OFFSHORE WIND ACCELERATOR (OWA)

Cable Protection Systems (CPS) best practice guideline

Cables technical working group

November 2024

OWA parties

Participants in the Offshore Wind Accelerator (OWA) programme (Stage IV): EnBW Energie Baden-Württemberg AG, RWE Offshore Wind GmbH, Equinor ASA, Ørsted Wind Power A/S, ScottishPower Renewables (UK) Limited, Shell Global Solutions International B.V, SSE Renewables Services (UK) Limited, Vattenfall Wind Power Ltd, TotalEnergies OneTech, and the Carbon Trust.

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1. Foreword

The Offshore Wind Accelerator ("OWA") is an industry-driven collaborative research, development and demonstration programme which was initially launched by the Carbon Trust in 2008 in collaboration with five offshore wind developers. The programme has since expanded during OWA Stages I, II, III and IV to include currently nine offshore wind developers from various countries within the European Economic Area (the "OWA Partners") – SSE Renewables Developments (UK) Limited, Ørsted Wind Power A/S, RWE Offshore Wind GmbH, ScottishPower Renewables (UK) Limited, Equinor ASA, Vattenfall Vindkraft A/S, EnBW Energie Baden-Württemberg AG, Shell Global Solutions International B.V. and TotalEnergies OneTech.

OWA Stage IV, dated 27th October 2020, aims to continue the cost reduction of offshore wind to make it cost competitive with other sources of energy generation, overcome market barriers, develop industry best practice, trigger the development of new industry standards and support the international expansion of offshore wind.

Research under the OWA currently falls into five research areas: Cables, Electricals, Foundations, Logistics and O&M, and Energy Yield & Performance. Research, development and demonstration projects are carried out in each of the five research areas to address technology challenges. Each of the five research areas is managed by the Carbon Trust and governed by a Technical Working Group ("TWG") consisting of technical experts appointed by the OWA Partners.

In recent years, multiple wind farms have experienced issues with failures of Cable Protection Systems (CPS) at the interface between the cable and the windfarm foundations (i.e. fixed Wind Turbine Generator, Offshore Substation). It is further acknowledged within the industry that there exists varying levels of qualification and standards related specifically to CPS design. It is recognised that CPS design and analysis requirements are both unclear and not adequately addressed within the existing codes and standards.

In order to address these gaps, the CPS IV project was initiated by the Cables OWA TWG, with the objective of developing and producing a recommended / best practice guidance for Cable Protection System (CPS) design for offshore wind farm applications, and specifically CPS design at the interface between the cable and the windfarm foundations.

The objective of the CPS IV project has been to consolidate current understanding of CPS system design based on industry learnings to date, including applicable codes and standards, and to establish a consistent set of requirements and guidance to be considered for CPS system design, analysis and qualification.

The purpose of this document is to present the Carbon Trust Offshore Wind Accelerator's (OWA) 'Best Practice Guidance for CPS Design'. This is a key deliverable from the OWA's CPS IV project. The document considers the CPS, cables and foundation as a whole system and not just as individual components.

This guidance document has been developed by Wood and the Cables Technical Working Group (TWG) on behalf of the Carbon Trust Offshore Wind Accelerator (OWA).

This guidance document is intended to offer a consistent and standardised set of guidance for CPS system design that may be used by all stakeholders involved in the development of an offshore wind farm.

2. Introduction

2.1. General

Submarine power cables are key components of an offshore wind farm installation as they allow for the transmission of electricity between the turbines to the substation and eventually to shore.

As the cables approach the foundations of a Wind Turbine Generator (WTG) and Offshore Substation (OSS), whether a jacket, gravity base or monopile foundation, there is an exposed section in which the cable needs to transition from burial in the seabed up to the J-tube or monopile entry hole before subsequently reaching the cable hang-off platform. This exposed area can be subject to both hydrodynamic (current and wave) and geophysical (scouring) phenomena. To withstand these dynamic forces a Cable Protection System (CPS) and Scour Protection are typically installed in this area to withstand the hydrodynamic forces and consequent scouring respectively.

A CPS is installed around the cable at the interface between the cable and the windfarm foundations and generally consists of a mechanical latch / connector (i.e. the foundation interface), and a number of different CPS components comprising of, and combining bend stiffeners, tubular elements and/or bend restrictors. There are several different designs and suppliers of CPS in the industry.

Additional measures for external cable protection are often used in conjunction with CPS, including burial, rock placement, concrete mattresses, rock bags. These additional cable protection measures are typically deployed where it has been identified that the CPS alone cannot fulfil the fundamental functional requirements that include provision of cable protection, and provision of CPS function to provide cable protection, for the specified design life of the system.

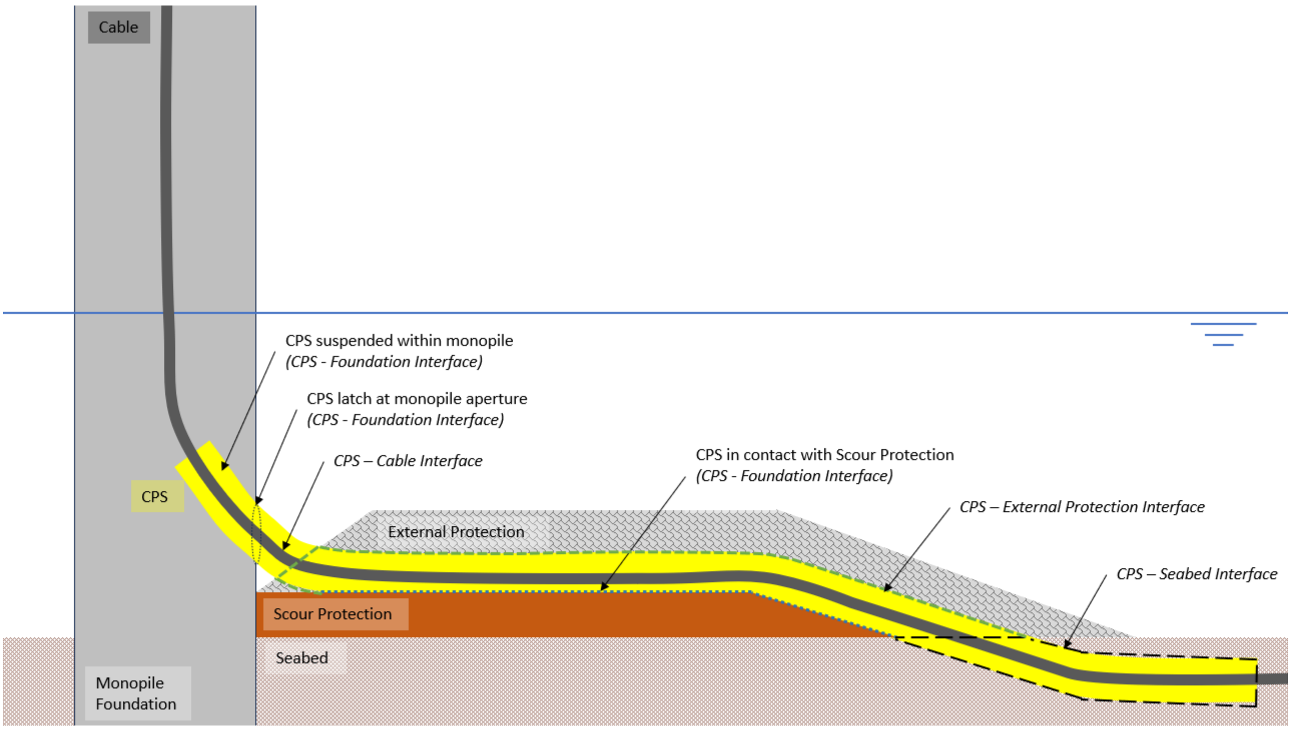

Figure 2-1: Generic illustration of monopile foundation cable protection system (CPS).

2.2. CPS design

The performance of a CPS is key for maintaining cable integrity in offshore wind farm installations over the design life of the system. Since the main function of the CPS is to protect the cable, the cable cross section and response characteristics must be considered and evaluated as part of the overall CPS design. In addition, the CPS layout configuration (exit height from foundation, distance to burial, seabed/scour protection geometry) must be considered along with changes to the configuration over time or due to installation tolerances.

While some degree of movement of the CPS and cable on the seabed/scour protection is expected, extreme and accumulated displacements of the CPS can lead to unforeseen problems such as abrasion of the CPS (outer surface against the seabed) and of the cable (outer surface of the cable against the inside of the CPS). For larger displacements under extreme loading conditions there is also a risk of obstructions on the seabed causing localised loads on the system which may not be intended or foreseen in the design. Where stabilisation using rock bags or bulk rock is used to mitigate CPS movement, it is key to understand the effect of the stabilisation. Concentrated loads and cable fatigue hotspots could develop where the CPS exits the stabilisation, depending on the length of CPS exposed to the environment outside of the stabilised region.

2.3. Existing codes and standards

In general, there is limited specific code guidance for CPS design for offshore wind. At time of writing, there exists no standard, guideline or recommended practice covering all aspects of cable / CPS system design, modelling and qualification. In addition, no hierarchy of codes has been identified, and in some instances, multiple different codes could be considered applicable.

Codes such as DNV-RP-0360 [1] and DNV-ST-0359 [2] tend to offer the broadest guidance in relation to cables / CPS system design. These codes include general requirements in relation to cable protection measures for cables at the interface of fixed offshore units, however, provide limited specific guidance in relation to input data, analysis methodologies and design criteria.

Offshore oil and gas codes provide guidance on specific aspects, such as load effect analysis, seabed interaction (e.g. on-bottom stability DNV-RP-F109 [10], burial DNV-RP-F114 [9]) and the design of ancillary equipment for flexible pipes and umbilical's such as bend stiffeners and restrictors (API SPEC 17L1 [24], API RP 17L2 [25]) which are relevant to some CPS designs.

Other codes provide guidance for dynamic cables (DNV-RP-F401 [3], DNV-ST-0119 [4], CIGRÉ TB 862 [31]) and umbilicals (ISO 13628-5 [21]) without explicitly referencing CPS.

Codes and standards readily acknowledge abrasion as a potential failure mode, however, provide little information in regard to input data and modelling methodologies that could be adopted to quantity this failure mode.

The impact of current and wave flow amplification around the foundations (e.g. monopile) on the cable / CPS system response is not explicitly covered within the codes and standards. However, flow amplification adjacent to large structures has been acknowledging from the point of view of flexible riser design (API-RP-17B [27]) as having a potentially significant impact on the system response.

A list of codes and standards relevant to CPS system design and modelling is provided in section 3.0. Codes and standards are also referenced through this guidance document were considered relevant and applicable.

2.4. CPS modelling

Developing representative analysis models of the proposed CPS and cable design is a key part of the CPS system design process. Global analysis is used to predict the loads in the whole CPS/cable system from hang off within the foundation to burial of the system in the seabed.

Some of the key aspects of global system modelling are illustrated in Figure 2-2 and include:

- Representation of CPS and cable behaviour, including contact modelling.
- Representation of seabed/scour protection geometry, and interaction between the CPS and seabed/scour protection, including burial of the CPS in the seabed or beneath external stabilisation.
- Hydrodynamics of environmental loading due to wave and current including the amplification of flow due to presence of the foundations and drag/lift amplification due to near-seabed effects.

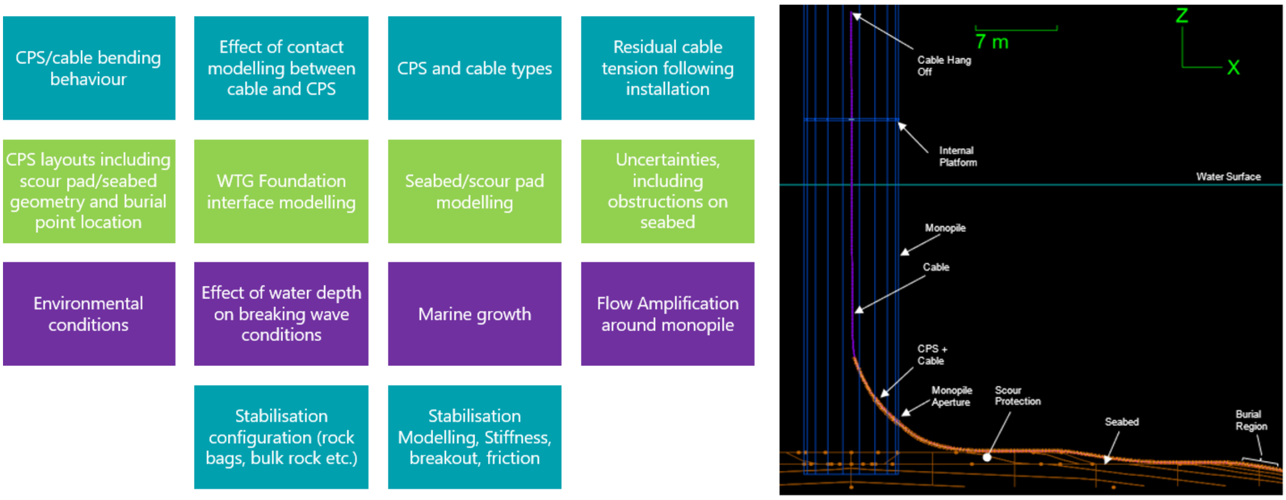

Figure 2-2: Global system modelling – Key aspects.

Local analysis/design refers to analysis/design of components to ensure that stress/strain limits of components are within allowable limits. Typically, loads from the global design are used as input to the local design. Local analysis tools are used to assess the fatigue performance of cable metallic components (armour wires, metallic screens, radial water barrier and conductors) as part of CPS assessments using the cable curvature and tension predictions of global analysis for FLS conditions. The individual CPS components can be assessed using local FEA analysis which can incorporate the effects of material and geometric nonlinearity, contact and bolting where applicable.

2.5. CPS qualification

Design verification testing is a key aspect of the overall CPS system design to demonstrate that the design of the CPS and associated ancillaries are fully qualified for their intended application and onsite environmental conditions.

The CPS qualification process should include material level testing and certification to the relevant standards, and CPS component level testing, to verify that project specific loads are within the allowable CPS capacity limits.

2.6. CPS IV project

The CPS IV project was initiated by the Cables OWA TWG, with the primary objective of developing and producing a recommended / best practice guidance for Cable Protection System (CPS) design for offshore wind farm applications, and specifically CPS design at the interface between the cable and the windfarm foundations. Some of the key objectives of this project were as follows:

- To understand current practice and guidance relevant to CPS design and modelling and identify gaps.
- To produce a specification of guidelines for the functional requirements of a CPS system design.
- To conduct scenario modelling and dynamic analysis to establish the behaviour of the CPS / cable system for a given set of design conditions.
- To define a testing proposal scope to fully qualify a whole CPS design to ensure it gives satisfactory lifetime performance.
- To outline the required exchanges and interfaces within different contracting strategies for the delivery of subsea cables and cable protection systems.
- To produce best practice process guidance for the whole CPS design (including CPS, cable and foundation as a whole system), CPS system modelling and CPS qualification.

The OWA partners have decided to publish the new ‘Best Practice Guidance for CPS Design’ in order to offer a consistent and standardised set of guidance for CPS system design that may be used by all stakeholders involved in the development of an offshore wind farm; however, the remainder of the project remains confidential to the OWA partners.

2.7. Document purpose

The purpose of this document is to present the Carbon Trust Offshore Wind Accelerators OWA’s ‘Best Practice Guidance for CPS Design’. This is a key deliverable from the OWA’s CPS IV project.

This ‘Best Practice Guidance for CPS Design’ should always be supplemented by sound engineering judgement on a project specific basis. It is further noted that as the industry evolves, and new learnings and new/updated codes and standard become available, these too should be considered in the overall CPS system design process.

2.8. Abbreviations

ALS	Accidental Limit State
API	American Petroleum Institute
ASTM	American Society for Testing and Materials
BM	Bending Moment
CAD	Computer Aided Design
CP	Corrosion Protection
CPS	Cable Protection System
DNV	Det Norske Veritas
EOL	End-of-Life
FEA	Finite Element Analysis
FLS	Fatigue Limit State
HSWL	Highest Seawater Level
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
KC	Keulegan-Carpenter Number
LSWL	Lowest Seawater Level
MBR	Minimum Bend Radius
NORSOK	Norwegian Standards Organisation
O&M	Operations and Maintenance
OSS	Offshore Substation
OWA	Offshore Wind Accelerator
ROV	Remotely Operated Vehicle
RP	Return Period
Sh	Shear
SLS	Serviceability Limit State
SMYS	Specified Minimum Yield Strength
SOL	Start-of-Life
ULS	Ultimate Limit State
UV	Ultraviolet
VIV	Vortex Induced Vibration
VMS	Von Mises Strain
WP	Work Package
WTG	Wind Turbine Generator
TWG	Technical Working Group
yr	Year
1D, 2D, 3D	1,2,3-dimensional

3. Relevant codes and standards

3.1. General

In general, there is limited specific code guidance for CPS design for offshore wind. Codes such as DNV-RP-0360 [1] and DNV-ST-0359 [2] primarily deal with cables rather than CPS, however some general guidance in relation to CPS is also provided. Offshore oil and gas codes provide guidance on specific aspects, such as seabed interaction (e.g. on-bottom stability DNV-RP-F109 [10], burial DNV-RP-F114 [9]) and the design of ancillary equipment for flexible pipes and umbilical's such as bend stiffeners and restrictors which are relevant to some CPS designs (API Spec 17L1 [24], API RP 17L2 [25]). Other codes provide guidance for dynamic cables (DNV-RP-F401 [3], DNV-ST-0119 [4], CIGRÉ TB 862 [31]) and umbilicals (ISO 13628-5 [21]) without explicitly referencing CPS.

3.2. Codes and standards

The codes and standards which have sections which are of relevance to cable / CPS design and modelling (not all provisions in all of the codes and standards are applicable) are detailed below. Codes and standards are also referenced through this guidance document were considered relevant and applicable.

It is noted that the codes and standards listed may not be inclusive of all codes and standards that could be considered applicable. Designers should be responsible for the identification of any additional codes or standards that may apply, and the use of such a code or standard should be justified. All codes and standards used should be referenced appropriately throughout the CPS system design process. Where conflict is found between these documents, in general, the most stringent should apply.

The codes and standards may be subject to update and amendment in the future, and as such the codes and standards should be the latest revisions that are available at the date of project contract signing, unless otherwise agreed with client.

The following documents are identified as the primary codes and standards applicable to CPS system design. The latest revisions should apply:

- DNV-ST-0359 - Subsea Power Cables for Wind Power Plants
- DNV-RP-0360 - Subsea Power Cables in Shallow Water
- DNV-RP-F401 - Electrical Power Cables in Subsea Applications
- DNV-ST-0119 - Floating Wind Turbine Structures
- DNV-ST-0126 - Support Structures for Wind Turbines
- DNV-ST-0145 - Offshore Substations
- DNV-RP-C205 - Environmental Conditions and Environmental Loads
- DNV-ST-0437 - Loads and Site Conditions for Wind Turbines
- DNV-RP-0416 - Corrosion Protection for Wind Turbines
- DNV-RP-B401 - Cathodic Protection Design
- DNV-RP-F114 - Pipe Soil Interaction for Submarine Pipelines
- DNV-RP-F109 - On-bottom Stability Design of Submarine Pipelines, Cables and Umbilicals
- DNV-RP-F107 - Risk Assessment of Pipeline Protection
- DNV-RP-F204 - Riser Fatigue
- DNV-RP-C203 - Fatigue Design of Offshore Steel Structures
- DNV-RP-F105 - Free Spanning Pipeline

- DNV-RP-F203 - Riser Interference
- DNV-OS-C101 – Design of offshore steel structures, general – LRFD method
- DNV-RP-C208 - Determination of Structural Capacity by Non-linear Finite Element Analysis Methods
- DNV-ST-N001 - Marine Operations and Marine Warranty
- API SPEC 17L1 - Specification for Ancillary Equipment for Flexible Pipes and Subsea Umbilicals
- API RP 17L2 - Recommended Practice for Ancillary Equipment for Flexible Pipes and Subsea Umbilicals
- API RP 17B - Recommended Practice for Flexible Pipe
- ISO 13628-5 - Design and Operation of Subsea Production Systems – Part 5: Subsea Umbilicals
- ISO 13628-2 - Design and Operation of Subsea Production Systems – Part 2: Unbonded Flexible Pipe Systems for Subsea and Marine Applications
- Norsok Standard, "Actions and action effects", N-003
- CIGRÉ TB 862 - Recommendations for Mechanical Testing of Submarine Cables for Dynamic Application
- CIGRÉ TB 623 - Recommendations for Mechanical Testing of Submarine Cables
- IEC 60287-2-1 Electric cables - Calculation of the current rating - Part 2-1: Thermal resistance - Calculation of thermal resistance

4. Functional requirements

4.1. General

There are two fundamental requirements associated with cable protection systems (CPS). These include, provision of cable protection, and provision of CPS function to provide cable protection, for the specified design life of the system (i.e. cable and CPS). These are described in section 4.3, and 4.4 and 4.5 respectively, while the CPS interfaces are described in section 4.6.

4.2. Design life

The system (cable and CPS) should be designed to have a minimum operational design life as specified by the project.

4.3. Cable protection

The functional requirements of the CPS with respect to providing cable protection should include the following:

- The CPS should provide cable protection for the specified design life of the system. This should include protection during installation, operations (temporary and permanent conditions), and intervention periods which may require disconnection and reconnection of the cable and CPS to facilitate cable repairs / replacement.
- The CPS should protect the primary functionality of the cable for the specified design life including:
    - Maintain all aspects of cable performance (including mechanical, electrical and thermal performance), accessibility, and maintainability over the specified design life.
    - Continuous power transmission with the required availability.
    - Operability under the site-specific environmental conditions.
    - Capability to withstand site-specific design loads and load combinations.
    - Dissipation of heat to prevent cable overheating.
    - Compatibility of cable materials with the surrounding environment, including CPS.
    - Capability of being, installed, recovered, repaired, and reinstated.
- The CPS should ensure that the mechanical and thermal limits of the cable are respected for the specified design life.
- The CPS should protect and facilitate the transition of the cable from burial in the seabed up to the foundation interface (monopile entry hole / J-tube) and onwards towards the cable hang-off platform. The CPS should provide protection to the cable along each of the key interfaces during the cable transition, including:
    - Transition of the cable from full burial depth in the seabed to the seabed surface. The CPS should have sufficient length to ensure it protects the cable until the cable has reached the required burial depth (depth of lowering). The CPS should also be of sufficient length such that it will not be pulled out of the burial region leading to cable exposure whilst maintaining the required depth of lowering. Where there is potential for this to occur, then consideration should be given to extending the length of the CPS into the burial region.

  - Transition of the cable across the seabed and / or scour protection, and / or beneath stabilisation as applicable (e.g., rock berm, rock bags, mattressing) prior to interfacing with the foundation (monopile entry hole / J-tube).
  - Spanning section of the cable between the seabed and / or scour protection and the foundation interface (monopile entry hole / J-tube).
  - Transition of the cable from horizontal to vertical alignment at the foundation interface (monopile entry hole / J-tube). The CPS should facilitate a smooth transition of the cable from the CPS exit in the vicinity of the foundation interface (monopile entry hole / J-tube) to the cable hang-off platform. The cable integrity, including minimum bend radius of the cable, should be respected at all times during installation and operation (temporary and permanent conditions), or during disconnection and reconnection of the cable and CPS.
  - Transition of free hanging cable section to cable hang-off platform (i.e., in the case of a monopile foundation). Dynamic cable interference and clashing with the inside of the foundation or structures within the foundation (including other cables) should be avoided. In some instances, allowance for cable contact may be permitted (e.g., cable-cable, cable-foundation) during extreme/abnormal conditions, provided that the impact energy is below the design limit. However, this should be subject to approval and agreement with client on a project specific basis.
  - The integrity of the cable components within the cable hang-off interface (e.g. clamped armour wires) should be ensured for the specified design life.
- The CPS should protect the cable against the following failure modes, for the specified design life of the system, and should not inadvertently cause any of these failure modes:
  - Overbending - The CPS should prevent overbending of the cable beyond its allowable limits. This should also account for allowable bending limits of the cable at varying levels of combined tension and bending (i.e., cable tension versus MBR capacity curve).
  - Excessive Tension - The CPS should prevent the cable from exceeding its allowable tension limit.
  - Compression - The CPS should prevent the cable from exceeding its allowable compression limit.
  - Sidewall Pressure - The CPS should prevent the cable from exceeding its allowable sidewall pressure limit.
  - Overheating - The CPS should have sufficient thermal performance to prevent overheating of the cable. The CPS design should also account for the installed thermal environment which may include as applicable:
    - seawater,
    - burial in seabed,
    - rock cover,
    - stabilisation,
    - marine growth,
    - ambient air.
  - External Impact - The CPS should protect the cable against all sources of external impact, including dropped objects, rock placement and collision (e.g., ROV impact). The CPS should contain the impact energy to a level below that to which the cable is qualified.
  - Radial Compression / Crush - The CPS should protect the cable from all sources of radial compression / crush loading, including loads applied by machinery onboard the cable

installation vessel and static loads during operating (e.g. additional stabilisation measures). The CPS should protect the cable from radial compression/crush loads beyond that to which the cable is qualified.

  - Fatigue (Wave / VIV) - The CPS should protect against fatigue failure of the metallic layers of the cable cross-section, including armour layer, conductor, metallic screen and radial water barrier as applicable.
  - Abrasion - The CPS should protect the cable from abrasion against the seabed/scour protection by preventing contact and relative movement between the cable and the seabed/scour protection. The CPS should also not cause abrasion of the cable due to relative movements between the cable and the inner surface of the CPS. The internal bore of the CPS and the interface points between adjacent CPS components should provide a smooth transition for the cable within the CPS with no sharp edges to avoid potential for abrasion hotspots at these locations. If there is a risk of cable abrasion, then suitable design mitigation measures should be implemented to reduce this risk.

- The CPS should be capable of protecting the cable against the most onerous combination of functional, environmental, and accidental loads expected to be experienced by the system due to extreme and fatigue (cyclic) loading conditions during the operational design life of the system and during installation. This should include, but may not be limited to:
  - Loads imparted by the CPS onto the cable.
  - Loads due to impact / clashing.
  - Loads due to handling and installation (including friction and clamping between the cable and CPS to facilitate pull-in of the CPS and during overpull/breakaway of the cable from the CPS).
  - Extreme wave and current loading.
  - Fatigue loading due to the operational wave environment.
  - Fatigue loading due to vortex induced vibration (VIV).
  - Loads due to maintenance, replacement, and intervention.

4.4. Cable Protection System (CPS)

The functional requirements associated with the overall CPS system design are summarised in section 4.4.1, while component specific requirements of the CPS are summarised in sections 4.4.2 to 4.4.4 as applicable. The requirements specified in section 4.4.1 are also applicable to the components described in sections 4.4.2 to 4.4.4.

4.4.1. General

The functional requirements of the overall CPS system design should include the following:

- The CPS should be designed for the specified design life of the system and should maintain functionality throughout this period. This should include transportation, storage, installation, operations (temporary and permanent conditions), and intervention periods which may require disconnection and reconnection of the cable and CPS to facilitate cable repairs / replacement.
- The CPS should maintain all aspects of performance, accessibility, and maintainability over the specified design life.
- The design of the CPS should ensure that the mechanical and thermal limits of the CPS are respected for the specified design life.

- The CPS should be of sufficient length such that it will not be pulled out of the burial region leading to cable exposure whilst maintaining the required depth of lowering. Where there is potential for this to occur, then consideration should be given to extending the length of the CPS into the burial region.
- The CPS materials should be selected such that they are compatible with the environment to which the materials will be exposed over the specified design life. The selection of CPS material should account for:
    - Creep due to long-term loads, dimensional changes, and strain to failure in the operating environment. The assessment of creep should account for temperatures induced in the CPS materials by the cable and the surrounding environment (i.e., seawater / air).
    - Corrosion of metallic components (including fasteners). The metallic parts of the CPS should be selected to be corrosion resistant, or, alternatively, be designed with adequate corrosion protection that will prevent loss of functionality throughout the specified design life in line with the requirements of API-Spec-17L1 [24]. The following should be considered:
        - All metallic surfaces of the CPS should be prepared and coated in accordance with an appropriate international standard for corrosion protection and suitable for the specified environment, unless the material is documented to be corrosion resistant, or a suitable corrosion allowance is employed. Where coating is employed, then the CPS design should account for potential corrosion coating breakdown for the specified design life and associated consequences for metallic components.
        - Selection of metallic materials should account for the effect of galvanic corrosion (due to dissimilar metals) to ensure that material loss due to galvanic corrosion does not occur.
        - All metallic surfaces of the CPS should be protected by a dedicated cathodic protection system (e.g., sacrificial anodes) that should have sufficient capacity to provide corrosion protection for the specified design life, in accordance with an appropriate international standard, unless any of the following apply:
            1. The material is documented to be corrosion resistant in the specified environment.
            2. A corrosion allowance is being employed.
            3. The structure is protected by an adjacent cathodic protection system (e.g., foundation).
        - If the CPS is reliant on an adjacent cathodic protection system (e.g., foundation), then it should be confirmed that the adjacent cathodic protection system is both compatible with and has sufficient capacity to give protection to the CPS for the specified design life.
        - The selection of metallic materials that are to be connected to a cathodic protection system should be confirmed not to suffer from hydrogen embrittlement (which may cause cracking) because of the cathodic protection system.
    - Aging of polymer and composite material due to mechanical, chemical, and thermal degradation. The selection of CPS materials should be resistant to seawater, chemical exposure, and suitable for the temperature ranges to which the CPS will be exposed to in the operating environment (i.e., cable temperatures, seawater / air temperatures).

  - Non-metallic CPS materials should be designed with UV (ultraviolet) resistance or UV protection when exposed to sunlight during storage, transportation, installation, and operation. Painted components (e.g., painted for corrosion protection) should also be assessed for UV protection.
- The CPS should provide sufficient thermal performance to prevent overheating of the cable and to prevent thermal degradation of the CPS materials for the specified design life. The CPS design should also account for the installed thermal environment which may include as applicable:
  - seawater,
  - burial in seabed,
  - rock cover,
  - stabilisation,
  - marine growth,
  - ambient air.
- The CPS should provide dynamic bend stiffening/restriction for bridging free spans at the foundation interface (monopile entry hole / J-tube). The design should protect the cable and CPS integrity under the most onerous combination of extreme loading, fatigue loading, and seabed scouring expected for the specified design life.
- The CPS should provide bend stiffening/restriction to support freespan transition to the seabed / scour protection including across seabed/scour protection, provide anchorage and shallow burial protection. The design should protect the cable and CPS integrity under the most onerous combination of extreme and fatigue loading for the specified design life. The CPS design should account for the layout and design of the scour protection at the foundation.
- The CPS should be capable of accommodating the full range of expected scour development, including edge scour and the case of no scour for the specified design life. The CPS should also not cause damage to the scour protection where applicable.
- The CPS should be designed with sufficient impact protection, to safeguard the cable and ensure CPS integrity for the specified design life. The CPS should be designed with sufficient impact protection to prevent damage to the CPS from dropped objects, rock placement and collision (e.g., ROV impact).
- The CPS should be capable of withstanding radial compression / crush loads imparted to the CPS during installation and operation, including crush loads due to the presence of additional stabilisation measures as applicable (e.g., rock berm, rock bags, mattressing).
- The CPS should be designed with sufficient abrasion resistance when in contact with the seabed / scour protection, or other interfacing structures (e.g. foundation monopile entry hole / J-tube) to ensure CPS integrity for the specified design life. The CPS should be designed with an abrasion / wear allowance where abrasion / wear is expected to occur during the design life of the system. The CPS should also not cause cable abrasion due to relative movements between the cable and the inner surface of the CPS.
- The CPS should be compatible with all relevant dimensions of the cable including design tolerances on the external diameter of the cable, as well as ovalisation when the cable bends. The design of CPS components should not result in restrictions to axial movement of the cable or localised pressure points on the cable.
- The CPS should be designed in so much as possible to minimise the hydrodynamic loading on the system.
- The CPS should provide alignment and secure the CPS at the foundation interface (monopile entry hole / J-tube).

- The CPS connection/lock-in facility should be designed compatible with the foundation interface (monopile entry hole / J-tube), including allowance for design tolerances.
- The CPS should be dimensionally compatible with the foundation interface structure (monopile entry hole / J-tube), accounting for all tolerances of the interface structure, including but not limited to:
    - CPS angle of entry to foundation relative to seabed.
    - Foundation interface height above seabed.
    - Dimensional tolerances.
- The CPS should be designed to accommodate dynamic behaviour (deflection) or vibration of monopile foundations if applicable.
- The CPS should have the capability to be retrieved and replaced at any time throughout the specified design life, i.e., it should not prevent the replacement of the cable in case of repair or replacement. The following should be considered:
    - Installation of the CPS should be non-obstructive, proven and a relatively simple procedure to minimise offshore activities and risk.
    - The installation of the CPS should not require divers and be performed with as minimum subsea intervention as is possible.
    - Retrieval of the CPS should preferably be performed using non-destructive recovery methods.
    - Installation / retrieval of the CPS should not require the removal of any in-situ equipment or structures.
    - Installation / retrieval of the CPS should be compatible with the foundation interface structure (monopile entry hole / J-tube) and should not cause damage to either the cable or CPS during these operations (e.g., wear, tears, or coating damage). The mechanical limits of the cable and CPS should be respected during installation / retrieval operations.
    - Installation / retrieval of the CPS should not cause damage to the foundation interface structure (monopile entry hole / J-tube).
    - Marine growth should be considered in the design of the connection system and should not impair disconnection / reconnection.
- The CPS fastener forces required to secure the components of the CPS together as applicable should ensure:
    - provision of sufficient residual load to secure the components together for the specified design life.
    - no damage caused to the CPS components.
    - pre-tension in fasteners satisfies strength / fatigue criterion.
- The CPS external structure should not contain any external hazards (e.g., excessive protrusions) that may cause pinch points along the CPS in response to environmental loading, e.g., excessive localised curvature due to a local restriction.
- The CPS should not require maintenance during the specified design life.
- The CPS should be capable of withstanding the most onerous combination of functional, environmental, and accidental loads expected to be experienced by the system due to extreme and fatigue (cyclic) loading conditions during the operational design life of the system and during installation. This should include, but may not be limited to:

- Loads imparted by the cable onto the CPS.
- Loads due to impact / clashing / crush.
- Loads due to handling and installation.
- Extreme wave and current loading.
- Fatigue loading due to the operational wave environment.
- Fatigue loading due to vortex induced vibration (VIV).
- Loads due to maintenance, replacement, and intervention.

4.4.2. Mechanical latch / connector

The function of the mechanical latch/connector is to connect and anchor the CPS to the foundation interface (i.e., monopile entry hole / J-tube) and safely transfer cable and CPS loads to the interface structure. The functional requirements of the mechanical latch/connector should include the following:

- The mechanical latch/connector should maintain the cable protection system in place for the specified design life of the system (unless retrieval of the cable / CPS is required to facilitate repair or replacement).
- The mechanical latch/connector should be capable of transferring loads generated from the cable and CPS to the foundation interface structure (monopile entry hole / J-tube). The extreme and fatigue loads transferred to the foundation interface structure should not exceed the capacity of the interface structure.
- The mechanical latch/connector should be easy to install and removable, i.e., it should not prevent the retrieval of the cable in case of repair or replacement. The design of the locking mechanism should account for the following:
  - Ensure that the mechanism is successfully and safely locked in position after cable pull-in.
  - Allow unlocking of the mechanism for cable pull-out operations as required.
  - Be capable of locking and unlocking without diver intervention.
  - Be capable of unlocking using non-destructive methods.
- The mechanical latch/connector should be compatible with all dimensions, including tolerances, of interfacing components and structures which may include the following:
  - Cable.
  - Monopile entry hole / J-tube.
  - Bend stiffener interface structure (if applicable).
  - Adjacent CPS components (e.g. clamps, fasteners, inserts, etc.).
- The mechanical latch/connector may be designed to accommodate a certain level of horizontal and vertical rotation at the interface point in so far as the design requirements and integrity of the cable and CPS are satisfied.
- The mechanical latch/connector should be designed to ensure that no localised over-bending of the cable can occur at the interface between the cable exit from the mechanical latch/connector (e.g., inside the J-tube). If there is a risk of localised over-bending at this interface, then suitable design mitigation measures should be implemented to reduce the risk.
- The mechanical latch/connector should not cause wear/abrasion damage to the cable, i.e., abrasion of the cable due to the relative movement between the cable and metallic parts of the

mechanical latch/connector. If there is a risk of abrasion, then suitable design mitigation measures should be implemented to reduce this risk.

- Corrosion protection should be provided to the mechanical latch/connector. The material of the mechanical latch/connector should be chosen to be compatible with the foundation interface (monopile entry hole / J-tube) to prevent galvanic corrosion unless electrically isolated from the foundation interface.

The design of the mechanical latch/connector should consider all potential failure modes over the specified design life. A list of potential failure modes that should be considered in the design of the mechanical latch/connector, as applicable, are presented in Table 4-1.

Table 4-1: Mechanical latch / connector – possible failure modes [25].

Defect	Consequence	Possible cause
Mechanical latch / connector failure	• Transfer of loads to other structures that are not, designed to sustain loads. • Possible damage to cable / CPS from failure.	• Excessive loading, • Fatigue failure, • Corrosion, • Failure of weld, • Manufacturing defect, • Hydrogen embrittlement, • Creep, • Inadequate design (under-prediction of stresses / strains), • Inadequate installation.
Failure of fasteners	• Transfer of loads to other structures that are not designed to sustain loads, • Possible damage to cable / CPS from failure.	• Excessive loading, • Fatigue failure, • Corrosion, • Manufacturing defect, • Hydrogen embrittlement, • Inadequate design (fasteners size too small), • Inadequate installation (e.g. fasteners not tightened properly).
Failure of latch / connector locking system	• Transfer of loads to other structures that are not designed to sustain loads, • Possible damage to cable / CPS from failure.	• Manufacturing defect, • Inadequate design, • Inadequate installation.
Paint coating removal	• Possible corrosion of structure.	• Damage caused during handling, storage, transport, installation, or service, • Manufacturing defect (e.g. paint coating not applied correctly), • Inadequate design (e.g. coating system selection).
CP reading differs from specification	• Possible corrosion of structure.	• Anode(s) broken off, • Inadequate CP system design (e.g. inadequate anode masses).
Corrosion of latch / connector structural components or fasteners	• Possible failure of structure.	• Excessively corrosive environment, • Inadequate CP system protection, • Damage to paint coating system, • Inadequate design (e.g. material selection, CP system design, coating system selection).

4.4.3. Bend stiffener

Bend stiffeners are used to protect cables from overbending beyond allowable limits and to increase the fatigue performance of the cable by reducing curvature variations at fatigue critical locations such as in the vicinity of the foundation interface (monopile entry hole / J-tube).

Bend stiffeners, as applicable, should be designed in accordance with the requirements of API-Spec-17L1 [24] Section 5.0. The functional requirements of the bend stiffener should include the following:

- The bend stiffener should prevent the cable from overbending, i.e., prevent overbending of the cable both within the bend stiffener and in the region immediately beyond the bend stiffener tip.
- The bend stiffener should provide progressive stiffness along its length and be capable of distributing cable curvatures to avoid fatigue hotspots.
- The bend stiffener should remain securely attached to its adjacent support structure and should be restrained axially, i.e., no axial slippage of the bend stiffener should occur.
- The bend stiffener should safely transfer loads from the cable / CPS to its adjacent support structure. The loads transferred should not exceed the capacity of the support structure.
- The bend stiffener metal-polymer interfaces, where a bond is required for structural strength or watertightness, should be designed to sustain all debonding forces for the specified design life.
- The bend stiffener construction should be such that no unacceptable localised loads are imparted at any location on the cable (e.g., at the polyurethane/steel interface).
- The bend stiffener design should account for the range of cable bend stiffness. This may also include nonlinear bend stiffness of the cable due to hysteresis behaviour.
- The bend stiffener body design should account for the material properties of the bend stiffener body when exposed to the combination of cable and surrounding seawater/air temperatures that induce the minimum and maximum temperatures in the material. The design should consider the nonlinear material properties of the bend stiffener body material.
- The bend stiffener should ensure compatibility with all dimensions, including tolerances, of interfacing components and structures which may include, but not be limited, to the following:
    - Cable.
    - Mechanical latch / connector.
    - Bend restrictors.
    - Adjacent bend stiffeners.
    - Clamps / other CPS components (e.g. fasteners, inserts, etc.).
- Ovalisation of the bend stiffener tip should not affect the performance of the bend stiffener.
- The bend stiffener interface structure (e.g. steel inserts) should not cause wear/abrasion damage to the cable, i.e., abrasion of the cable due to the relative movement between the cable and metallic parts of the interface structure. If there is a risk of abrasion, then suitable design mitigation measures should be implemented to reduce this risk.

The design of the bend stiffener should consider all potential failure modes over the specified design life. A list of potential failure modes that should be considered in the design of the bend stiffeners, as applicable, are presented in Table 4-2.

Table 4-2: Bend stiffener – potential failure modes [25].

Failure mode	Consequence	Possible cause
Failure of bend stiffener body	• Possible loss of bend stiffener and its protection, over-bending of and possible failure of cable due to fatigue.	• Excessive loading, • Impact from dropped object, • Fatigue failure, • Manufacturing defect, • Aging of material due to seawater, high temperature, • Creep, • Inadequate design, • Abrasion (inadequate thickness), • Damage caused during handling, storage, transport or installation.
Failure of Interface structure	• Possible loss of bend stiffener and its protection, over-bending of and possible failure of cable due to fatigue.	• Excessive loading, • Fatigue failure, • Corrosion, • Failure of weld, • Manufacturing defect, • Hydrogen embrittlement, • Inadequate design.
Failure of interface structure fasteners	• Possible loss of bend stiffener and its protection, over-bending of and possible failure of cable due to fatigue, • Excess loading on remaining fasteners.	• Excessive loading, • Fatigue failure, • Corrosion, • Manufacturing defect, • Hydrogen embrittlement, • Inadequate design (fastener size too small), • Inadequate installation (e.g., fasteners not tensioned properly).
Cable not properly protected from over-bending	• Over-bending of and possible failure of cable	• Excessive loading, • Manufacturing defect (e.g. voids in molding), • Aging of material due to seawater, high temperature, • Inadequate design.

4.4.4. Bend restrictor

Bend restrictors are used to prevent bending of cables beyond a predefined threshold value under static loading conditions. Bend restrictors should not be used in sections of the CPS where dynamic loading is expected. They comprise of a number of interlocking elements that fit around the cable that form a semi rigid curved structure.

Bend restrictors, as applicable, should be designed in accordance with the requirements of API-Spec-17L1 [24] Section 6.0. The functional requirements of the bend restrictor should include the following:

- The bend restrictor should prevent the cable from overbending, i.e., the bend restrictors should have a minimum bend radius in excess of the cable which they protect.
- The bend restrictor should remain securely attached to its adjacent support structure and should be restrained axially, i.e., no axial slippage of the bend restrictors should occur.
- Bend restrictor elements should be designed such that adjacent elements will be dimensionally compatible with each other when the bend restrictor is assembled:

- The bore of a string of bend restrictor elements should be designed to ensure that localised over-bending of the cable does not occur at the interface between adjacent elements.
- The bend restrictor elements should be designed to ensure that during lock-up the cable outer surface does not get trapped and damaged between adjacent elements, i.e., there should be a smooth transition within the bore of the bend restrictors with no sharp edges that may otherwise cause abrasion/wear of the cable.

- The bend restrictor should not cause wear/abrasion damage to the cable, i.e., abrasion of the cable due to the relative movement between the cable and bend restrictor elements. If there is a risk of abrasion, then suitable design mitigation measures should be implemented to reduce this risk.
- Corrosion protection should be provided to metallic bend restrictor elements (as applicable).
- The bend restrictor should ensure compatibility with all dimensions, including tolerances, of interfacing components and structures which may include, but not be limited, to the following:
  - Cable
  - Bend stiffeners
  - Adjacent bend restrictors
  - Clamps / other CPS components (e.g. fasteners, etc.).
- The bend restrictor design should ensure that bending moments and shear forces transferred along the length of the bend restrictor do not damage the cable at either end of the bend restrictor.
- The sizing of the bend restrictor bore should account for tolerances on the external diameter of the cable, as well as the increased external diameter due to ovalisation when the cable bends to the maximum curvature predicted during installation or operation.
- The bend restrictor internal diameter should be such that they can be easily fitted around the cable and do not impart significant loads on the cable during installation or operation.
- The bend restrictor design should allow for quick and easy attachment of the bend restrictors to the cable on-board the installation vessel as the cable is being installed.

The design of the bend restrictor should consider all potential failure modes over the specified design life. A list of potential failure modes that should be considered in the design of the bend restrictors, as applicable, are presented in Table 4-3.

Table 4-3: Bend Restrictor – Possible failure modes [25].

Failure mode	Consequence	Possible cause
Failure of bend restrictor element	• Possible detachment of bend restrictor from support structure, loss of its protection, over-bending of and possible failure of cable. • Possible damage to cable from broken edges of bend restrictor element.	• Excessive loading • Impact from dropped object • Fatigue failure (dynamic applications) • Manufacturing defect (e.g., voids in moulding of polymer bend restrictor element) • Aging of material due to seawater, high temperature. • Creep • Inadequate design • Abrasion (inadequate thickness)
Denting to metallic bend restrictor elements	• Dents may protrude and contact cable, thus causing damage to the cable	• Excessive loading • Impact from dropped object

Failure mode	Consequence	Possible cause
		• Damage caused during handling, storage, transport or installation.
Failure of bend restrictor element fasteners	• Loosening of bend restrictor element, and reduction in bend restrictor protection • Excess loading on remaining fasteners	• Excessive loading • Fatigue failure (dynamic applications) • Corrosion • Manufacturing defect • Hydrogen embrittlement • Inadequate design (fastener size too small) • Inadequate installation (e.g., fasteners not tensioned properly)
Failure of interface structure	• Possible detachment of bend restrictor from support structure, loss of its protection, over-bending of and possible failure of cable. • Possible damage to cable from broken edges of interface structure	• Excessive loading • Fatigue failure (dynamic applications) • Corrosion • Failure of weld • Manufacturing defect • Hydrogen embrittlement • Inadequate design • Inadequate installation (e.g., fasteners not tensioned properly)
Failure of interface structure fasteners	• Possible detachment of bend restrictor from support structure, loss of its protection, over-bending of and possible failure of cable. • Excess loading on remaining fasteners	• Excessive loading • Fatigue failure (dynamic applications) • Corrosion • Manufacturing defect • Hydrogen embrittlement • Inadequate design (fastener size too small) • Inadequate installation (e.g., fasteners not tensioned properly)
Cable not properly protected from overbending	• Over-bending and possible failure of cable	• Excessive loading • Manufacturing defect (e.g., voids in moulding of polymer bend restrictor element) • Aging of material due to seawater, high temperature. • Inadequate design. • Abrasion of restrictor elements at their joints (i.e., from sand or other particulates) may lead to a lack of protection of the cable due to decreased bend radii.
Paint-coating removal (metallic bend restrictors only)	• Possible corrosion of structure	• Damage caused during handling, storage, transport installation or service. • Manufacturing defect (e.g. paint coating not applied correctly) • Inadequate design (e.g. coating system selection)
CP reading differs from specification	• Possible corrosion of bend restrictor metallic components	• CP system cable disconnected. • Anode(s) broken off. • Inadequate CP system design (i.e. inadequate anode masses).

Failure mode	Consequence	Possible cause
Corrosion of metallic bend restrictor elements or fasteners.	• Possible failure of structure	• Excessively corrosive environment • Inadequate CP system protection • Damage to paint coating system • Disconnection of CP system cables • Inadequate design (i.e. material selection, CP system design)

4.5. Additional cable protection measures

Where the CPS cannot fulfil all the functional requirements in Section 4.3 and Section 4.4 to provide sufficient protection to the cable and to itself, there may be a requirement to incorporate additional cable protection measures to stabilise the cable/CPS system. These may include, but not be limited to:

- Rock placement/berm.
- Rock bags / mattressing.
- Tubular products.
- VIV suppression devices.

These additional cable protection measures should also be designed to satisfy the functional requirements specified in Section 4.3 and Section 4.4 in terms of ensuring provision of cable protection, and provision of CPS function to provide cable protection for the specified design life of the system. The requirements associated with additional cable protection measures are summarised in sections 4.5.1 to 4.5.4.

4.5.1. Rock placement / berm

Rock placement (or rock berm) involves the subsea installation of crushed rock of varying size to form a protective barrier over the cable / CPS, shielding the cable / CPS from hydrodynamic loading and providing additional stability to the system.

The rock berms, as applicable, should be designed to protect and stabilise the cable/CPS for the specified design life of the system considering the site-specific environmental and seabed conditions. The design of the rock berm should account for:

- Long term hydraulic stability to provide cable/CPS protection/stabilisation for the specified design life of the system. This should include:
  - External stability - The rock berm should be sufficiently stable when exposed to the design environmental conditions i.e., wave and current.
  - Internal stability - The wash out of sediment below the rock berm through the pores of the rock berm should be prevented or mitigated, i.e., to prevent potential sinking of the rock berm. This may be achieved by means of a filter layer as required.
  - Flexibility - The rock berm should be able to handle the possible development of edge scour and possible morphodynamic bed level changes, i.e., lowering of the surrounding seabed level. This may be achieved by means of a falling apron, i.e., a rock berm toe protection.
- Material used for the rock berm should be suitable for the onsite conditions.
- Rock berm installation should be performed in a controlled manner. The method of rock installation should be suitable for the product to be deployed with the required profile and accuracy in the water depth at site. Rock impact energy during installation should be confirmed to not compromise the integrity of the cable/CPS.

- Radial compression or crush resistance of the cable/CPS should not be exceeded.
- The thermal performance of the cable / CPS should not be impacted by the presence of the rock berm, i.e. there should be sufficient thermal performance to prevent overheating of the cable and to prevent thermal degradation of the CPS materials for the specified design life.
- Ratcheting effects on the CPS due to the presence of the rock berm should be avoided.

4.5.2. Rock bags / mattressing

Mattresses typically comprise of lattices of segmented, mould-produced blocks of concrete or bitumen, connected by polypropylene ropes which can be laid over a cable / CPS to protect, stabilise and shield it from hydrodynamic loading. Rock bags can also be used to intermittently shield and stabilise parts of the cable / CPS. These typically consist of pre-filled sand/grout bags, or gabion (rock filled) bags.

Rock bags / mattressing, as applicable, should be designed to protect and stabilise the cable/CPS for the specified design life of the system considering the site-specific environmental and seabed conditions. The design of rock bags / mattressing should account for:

- Long term hydraulic stability, e.g., through overall weight, increased density, and configuration.
- Multi-flexibility (mattresses), i.e. ability to bend over two axes.
- Adaptation to scour at the periphery as applicable.
- Placing of mattresses and bags should be performed in a controlled manner, such that the mattresses or bags are placed as required. Impact energy during installation should be confirmed to not compromise the integrity of the cable/CPS.
- Radial compression or crush resistance of the cable/CPS should not be exceeded.
- The thermal performance of the cable / CPS should not be impacted by the presence of the rock bags / mattressing, i.e. there should be sufficient thermal performance to prevent overheating of the cable and to prevent thermal degradation of the CPS materials for the specified design life.

4.5.3. Tubular products

Tubular protection includes protective sleeves consisting of sections made of polymer or metallic structure. The segments typically comprise cylindrical half-shells ('split pipe') that overlap, interlock and fit around the cable. Some products provide a degree of flexibility (e.g. polymer), some are articulated structures (e.g. polymer or metallic). Tubular products provide added weight to the cable which improves the overall stability of the system; however, these can also make the cable more susceptible to hydrodynamic loading by increasing the exposed area.

Tubular products are often used in combination with mattresses or rock placement to protect the cable against radial compression and crush loads. Tubular products should be designed to protect and stabilise the cable/CPS considering the site-specific environmental and seabed conditions. Design requirements are similar to those covered in sections 4.4.1, 4.4.3 and 4.4.4, including:

- Bend restriction (section 4.4.4), to prevent bending below the minimum bending radius of the cable, or bend stiffening (section 4.4.3).
- Impact protection.
- Stability improvement by mass addition.
- Abrasion resistance.
- Durability (i.e. material selection).
- Thermal conductance, to prevent overheating of the cable during operation for the installed thermal environment.

- Corrosion protection, the metallic parts should be selected to be corrosion resistant, or, alternatively, be designed with adequate corrosion protection.

4.5.4. VIV suppression devices

VIV suppression devices (e.g., strakes) have been used in the offshore industry on pipelines, risers and umbilicals to counteract vortex induced vibrations (VIV) by disrupting flow velocities around these structures and mitigating against VIV oscillations. If VIV suppression devices are employed, the following design aspects should be considered:

- The VIV suppression device should be designed with sufficient coverage and profile to provide the required VIV suppression to mitigate against VIV fatigue damage of the cable/CPS. A VIV fatigue assessment should be performed to inform the design of the VIV suppression device.
- VIV suppression devices can influence the mass and hydrodynamic loading of the cable/CPS system. This should be accounted for in the ULS (strength) and FLS (wave and VIV) analyses to ensure design limits are not exceeded.
- The VIV suppression device should not compromise the primary functionality of the cable over the specified design life. This should include maintaining the mechanical and thermal aspects of performance of the cable as discussed in section 4.3.
- The VIV suppression device materials should be selected to be compatible with the environment to which the materials will be exposed over the specified design life. The material should display the following properties:
    - Limited degradation of material properties due to aging, i.e. mechanical, chemical, thermal.
    - UV resistance.
    - Abrasion resistance against the seabed/scour protection.
    - Impact resistance from dropped objects and collision (e.g., ROV impact).
    - Sufficient thermal performance to prevent overheating of the cable and to prevent thermal degradation of the CPS materials as applicable.
    - Corrosion resistance of fasteners.
- The VIV suppression device should remain securely attached to the cable/CPS for the specified design life. In addition, the VIV suppression device clamping/fasteners should have sufficient capacity to prevent slippage along and rotation around the cable/CPS.
- The VIV suppression device design should provide the required VIV suppression with and without marine growth. If marine growth reduces the functionality of the VIV suppression device, then anti-fouling coating should be considered.
- The VIV suppression device fastening assemblies should be configured to minimise the installation time offshore. The device should be capable of withstanding the installation loads imposed during the deployment process without introducing damage.

4.6. CPS interfaces

4.6.1. CPS physical interfaces

The key physical interfaces of the CPS may be summarised as follows:

- CPS – Cable Interface:

Cable within CPS, along length of CPS.

- CPS – Foundation Interface:

  CPS mechanical latch / connector at monopile entry hole / J-tube

  CPS suspended within monopile (as applicable)

  CPS in contact with scour protection and/or buried in scour protection.

- CPS – Other Interfaces:

  CPS in contact with seabed and/or buried in seabed.

  CPS in contact with external cable protection measures and/or buried beneath external protection (as applicable).

These physical interfaces are illustrated in Figure 4-1, for a monopile WTG foundation. The key parameters relating to each interface are summarised in Table 4-4.

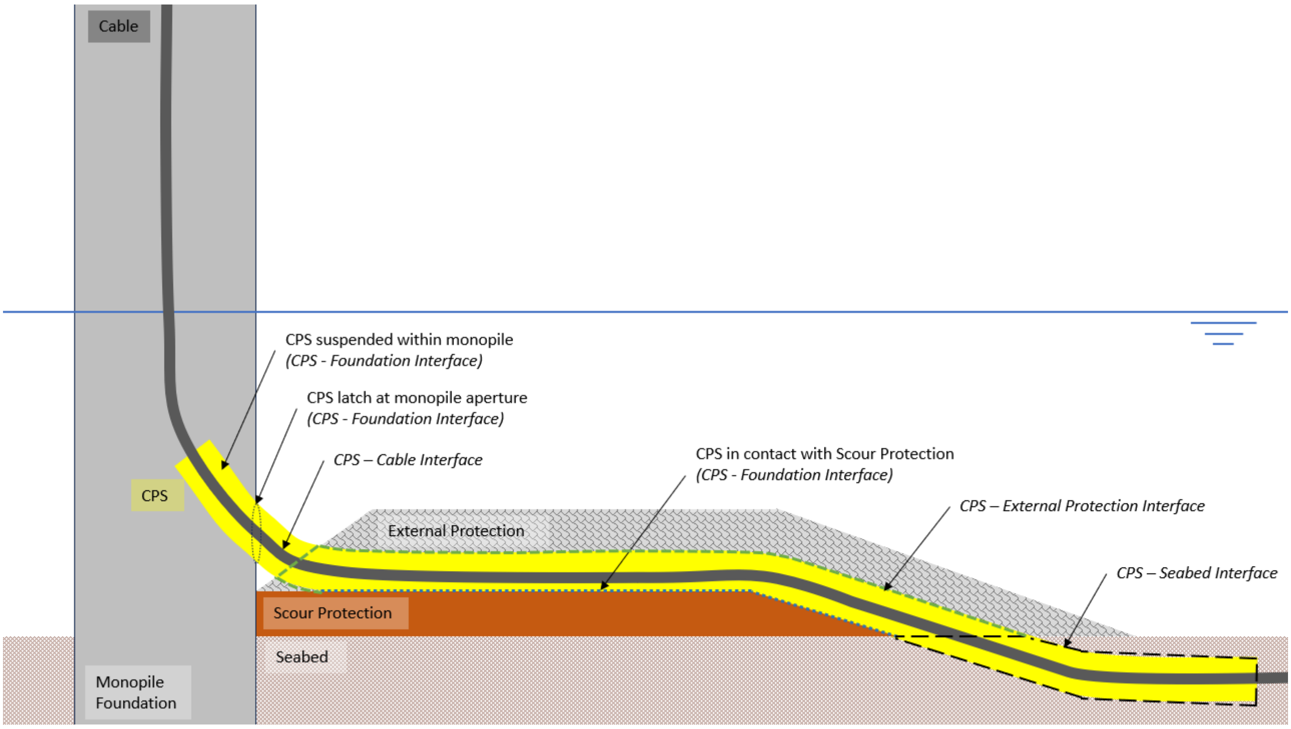

Figure 4-3: Physical interfaces with CPS (not to scale).

Table 4-4: Key parameters relating to CPS physical interfaces.

Physical interface		Relevant parameter
CPS – Cable Interface	CPS	CPS geometric properties (e.g. length, inner/outer diameter, profile)
		CPS mechanical properties (e.g. weights, stiffness, locking radius)
		CPS thermal properties (e.g. thermal conductivity)
		CPS materials
	Cable	Cable geometric properties (e.g. outer diameter, weight)

Physical interface		Relevant parameter
		Cable mechanical properties (e.g. stiffness, cable capacities, abrasion/wear characteristics, fatigue properties)
		Cable thermal properties (e.g. max / design temperature)
		Cable materials / construction (e.g. metallic components, outer serving/sheath)
CPS – Foundation Interface (including scour Protection)	CPS	CPS latching mechanism (geometry, stiffness, materials)
		CPS/cable weight
		CPS maximum interface loads (i.e. mechanical latch / connector)
		CPS materials
		CPS corrosion protection (CP) system
	Foundation	Foundation monopile entry hole/bellmouth/J-tube geometry & materials
		Foundation allowable loads at CPS Interface
		Scour protection geometry & materials
		Foundation corrosion protection (CP) system
CPS – Seabed	CPS	CPS materials
		CPS/cable weight
		CPS depth of burial
	Seabed	Seabed geotechnical properties (e.g. stiffness, friction)
		Seabed thermal properties (e.g. thermal conductivity)
CPS – External Cable Protection	CPS	CPS materials
		CPS thermal properties
		CPS geometric properties
		CPS/cable weight
		CPS mechanical properties (impact / crush resistance)
		External protection materials

Physical interface		Relevant parameter
	External Protection	External protection geometric properties
		External protection thermal properties
		External protection mechanical properties
		External protection weight

4.6.2. CPS interface matrix

Provision of CPS to a project can be achieved through a variety of different contracting strategies, each involving several interfaces between parties. The key interfacing parties associated with an offshore wind farm project can include:

- Project developer.
- CPS supplier.
- Cable supplier.
- Cable installation contractor.
- Foundation supplier.
- Foundation installation contractor.

A list of key data that is typically required during the supply of a CPS for an offshore wind farm project is summarised in Table 4-5. This information includes parameters relating to the physical interfaces discussed in Section 4.6.1, as well as other project-specific data that is relevant to the CPS design and installation. The layout of this table is selected to be consistent with the tables in Appendix B of DNV-RP-0360 [1], where three project stages are presented. These include:

- Enquiry stage (Purchaser approaches CPS Manufacturer(s) to make initial request for CPS for a particular project),
- Offer stage (CPS Manufacturer provides Purchaser with their offer, including details of the design), and
- Supply stage (CPS Manufacturer provides Purchaser with the CPS along with details of as-built system).

It is noted that there is likely to be multiple exchanges of data between contracting parties as the design matures, and that the number of exchanges between contracting parties will not be limited to only those exchanges at three project stages described in Table 4-5.

In Table 4-5, the Manufacturer of the CPS is denoted by "M", while the Purchaser of the CPS (entity dependent on the contracting strategy adopted) is denoted by "P". Optional information is denoted by parentheses "( )".

Table 4-5: Interface matrix – Direction of information flow for key data exchanges relating to CPS.

No.	Category	Responsibility at stage		
		Enquiry	Offer	Supply
1.	**General Project Information**			
1.1	Project name	P		

No.	Category	Responsibility at stage		
		Enquiry	Offer	Supply
1.2	Location of project	P		
1.3	Life (Design / Service)	P	M	M
2.	**Site Data**			
2.1	Water depth	P		
2.2	Seabed properties (e.g. geotechnical / thermal)	P		
2.3	Seawater properties (e.g. density / thermal)	P		
2.4	Metocean data	P		
2.5	Marine growth characteristics	P		
3.	**Cable Properties**			
3.1	Cable outer diameter	P		
3.2	MBR (installation / operation / combined tension & bending)	P		
3.3	Weight (in air / in water)	P		
3.4	Maximum allowable tension	P		
3.5	Maximum allowable axial compression	P		
3.6	Maximum sidewall pressure	P		
3.7	Maximum crush strength and allowable impact energy (e.g., due to dropped object).	P		
3.8	Stiffness (bending/axial/torsional)	P		
3.9	Thermal properties (e.g. design / allowable temperatures)	P		
3.10	Materials (e.g. outer sheath/serving)	P		
3.11	Cable wear / abrasion characteristics	P		
4.	**Foundation Properties**			
4.1	Foundation type (I-/J-tube / tubeless)	P		
4.2	Foundation interface information (e.g. monopile entry hole/bellmouth dimensions, physical location, orientation, materials)	P		
4.3	Interface Loads (max. / allowable)	(P)	M	M

No.	Category	Responsibility at stage		
		Enquiry	Offer	Supply
4.4	Scour protection provision (if required / geometry / layout / materials)	P		
4.5	Details of Foundation CP System (is CPS protected by Foundation CP? / material compatibility)	P		
5.	**CPS Properties**			
5.1	Geometry (e.g. length, inner/outer diameter, profile)		M	M
5.2	Weight (in air / in water)		M	M
5.3	Maximum allowable tension		M	M
5.4	Maximum allowable bending moment		M	M
5.5	Maximum allowable shear force		M	M
5.6	Maximum allowable VMS (von Mises Strain)		M	M
5.7	Locking radius of bend restrictors		M	M
5.8	Bend stiffener curve		M	M
5.9	Friction and wear / abrasion properties		M	M
5.10	Maximum allowable impact energy		M	M
5.11	Maximum crush resistance		M	M
5.12	Materials	(P)	M	M
5.13	Thermal performance / limits	P	M	M
5.14	Latching mechanism properties (e.g. geometry, stiffness, materials)		M	M
5.15	Interface loads (max. / allowable)	(P)	M	M
6.	**External Protection Properties**			
6.1	Type of external protection (materials / geometry)	P		
6.2	Volume / quantity (of rock etc.)	P	(M)	
6.3	Thermal properties	P		
7.	**Installation Parameters**			
7.1	Vessel deck area requirements	(P)	M	
7.2	Installation procedure		M	

No.	Category	Responsibility at stage		
		Enquiry	Offer	Supply
7.3	Depth of burial	P		

4.6.3. CPS interface timelines

A key challenge associated with the supply of a CPS for a given project is balancing its delivery time with the delivery times associated with other key interface packages (i.e. cables and foundations), to ensure that there exists sufficient quality of design data to validate a CPS proposal, but also sufficient time to allow for holistic design update to interface packages if required (e.g. facilitated via design feedback loops between interfacing parties).

In general, there should exist a point during the overall design process, where there is an adequate balance between the quality of interface design data (to be provided to the CPS supplier) and the ability to incorporate holistic design updates if required. This will be specific to different projects depending on contract signing times for the key interface packages. However, it is considered appropriate to have a minimum of one design review cycle between interfacing parties during the course of the project, in addition to verification of the final design at the end of design process, i.e. when the maturity of design data is at its highest.

5. Design basis

5.1. General

A CPS design basis should be produced for the project. The design basis, as a minimum, should detail the methodologies, design parameters, data sources, codes and standards, and assumptions considered in the CPS design process, including for those design assessments detailed in section 6.1. The design basis should, as a minimum, include the parameters and requirements highlighted in the following sections.

5.2. Scope of supply

A detailed description of the scope of supply for the intended CPS system design should be specified, including:

- CPS system description (including ancillaries).
- CPS components and quantities.
- CPS size, length and compatible cable size.
- CPS stabilisation measures (as applicable).

5.3. Design parameters

5.3.1. System layout data

System layout definition of the cable/CPS at the foundation interface should be specified, including:

- Cable hang-off arrangement:

- Cable hang-off location wrt to vertical and horizontal reference point.
- Cable hang-off end constraint.

- Monopile / OSS foundation (as applicable):
    - Monopile outer diameter.
    - Monopile inner diameter or wall thickness.
    - Monopile entry hole / J-tube exit height above seabed / scour protection.
    - Monopile entry hole / J-tube exit angle relative to seabed / scour protection.
    - Geometric constraint at monopile entry hole / J-tube interface.
    - Design tolerances.
    - J-tube geometrical definition including:
        - outer diameter.
        - inner diameter.
        - straight section lengths.
        - bend section radii.
        - angular alignment with the vertical / horizontal.

- Scour protection geometrical definition (see Figure 5-1):
    - Scour protection geometry including (as applicable):
        - armour layer horizontal distance (to top edge) from monopile entry hole / J-tube exit.
        - armour layer horizontal distance (to bottom edge) from monopile entry hole / J-tube exit.
        - armour layer thickness and slope.
        - filter layer horizontal distance (to top edge) from monopile entry hole / J-tube exit.
        - filter layer horizontal distance (to bottom edge) from monopile entry hole / J-tube exit.
        - filter layer thickness and slope.
        - Design tolerances.
    - Horizontal distance from monopile entry hole / J-tube exit to start of cable/CPS burial.
    - Cable/CPS burial gradient.
    - Burial depth (i.e. depth of lowering).
    - Burial transition distance.
    - Potential for Edge Scour should be considered in geometries assessed.

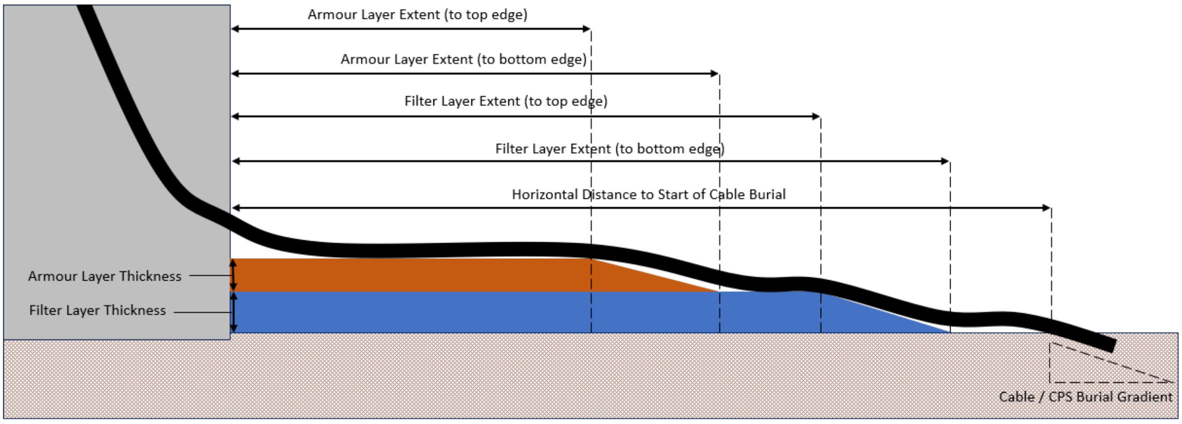

Figure 5-4: Scour protection geometry.

- No scour protection / seabed geometry:
  - Seabed and worst-case scour hole geometry including:
    - scour hole depth.
    - scour hole horizontal distance from monopile entry hole / J-tube exit.
  - Horizontal distance from monopile entry hole / J-tube exit to start of cable/CPS burial.
  - Cable/CPS burial gradient.
  - Burial depth (i.e. depth of lowering).
  - Burial transition distance.
- Stabilisation geometry as applicable (e.g., but not limited to, rock berm, rock bags, mattressing, etc.):
  - Rock berm protection geometry (as per scour protection geometry detailed above).
  - Rock grade and weight.
  - Location / distribution of rock bags / mattressing.

5.3.2. Cable data

Cable input parameters considered in the design and analysis of the CPS/cable system should be specified, including:

- Detailed description of the cable cross-section (e.g. conductor size, cable layers / components, quantities, dimensions, material properties, interlayer friction and stick-slip behaviour of the cable cross-section, etc.).
- Outer diameter (including tolerance).
- Weight in air and water.
- Axial stiffness.
- Bending stiffness, i.e. linear and/or non-linear (hysteretic).
- Torsional stiffness.
- MBR (installation / operation / combined tension and bending).
- Maximum allowable tension.
- Maximum allowable axial compression.

- Maximum allowable sidewall pressure.
- Maximum crush strength.
- Maximum allowable impact energy.
- Thermal properties / capacities.
- Fatigue data (e.g. SN curves, factors of safety, stress/strain factors, etc.).
- Wear / abrasion characteristics.

Cable bending stiffness may be modelled using either a linear or non-linear (hysteresis) approach. Where linear bending stiffness is considered in the global analysis then this should be based on the 'slipped' (lower bound) bending stiffness of the cable as this will induce larger cable curvatures and displacements in response to hydrodynamic loading, however, for the local stress analysis of the cable components a 'full stick' (upper bound) bending stiffness should be considered which is more conservative.

Where both linear and non-linear bending stiffnesses are available then sensitivities should be performed to ascertain the most onerous condition for design.

5.3.3. CPS data

CPS input parameters considered in the design and analysis of the CPS/cable system should be specified, including:

- Geometry (e.g. component lengths, inner / outer diameters, etc.).
- Components weights in air (empty and full of water).
- Component weights in water (empty and full of water).
- Axial stiffness.
- Bending Stiffness.
- Torsional stiffness.
- Material properties of components/sub-components, including stress/strain limits.
- Non-linear material characteristics (e.g. stress-strain curves) including temperature dependencies (e.g. polymer materials such as bend stiffener).
- Bend restrictor (as applicable) non-linear bending moment versus curvature lock-out relationship.
- Maximum allowable tension.
- Maximum allowable axial compression.
- Maximum allowable bending moment.
- Maximum allowable shear force.
- Maximum allowable von mises strain (VMS).
- Maximum crush strength.
- Maximum allowable impact energy.
- Maximum allowable stress / strain.
- Thermal properties / capacities.
- Fatigue data (e.g. SN curves, factors of safety, stress concentration factors, etc.).
- Abrasion / wear characteristics.

Bend stiffeners should be modelled with a cross-sectional area that varies from the bend stiffener base to the bend stiffener tip, and the non-linear material properties (non-linear stress-strain relationship) of the bend stiffener (polymer) should be captured. The non-linear material properties associated with the minimum and maximum service temperatures should be assessed as part of the design.

For bend restrictors, the non-linear bending moment versus curvature lock-out relationship should be captured. Due to the complex geometry at the interfaces of each of the bend restrictor components, local modelling of the bend restrictors and/or physical testing should be performed to determine the characteristic curve to represent the bend restrictor response to bending. This characteristic curve should be utilised as an input in the global system model to accurately capture the bend restrictor lock-out response.

5.3.4. Hydrodynamic data

Hydrodynamic load coefficients considered in the design and analysis of the CPS/cable system should be specified, including:

- drag coefficients.
- added mass coefficients.
- inertia coefficients.
- lift coefficients.
- seabed Interaction effects.

The selection of appropriate hydrodynamic load coefficients should account for CPS / cable surface roughness, marine growth, start-of-life (SOL) and end-of-life (EOL) conditions.

Guidance on the selection of hydrodynamic coefficients for cylindrical elements can be found in a number of codes and standards, including DNV-RP-C205 [7], ISO 13628-11 [23], API-RP-17B [27] and Norsok N-003 [29].

DNV-RP-C205 [7] is recommended as the primary reference code for cable / CPS design as it includes recommendations and formulations for capturing wall interaction effects i.e., hydrodynamic coefficients for circular cylinders close to a fixed boundary. Wall interaction effects should be captured as part of the global system model to capture the response of the cable / CPS in close proximity to the seabed / scour protection.

5.3.5. Marine growth data

Marine growth characteristics considered in the design and analysis of the CPS/cable system should be specified, including:

- Marine growth thickness
- Marine growth density
- Thermal properties

Marine growth build-up should be fully captured to account for the increased mass, buoyancy, added mass and drag of the cable / CPS, and in doing so capture its influence on the hydrodynamic loads and dynamic system response.

The density and thickness of marine growth should be based on site specific data where available, and the influence of water depth on marine growth thickness should be captured. Where no site specific data is available, then guidance based on recommendations from DNV-ST-0437 [8] should be considered. It may be assumed (in the absence of site-specific data) that the thickness of marine growth increases linearly to the given thickness over a period of 2 years after the cable / CPS has been placed in the water as per guidance in DNV-RP-C205 [7] and Norsok N-003 [29].

The hydrodynamic diameter to be used for prediction of added mass and drag loading should be taken as D + 2t, where D is the diameter without marine growth, and t is the marine growth thickness ([7], [29]).

Marine growth should not be considered in the start-of-life (SOL) assessment, while full marine growth thickness (100%) should be considered in the end-of-life (EOL) assessment. As marine growth build-up is expected to fully develop after approximately 2 years ([7], [29]), then 100% marine growth thickness should be considered in the fatigue analysis for the permanent condition. Marine growth build-up for the temporary condition should reflect the time period between the temporary and permanent installation conditions.

It is acknowledged that marine growth may not be present underneath the cable / CPS in contact with the seabed / scour protection. However, it is recommended that full marine growth thickness (100%) be conservatively assumed as the level of embedment that the cable / CPS may experience throughout the specified design life may vary.

5.3.6. Corrosion data

Corrosion and cathodic protection inputs considered in the design and analysis of the CPS/cable system should be specified, including:

- Corrosion rates.
- Corrosion protection design methods (coating, corrosion allowance, cathodic protection, corrosion resistant materials, bitumen, etc.).
- Seawater temperature.
- Seawater salinity.
- Water depth.
- Nutrition content (e.g. dissolved inorganic nitrogen).
- Microbial activity.

Corrosion allowance for metallic CPS components should be considered in the design/analysis if specified as part of the corrosion protection design. The maximum surface corrosion for both the outer and inner metallic CPS surfaces should be considered for the EOL condition, while no corrosion should be considered for the SOL condition.

As corrosion develops gradually during the specified service life of the cable / CPS, then an average corrosion on both surfaces should be considered in the fatigue analysis.

5.3.7. Geotechnical data

Geotechnical input parameters considered in the design and analysis of the CPS/cable system for the seabed, scour protection and stabilisation should be specified, including:

- Soil stiffness.
- Soil friction coefficients.
- Vertical, axial and lateral restraint when the cable/CPS is buried in the seabed / stabilisation.

The resistance to cable / CPS movement on the seabed (or scour protection) may be represented using normal resistance (vertical stiffness) and a coulomb friction model (axial and lateral friction coefficients).

Soil stiffness and friction coefficients should be based on site specific data, however DNV-RP-F114 [9], DNV-RP-F109 [10] and API-RP-17B [27] provide recommendations for these parameters that may be considered in the absence of more detailed information.

The soil restraint acting on those sections of the cable / CPS that are in burial, either in the seabed, the rock stabilisation, or constrained by rock bags, may be represented using formulations presented in DNV-RP-F114 [9] to capture the axial, vertical and lateral behaviour of the cable / CPS as follows:

- The axial restraint acting on the cable / CPS may be calculated according to DNV-RP-F114 [Section 5.3.2]. The overall axial resistance should be taken as the lowest resistance of the deep and shallow failure modes as recommended in DNV-RP-F114.
- The vertical uplift resistance for the cable / CPS may be calculated according to DNV-RP-F114 [Section 5.5.1].
- The vertical stiffness for downward movement of the cable / CPS may be calculated according to DNV-RP-F114 [Section 7.2.4]. The stiffness factor, C_V, may be obtained from DNV-RP-F114 guidance based on the friction angle of the soil type being considered.
- The lateral stiffness of the burial layer may be calculated according to DNV-RP-F114 [Section 7.2.4] The stiffness factor, C_L, may be obtained from DNV-RP-F114 guidance based on the friction angle of the soil type being considered.

5.3.8. SN data

SN curves should be established for assessing fatigue damage of the cable and CPS components.

If fatigue data does not exist for the material, detail, and environment under consideration, then SN curves should be developed by testing. SN curves should be based on the mean-minus-two-standard deviations curve for the relevant experimental data based on recommendation in DNV-RP-F204 [13].

5.3.9. Wear / Abrasion data

The wear characteristics/coefficients and material hardness values of the cable and CPS components should be specified.

Wear characteristics/coefficients and material hardness values should be determined through appropriate material testing.

A wear / abrasion allowance should be specified as part of the design where wear / abrasion is expected during the design life of the system.

5.3.10. Thermal data

Thermal input parameters considered in the design and analysis of the CPS/cable system should be specified, including for the following:

- Cable.
- CPS.
- Seabed / soil.
- Scour protection.
- Stabilisation (e.g., rock berm, rock bags, mattressing, etc.).
- Seawater.
- Ambient air.
- Marine growth.
- Foundation (monopile / J-tube).

5.4. Metocean Data

5.4.1. Seawater

Seawater parameters considered in the design and analysis of the CPS/cable system should be specified, including:

- Density
- Temperature
- Salinity

Seawater parameters should be based on site specific data. Where no site-specific data is available, then guidance based on recommendations from DNV-ST-0437 [8] should be considered.

5.4.2. Water level

The range of water levels should be based on site-specific data. The water level that generates the most onerous hydrodynamic loads on the cable/CPS system should be assessed as part of the design.

The lowest seawater level (LSWL) should be used for design for sites outside the breaking wave zone. This is the most conservative as it maximises the hydrodynamic loading on the system due to the increased water particle velocities and accelerations in shallower water.

For sites inside the breaking wave zone (i.e., where wave heights are depth limited), then sensitivities should be performed to identify the water level between LSWL and HSWL that maximises the hydrodynamic loading on the system. The water level that maximises the hydrodynamic loading on the system should be considered for design.

5.4.3. Current

Current velocities and depth profiles should be based on site-specific data. The extreme and operational current data, including directionality, to be considered in the design and analysis of the CPS/cable system should be specified.

Where no site-specific depth profile is available, it is recommended that a depth profile based on the 1/7th power law as defined in DNV-RP-C205 [7] and DNV-ST-0437 [8] should be considered.

5.4.4. Wave

Wave data, including wave heights and wave periods should be based on site specific data. The extreme and operational wave data, including directionality, to be considered in the design and analysis of the CPS/cable system should be specified.

A regular or irregular wave representation may be applied to model the wave environment.

The regular-wave approach is based on a deterministic sea-state description of the wave environment using a single maximum wave height and associated period to model the sea-state. These parameters are derived using wave statistics and should be included in a site-specific metocean report. Where a regular wave approach is considered, the applicable regular wave theory and breaking wave limit should be captured in the model as per the recommendations provided in DNV-RP-C205 [7]. The duration of the simulation should be sufficient to achieve a steady state response in the cable and CPS parameters. The regular wave approach is considered standard industry practice.

The irregular-sea approach is based on a stochastic description of the wave environment. The seastate is modelled as a wave spectrum with energy distributed over a range of frequencies. The most common spectra used are the Pierson-Moskowitz (fully developed sea) and the JONSWAP (developing sea) spectra.

A description of the site-specific seastate parameters should be included in a site-specific metocean report. A 3-hour irregular-wave simulation duration is normally considered, with multiple realisations.

5.4.5. Wave scatter blocking

Long-term wave loading, for application in fatigue analysis, should be based on a site-specific operational wave scatter diagram, i.e., a tabular representation of the joint probabilistic distribution of the characteristic wave height and period. The scatter diagram may take one of the following forms:

- Regular wave scatter diagrams giving the joint probability of occurrence of individual wave height (H) and wave period (T).
- Irregular wave scatter diagram giving the joint probability of occurrence of significant wave height (Hs) and peak wave period (Tp).

Wave directionality and seasonal variation in wave climate can also be described by wave scatter diagrams:

- Regular/irregular directional wave scatter diagrams (i.e. multiple scatter diagrams given for specific wave directions).
- Regular/irregular seasonal wave scatter diagrams, (e.g. monthly).

Where the number of load cases associated with the wave scatter diagram results in a substantial computational effort, then blocking of the wave scatter diagram may be considered, i.e., division of the scatter diagram into blocks that are representative of the individual wave heights and periods within the block.

Guidance in relation blocking of the wave scatter diagram is provided in DNV-RP-F204 [13] and API-RP-17B [27]. The following recommendations are provided:

- The probability of occurrence of the block is the sum of the probability of occurrence of all individual waves within the block.
- Wave height, should be selected as the maximum wave height within the block. The blocks should be selected so that they do not span over a wide range of wave heights (to avoid over-conservatism).
- Wave period, should be selected as the weighted average wave period of the block which is considered most representative of the block.
- It is estimated that 15-20 blocks would be required to represent the annual operating conditions adequately.

The Longuet-Higgins distribution is recommended to convert a stochastic seastate (irregular sea) scatter diagram to a deterministic (regular wave) scatter diagram if required (API-RP-17B [27]).

5.4.6. Environmental directionality

Environmental loading (wave and current) should be applied collinearly and perpendicular (90^0) to the plane of the cable / CPS. This is the most conservative environmental direction as it imparts the largest hydrodynamic loading onto the system resulting in the most onerous cable/CPS response.

Environmental direction sensitivities should also be assessed as part of the design.

5.4.7. Flow amplification effects

The impact of current and wave flow amplification around the monopile on the cable / CPS system response should be accounted for in the global system model. Flow amplification around the monopile imparts larger hydrodynamic loading onto the system resulting in a more onerous cable/CPS response.

Flow amplification has also been acknowledged in codes and standards, such as API-RP-17B [27] and ISO 13628-11 [23], as having a potentially significant impact on the system response.

5.5. Design criteria

Design criteria / allowable limits considered in the analysis and design of the CPS / cable system should be specified, including:

- Cable criteria.
- CPS criteria.
- Design factors of safety.
- Stabilisation criteria (as applicable).

See also section 6.1.

5.6. Design assumptions

Details of all assumptions considered in the design and analysis of the CPS / cable system including reference and justification for these assumptions should be specified. This should include assumptions in relation to design parameters, methodologies, load case selection, etc.

Sensitivity studies should be performed as required in order to validate and justify design assumptions, particularly were there exists uncertainty regarding these assumptions. Details and outcomes of the sensitivity studies should be documented. See also section 7.1.2.

5.7. Design methodology

A detailed description of the full suite of design and analysis activities to be performed as part of the CPS design process, including for those design assessments detailed in section 6.1. This should include, but may not be limited to:

- Design / analysis workflows.
- Methodologies (ULS, FLS, VIV, thermal, abrasion, stabilisation, extracting of interface loads, etc).
- Temporary and permanent conditions (as applicable).
- Software
- Load Case Matrix
- Design Criteria
- Assumptions

5.8. Design codes and standards

All design codes and standards used as part of the CPS / cable system design process should be referenced appropriately in the design basis and throughout the applicable design documentation as appropriate.

5.9. Design verification / Validation

A detailed description of the design verification / validation activities and tests to be performed to ensure that the CPS/cable system is fully qualified for its intended application, and site-specific environmental conditions, should be specified. See also section 7.0.

6. Design Methodology

6.1. Design assessments

The following design assessments should be performed as part of the cable and CPS system design:

- Material – a material assessment should be performed to assess the expected degradation of materials in the operating environment over the specified design life and the implications on the strength of the system.
- Corrosion – a corrosion protection assessment should be performed to ensure that the CPS has sufficient corrosion protection in the operating environment for the specified design life of the system.
- Strength (global and local) – a strength assessment should be performed to demonstrate the ability of the system to withstand extreme environmental loading and accidental events, and the ability of the system to protect the cable and CPS during these events for the specified design life. Temporary and permanent cable/CPS configurations should be assessed as applicable.
- Fatigue (global and local) – a fatigue assessment should be performed to ensure that the cable and CPS has sufficient fatigue capacity to withstand fatigue loading throughout the specified design life. This should include fatigue due to wave and vortex induced vibration (VIV). Temporary and permanent cable/CPS configurations should be assessed as applicable.
- Abrasion (CPS and cable) – an abrasion assessment should be performed to ensure that the CPS has sufficient resistance to abrasion due to the relative movement between the CPS and the seabed/scour protection for the specified design life. An abrasion assessment should also be performed on the cable to ensure it has sufficient abrasion resistance due to the relative movement between the cable and CPS for the specified design life. The ability of the cable and CPS component materials to withstand abrasion should be demonstrated through mechanical testing, and by using analytical methods (using outputs from the global system model).
- Interference – an interference assessment should be performed (as applicable) to ensure that the cable/CPS does not experience clashing with other subsea infrastructure, including clashing of the cable inside the foundation (i.e., in the case of a monopile foundation – the cable should not come into contact with the foundation internals). In some instances, allowance for cable contact may be permitted (e.g., cable-cable, cable-foundation) during extreme/abnormal conditions, provided that the impact energy is below the design limit. However, this should be subject to approval and agreement with client on a project specific basis.
- Thermal – a representative thermal assessment should be performed to identify thermal limitations of any materials within the cable and CPS and ensure that the CPS has sufficient thermal performance to prevent overheating of the cable. The allowable limits of cable and CPS materials should not be exceeded.
- Impact Assessment – an impact assessment should be performed to ensure that the CPS is capable of containing the impact energy (from all potential sources of external impact, including dropped object, rock placement, ROV impact) to a level below that to which the cable has been qualified and ensure CPS integrity. The impact assessment should be performed at CPS component locations most vulnerable to impact energy. This may include interface connections and/or central locations of the component. The impact assessment should be performed using numerical modelling and supplemented via physical testing to verify/qualify the design of the CPS for the project.
- Crush Assessment – a crush capacity assessment should be performed to ensure that the CPS has sufficient crush capacity to resist the potential range of crush loads that may be imparted to the CPS over the specified design life of the system, i.e. crush loads applied by machinery onboard

the cable installation vessel and static loads during operating (e.g. additional stabilisation measures). The crush assessment should be performed at CPS component locations most vulnerable to crush loads. This may include interface connections and/or central locations. The crush assessment should be performed using numerical modelling and supplemented via physical testing to verify/qualify the design of the CPS for the project.

- CPS Stabilisation – a CPS stabilisation design should be performed (as applicable) to ensure long term hydraulic stability of the CPS/cable and stabilisation, to ensure cable and CPS integrity for the specified design life.
- Cable Hang-off Interface Loads Assessment – an extreme and fatigue loading assessment should be performed to ensure the integrity of the cable components within the cable hang-off interface (e.g. clamped armour wires) for the specified design life.
- CPS / foundation Interface Loads Assessment – an extreme and fatigue loading assessment should be performed to ensure the CPS/foundation interface loads are within the allowable structural limits of foundation interface (e.g., monopile entry hole / J-tube) for the specified design life. The structural integrity analysis should account for the interface loads imposed by the cable/CPS to ensure that the structural capacity of the foundation interface is not exceeded.
- CPS Installation Analysis – CPS/cable installation analysis should be performed to ensure the integrity of the cable, CPS and foundation interface (e.g., monopile entry hole / J-tube) during all stages of the installation campaign, including overboarding, laying and pull-in operations. The analyses should establish the operational parameters (e.g., layback, departure angle, pulling tension, back tension, etc.) for each stage of the installation and the associated limiting environmental conditions to ensure that all operations associated with the installation will be safely completed within the allowable integrity limits of all equipment used (including ancillary installation equipment such as pull-in heads, etc.), and to ensure the integrity of the cable, CPS and foundation interface throughout the installation process.

6.2. Design FMECA / Risk register

A design FMECA / risk register that documents the range of potential CPS failure modes over the specified design life of the system should be developed on a project specific basis. In doing so, the safeguards, including the design and operational barriers that mitigate against the risk of each of the failure modes should be specified.

6.3. Design loads

The cable and CPS should be designed to withstand all functional, environmental, and accidental loading that is expected to be experienced by the system under extreme and fatigue loading conditions during the specified design life of the system. These loads may include, but not be limited to the following:

a) Functional Loads:

   - System weights, i.e., cable, CPS, attachments, buoyancy, marine growth.
   - Reactions from components (clamps, terminations, CPS, foundation interface structure).
   - Reactions from seabed / scour protection (including friction loads).
   - Loads from protective cover / additional stabilisation (soil, rock, mattress, etc.).
   - Loads due to positioning tolerances.
   - Residual cable lay tension following installation.
   - Heat (internal / external).

- Cable loads transmitted to CPS and vice versa.

b) Environmental Loads:

- Wave, Current (including loading due to VIV)

c) Accidental Loads:

- Dropped Object / Collision

The cable / CPS system should be able to withstand the most onerous combination of loads that can be predicted to occur simultaneously in accordance with the limit state design approach detailed in Section 6.4.

6.4. Limit states and characteristic Load Effects

The system capacity can be described by a set of limit states covering the significant failure modes and can be defined as a state beyond which the component no longer satisfies its design requirements. The limit states are defined in Table 6-1 based on DNV codes and standards.

For each of the limit states, DNV-ST-0126 [5] and DNV-ST-0145 [6] define that the characteristic load effects to be considered at wind turbine generator (WTG) and offshore substation (OSS) locations respectively. These are summarised in Table 6-1.

The cable and CPS should be capable of withstanding the characteristic load effects associated with the limit states presented in Table 6-1.

Table 6-6: Limit states and characteristic load effects.

Limit State	Definition DNV-RP-0360 [1]	Characteristic Load Effects	
		WTG DNV-ST-0126 [5]	OSS DNV-ST-0145 [6]
Ultimate Limit State (ULS)	a condition which, if exceeded, compromises the integrity of the item, e.g., exceeding minimum bend radius of cable.	the characteristic value of the resulting load effect is defined as a load effect with an annual probability of exceedance equal to or less than 0.02, i.e., 50yr RP.	the characteristic value of the resulting load effect is defined as a load effect with an annual probability of exceedance equal to or less than 0.01, i.e., 100yr RP.
Fatigue Limit State (FLS)	a ULS condition accounting for accumulated cyclic load effects, e.g., cyclic cable bending, wear / abrasion.	the characteristic load effect history is defined as the expected load effect history.	
Accidental Limit State (ALS)	a ULS condition due to accidental (infrequent) loads, e.g., dropped objects.	None defined	the characteristic load effect is a specified value, dependent on operational requirements.
Serviceability Limit State (SLS)	a condition which, if exceeded, renders the item unsuitable for normal operations; exceedance of a serviceability limit state category should be evaluated as an accidental limit state, e.g., damage to cable sheath or armour.	the characteristic load effect is a specified value, dependent on operational requirements.	

6.5. Design Criteria

6.5.1. Cables

The following cable capacities should be provided by the cable manufacturer. In each case the design loads should be assessed and shown not to exceed the manufacturers specified design limits.

- maximum allowable tension.
- maximum allowable axial compression.
- minimum allowable bending radius at varying levels of combined tension and bending (tension v MBR capacity curve).
- maximum allowable sidewall pressure.
- maximum crush strength.
- maximum allowable impact energy.
- maximum thermal capacities of the cable that should not be exceeded including:
    - allowable conductor temperature (^{0}C).
    - allowable cable surface temperature (^{0}C).

The following cable capacities are not traditionally provided by the cable manufacturers but should be requested. If not available a suitable criterion should be assigned by reference to codes and standards where possible or by risk assessment and agreement with the client:

- maximum fatigue damage for cable components within the cable cross-section, for specified load combinations (i.e., tension and curvature).
- maximum allowable wear (due to abrasion).

Guidance in relation to the allowable design criteria for the cable can also be found in the codes and standards. These are summarised as follows:

- Allowable stress utilisation factors for cable steel armour layers are provided in DNV-RP-F401 [3] and DNV-ST-0119 [4].
- An allowable 1% strain utilisation is recommended in CIGRÉ [30] for conductor insulation due to the risk of water treeing.
- Fatigue failure criteria and fatigue safety factors associated with the metallic layers of the cable cross-section, namely the armour layer, metallic screen / sheath and cable conductor are provided in DNV-RP-F401 [3].
- DNV-ST-0119 [4] specifies that for metallic components of the cable cross section, the design fatigue factor should not be taken less than 10 unless specified otherwise. It is further noted that the effects of friction and stick / slip behaviour between layers in the cable cross-section should be included in calculations of fatigue damage.

  Note, that in the absence of a non-linear (hysteresis) approach and where linear stiffness is considered then, a linear ‘slipped’ (lower bound) bending stiffness should be considered in the global analysis as this this will induce larger cable curvatures and displacements in response to hydrodynamic loading, while for the local stress analysis of the cable components a linear 'full stick' (upper bound) stiffness should be considered which is more conservative.

6.5.2. CPS

The following CPS capacities should be assessed against the global design loads. The CPS designer should determine the capacities of the CPS components for each of the global loads below based on calculations against allowable material stress and strain, supplemented by verification testing (see Section 8.0).

- maximum allowable tension.
- maximum allowable axial compression.
- maximum allowable bending moment.
- maximum allowable shear force.
- maximum allowable VMS (as applicable).
- maximum crush strength.
- maximum allowable impact energy.
- maximum allowable fatigue damage for CPS components.
- maximum allowable wear (due to abrasion).
- allowable thermal capacities of the CPS materials that should not be exceeded.

In addition to the above capacities the CPS should be of sufficient length such that it will not be pulled out of the burial region leading to cable exposure whilst maintaining the required depth of lowering. Where there is potential for this to occur, then consideration should be given to extending the length of the CPS into the burial region.

Guidance in relation to the allowable design criteria for the CPS can be found in the codes and standards API-Spec-17L1 [24], API-RP-17L2 [25] and DNVGL-OS-C101 [17].

7. Analysis Methodology

7.1. Global System Analysis

7.1.1. Global Model Development

The cable and CPS system modelling should be performed to identify the global loads and displacements for the extreme and fatigue load case combinations that may be experienced by the system over the specified design life. Global system modelling should be performed in a suitable and recognised dynamic analysis software package.

The following should be considered as part of cable / CPS system modelling:

- The cable hang-off termination at the foundation interface should be modelled as per the specified design, including hang-off elevation, lateral location, and representative end constraint considering the installation methodology. The method of modelling the cable hang-off can influence the system response, particularly cable curvature, and as such this detail should be accurately represented in the model.
- The cable end at burial should be representative of the post-installed cable condition, including residual lay tension as applicable.
- The cable and CPS should be modelled as separate structures, each with its own properties and characteristics. The interaction between these structures should be accurately represented, including friction and contact stiffness effects. The cable should be allowed to move independently from the CPS in the axial direction, and the CPS inner bore should be modelled as free flooding.
- The CPS interface with the foundation (monopile entry hole / J-tube) should be modelled as per the specified design, including height above seabed/scour protection and angle of entry relative to seabed/scour protection. Installation tolerance on height above seabed/scour protection and angle of entry relative to seabed/scour protection should also be assessed to determine the most onerous/conservative configuration for design purposes.
- The CPS constraints at the foundation interface (monopile entry hole / J-tube) should be representative of the CPS latching mechanism design and its interaction with the interface structure in the 6 degrees of freedom, including if there is an allowance for some degree of rotation as applicable.
- The cable and J-tube, as applicable, (and section of CPS inside the J-tube) should be modelled as separate structures each with its own properties and characteristics. The interaction between these structures should be accurately represented, including friction and contact stiffness effects. The geometrical arrangement of the J-tube should be modelled as representative, including straight section, bend sections, inner diameter, etc.
- The CPS end at burial should be representative of the post-installed condition.
- The resistance to CPS/cable movement on the seabed / scour protection should be representative of the soil and scour protection conditions onsite and should accurately account for stiffness and friction effects.
- The soil restraint acting on those portions of the CPS/cable that are in burial in the seabed or beneath stabilisation (as applicable) should be representative of the soil conditions onsite and should account for the lateral, vertical and axial behaviour of the CPS/cable as per guidance provided in DNV-RP-F114 [9] (see Section 5.3.7). Those sections of the cable and CPS in burial in the seabed or beneath stabilisation (as applicable) should be represented by applying soil spring restraints. SOL and EOL soil restraints may be captured to account for depth of cover and corrosion allowance if applicable.

- The length of CPS in the burial zone should be accurately modelled to ensure that the CPS will not be pulled out of the burial region leading to cable exposure whilst maintaining the required depth of lowering, as detailed in section 6.5.2.
- The seabed / scour protection should be modelled as representative, including:
    - Seabed geometry (including scour hole geometry)
    - Scour protection geometry, i.e., armour / filter layer extents, thicknesses, slopes and design tolerances. The most onerous tolerance should conservatively be considered for design purposes.
    - CPS / cable burial start point, i.e., distance from scour protection.
    - CPS cable burial gradient.
    - CPS to seabed / scour protection friction (normal and axial) and stiffness.
- The weight in water of the cable/CPS cross-section (as applicable) including the seawater contained within the CPS and the buoyancy/upthrust of the system should be accurately modelled. The seawater density should reflect the specific onsite conditions.
- Non-linear material properties of the polymer bend stiffeners (where applicable) should be captured in the model. The non-linear material properties associated with the minimum and maximum service temperatures should be assessed as part of the design.
- The non-linear bending moment versus curvature lock-out relationship of the bend restrictors (where applicable) should be captured in the model. Due to the complex geometry at the interfaces of each of the bend restrictor components, local modelling of the bend restrictors and/or physical testing should be performed to determine the characteristic curve to represent the bend restrictor response to bending. This characteristic curve should be utilised as an input in the global model to accurately capture the bend restrictor lock-out response.
- Linear or non-linear cable bending stiffness should be captured in the model where available. Where linear bending stiffness is considered then this should be based on the 'slipped' (lower bound) bending stiffness of the cable as this will induce larger curvatures and displacements in response to hydrodynamic loading. Where both linear and non-linear bending stiffnesses are available then sensitivities should be performed to ascertain the most onerous condition for design.
- Marine growth should be captured in the model. It is recommended to assess a start-of-life (SOL) CPS system configuration with no marine growth and an end-of-life (EOL) CPS configuration with full marine growth profile.
- CPS surface corrosion should be considered in the model where applicable (i.e., where a corrosion allowance is considered as part of the corrosion protection system). It is recommended to assess a start-of-life (SOL) CPS system configuration with no surface corrosion and an end-of-life (EOL) CPS configuration that captures the maximum surface corrosion for both the outer and inner CPS surfaces.
- A start-of-life (SOL) CPS system configuration and an end-of-life (EOL) CPS configuration should be assessed as part of the design. A mid-life configuration should also be assessed where a SOL and EOL configuration is not anticipated to sufficiently bound the results of the analysis.
- The water depth should reflect the specific onsite conditions. The most onerous water depth that imparts the largest hydrodynamic loading on the cable/CPS system should be assessed. The low water level is typically the most onerous condition as it will maximise the hydrodynamic loading on the system due to increased water particle velocities and accelerations in shallower water. However, it is recommended that a number of sensitivities from low water depth to high water depth be performed, (particularly for the extreme assessment for sites inside the breaking wave

zone) as the combination of water depth and depth limiting breaking wave height can influence the magnitude of water particle velocities and accelerations at the CPS elevation. See also Section 5.4.2.

- Environmental loading due to wave and current should reflect the specific onsite conditions. Where the wave height is limited by water depth onsite, then this should be captured in the model. Hydrodynamic loading on the CPS should consider the following:
    - Influence of near seabed effects (e.g., drag, lift and added mass).
    - Flow amplification around monopile foundations as applicable.

  Those sections of the cable and CPS that are shielded by the monopile, J-tube, seabed, or rock stabilisation (where applicable) should not be subjected to hydrodynamic loading. Similarly, the cable should not be subjected to hydrodynamic loading when shielded inside the CPS.
- Abrasion assessment should consider the wear characteristics between the CPS and the seabed/scour protection, and wear characteristic between the cable and the internal bore of the CPS where available.
- CPS system modelling should be capable of capturing the following system responses:
    - Extreme response due to wave and current.
    - Fatigue response due to wave and vortex induced vibration (VIV).

7.1.2. Sensitivites

The analysis work should allow for sensitivity studies to assess the impact of uncertainties, assumptions and variations within the input parameters of the global analysis. The analysis should define the envelope in which the CPS and cable are able to perform their intended functions (without comprising allowable limits), whilst considering all reasonable tolerances and their effects that should include, but be not limited to, the following:

- Residual lay tension of cable after pull-in.
- Foundation interface tolerances, e.g. height, angle.
- Scour protection tolerances.
- Scour hole geometry.
- CPS material properties.
- Cable properties.
- Environmental directionality.
- Water depth (particularly in the breaking wave zone)
- Cable / CPS line to line friction coefficient and line contact stiffness.
- Impact of abrasion on the affected section(s) of the CPS, where predicted to occur as applicable. The stiffness and mechanical properties of affected sections should be altered to reflect the amended mechanical properties that are subject to abrasion.

7.1.3. ULS Analysis

The cable and CPS should be designed to withstand the maximum environmental load combinations (wave and current) it is likely to be subjected to throughout its specified design life, including for permanent and temporary conditions as applicable.

The following hydrodynamic loads should be considered in the ULS analysis ([5], [6], [10]) Offshore Substation (OSS) location for permanent conditions ([6], [10]):

- For permanent operational conditions and temporary phases with a duration exceeding 12 months, a 100yr return period (RP) should apply, i.e. the characteristic load condition is the load condition with 0.01 annual exceedance probability ([7], [6]). When detailed information about the joint probability of waves and current is not available, the following load case combinations should be assessed [6]:
  - 100yr RP for wave combined with 10yr RP for current
  - 10yr RP for wave combined with 100yr RP for current

Wind Turbine Generator (WTG) location for permanent conditions ([5], [10]):

- For permanent operational conditions and temporary phases with a duration exceeding 12 months, a 50yr return period (RP) should apply, i.e. the characteristic load condition is the load condition with 0.02 annual exceedance probability ([7], [6]). When detailed information about the joint probability of waves and current is not available, the following load case combinations should be assessed [6]:
  - 50yr RP for wave combined with 10yr RP for current
  - 10yr RP for wave combined with 50yr RP for current

Offshore Substation (OSS) & Wind Turbine Generator (WTG) locations for temporary conditions ([10]):

- For a temporary phase with duration less than 12 months, but in excess of three days, a 10yr return period (RP) for the actual seasonal environmental condition applies. The following load case combinations should be assessed [10]:
  - Seasonal 10yr RP for waves combined with the seasonal 1yr RP for current
  - Seasonal 1yr RP for waves combined with the seasonal 10yr RP for current

  The season covered by the environmental data should be sufficient to cover uncertainties in the beginning and end of the temporary condition to account for e.g. delays.
- For a temporary phase less than three days, an extreme load condition may be specified based on reliable weather forecasts [10].
- Where the above guidance for the temporary condition is considered overly conservative in terms of achieving a feasible solution, then further refinement of the return period environment may be considered in line with the guidance provided in Table 3-1 of DNV-ST-N001 [20] (see Figure 7-1). However, this should be subject to approval and agreement with client on a project specific basis.

Table 3-1 Metocean minimum design return periods, T_d – unrestricted marine operations

Operation reference period	*ASD / WSD* 3)		*LRFD* 3)	
	Wind 1)	Wave 2) and current	Wind 1)	Wave 2) and current
Up to 3 days 4)	$T_d \geq 5$ year	$T_d \geq 3$ month	$T_d \geq 10$ year	$T_d \geq 1$ month
3 to 7 days	$T_d \geq 10$ year	$T_d \geq 1$ year	$T_d \geq 10$ year	$T_d \geq 3$ month
7 days to 1 month	$T_d \geq 25$ year, (or obtain from 10 yr and 50 yr environmental criteria values using: 10 yr + 0.7*(50 yr-10 yr))	$T_d \geq 10$ year	$T_d \geq 10$ year	$T_d \geq 1$ year
1 month to 1 year	$T_d \geq 75$ year (or obtain from 50 yr and 100 yr environmental criteria values using: 50 yr +0.7*(100 yr-50 yr))	$T_d \geq 50$ year	$T_d \geq 100$ year	$T_d \geq 10$ year
More than 1 year	100 year return	$T_d \geq 100$ year	$T_d \geq 100$ year	$T_d \geq 100$ year

NOTE:

— When seasonal or monthly data are used these shall comply with the requirements of [3.4.3.6], as discussed in [3.4.3.2]

— Return periods for platforms that remain in-situ during decommissioning prior to the marine operation to remove them are given in [18.2.5].

1) More accurate design wind speeds may be determined as a function of the operation reference period and site-specific metocean parameters using the method shown in [C.1].

2) More accurate design waves may be determined as a function of the operation reference period and site-specific metocean parameters using the method shown in [C.3].

3) See [3.4.3.4].

4) Operations up to three (3) days may also be defined as weather restricted operations, see [2.6.7].

Figure 7-5: DNV-ST-N001 – Metocean minimum design return periods – Unrestricted marine operations [20].

Environmental loading (wave and current) should be applied collinearly and perpendicular (90^0) to the plane of the cable / CPS as this will conservatively impart the largest hydrodynamic loading on system and induce the most extreme response. However, sensitivities assessing environmental directionality should be considered to prove the CPS system can operate within the most unfavourable combination without exceedances in any of the allowable cable and CPS criteria.

The ULS assessment of the cable and CPS should consider both a start-of-life (SOL) and end-of-life (EOL) condition that accounts for both marine growth and corrosion allowance (as applicable). A mid-life configuration should also be assessed where a SOL and EOL configuration is not anticipated to sufficiently bound the results of the analysis.

The key parameters of interest include, but may not be limited to:

- Cable lateral displacement
- Cable tension
- Cable compression
- Cable curvature / MBR
- Cable normalised curvature (for varying levels of combined tension and bending)
- Cable sidewall pressure
- CPS tension
- CPS compression
- CPS bending moment

- CPS shear force
- CPS von mises strain (VMS) as applicable

In addition, the CPS should be of sufficient length such that it will not be pulled out of the burial region leading to cable exposure whilst maintaining the required depth of lowering.

Results plots should be provided along the length of the cable and CPS for each of these parameters.

The global extreme loads should be extracted for input to the local stress / strain analysis.

7.1.4. Wave (FLS) Analysis

The cable and CPS should be designed to withstand fatigue loading due to bending and tension throughout its specified design life, including for permanent and temporary conditions as applicable. An operational wave environment should be considered for the purposes of this assessment.

The following should be considered as part of the wave fatigue assessment:

- Long-term wave loading for application in the fatigue analysis should be based on an operational wave scatter diagram. See section 5.4.5.
- An omnidirectional wave scatter diagram should be conservatively considered, and all wave loading should be applied perpendicular (90^0) to the plane of the cable / CPS as this will induce the largest bending response in the system.
- Blocking of the wave scatter diagram may be considered and should follow the recommendations provided in section 5.4.5.
- Cable and CPS mechanical properties should represent the most conservative properties from a FLS perspective. i.e. the properties which result in the highest bending of the cable and CPS under environmental loading conditions.
- Marine growth build-up is expected to fully develop after approximately 2 years (see section 5.3.5), and therefore 100% marine growth thickness should be accounted for in the fatigue assessment for the permanent condition. Marine growth build-up for the temporary condition should reflect the time period between the temporary and permanent installation conditions.
- The average corrosion (over the specified design life) on both the inner and outer surfaces of the metallic components of the CPS should be considered where applicable.
- The inclusion of current loading, or not, in the fatigue analysis should be assessed to ascertain its impact on the on the fatigue performance. Where the inclusion of current is demonstrated to have an onerous impact on the fatigue performance, then the use of an operational current should be considered as per recommendations in API-RP-17B [27]. Where applicable, current should be applied collinear with wave, i.e. applied perpendicular (90^0) to the plane of the cable / CPS.
- The global fatigue response (i.e., tension and curvature) should be extracted at each location along the cable and CPS for input to the local stress analysis.
- The global fatigue response may also be extracted at fatigue hotpots (locations where bending and tension ranges are comparatively large) along the cable and CPS for input to the local stress analysis. The standard deviation of tension and curvature response provide a method for determining fatigue hotspots as described in API-RP-17B [27]. The following approach may be used to identify fatigue hotspots as appropriate:
    - Standard deviation of tension and curvature along the component length are extracted for all load cases.
    - The standard deviation of each load case is weighted based on its percentage of occurrence.

- Weighted standard deviations of tension and curvature are used to identify locations of maximum standard deviation in the fatigue critical regions.

The format of the global fatigue outputs should be compatible with local analysis software.

7.1.5. VIV (FLS) Analysis

The cable and CPS should be assessed for VIV (Vortex-Induced Vibration) response, including for permanent and temporary conditions as applicable. The initial focus of this assessment should involve determining whether VIV excitation will occur, i.e., whether the natural frequencies of the cable / CPS are within the bandwidth of the vortex shedding frequency which would lead to lock-in vibration to occur. The following should be considered as part of the VIV screening assessment:

- Modal analysis should be performed to determine the natural frequencies and mode shapes of the cable / CPS. The modal analysis should reflect the physical cable / CPS configuration (i.e., geometrical layout, tension, boundary conditions, etc.).
- The number of modes extracted from the modal analysis should be sufficient to determine the system response for the full range of potential vortex shedding frequencies associated with combined current and wave particle velocities as per DNV-RP-F105 [11]. A joint probability distribution of combined current and wave particle velocities should be provided as part of a site specific metocean report for the purposes of this assessment.
- The impact of current and wave flow amplification around the monopile should be accounted for as applicable.
- Combined current and wave particle velocities should be applied perpendicular (90^0) to the plane of the cable / CPS which is most conservative.
- VIV screening should be performed with the use of a suitable mode superposition software package.

Where VIV excitation is predicted to occur a VIV fatigue analysis should be performed to ensure the cable and CPS can withstand fatigue loading due to bending and tension throughout its specified design life. Similar to the wave fatigue assessment (section 7.1.4), the VIV fatigue assessment involves the extraction of global fatigue loads along the cable / CPS (or at fatigue hotspots) for input to the local stress analysis.

The format of the global fatigue outputs should be compatible with local analysis software.

7.1.6. Abrasion Assessment

The cable and CPS should be designed to withstand abrasion (leading to failure) due to relative motion between the cable and CPS, and relative motion between CPS and seabed / scour protection for the specified design life of the system.

The ability of the cable and CPS component materials to withstand abrasion should be demonstrated through mechanical testing, and analytical methods (using outputs from the global system model).

A methodology for predicting wear damage based on the Archard Wear Abrasion formulation may be used as an analytical approach for the purposes of this assessment.

$$V = \frac{kWL}{H}$$

where:

V = wear volume due to abrasion	k = wear coefficient	W = normal load
L = sliding length	H = material hardness	

The following should be considered when using the Archard Wear formulation as part of the abrasion assessment:

- The wear volume due to abrasion should be calculated at each point along the cable / CPS (as applicable) for each individual wave fatigue load case (from the wave scatter diagram) and combined with all load cases to give an accumulated wear volume based on annual occurrence per load case. The wear volume per load case may be determined as follows:
    - The accumulative movement of the cable relative to the CPS, and accumulative movement of the CPS relative to the seabed/scour protection should be output from the global model at each point along the cable / CPS for input into the Archard Wear formulation. All sources of relative movement should be considered as applicable, including axial, sliding and rotation.
    - The mean contact force between the cable and CPS, and CPS and seabed/scour protection should also be output from the global model at each point along the cable / CPS and input into the Archard Wear formulation.
    - Wear coefficients and material hardness values which are required as input to the Archard Wear formulation should be determine through appropriate material testing of the applicable cable and CPS component materials.
- The cable abrasion assessment should consider wear of the outer surface of the cable (i.e., polypropylene rovings or outer sheath) and steel armour wires, while CPS abrasion should consider wear of the CPS component.
- The annual accumulated wear volume should be computed by combining the total wear associated with each of the individual wave fatigue load cases based on annual occurrence per load case. The annual accumulated wear volume should be compared to allowable wear volume of the cable / CPS component so that the number of years to wear of the allowable volume can be predicted. Results plots should be provided along the length of the cable and CPS predicting the number of years to wear of the allowable volume.

Similarly, to the wave fatigue analysis (see Section 7.1.4), the inclusion of current, or not, in the fatigue analysis load cases for the purposes of the abrasion assessment, should be assessed to ascertain its impact on abrasion. Where the inclusion of current is demonstrated to have an onerous impact on abrasion, then the use of an operational current should be considered. Where applicable, current should be applied collinear with wave, i.e. applied perpendicular (90^0) to the plane of the cable / CPS.

7.1.7. Interference

An interference assessment should be performed to ensure that the cable/CPS inside the foundation (i.e., in the case of a monopile foundation) does not come into contact with the internal wall of the monopile or foundation internals. Further guidance on this topic is provided DNVGL-RP-F203 [19].

7.2. Local cable analysis

Local analysis of the cable cross-section should be performed to ensure that the accumulative fatigue damage within the metallic cable components is within allowable limits for the specified design life.

The metallic layers of the cable cross-section may include armour layer, conductor, metallic screen and radial water barrier as applicable.

The stress for each metallic layer should be computed in the local analysis using the global load responses and cable cross-section properties.

Local analysis of the cable may be performed using either analytical or finite element models as appropriate.

Input data for local cable analysis should include the following:

- Component by component data including, dimensions, lay angle, mass, number of components, Young's modulus, Poisson's ratio.
- Friction coefficient between component and adjacent layers; wires, or screen.
- The tension and curvature ranges for each of the load cases defined as part of the global wave fatigue analysis (see Section 7.1). Resultant curvature may be conservatively assumed to occur in the same plane. A more refined approach could be taken if time traces (to account for phasing) of the curvatures, about two axes, were to be provided for each wave fatigue load case.
- SN Data. SN curves should be established for assessing fatigue damage of the metallic cable components. If fatigue data does not exist for the material, detail, and environment under consideration, then SN curves should be developed by testing.

In the event of high contact pressures occurring within the components of the cable, high friction will result. With a high friction load on the components, it is possible that a 'no slip' condition will result at least for the initial onset of curvature until such time as the friction is overcome and the internal components begin to slip. Therefore, the internal components prior to slip will bend about the neutral axis of the cable rather than their own neutral axis. This will result in larger bending stresses and smaller fatigue lives than for the slip condition. Ignoring these effects can potentially result in an unconservative fatigue life estimation. Therefore, the effects of friction and stick/slip behaviour between layers in the cable cross-section should be considered in calculations of fatigue damage as per guidance in DNV-ST-0119 [4].

Stress in the cable cross-section should account for the combined effects of axisymmetric, wire bending, and (bending-induced) friction stress in calculations of fatigue damage.

Minimum fatigue lives for each component in the cable cross section should be output as part of the local cable fatigue analysis, based on the calculated stress ranges, SN curves and Miners Rule for damage summation. A fatigue factor of safety of 10 should be considered in line with recommendations provided in DNV-RP-F401[9], and DNV-ST-0119 [23].

7.3. Local CPS analysis

The local analysis of the CPS should be performed to evaluate the performance of the individual components of the CPS (including banding or fasteners such as nuts and bolts) and check to ensure that the structural integrity of the components is not compromised during extreme (ULS) conditions and operational (FLS) environmental conditions, including for permanent and temporary conditions as applicable, for the specified design life of the system. Local analysis of the CPS should be performed using 3D finite element analysis techniques for which a number of commercial software packages exist.

The local analysis should confirm acceptable performance for all CPS components to satisfy the design life of the system. CPS components may include, but are not limited to:

- Bend stiffeners,
- Bend restrictors,
- Interface unit or mechanical latch / connector,
- Connection units between adjacent CPS components, e.g. clamps, inserts, etc.,
- Banding or fasteners (bolts and nuts) for the entire CPS.

The local analysis should demonstrate that all CPS system components are within allowable design limits for both extreme and fatigue loading. The local analysis should also account for the impact of manufacturing tolerances and the degradation of the materials during the operational lifetime. i.e., sufficient structural strength should be proven for both start of life (SOL) and end of life (EOL) conditions. Corrosion allowance for metallic materials should be considered in the analysis which may impact the performance of the CPS during the design lifetime. Abrasion of CPS components, where predicted to occur, should also be considered in the analysis as this may also impact the performance of the CPS during the design lifetime, i.e. reduction in structural capacity of the CPS.

The local analysis of the CPS should be performed to determine the local stress / strain response of the CPS components in response to the global loads obtained from the global system analysis as described in section 7.1. The global loads required for input to the local analysis may include as applicable:

- Effective tension
- Shear force
- Bending moment
- Rotation
- Axial Compression

The following describes some of the key aspects to be considered in the local analysis:

- The local analysis of the CPS may be modelled as individual components (i.e., bend stiffener, mechanical latch, bend restrictor, etc.) as applicable in order to minimise the system complexity and reduce the computational effort required to simulate the response of the CPS. This will require an accurate representation of boundary conditions and load application, including extraction of global loads at the associated component interfaces for input to the local analysis.
- CPS bend restrictors (as applicable) are typically half shell structures clamped together during installation. As a result, determining the worst-case loads on these CPS components may require performing separate load cases to account for different orientations on the interface, i.e.
  - with the CPS half shell interface in-plane with the applied loads.
  - with the CPS half shell interface out-of-plane with the applied loads.

  In general, the worst-case loading orientation of the CPS components should be assessed.
- The geometry of the CPS components should be accurately represented in the local analysis. Where considered appropriate, planes of symmetry may be considered to reduce the model's computational requirements. This will depend on the component geometry and the plane of loading.
- The material properties of the CPS components should be documented and accurately represented in the local analysis. This may include elastic-plastic (metallic) and/or hyper-elastic (polymer) materials with non-linear stress-strain relationships. Material properties used in a local analysis can be based on specific test data or generated from typical or referenced data. Representative non-linear stress-strain curves can be generated from typical physical data (elastic modulus, yield stress, tensile strength, and elongation) using curve fitting techniques (e.g., Ramberg-Osgood). Alternatively, simple bilinear stress-strain curves can be used.
- The local analysis of CPS should consider the degradation of the materials during the operational lifetime. i.e., sufficient structural strength should be proven for both start of life (SOL) and end of life (EOL) conditions. Corrosion allowance for metallic materials should be considered in the analysis, i.e., reduction in wall thickness at EOL to account for corrosion. The impact of abrasion on the structural capacity of the CPS should also be assessed where this is predicted to occur within the specified design life.
- Meshing of CPS components should be of sufficient quality to accurately capture the stress and strain response of the components. This includes selection of mesh type and dimension to ensure sufficient accuracy in critical areas (e.g., bolt holes, etc.), including accurately capturing the through-thickness response of the components. Mesh sensitivity studies should be carried out to ensure sufficient mesh quality.

- Bolt pre-tensions should be applied to bolted connections where applicable and allow for correct interaction of pre-tension and applied loads. Bolt tension range during pre-tension and operational loading can usually be extracted directly from a local analysis for assessment against code allowable (e.g., DNV-OS-C101[17]). The low estimate bolt tension should be assumed.
- Frictional sliding contact between all interacting surfaces should be included in the model as applicable.
- The load cases and combinations should be clearly stated and referenced against the global analysis. Where appropriate load and material factors are applied to global loads (as per DNV-OS-C101 [17]) then these should be clearly identified.
- In simulations, a linear ramp profile may be used to apply the applicable loads on a component including loading from moment, shear and tension, etc. The maximum increment size in the load step of each analysis should be controlled to provide a sufficient number of output requests to enable each component's nonlinear response to load to be accurately represented as applicable.
- Each component analysed should be represented with a max stress and / or strain output from the local analysis and compared against limiting values of stress and /or strain for the constituent material to provide associated utilisations per load case.
- The worst-case fatigue life including factor of safety should be documented.

Further guidance in relation to establishing structural resistance by use of non-linear finite element methods is provided in DNV-RP-C208 [18].

7.4. Thermal analysis

7.4.1. General

A representative thermal analysis to demonstrate the thermal limitations of any materials within the cable or CPS should be performed. The design of the CPS should have sufficient thermal performance to prevent overheating of the cable and to prevent thermal degradation of the CPS components for the specified design life. The CPS design should also account for each of the installed thermal environments and interfaces which may include as applicable:

- seawater,
- burial in seabed,
- rock cover,
- stabilisation,
- mattresses,
- marine growth,
- ambient air,
- foundation interface (e.g. J-tube).

The results of the analysis should show that the maximum temperature in any given material in both the cable and CPS components are within allowable limits. The thermal analysis should ensure that the nominal load that the cable needs to carry is not compromised due to the presence of the CPS in its installed thermal environment, i.e., there should not be curtailment of the current rating.

The thermal analysis may be performed as either a higher 2D screening study or as a more complex 3D assessment. 1D assessments for screening purposes can also be beneficial to broadly determine the suitability of CPS section materials and thicknesses at the early stages of design.

7.4.2. Thermal screening assessment

Thermal screening assessments are typically performed using a radial conduction approach in line with IEC60287 [33] analytical methods as appropriate. These assessments are performed to understand the general performance of the CPS and identify potential thermal hotspot areas where temperatures are close to or have exceeded allowable cable and CPS limits. Where the temperatures calculated by the thermal screening assessment are within ±10% of the allowable limit a more detailed and representative 3D FEA assessment is considered appropriate.

The IEC60287 [33] approach is considered conservative as it only considers heat transfer from the outside of the cable to the surrounding medium by conduction. Convection in both axial and radial directions, or radiation through the CPS is not considered, however these mechanisms may exist (as applicable), and can contribute to the dissipation of heat losses from the cables and through the CPS.

A detailed 3D FEA assessment would be required in order to accurately capture the combined heat loss mechanisms of conduction, convection and radiation in both the radial and transverse directions.

7.4.3. Detailed 3D FEA assessment

Modelling the thermal performance of a CPS may be undertaken by a number of commercial software packages. However, it should be understood that the accuracy of the results will strongly depend on the physical phenomena which need to be simulated. For instance, the presence of air gap or vacuum between different layers would imply that radiation would need to be considered as it could become one of the main contributors of the CPS performance. A good understanding of the physics which is needed to be simulated is important for the selection of the appropriate package to reproduce it.

The following describes some of the key aspects to be considered in the thermal analysis:

- The 3D model should capture all thermally critical transitional features from buried bare cable, cable in CPS, bare cable in water within monopile/J-tube, or bare cable in air in J-tube, etc.
- The CPS should be modelled as per the general arrangement drawings of both the overall construction and individual elements. Due to the inherent low thermal conductivity of the polymers, the modelling of the metallic components is an important consideration to ensuring that a non-overly conservative solution is obtained.
- Where the cable manufacturer has performed a thermal analysis and provided a maximum heat dissipation (W/m) from the cable, the cable may be considered as a homogenous tube within the calculation. Where this information is not available the cable should be included in the model. The cable model should be detailed enough to assign thermal losses for appropriate layers of the cable system, i.e., conductor, dielectric (insulation), metallic screen/sheath and armour wires.
- Marine growth should be applied to those exposed sections of the CPS as applicable. Marine growth thickness and thermal resistivity based on site specific data should be used, or in its absence recommendations from codes and standards (see section 5.3.5).
- The key dimensions of the monopile or J-tube interface for the cable and CPS should be incorporated into the model. An engineering evaluation of the worst-case height (based on potential scour, mobile sediment overburden and/or stabilisation) should be made, or sensitivity analysis performed.
- Scour protection should be considered in the model.
- Seabed or rock berm material (as applicable) around or on top of the cable / CPS should be modelled as applicable. The addition of stabilisation adds additional thermal load and should be captured in the model.
- Any slope from the start of burial to full depth should be included in the model.

- Sensitivities should be performed on the extent of the seabed domain (i.e., below the sea floor level and radially around the cable / CPS) such that the system response has been stabilised in the numerical simulation.
- The overall arrangement modelled may use symmetry (as applicable) to half the overall model size to improve computation efficiency and to generate a higher-quality general arrangement representation where possible.
- Component materials and their associated thermal properties (e.g., thermal conductivity) should be assigned to each domain of the system. It is important to ensure that the model is analytically accurate and captures the thermally critical elements of the system with appropriate conservatism. Where critical material properties vary with temperature, the influence may be captured with temperature dependent functions, e.g., seawater has thermal characteristics (thermal conductivity) that vary with temperature.
- The appropriate physics of heat transfer should be applied across all domains within the model. This should include conduction, convection, and radiation as applicable in both the radial and transverse directions.
- Model boundaries should be set according to the most appropriate physics.
- Where applicable thermal modelling may be performed considering steady-state or transient conditions (e.g., to account for margins to allow for power transmission changes).
- Mesh sensitivity should be carried out to ensure sufficient mesh quality.
- Consideration should be given for appropriate sensitivity studies for parameters to determine the model dependency.

  Analytical parameters that may be considered include:
    - Mesh type, size, quality
    - Convergence criteria
    - Boundary conditions
    - Material properties
    - Time dependency

  Geometric parameters that may be considered include:
    - Marine growth
    - Mobile sediment
    - Scour
    - Temporary conditions
    - Monopile/J-tube entry height.

8. Qualification process

8.1. Purpose

The qualification process should provide the following allowable limits for a given CPS design which can then be compared to project specific loads to determine the suitability of the CPS for a given project.

- maximum allowable tension.
- maximum allowable axial compression.

- maximum allowable bending moment.
- maximum allowable shear force.
- maximum allowable VMS
- maximum fatigue damage for CPS components.
- maximum allowable wear (due to abrasion).
- maximum allowable impact energy (e.g., due to dropped object).
- maximum allowable crush capacity.
- thermal limits of the CPS.

8.2. Process

The qualification process is summarised below and in Figure 8-1. Further details on each element of the process are provided in the following sections of this document.

8.2.1. Material selection

Material level tests define the characteristics of the materials within the construction and the capacity of the materials against relevant failure modes. These are adequately covered in API-Spec-17L1 [24]. This standard should be considered for Material Tests.

8.2.2. Numerical modelling

Material characteristics are input into the numerical models of the CPS in order to calculate the component level capacities of the CPS.

8.2.3. Verification testing

The component level tests verify the capacity of the CPS system against failure modes driven by mechanical loads as defined by the numerical model over the lifetime of the CPS. The majority of these are adequately covered in API-RP-17L2 [25]. This recommended practice should be considered for verification testing.

8.2.4. Qualification

The CPS numerical modelling is qualified by comparison with the verification testing. The numerical model may also need to be calibrated with the results of the verification testing. The CPS is qualified to loads up to the allowable loads as defined by the benchmarked numerical model with a safety factor applied for Operation, Installation and Abnormal conditions.

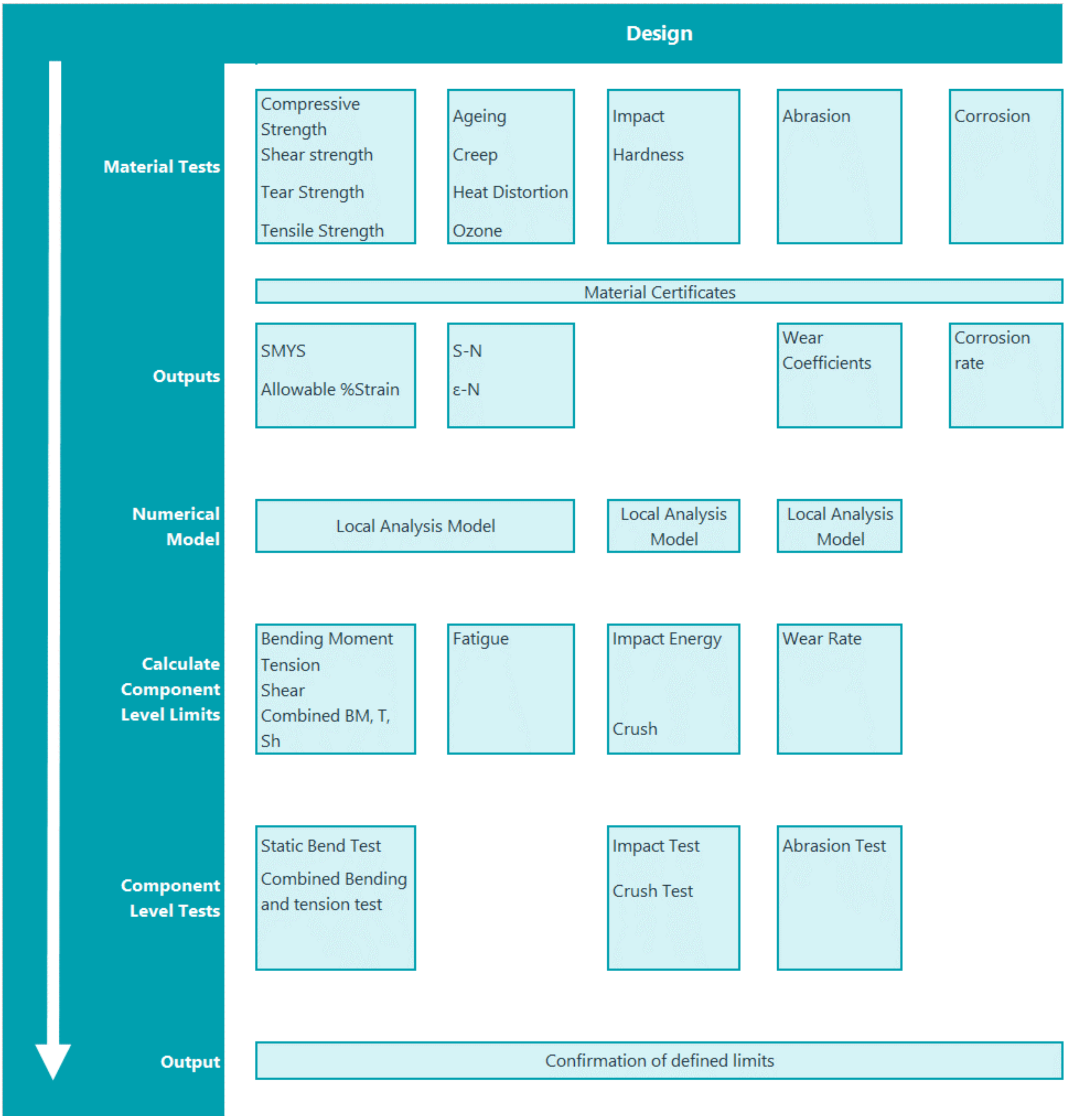

Figure 8-6: CPS qualification process.

8.3. Material selection

8.3.1. Requirements

The CPS materials should be selected such that they are compatible with the environment to which the materials will be exposed over the specified design life. The selection of CPS material should account for the functional requirements as summarised in Section 4.4.1.

8.3.2. Material testing

Material level tests define the characteristics of the materials within the construction and the capacity of the materials against relevant failure modes. API-Spec-17L1 [24] provides details on the material level testing required for bend stiffeners and bend restrictors (the constituent components in a CPS system) to define the characteristics and capacity of the materials. These requirements are re-produced in the following tables.

Testing should account for the influence of temperature and environment on the mechanical properties of the materials over time. Testing procedures are provided in the referenced standards.

Table 8-1 provides the general testing requirements for polymeric materials as defined by API-Spec-17L1.

Table 8-7: General test procedures for polymer materials – API-Spec-17L1.

Tests	Test Procedure
Abrasion resistance	ISO 7784-2 [a], ASTM D4060 [a], BS 903-A9, DIN 53516
Aging resistance	See 4.4.4
Creep resistance [c]	ASTM D2990, ISO 899-1
Compressive properties	ISO 7743, ISO 604 [b], ASTM D575, ASTM D695 [b]
Density	ISO 1183, ISO 2781, ASTM D792
Hardness	ISO 868 [b], ASTM D2240
Heat distortion temperature	ISO 75-1, ISO 75-2, ASTM D648
Impact resistance	ISO 179-1, ISO 179-2, ISO 180 [b], ASTM D256
Ozone resistance	ISO 1431–1
Shear properties	ISO 1827, ASTM D732
Tear strength	ISO 34-1, ASTM D624
Tensile properties	ISO 37, ISO 527-1 [b], ISO 527-2 [b], ASTM D638 [b]
Water absorption	ISO 62 [b], ASTM D570 [b]
Thermal Conductivity	ASTM C177, ASTM C518
Compression Set	ISO 815–1, ISO 815–2, ASTM D395, ASTM D1229
Flexural properties	ISO 178
Stress Relaxation	ISO 3384–1

[a] Standards similar in content but not technically equivalent.
[b] Standards are technically equivalent or identical for the test in question.
[c] A creep test should be performed if it can be demonstrated to be relevant to the design of the product.

Table 8-2 and Table 8-3 provides a list of the standards for a variety of metallic materials for structural components and fasteners respectively as defined in API-Spec-17L1. In addition, API-Spec-17L1 specifies that as a minimum, metallic materials should be certified to 3.1b) of ISO 10474:1991 (EN 10204 3.1) and that materials should be tested at raw materials suppliers or manufacturers work site.

Table 8-8: Standards for metallic structural materials – API-Spec-17L1.

Designation	Title
API 2A-WSD	*Planning, Designing, and Constructing Fixed Offshore Platforms—Working Stress Design*
DNVGL-RP-B101	*Corrosion Protection of Floating Production and Storage Units*
EN/BS 10025	*European Structural Steel Standard*
NORSOK M-001	*Materials Selection*
NORSOK M-120	*Material Data Sheets for Structural Steel*

Table 8-9: Standards for metallic fastener materials – API-Spec-17L1.

Designation	Title
ISO 898–1	*Mechanical properties of fasteners made of carbon steel and alloy steel—Part 1: Bolts, screws and studs*
ISO 3506–1	*Mechanical properties of corrosion-resistant stainless-steel fasteners—Part 1: Bolts, screws and studs*
API 20E	*Alloy and Carbon Steel Bolting for use in the Petroleum and Natural Gas Industries*
API 20F	*Corrosion-resistant Bolting for Use in the Petroleum and Natural Gas Industries*
ASTM A193	*Standard Specification for Alloy-Steel and Stainless Steel Bolting Materials for High Temperature or High Pressure Service and Other Special Purpose Applications*
ASTM A276	*Standard Specification for Stainless Steel Bars and Shapes*
ASTM A320	*Standard Specification for Alloy-Steel and Stainless Steel Bolting Materials for Low-Temperature Service*
ASTM A484	*Standard Specification for General Requirements for Stainless Steel Bars, Billets, and Forgings*
ASTM A1014	*Standard Specification for Precipitation-Hardening Bolting Material (UNS N07718) for High Temperature Service*
ASTM B637	*Standard Specification for Precipitation-Hardening Nickel Alloy Bars, Forgings, and Forging Stock for High-Temperature Service*
ASTM F2281	*Standard Specification for Stainless Steel and Nickel Alloy Bolts, Hex Cap Screws, and Studs, for Heat Resistance and High Temperature Applications*
EN 10025	*European Structural Steel Standard*
BS/EN 10083-1	*Steels for quenching and tempering. General technical delivery conditions*
BS/EN 10083-2	*Steels for quenching and tempering. Technical delivery conditions for non-alloy steels*
EEMUA 194	*Guidelines for Materials Selection and Corrosion Control for Subsea Oil and Gas Production Equipment*
NORSOK M-001	*Materials Selection*
NOTE This table is not an exhaustive list. As stated in 4.1, standards referenced in this table may be replaced by other international or national standards that can be shown to meet or exceed the requirements of the referenced standard.	

8.3.3. Deliverables

The CPS Manufacturer should provide material certificates for all materials used in the construction of the CPS. The certificates should include the results of all the material tests in Table 8-1 for polymer materials and certification to the relevant ISO/ASTM/EN standards in Table 8-3 for metallic materials. The certificates should provide all the properties of the materials required for the numerical model of the CPS. These can be based on historical qualification test data.

8.4. Numerical modelling

8.4.1. Material data input

The minimum material information required for the CPS capacity calculations are:

- Material Properties
    - Elastic Modulus
    - Wear Coefficients
    - Corrosion rates
    - Hardness
- Material Capacities
    - Yield Strength

- Allowable Strain
- S-N / ε-N

Further definition of the input data requirements is described in Section 4.6 to Section 7.0.

8.4.2. CPS modelling

Definition of CPS modelling requirements are described in Section 5.0 to Section 7.0.

8.4.3. Capacity calculations

The purpose of the capacity calculations is to define the allowable loads on a given CPS construction irrespective of project loads and define the inputs to testing of the CPS to qualify the design for loads up to the allowable loads.

The capacity calculations can be performed using certified Finite Element Analysis software models or certified calculations.

The calculations should provide the capacities for the following loads:

- Bending Moment (Global Curvature/MBR)
- Tension
- Shear
- Combined Bending, Tension and Shear
- Impact load
- Crush Load

The capacities should be defined as a utilisation of 1.0 against the yield stress or allowable strain of the materials. Additional safety factors may then be applied in the design, for Operation, Installation and Abnormal conditions.

8.5. CPS verification testing

8.5.1. General

The component level tests define the capacity of the CPS system against failure modes driven by mechanical loads over the lifetime of the CPS.

API-RP-17L2 [25] provides details on the component level testing required for bend stiffeners and bend restrictors (the constituent components in a CPS system). API-RP-17L2 [25] is aimed towards project specific testing rather than to define the characteristics and capacity of the components. The tests remain the same, however, the definition of the loads for the CPS verification tests should be based on capacity calculations. These requirements are summarised in the sections below and modified as required to reflect a capacity test rather than a project specific test.

8.5.2. Static bend test

Bend stiffeners / Tubular elements

The objective of the static bend test is to verify that the bend stiffener / tubular elements of the CPS deflect (bend) to the same profile as predicted by the numerical model for a range of angular variations up to the maximum allowable curvature based on strain limits and that the strain in the polymer through the range of angular variations and at the curvature limit reflects the model.

Procedure

The bend stiffener/tubular element should be subjected to a particular tension and angle combination which is representative of the capacity of the bend stiffener element as defined by the strain in the polymer. The test should be applied over time and the curvature and strain in the polymer measured. However, if the test equipment has a load limitation that restricts application of the capacity load, then the test may be modified (with agreement from the purchaser) to the maximum allowable load for the test equipment. The applied load must still be sufficient to show that the bend stiffener element deflects to the same profile (±0.01m^{-1} on curvature) as predicted by the design software and the stress/strain relationship is in line with the design software to allow for extrapolation to the defined capacity limit. The integrity of the polymer/metallic interface at the mechanical fixation should also be evaluated.

As the cable is not the focus of these tests a representative structure can be used in place of the cable provided the numerical model which is used to predict the capacity of the CPS accounts for the influence of the representative structure.

Bend restrictor elements

The objective of the static bend test is to verify that the bend restrictor elements lock-out at the defined MBR and that as the bending moment increases on the locked-out system the moment versus strain relationship is in line with the results from the design software up to the defined capacity limit based on allowable stress/strain in the CPS elements.

Procedure

The number of bend restrictor elements that are assembled for the test should be sufficient to simulate the maximum load in one of the elements while ensuring that boundary effects due to the test set up are representative of the operational condition or negligible in the element which is being tested. Therefore, assembly of the entire set of elements is not necessarily needed.

The required number of bend restrictor elements should be assembled onto the interface structure, or onto dimensionally and geometrically representative mock-ups of the interface structure. As this is not a project specific acceptance test, the test support structure does not need to be dimensionally and geometrically representative of the support structure during service.

The elements should be fastened together using fasteners of the same specification and fastened to the same fastening force as determined in the numerical model. Before application of loads, the bend restrictor should be checked to ensure that all fasteners are in position.

The bend restrictor should be subjected to lock-up and then gradually loaded up to the defined capacity for an agreed time period. The load is typically applied by running straps or ropes through the centre of the bend restrictor and applying lateral tension using a tensioning device. The deformed locking radius should then be measured. The bend restrictor should then be disassembled.

The disassembled bend restrictor elements, when examined, should be free from any damage. Typical signs of damage are cracking or warping in the bend restrictor elements. The deformed locking radius should be equal to or greater than the specified operating MBR and should correspond to that calculated at the design stage.

API-RP-17L2 [25] also defines a destructive test. The objective of the destructive test is to identify the failure load of the bend restrictor, and to compare this load to design calculations. The procedure is the same as the proof load testing procedure except that the load is gradually increased until failure of the bend restrictor occurs. There should be added safety requirements specified before the test, since failure of bend restrictor elements may cause broken pieces to be projected from the point of failure. Test personnel should therefore be standing at a safe distance and wear protective clothing and safety glasses. The failure load should be equal to or greater than that calculated in the design, accounting for material utilisation factors.

8.5.3. Combined tension and bending test

The tests above should be repeated with combined tension and bending load to the defined maximum limits. Multiple tension and bending load combinations may be required to fully define the capacity of the system.

8.5.4. Dynamic fatigue test

Full-scale dynamic fatigue tests are not mandatory but may be requested by the purchaser. The manufacturer may be able to rely on historical test data or other means to justify the omission of full-scale dynamic fatigue testing.

Full-scale dynamic fatigue tests are described in API-RP-17L2 [25] for bend stiffeners and CIGRE TB 623 [32] and CIGRE TB 862 [31] for submarine cables. These tests are aimed towards project specific fatigue of the cables/flexibles/umbilicals which the bend stiffener/CPS protects, however, the principle remains the same here but with a focus on understanding the fatigue performance capacity of the CPS itself.

The key objective is to verify that the S-N / ε-N or equivalent κ-N properties of the CPS from the material level tests are appropriate for the specific geometries of the CPS and understand any potential impact on the metallic/polymer interfaces including adhesion and mechanical connections.

Procedure

The testing procedures outlined in API-RP-17L2 [25] Section 5.5.3 and CIGRE TB 862 [31] Section 6.3 should be adopted for fatigue testing of each component within the CPS. These describe the set-up requirements including the bend stiffener and other CPS elements.

As the cable is not the focus of these tests a representative structure can be used in place of the cable provided the numerical model which is used to predict the required cyclical loading to verify the fatigue performance of the CPS accounts for the influence of the representative structure.

The procedures call for the definition of at least 5 load blocks. For these capacity definition tests the five blocks should represent a point on the s-N/ε-N curve. As this is not a project specific acceptance test the test support structure does not need to be dimensionally and geometrically representative of the support structure during service. However, the test support structure and all fastenings should be included in the model used to define the 5 loading blocks.

A successful dynamic fatigue test of a CPS does not imply that any cable placed within the CPS will not be subjected to excessive fatigue loading. This test is only for the fatigue performance of the CPS. Separate dedicated fatigue testing of the cable would be required to confirm its fatigue performance.

As described in API-RP-17L2 [25] it can be difficult to predict the failure point of the bend stiffener with any accuracy, due to the effect of heat generation and surface defects. Therefore, the load application should consider the effects of temperature and results of this verification test should be used to refine the numerical model where appropriate.

8.5.5. Impact test

All CPS (Bend Stiffeners/Tubular Elements and Bend Restrictors)

Impact tests for ancillary equipment are described in API-RP-17L2 [25] and for submarine cables in CIGRE TB 623 [32].

The allowable impact energy on a CPS is driven by stress/strain and ovalisation of the CPS.

Procedure

The impact test procedures are outlined in API-RP-17L2 [25] and CIGRE TB 623 [32]. The test involves dropping a mass on the CPS to achieve a calculated impact energy. The CPS should be laid on a surface that is representative of a scour protection or a hard surface to provide a conservative estimate of allowable impact energy. The impact energy applied in the test should be based on the impact energy which will cause damage to the CPS (excessive stress/strain, indentation, ovalisation whichever is the driving factor from the numerical models).

The load application should consider the component or location within the CPS which is most vulnerable to impact energy based on the numerical model or which transfers the highest energy to the cable as determined by the numerical model.

8.5.6. Crush Test

All CPS (Bend Stiffeners/Tubular Elements and Bend Restrictors)

Crush tests for ancillary equipment are described in API-RP-17L2 [25], (which references API-RP-17B [28]), and for submarine cables in CIGRE TB 623 [32] and CIGRE TB 862 [31]. The purpose of the crush strength test is to determine the crush capacity of the CPS. Crush loads may be applied to the CPS from forces applied by machinery onboard the cable installation vessel and static loads during operating. The crush strength test should be used to validate the design methodology and calculation tools (e.g., numerical models) used to define the crush capacity of the CPS.

Procedure

The CPS should be positioned, empty without internal pressure, on the test device. The test device should be represented using a clamping device with contact loads being exerted onto the CPS from two opposing sides.

The crush load should be increased from zero up to the maximum allowable crush load determined by the CPS manufacturer, i.e., based on excessive stress/strain, indentation, ovalisation whichever is the driving factor from the numerical models. The crush load should be applied at a rate not greater than 1% of the maximum load per second (1%/s) API-RP-17B [28], and it is recommended that the maximum crush load is kept constant (within ±2 % API-RP-17B [28]) for a minimum of 1 hour (CIGRE TB 623 [32], API-RP-17B [28]).

The CPS diameter, and CPS ovalisation should be measured prior to the test and measured continuously during the test (including at maximum loading) using a suitable device. The diameter and ovalisation of the CPS may change over time due to the applied load. The applied load should also be measured and recorded throughout the test. To account for long term crush loading and the reduction in diameter due to creep effects, it is recommended in CIGRE TB 862 [31] and CIGRE TB 623 [32] that the maximum crush load be applied for a period of at least 5 to 7 days respectively.

For polymer CPS designs, crush tests should be performed for a range of different temperature conditions as stiffness and creep properties of polymeric materials are temperature dependent.

The crush test should also be applied to each of the constituent components that comprise the CPS and performed at locations on each of these components that are identified as most vulnerable to crush loads based on the outputs predicted from the numerical model. The sample length of the CPS should be selected such that end effects are minimised at the point of load application.

The objective of the test is to validate the manufacturer's design methodology, i.e., the max crushing load should be greater than that predicted by the design methodology. There should be no cracks, holes or harmful indentations in the CPS.

8.5.7. Abrasion Test

All CPS (Bend Stiffeners/Tubular Elements and Bend Restrictors)

Full scale abrasion testing of the individual CPS components considering a surface representative of a scour protection including expected sediment levels and in a seawater environment at a representative temperature is required. Material level testing is informative, however, the interaction between the CPS component geometry and the scour protection is important to understand and this can only be replicated by fullscale (component level) testing. The objective of the test is to determine the reduction in load capacity of the CPS component with increasing distance of travel per unit contact force. The reduction in capacity is linked to the reduction in wall thickness which is linked to the volumetric wear rate and the geometry of the CPS in contact with the scour protection. Therefore, calculation of the volumetric wear rate per metre per unit force considering all the materials in the CPS cross-section is the key output from the test. This wear rate may change depending on the materials which become exposed and contact the seabed as wear develops. Therefore, destructive testing through the full wall thickness of the CPS is recommended.

Procedure

The test set-up should ensure that the CPS component is in contact with the representative scour protection surface with a known contact force. The CPS or scour protection surface is then moved either linearly or rotationally and the distance of travel of the CPS on the scour protection continuously measured. At regular intervals the test is paused, and dimensional reading taken of the wall thickness of the CPS in contact with the scour protection surface in order to allow the calculate of a volumetric wear rate and wall thickness reduction rate to generate a load capacity curve based on distance travelled.

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