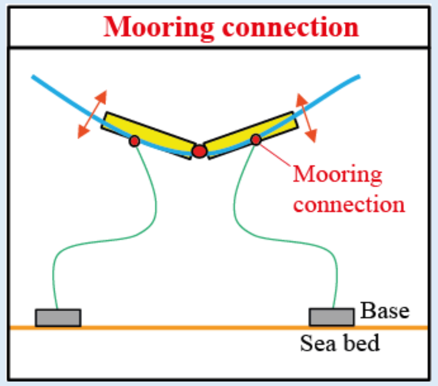
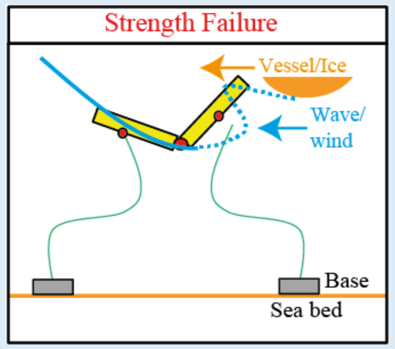
Failure Location	Schematic of Selected Failure Modes	Possible Structural Failure Modes	Cause	Governing Failure Mode?	Consequence	Relevant DLCs
		Strength	ULS environmental loads (wave slamming, wind, currents, tidal effects)	3: Definitely	3: Machine Failure	1.x, 2.x, 3.x, 4.x, 5.x 6.x, 7.x, 9.x, 10.x
			ALS loads (vessel/ice impact, tsunami, seismic effects, seabed instability)			9.1, 9.2, 9.3 10.3, 10.6
			Transportation and installation loads			8.x
			Incorrect assessment of mechanical properties of soil			9.4
			Marine growth			1.6
			Ballast failure			10.3, 10.6
			Seabed anchor failure			10.1, 10.4
		Fatigue - high cycle	FLS environmental loads (wave, wind, currents)	2: Likely	3: Machine Failure	1.1, 1.5, 2.3, 9.2
			Stress concentration around geometric discontinuity			6.4, 7.3
			Mooring load induced excitation			1.1, 1.5, 2.3, 9.2
			Any other excitation of global resonance modes			8.4
		Material Loss	Corrosion	1: Possibly	3: Machine Failure	1.6, 6.x, 7.x, 9.x, 10.x
			Scouring			1.6, 6.x, 7.x, 9.x, 10.x
			Marine activity			8.x, 9.x
			Interface between dissimilar materials			2.x, 5.x, 9.x, 10.x
			Sudden change in temperature			2.x, 5.x, 9.x, 10.x
		Stability	Ballast failure	2: Likely	3: Machine Failure	10.3, 10.6
			Seabed anchor failure			10.2, 10.5
		Strength	ULS environmental loads (wave slamming, wind, currents, tidal effects)	3: Definitely	3: Machine Failure	1.x, 2.x, 3.x, 4.x, 5.x 6.x, 7.x, 9.x, 10.x
			ALS loads (vessel/ice impact, tsunami, seismic effects)			9.1, 9.2, 9.3 10.3, 10.6
			Transportation and installation loads			8.x
			Transient snatch loads in cable systems			2.x, 5.x, 9.x, 10.x
			Marine growth			1.6
			Mooring connection failure			10.2, 10.5
			Seabed anchor failure			10.1, 10.4
		Fatigue - high cycle	FLS environmental loads (wave, wind, currents)	3: Definitely	3: Machine Failure	1.1, 1.5, 2.3, 9.2
			Stress concentration around geometric discontinuity			6.4, 7.3
			Turbine induced excitation			1.1, 1.5, 2.3, 9.2
			Mooring load induced excitation			1.1, 1.5, 2.3, 9.2
			Any other excitation of global resonance modes			8.4
		Fatigue - low cycle	Extreme loads for all causes listed under high cycle fatigue that may lead to plastic response	2: Likely	3: Machine Failure	3.1, 4.1, 4.2, 9.2
			Transportation and installation loads			8.x
			Vortex induced vibrations			10.1, 10.4
		Material Loss	Corrosion	1: Possibly	3: Machine Failure	1.6, 6.x, 7.x, 9.x, 10.x
			Scouring			1.6, 6.x, 7.x, 9.x, 10.x
			Marine activity			8.x, 9.x
			Sudden change in temperature			2.x, 5.x, 9.x, 10.x

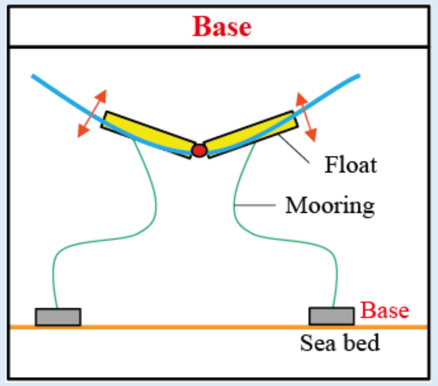
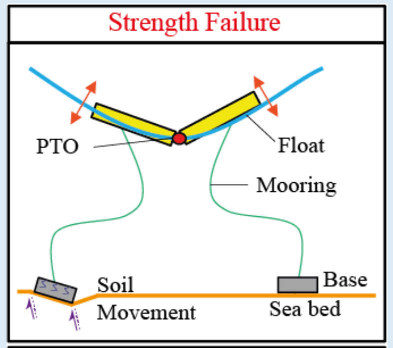
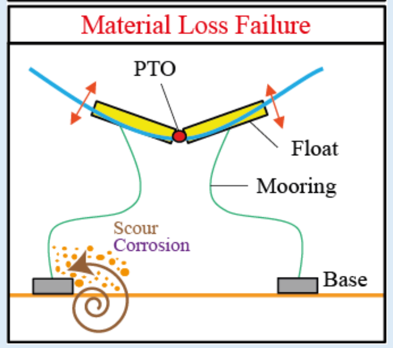
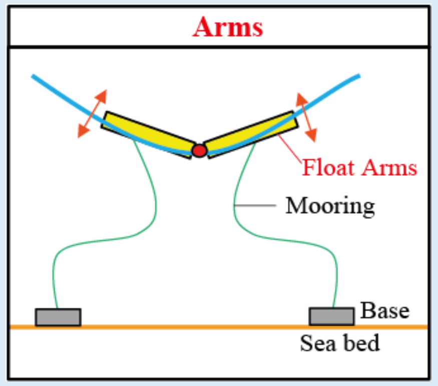
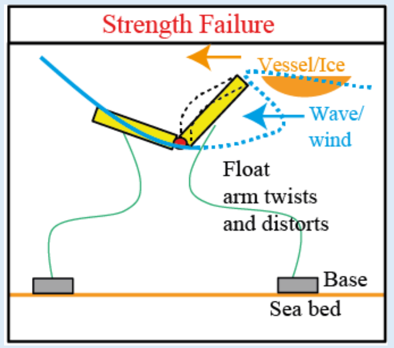




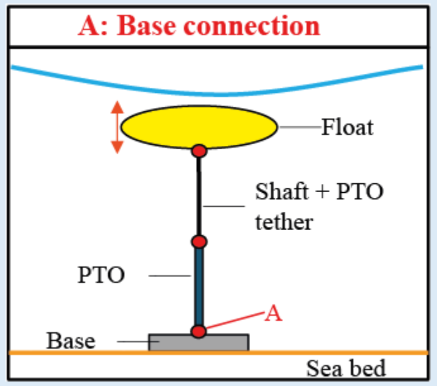
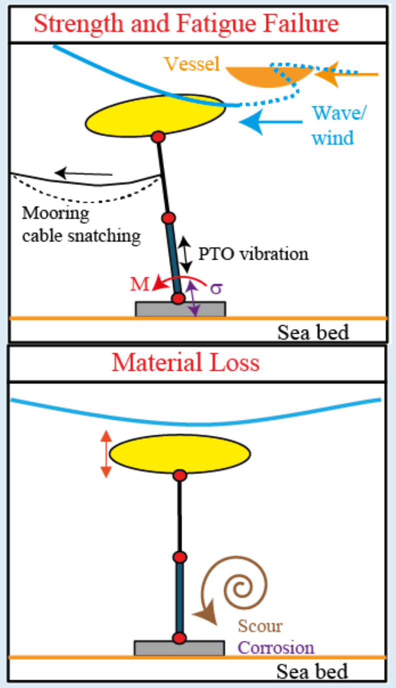
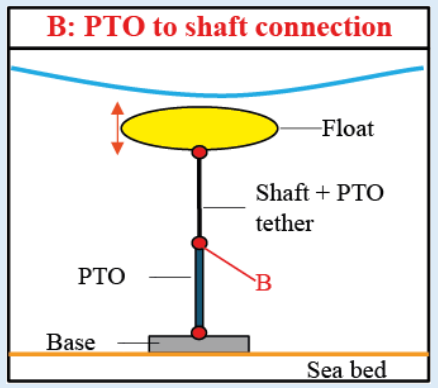
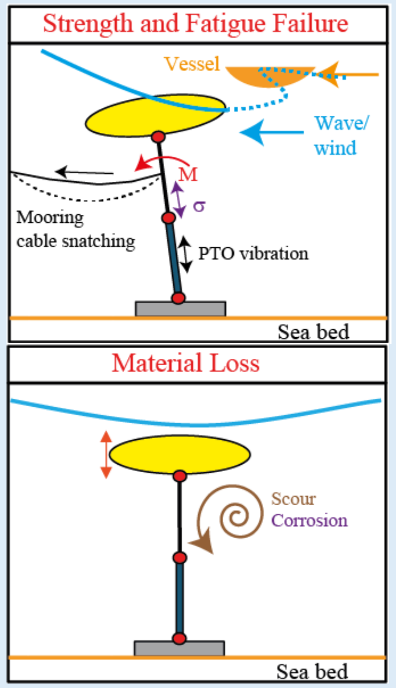
Failure Location	Schematic of Selected Failure Modes	Possible Structural Failure Modes	Cause	Governing Failure Mode?	Consequence	Relevant DLCs
		Strength	ULS environmental loads (wave slamming, wind, currents, tidal effects)	3: Definitely	2: Component Failure	1.x, 2.x, 3.x, 4.x, 5.x 6.x, 7.x, 9.x, 10.x
			ALS loads (vessel/ice impact, tsunami, seismic effects, seabed instability)			9.1, 9.2, 9.3 10.3, 10.6
			Transportation and installation loads			8.x
			Failure due to large bulge pressure			1.x, 2.x, 3.x, 4.x, 5.x 6.x, 7.x, 9.x, 10.x
			Transient snatch loads in cable systems			2.x, 5.x, 9.x, 10.x
			Mooring connection failure			10.2, 10.5
			Survivability mode failure			6.2, 7.2
		Fatigue - high cycle	FLS environmental loads (wave, wind, currents)	3: Definitely	2: Component Failure	1.1, 1.5, 2.3, 9.2
			Stress concentration around geometric discontinuity			6.4, 7.3
			PTO induced excitation			1.1, 1.5, 2.3, 9.2
			Mooring load induced excitation			1.1, 1.5, 2.3, 9.2
		Material Loss	Corrosion	1: Possibly	2: Component Failure	1.6, 6.x, 7.x, 9.x, 10.x
			Scouring			1.6, 6.x, 7.x, 9.x, 10.x
			Marine activity			8.x, 9.x
			Interface between dissimilar materials			2.x, 5.x, 9.x, 10.x
			Sudden change in temperature			2.x, 5.x, 9.x, 10.x

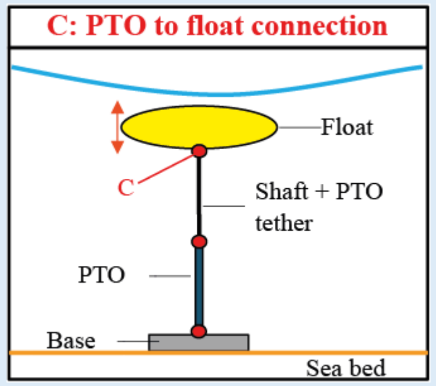
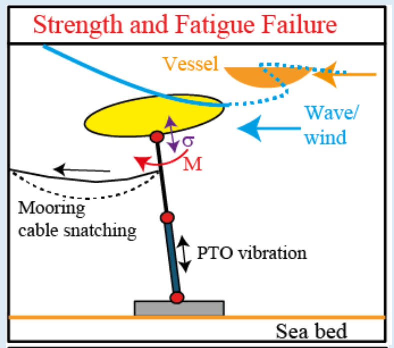
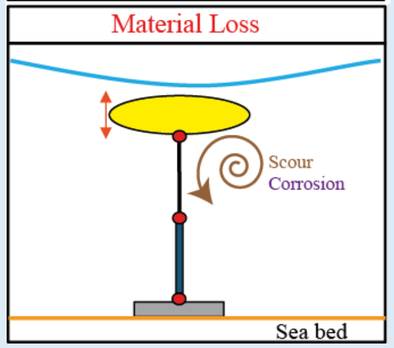
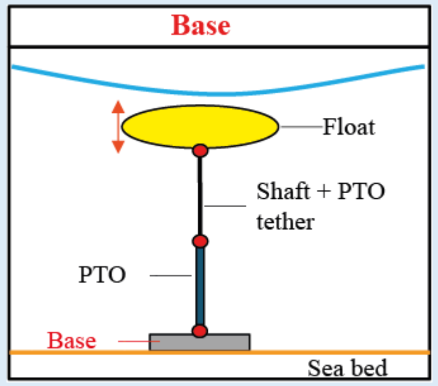
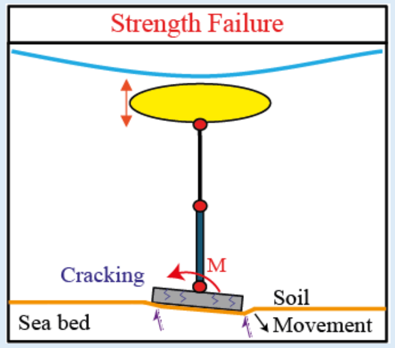
A1.5 Attenuator

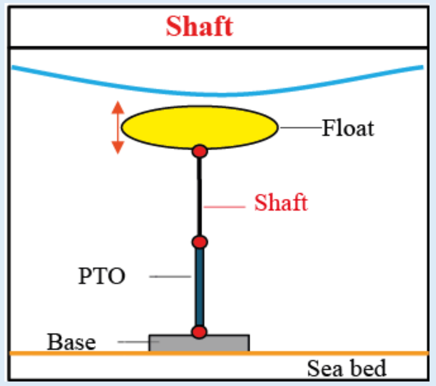
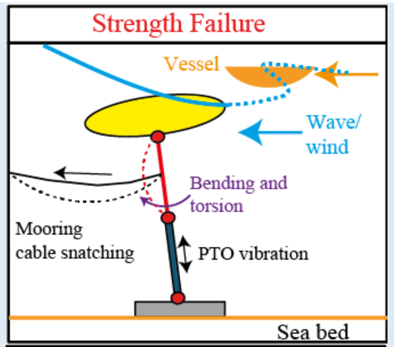
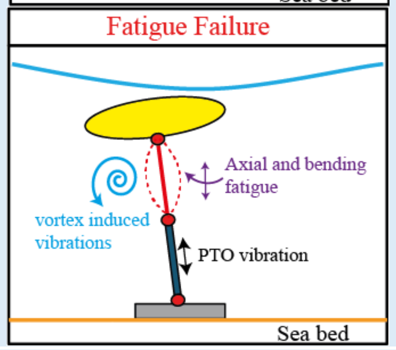
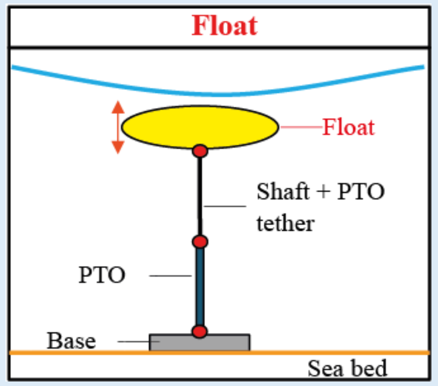
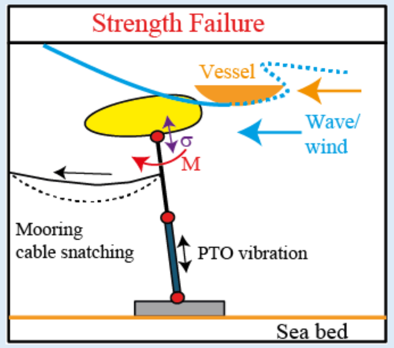
Failure Location	Schematic of Selected Failure Modes	Possible Structural Failure Modes	Cause	Governing Failure Mode?	Consequence	Relevant DLCs
		Strength	ULS environmental loads (wave slamming, oblique waves/ wind, currents, tidal effects)	3: Definitely	3: Machine Failure	1.x, 2.x, 3.x, 4.x, 5.x 6.x, 7.x, 9.x, 10.x
			ALS loads (vessel/ice impact, tsunami, seismic effects)			9.1, 9.2, 9.3 10.3, 10.6
			Transportation and installation loads			8.x
			Transient snatch loads in cable systems			2.x, 5.x, 9.x, 10.x
			Joint seizure leading to machine parking			6.1, 6.2, 6.3 7.1, 7.2
			Material and Section discontinuity at composite joints			6.1, 6.2, 6.3 7.1, 7.2
			Marine growth			1.6
			PTO/ controller failure			2.1, 2.2, 2.3
			Mooring connection failure			10.2, 10.5
			Seabed anchor failure			10.1, 10.4
		Fatigue - high cycle	FLS environment loads (wave, wind, currents)	3: Definitely	3: Machine Failure	1.1, 1.5, 2.3, 9.2
			Stress concentration around geometric discontinuity			6.4, 7.3
			PTO induced excitation			1.1, 1.5, 2.3, 9.2
			Mooring load induced excitation			1.1, 1.5, 2.3, 9.2
			Any other excitation of global resonance modes			8.4
		Fatigue - low cycle	Extreme loads for all causes listed under high cycle fatigue that may lead to plastic response	1: Possibly	3: Machine Failure	3.1, 4.1, 4.2, 9.2
			Transportation and installation loads			8.x
		Material Loss	Corrosion	2: Likely	3: Machine Failure	1.6, 6.x, 7.x, 9.x, 10.x
			Scouring			1.6, 6.x, 7.x, 9.x, 10.x
			Marine activity			8.x, 9.x
			Interface between dissimilar materials			2.x, 5.x, 9.x, 10.x
			Sudden change in temperature			2.x, 5.x, 9.x, 10.x
		Strength	ULS environmental loads (wave slamming, oblique waves/ wind, currents, tidal effects)	3: Definitely	2: Component Failure	1.x, 2.x, 3.x, 4.x, 5.x 6.x, 7.x, 9.x, 10.x
			ALS loads (vessel/ice impact, tsunami, seismic effects)			9.1, 9.2, 9.3 10.3, 10.6
			Transportation and installation loads			8.x
			Joint seizure leading to machine parking			6.1, 6.2, 6.3 7.1, 7.2
			Material and Section discontinuity at composite joints			6.1, 6.2, 6.3 7.1, 7.2
			Marine growth			1.6
			PTO/ controller failure			2.1, 2.2, 2.3
			Mooring connection failure			10.2, 10.5
			Seabed anchor failure			10.1, 10.4
		Fatigue - high cycle	FLS environment loads (wave, wind, currents)	3: Definitely	2: Component Failure	1.1, 1.5, 2.3, 9.2
			Stress concentration around geometric discontinuity			6.4, 7.3
			PTO induced excitation			1.1, 1.5, 2.3, 9.2
			Any other excitation of global resonance modes			8.4
		Fatigue - low cycle	Extreme loads for all causes listed under high cycle fatigue that may lead to plastic response	1: Possibly	2: Component Failure	3.1, 4.1, 4.2, 9.2
			Transportation and installation loads			8.x
		Material Loss	Corrosion	2: Likely	2: Component Failure	1.6, 6.x, 7.x, 9.x, 10.x
			Scouring			1.6, 6.x, 7.x, 9.x, 10.x
			Marine activity			8.x, 9.x
			Interface between dissimilar materials			2.x, 5.x, 9.x, 10.x
			Sudden change in temperature			2.x, 5.x, 9.x, 10.x

Failure Location	Schematic of Selected Failure Modes	Possible Structural Failure Modes	Cause	Governing Failure Mode?	Consequence	Relevant DLCs
	 	Strength	ULS environmental loads (wave slamming, oblique waves/ wind, currents, tidal effects)	3: Definitely	3: Machine Failure	1.x, 2.x, 3.x, 4.x, 5.x 6.x, 7.x, 9.x, 10.x
			ALS loads (vessel/ice impact, tsunami, seismic effects)			9.1, 9.2, 9.3 10.3, 10.6
			Transportation and installation loads			8.x
			Transient snatch loads in cable systems			2.x, 5.x, 9.x, 10.x
			Joint seizure leading to machine parking			6.1, 6.2, 6.3 7.1, 7.2
			Material and Section discontinuity at composite joints			6.1, 6.2, 6.3 7.1, 7.2
			Marine growth			1.6
			PTO/ controller failure			2.1, 2.2, 2.3
			Seabed anchor failure			10.1, 10.4
		Fatigue - high cycle	FLS environment loads (wave, wind, currents)	3: Definitely	3: Machine Failure	1.1, 1.5, 2.3, 9.2
			Stress concentration around geometric discontinuity			6.4, 7.3
			PTO induced excitation			1.1, 1.5, 2.3, 9.2
			Mooring load induced excitation			1.1, 1.5, 2.3, 9.2
			Any other excitation of global resonance modes			8.4
		Fatigue - low cycle	Extreme loads for all causes listed under high cycle fatigue that may lead to plastic response	1: Possibly	3: Machine Failure	3.1, 4.1, 4.2, 9.2
			Transportation and installation loads			8.x
			Vortex induced vibrations			10.1, 10.4
		Material Loss	Corrosion	2: Likely	3: Machine Failure	1.6, 6.x, 7.x, 9.x, 10.x
			Scouring			1.6, 6.x, 7.x, 9.x, 10.x
			Marine activity			8.x, 9.x
			Interface between dissimilar materials			2.x, 5.x, 9.x, 10.x
			Sudden change in temperature			2.x, 5.x, 9.x, 10.x
		Strength	ULS environmental loads (wave slamming, oblique waves/ wind, currents, tidal effects)	3: Definitely	3: Machine Failure	1.x, 2.x, 3.x, 4.x, 5.x 6.x, 7.x, 9.x, 10.x
			ALS loads (vessel/ice impact, tsunami, seismic effects, seabed instability)			9.1, 9.2, 9.3 10.3, 10.6
			Transportation and installation loads			8.x
			Incorrect assessment of mechanical properties of soil			9.4
			Marine growth			1.6
			Buoyancy system failure			10.x
			Mooring connection failure			10.2, 10.5
			Seabed anchor failure			10.1, 10.4
		Fatigue - high cycle	FLS environmental loads (wave, wind, currents)	3: Definitely	3: Machine Failure	1.1, 1.5, 2.3, 9.2
			Stress concentration around geometric discontinuity			6.4, 7.3
			PTO induced excitation			1.1, 1.5, 2.3, 9.2
			Mooring load induced excitation			1.1, 1.5, 2.3, 9.2
			Any other excitation of global resonance modes			8.4
		Fatigue - low cycle	Extreme loads for all causes listed under high cycle fatigue that may lead to plastic response	2: Likely	3: Machine Failure	3.1, 4.1, 4.2, 9.2
			Transportation and installation loads			8.x
			Vortex induced vibrations			10.1, 10.4
		Material Loss	Corrosion	2: Likely	3: Machine Failure	1.6, 6.x, 7.x, 9.x, 10.x
			Scouring			1.6, 6.x, 7.x, 9.x, 10.x
			Marine activity			8.x, 9.x
			Interface between dissimilar materials			2.x, 5.x, 9.x, 10.x
			Sudden change in temperature			2.x, 5.x, 9.x, 10.x

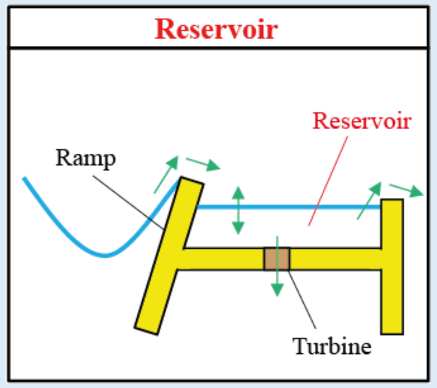
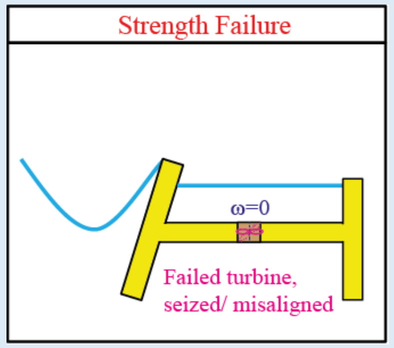
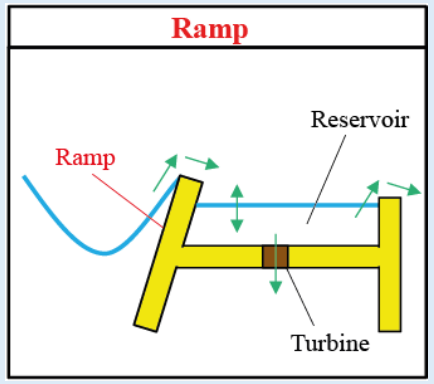
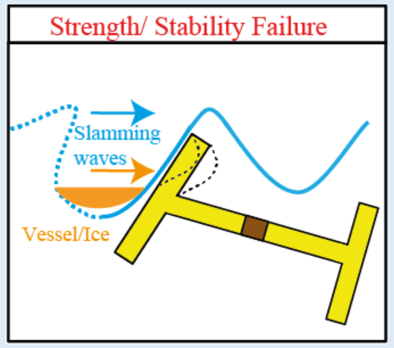
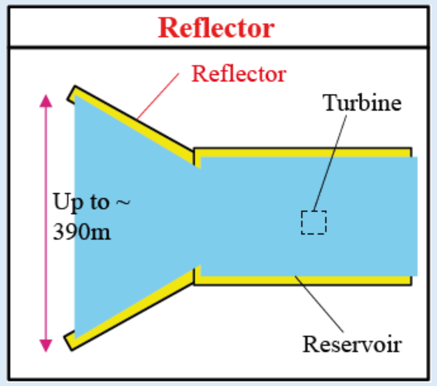
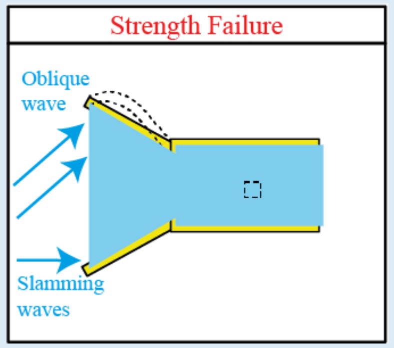
A1.6 Submerged Pressure Differential

Failure Location	Schematic of Selected Failure Modes	Possible Structural Failure Modes	Cause	Governing Failure Mode?	Consequence	Relevant DLCs
		Strength	ULS environmental loads (wave slamming, wind, currents, tidal effects)	3: Definitely	3: Machine Failure	1.x, 2.x, 3.x, 4.x, 5.x 6.x, 7.x, 9.x, 10.x
			ALS loads (vessel/ice impact, tsunami, seismic effects)			9.1, 9.2, 9.3 10.3, 10.6
			Transportation and installation loads			8.x
			Transient snatch loads in cable systems			2.x, 5.x, 9.x, 10.x
			Joint seizure leading to machine parking			6.1, 6.2, 6.3 7.1, 7.2
			Material and Section discontinuity at composite joints			6.1, 6.2, 6.3 7.1, 7.2
			Marine growth			1.6
			PTO/ controller failure			2.1, 2.2, 2.3
			Mooring connection failure			10.2, 10.5
			Seabed anchor failure			10.1, 10.4
		Fatigue - high cycle	FLS environment loads (wave, wind, currents)	3: Definitely	3: Machine Failure	1.1, 1.5, 2.3, 9.2
			Stress concentration around geometric discontinuity			6.4, 7.3
			PTO induced excitation			1.1, 1.5, 2.3, 9.2
			Mooring load induced excitation			1.1, 1.5, 2.3, 9.2
			Any other excitation of global resonance modes			8.4
		Fatigue - low cycle	Extreme loads for all causes listed under high cycle fatigue that may lead to plastic response	1: Possibly	3: Machine Failure	3.1, 4.1, 4.2, 9.2
			Transportation and installation loads			8.x
			Vortex induced vibrations			10.1, 10.4
		Material Loss	Corrosion	2: Likely	3: Machine Failure	1.6, 6.x, 7.x, 9.x, 10.x
			Scouring			1.6, 6.x, 7.x, 9.x, 10.x
			Marine activity			8.x, 9.x
			Interface between dissimilar materials			2.x, 5.x, 9.x, 10.x
			Sudden change in temperature			2.x, 5.x, 9.x, 10.x
		Strength	ULS environmental loads (wave slamming, wind, currents, tidal effects)	3: Definitely	3: Machine Failure	1.x, 2.x, 3.x, 4.x, 5.x 6.x, 7.x, 9.x, 10.x
			ALS loads (vessel/ice impact, tsunami, seismic effects)			9.1, 9.2, 9.3 10.3, 10.6
			Transportation and installation loads			8.x
			Joint seizure leading to machine parking			6.1, 6.2, 6.3 7.1, 7.2
			Material and Section discontinuity at composite joints			6.1, 6.2, 6.3 7.1, 7.2
			Marine growth			1.6
			PTO/ controller failure			2.1, 2.2, 2.3
			Mooring connection failure			10.2, 10.5
			Seabed anchor failure			10.1, 10.4
		Fatigue - high cycle	FLS environment loads (wave, wind, currents)	3: Definitely	3: Machine Failure	1.1, 1.5, 2.3, 9.2
			Stress concentration around geometric discontinuity			6.4, 7.3
			PTO induced excitation			1.1, 1.5, 2.3, 9.2
			Mooring load induced excitation			1.1, 1.5, 2.3, 9.2
			Any other excitation of global resonance modes			8.4
		Fatigue - low cycle	Extreme loads for all causes listed under high cycle fatigue that may lead to plastic response	1: Possibly	3: Machine Failure	3.1, 4.1, 4.2, 9.2
			Transportation and installation loads			8.x
			Vortex induced vibrations			10.1, 10.4
		Material Loss	Corrosion	2: Likely	3: Machine Failure	1.6, 6.x, 7.x, 9.x, 10.x
			Scouring			1.6, 6.x, 7.x, 9.x, 10.x
			Marine activity			8.x, 9.x
			Interface between dissimilar materials			2.x, 5.x, 9.x, 10.x
			Sudden change in temperature			2.x, 5.x, 9.x, 10.x

Failure Location	Schematic of Selected Failure Modes	Possible Structural Failure Modes	Cause	Governing Failure Mode?	Consequence	Relevant DLCs
		Strength	ULS environmental loads (wave slamming, wind, currents, tidal effects)	3: Definitely	2: Component Failure	1.x, 2.x, 3.x, 4.x, 5.x 6.x, 7.x, 9.x, 10.x
			ALS loads (vessel/ice impact, tsunami, seisemic effects)			9.1, 9.2, 9.3 10.3, 10.6
			Transportation and installation loads			8.x
			Transient snatch loads in cable systems			2.x, 5.x, 9.x, 10.x
			Joint seizure leading to machine parking			6.1, 6.2, 6.3 7.1, 7.2
			Material and Section discontinuity at composite joints			6.1, 6.2, 6.3 7.1, 7.2
			Marine growth			1.6
			PTO/ controller failure			2.1, 2.2, 2.3
			Mooring connection failure			10.2, 10.5
			Seabed anchor failure			10.1, 10.4
			Survivability mode failure			6.2, 7.2
		Fatigue - high cycle	FLS environment loads (wave, wind, currents)	3: Definitely	2: Component Failure	1.1, 1.5, 2.3, 9.2
			Stress concentration around geometric discontinuity			6.4, 7.3
			PTO induced excitation			1.1, 1.5, 2.3, 9.2
			Mooring load induced excitation			1.1, 1.5, 2.3, 9.2
			Any other excitation of global resonance modes			8.4
		Fatigue - low cycle	Extreme loads for all causes listed under high cycle fatigue that may lead to plastic response	1: Possibly	2: Component Failure	3.1, 4.1, 4.2, 9.2
			Transportation and installation loads			8.x
			Vortex induced vibrations			10.1, 10.4
		Material Loss	Corrosion	2: Likely	2: Component Failure	1.6, 6.x, 7.x, 9.x, 10.x
			Scouring			1.6, 6.x, 7.x, 9.x, 10.x
			Marine activity			8.x, 9.x
			Interface between dissimilar materials			2.x, 5.x, 9.x, 10.x
			Sudden change in temperature			2.x, 5.x, 9.x, 10.x
		Strength	ULS environmental loads (wave slamming, wind, currents, tidal effects)	3: Definitely	3: Machine Failure	1.x, 2.x, 3.x, 4.x, 5.x 6.x, 7.x, 9.x, 10.x
			ALS loads (vessel/ice impact, tsunami, seisemic effects, seabed instability)			9.1, 9.2, 9.3 10.3, 10.6
			Transportation and installation loads			8.x
			Incorrect assessment of mechanical properties of soil			9.4
			Marine growth			1.6
			Ballast failure			10.3, 10.6
			Mooring connection failure			10.2, 10.5
			Seabed anchor failure			10.1, 10.4
		Fatigue - high cycle	FLS environmental loads (wave, wind, currents)	1: Possibly	3: Machine Failure	1.1, 1.5, 2.3, 9.2
			Stress concentration around geometric discontinuity			6.4, 7.3
			PTO induced excitation			1.1, 1.5, 2.3, 9.2
			Mooring load induced excitation			1.1, 1.5, 2.3, 9.2
			Any other excitation of global resonance modes			8.4
		Material Loss	Corrosion	2: Likely	3: Machine Failure	1.6, 6.x, 7.x, 9.x, 10.x
			Scouring			1.6, 6.x, 7.x, 9.x, 10.x
			Marine activity			8.x, 9.x
			Interface between dissimilar materials			2.x, 5.x, 9.x, 10.x
			Sudden change in temperature			2.x, 5.x, 9.x, 10.x
		Stability	Sea bed anchor failure	2: Likely	3: Machine Failure	10.2, 10.5
			Ballast failure			10.3, 10.6

Failure Location	Schematic of Selected Failure Modes	Possible Structural Failure Modes	Cause	Governing Failure Mode?	Consequence	Relevant DLCs
		Strength	ULS environmental loads (wave slamming, wind, currents, tidal effects)	3: Definitely	2: Component Failure	1.x, 2.x, 3.x, 4.x, 5.x 6.x, 7.x, 9.x, 10.x
			ALS loads (vessel/ice impact, tsunami, seismic effects)			9.1, 9.2, 9.3 10.3, 10.6
			Transportation and installation loads			8.x
			Transient snatch loads in cable systems			2.x, 5.x, 9.x, 10.x
			Marine growth			1.6
			PTO/ controller failure			2.1, 2.2, 2.3
			Mooring connection failure			10.2, 10.5
			Seabed anchor failure			10.1, 10.4
		Fatigue - high cycle	FLS environmental loads (wave, wind, currents)	3: Definitely	2: Component Failure	1.1, 1.5, 2.3, 9.2
			Stress concentration around geometric discontinuity			6.4, 7.3
			PTO induced excitation			1.1, 1.5, 2.3, 9.2
			Mooring load induced excitation			1.1, 1.5, 2.3, 9.2
			Any other excitation of global resonance modes			8.4
		Fatigue - low cycle	Extreme loads for all causes listed under high cycle fatigue that may lead to plastic response	1: Possibly	2: Component Failure	3.1, 4.1, 4.2, 9.2
			Transportation and installation loads			8.x
			Vortex induced vibrations			10.1, 10.4
		Material Loss	Corrosion	2: Likely	2: Component Failure	1.6, 6.x, 7.x, 9.x, 10.x
			Scouring			1.6, 6.x, 7.x, 9.x, 10.x
			Marine activity			8.x, 9.x
			Sudden change in temperature			2.x, 5.x, 9.x, 10.x
		Strength	ULS environmental loads (wave slamming, wind, currents, tidal effects)	3: Definitely	2: Component Failure	1.x, 2.x, 3.x, 4.x, 5.x 6.x, 7.x, 9.x, 10.x
			ALS loads (vessel/ice impact, tsunami, seismic effects)			9.1, 9.2, 9.3 10.3, 10.6
			Transportation and installation loads			8.x
			Transient snatch loads in cable systems			2.x, 5.x, 9.x, 10.x
			Marine growth			1.6
			PTO/ controller failure			2.1, 2.2, 2.3
			Mooring connection failure			10.2, 10.5
			Seabed anchor failure			10.1, 10.4
		Fatigue - high cycle	FLS environmental loads (wave, wind, currents)	3: Definitely	2: Component Failure	1.1, 1.5, 2.3, 9.2
			Stress concentration around geometric discontinuity			6.4, 7.3
			PTO induced excitation			1.1, 1.5, 2.3, 9.2
			Mooring load induced excitation			1.1, 1.5, 2.3, 9.2
			Any other excitation of global resonance modes			8.4
		Material Loss	Corrosion	2: Likely	2: Component Failure	1.6, 6.x, 7.x, 9.x, 10.x
			Scouring			1.6, 6.x, 7.x, 9.x, 10.x
			Marine activity			8.x, 9.x
			Sudden change in temperature			2.x, 5.x, 9.x, 10.x

A1.7 Overtopping

Failure Location	Schematic of Selected Failure Modes	Possible Structural Failure Modes	Cause	Governing Failure Mode?	Consequence	Relevant DLCs
		Strength	ULS environmental loads (waveslamming, wind, currents, tidal effects)	3: Definitely	3: Machine Failure	1.x, 2.x, 3.x, 4.x, 5.x 6.x, 7.x, 9.x, 10.x
			ALS loads (vessel/ice impact, tsunami, seismic effects)			9.1, 9.2, 9.3 10.3, 10.6
			Transportation and installation loads			8.x
			Marine growth			1.6
			Turbine failure			2.1, 2.2, 2.3
		Fatigue - high cycle	FLS environment loads (wave, wind, currents)	1: Possibly	3: Machine Failure	1.1, 1.5, 2.3, 9.2
			Stress concentration around geometric discontinuity			6.4, 7.3
			Turbine induced excitation			1.1, 1.5, 2.3, 9.2
		Material Loss	Corrosion	1: Possibly	3: Machine Failure	1.6, 6.x, 7.x, 9.x, 10.x
			Scouring			1.6, 6.x, 7.x, 9.x, 10.x
			Marine activity			8.x, 9.x
			Interface between dissimilar materials			2.x, 5.x, 9.x, 10.x
			Sudden change in temperature			2.x, 5.x, 9.x, 10.x
		Stability	Buoyancy system failure	2: Likely	3: Machine Failure	10.3, 10.6
			Mooring connection failure			10.2, 10.5
		Strength	ULS environmental loads (waveslamming/slapping/snatching, oblique waves/ wind, currents, tidal effects)	3: Definitely	2: Component Failure	1.x, 2.x, 3.x, 4.x, 5.x 6.x, 7.x, 9.x, 10.x
			ALS loads (vessel/ice impact, tsunami, seismic effects)			9.1, 9.2, 9.3 10.3, 10.6
			Transportation and installation loads			8.x
			Marine growth			1.6
		Fatigue - high cycle	FLS environment loads (wave, wind, currents)	1: Possibly	2: Component Failure	1.1, 1.5, 2.3, 9.2
			Stress concentration around geometric discontinuity			6.4, 7.3
			Turbine induced excitation			1.1, 1.5, 2.3, 9.2
			Any other excitation of global resonance modes			8.4
		Material Loss	Corrosion	1: Possibly	2: Component Failure	1.6, 6.x, 7.x, 9.x, 10.x
			Scouring			1.6, 6.x, 7.x, 9.x, 10.x
			Marine activity			8.x, 9.x
			Interface between dissimilar materials			2.x, 5.x, 9.x, 10.x
			Sudden change in temperature			2.x, 5.x, 9.x, 10.x
		Stability	Buoyancy system failure	2: Likely	3: Machine Failure	10.3, 10.6
			Mooring connection failure			10.2, 10.5
		Strength	ULS environmental loads (waveslamming, oblique waves/ wind, currents, tidal effects)	3: Definitely	2: Component Failure	1.x, 2.x, 3.x, 4.x, 5.x 6.x, 7.x, 9.x, 10.x
			ALS loads (vessel/ice impact, tsunami, seismic effects, seabed instability)			9.1, 9.2, 9.3 10.3, 10.6
			Transportation and installation loads			8.x
			Mooring connection failure			10.2, 10.5
		Fatigue - high cycle	FLS environmental loads (wave, wind, currents)	3: Definitely	2: Component Failure	1.1, 1.5, 2.3, 9.2
			Stress concentration around geometric discontinuity			6.4, 7.3
			Turbine induced excitation			1.1, 1.5, 2.3, 9.2
			Mooring load induced excitation			1.1, 1.5, 2.3, 9.2
		Fatigue - low cycle	Extreme loads for all causes listed under high cycle fatigue that may lead to plastic response	2: Likely	2: Component Failure	3.1, 4.1, 4.2, 9.2
			Transportation and installation loads			8.x
			Vortex induced vibrations			10.1, 10.4
		Material Loss	Corrosion	1: Possibly	2: Component Failure	1.6, 6.x, 7.x, 9.x, 10.x
			Scouring			1.6, 6.x, 7.x, 9.x, 10.x
			Marine activity			8.x, 9.x
			Interface between dissimilar materials			2.x, 5.x, 9.x, 10.x
			Sudden change in temperature			2.x, 5.x, 9.x, 10.x
		Stability	Buoyancy system failure	3: Definitely	2: Component Failure	10.3, 10.6
			Mooring connection failure			10.2, 10.5