Navigating the Valley of Death: Reducing Reliability Uncertainties for Marine Renewable Energy

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ABSTRACT

Technology Readiness Levels (TRLs) are a widely used metric of technology maturity and risk for marine renewable energy (MRE) devices. To-date, a large number of device concepts have been proposed which have reached the early validation stages of development (TRLs 1-3). Only a handful of mature designs have attained pre-commercial development status following prototype sea trials (TRLs 7-8). In order to navigate through the aptly named 'valley of death' (TRLs 4-6) towards commercial realisation it is necessary for new technologies to be de-risked in terms of component durability and reliability. Due to a lack of deployment experience a conservative design approach is often adopted utilising existing offshore certification guidance. Developers must therefore balance the competing requirements of designing economically viable and yet robust devices. Reliability assessment (including physical component testing and statistical analysis) enables device developers to determine component suitability and reliability in a cost-effective way prior to full-scale prototype deployment.

Within the context of the collaborative European project DTOcean (Optimal Design Tools for Ocean Energy Arrays), this paper summarises recent research activities conducted by the University of Exeter at two purpose-built test facilities designed for MRE device concepts that are at TRLs 4-7; post-design validation and pre-full-scale testing. Studies investigating the performance and long-term durability of mooring components for MRE devices are reported which have utilised the Dynamic Marine Component (DMaC) test facility and the South West Mooring Test Facility (SWMTF). In addition progress is reported on the development of numerical methods to predict component reliability. This research provides valuable and previously unreported insight into long-term component use and system design for MRE devices.

1. INTRODUCTION

It is widely acknowledged that marine renewable energy (MRE) has a significant role to play in the transition towards a global green economy. The 20% target for electricity generation set within the European Commission's *Europe 2020* strategy [1] includes 200-300MW of installed MRE capacity in the United Kingdom [2] which could equate to the creation of 10,000 jobs by 2020 and be worth £6.1 billion by 2035 [3]. With the current installed capacity around 9MW, such projections are ambitious considering the current nascent state of the industry in which only a few notable projects have reached the commercial demonstration stage (TRLs 7-8). As yet no device operators have deployed large scale array projects, although the current installed capacity will be bolstered by two tidal array projects that have recently been approved (MeyGen's 10MW Phase 1 and Scottish Power Renewables 10MW Sound of Islay Tidal Array) [4].

Despite the forecasted growth of the industry over the next two decades and support of funding incentives in the UK (e.g. the Marine Energy Array Demonstrator scheme, Marine Renewables Commercialisation Fund, Saltire Prize and various Technology Strategy Board and EU initiatives) a number of barriers have been identified which must be overcome before large scale deployments are realised. The *Wave and Tidal Energy in the UK. Conquering Challenges, Generating Growth* report produced by RenewableUK [3] identified four key risk areas to progress: finance, technology development, grid and consenting. Confidence in the ability of the MRE industry to deliver a localised cost of energy (LCOE) which is competitive with other forms of power generation in an acceptable time-frame is essential for continued investment in the sector. In order to achieve this, an operational availability threshold of 75% has been identified [4]. In order for the sector to progress towards higher TRLs the reliability of components and sub-systems must be demonstrated as this plays a key role in the overall availability of the device [5] as well as shaping efficient maintenance intervals [6].

DTOcean (Optimal Design Tools for Ocean Energy Arrays: www.dtocean.eu) is a collaborative project funded by the European Commission under the FP7 call ENERGY 2013-1. It aims to accelerate the deployment of the first generation of wave and tidal energy arrays through the development of a Design Tool which will be able to assess the i) economics, ii) reliability and iii) environmental impact of wave or tidal energy arrays. The developed tool will comprise a number of sub-modules which will be used to analyse and optimise several key aspects; array layout, electrical system architecture, mooring and foundation systems, lifecycle logistics as well as system control and operation. As part of the consortium comprising 18 partners from 11 countries, the Offshore Renewable Energy group at the University of Exeter is lead partner of the mooring and foundation work package and is responsible for the over-arching assessment of reliability. The Offshore Renewable Energy group has experience of marine component testing and reliability prediction which will be discussed in the following sections.

2. RELIABILITY ASSESSMENT

Reliability assessment has the following objectives:

1. To ensure that an acceptable level of system reliability can be achieved
2. To quantify lifecycle costs over the expected lifetime of the array (i.e. 25 years)
3. To plan operations and maintenance strategies
4. To identify design weaknesses for system improvement

A widely used metric for assessing the multi-level reliability of systems (comprising sub-systems and components) is the mean time to failure (MTTF) based on the reliability function $R(t)$ of a component, sub-system or system:

$$MTTF(T) = \int_0^{\infty} R(t)\,dt$$

The function $R(t)$ describes the probability of continued reliability from a particular point in time and is based on a statistical probability density function (PDF) of reliability performance gathered from laboratory component testing, field analysis or numerical analysis. The most basic PDF is exponential which is used to describe failures which occur during the 'useful' life of the component illustrated as the central portion of the 'bathtub' curve in Figure 1. Fundamentally this approach assumes that components have a constant rate of random failures and have therefore not started to degrade or wear out with use. In reality the early life of a component is characterised by high (but decreasing failures) which then increase at the end of the component life. Alternative distributions are more suitable for describing failures before and after the useful interval of component life, for example the Weibull distribution tends to gives a good representation of end-of-life failures.

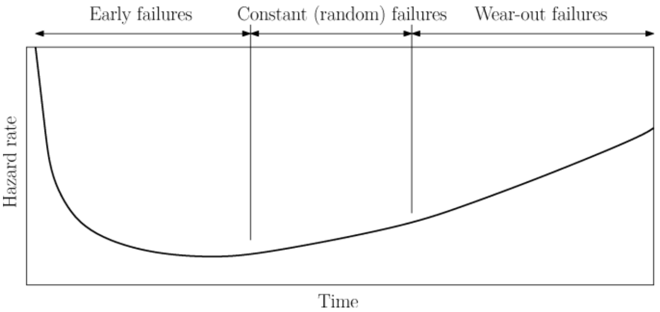


Figure 1: 'Bathtub' curve of hazard rate (the failure rate within a certain time interval) for three different lifecycle stages.

The sensitivity of component failure rates to different applications is accounted for in *bottom-up statistical methods* in which influence factors are applied to base failure rates to account for variations in quality, environment and stress (i.e. temperature, use rate or load). Using this approach, reliability calculations can be carried out with a relatively low amount of information such as the type and number of components and operating and environmental conditions. Whilst this method is straightforward to implement it is highly reliant on the underlying data and although influence factors are available in databases such as Mil-Hdbk-217F [7] for electronic components or OREDA$^{®}$ database [8] produced by the oil and gas industry, the use of factors designed for other applications introduces uncertainty to the predicted failure rate. To illustrate this point Table 1 lists environmental influence factors for a commercial-off-the-shelf (COTS) piece of equipment: the electric motor. Clearly the use of the *naval*, *unsheltered* factor will result in a conservative failure rate which is representative of equipment exposed to the ocean environment. In the absence of actual performance data a failure estimation based on this approach is highly simplified, as it: i) focuses only on the central portion of the 'bathtub' curve, ii) does not take into account developments in manufacturing or design to improve reliability and iii) treats failures as independent events in a system (i.e. ignores cascade failures).

Table 1: Environmental influence factors for electric motors adapted from Mil-Hdbk-217F [7]

Environment	Factor	Description
Ground, benign	1.0	Non-mobile, temperature and humidity controlled environment, readily maintainable
Naval, sheltered	7.0	Sheltered or below deck conditions
Naval, unsheltered	18.0	Unprotected, surface equipment exposed to weather conditions and salt water immersion

A more detailed approach to assessing reliability is provided by *physics of failure bottom-up methods.* These are used to identify principal failure mechanisms (i.e. structural, mechanical, electrical, thermal or chemical) which contribute to component failure as well as their effect. The aim of this approach is to develop empirical relations between the dominant failure mechanisms and the predicted MTTF. Crucially, unlike the bottom-up statistical approach, this enables a greater depth of understanding regarding event or time-dependent failure mechanisms (e.g. the load-bearing capacity or degradation of components). Although empirical relations for particular components exist (e.g. [9]), as with bottom-up statistical methods it is possible that nuances of the application will not be fully accounted for. Whilst both approaches introduced in this section have widely recognised limitations, they still provide a first order estimate for reliability studies to identify critical sub-systems and components.

As yet a common failure database has not been established within the MRE industry, despite the development of initial reliability models [10]. A similar endeavour to the offshore wind SPARTA (System performance, Availability and Reliability Trend Analysis, https://ore.catapult.org.uk/sparta) project for the MRE sector is likely to occur in the near-future. The absence of a database is due to a lack of design convergence within the sector (particularly for wave energy devices), the use of custom-made components and also the commercial confidentiality of designs. At present, developers must therefore rely on the adaptation of existing reliability assessment methods, as well as knowledge gained during earlier TRL stages to predict operating conditions. Component reliability testing either in the field or laboratory environment plays a pivotal role in providing a means of validation for prediction methods.

3. COMPONENT RELIABILITY TESTING

Technology developers at TRLs 4-6 are subject to competing demands; the need to prove that their technology is reliable to strengthen investor confidence whilst at the same time reducing costs to make their technology commercially viable. Necessary savings of 50-75% by 2025 are suggested by [11] if the sector is to become a commercial reality. Striking the difficult balance between robust yet affordable designs is a key engineering challenge for developers at this stage.

3.1 TESTING FACILITIES: THE SOUTH WEST MOORING TEST FACILITY (SWMTF) AND DYNAMIC MARINE COMPONENT TEST FACILITY (DMAC)

Component reliability testing is a cost effective means of establishing component or sub-system performance in a controlled, low-risk environment before heading offshore [12]. Whilst costs are associated with running laboratory equipment and employing trained personnel, funding programmes such as MaRINET (Marine Renewables Infrastructure Network: http://www.fp7-marinet.eu/) have provided technology developers with transnational access to a wide range of facilities. Two such MaRINET facilities owned and operated by the University of Exeter are the South West Mooring Test Facility (SWMTF) and Dynamic Marine Component test rig (DMaC) [13].

The SWMTF is an instrumented buoy funded through the Peninsula Research Institute for Marine Renewable Energy (PRIMaRE). SWMTF provides a highly dynamic floating platform for field-testing of mooring and umbilical components and systems at sea. It comprises a highly instrumented buoy together with a seabed-mounted Acoustic Doppler Current Profiler (ADCP) with directional wave measuring capability. SWMTF provides a means of assessing the dynamic response and mooring tensions of buoy-like offshore equipment to incident wave, current and wind conditions. Because the SWMTF does not possess a power take-off system (PTO), it is essentially a technology neutral facility which can, for instance, be used to study the response of point absorber wave energy converters (WECs) in a PTO-offline scenario. Since it was commissioned in 2009 a significant body of research has arisen from measurements recorded by the SWMTF including studies into different mooring line and anchor configurations.

Constructed during 2010, the DMaC test rig has been designed to replicate the dynamic conditions that offshore components typically experience in-service, such as operational loads and deformations. The facility includes a hydraulically powered tailstock for the application of user-defined loads or displacements (harmonic and irregular time-series). Unlike existing tension test machines it also has a hydraulically powered headstock, providing an additional three degrees-of-freedom (roll, pitch and yaw). This feature is particularly useful for the testing of subsea components which are subjected to bending or torsion at one end (for example power umbilicals used for power transmission). DMaC's tailstock and headstock can operate according to either force or displacement time series and both operate under full feedback control independently of each other. Another unique feature of the DMaC is that the components being tested can be fully submerged in fresh water.

Subsea components such as those used in mooring system, risers and umbilicals are prime examples of components which require testing prior to use. These components have to be highly reliable to be fit for purpose (i.e. to ensure that the device is kept on station in the case of mooring components), whilst being cost-effective. Novel solutions may offer lower lifecycle costs or functionality which is not present in conventional components but these require thorough testing to ensure that performance and reliability levels are adequately met. The following sub-sections will summarise several examples of component testing carried out by the University of Exeter with collaborating partners.

3.2 RELIABILITY ASSESSMENT; A CASE STUDY TO REVIEW SAFETY FACTORS IN MOORING DESIGN

In this case study a combined approach for reviewing safety factors and reliability was developed using three key techniques:

- Numerical modelling using finite element software
- Accelerated testing using DMaC
- Field trials at the SWMTF.

Data collected from previous field trials at the SWMTF provided realistic load data to inform the case study. A review of how these techniques can be used to speed up the reliability verification process was conducted.

Component and assembly models of the shackle bow and pin were developed and a range of load cases were reviewed, including the maximum load measured at the SWMTF (53kN) and the supplier specified minimum breaking load of the shackle (MBL=122.6kN).

Controlled break load and accelerated fatigue performance of the shackles was investigated using DMaC. The break tests established an average break load of 210kN; a safety factor of 8.6 on the shackle working load limit (WLL) and a safety factor of 1.7 on the MBL. Both failures occurred on the thread of the pin. The break tests also allowed identification of the yield point of the shackles; just over 100kN. This was used to specify the fatigue trials, ensuring they were conducted within the elastic range of the shackles. Force driven cyclical loading of 10 – 90kN was specified for the fatigue trials at a frequency of 2Hz. A total of 11 shackles were fatigue tested resulting in failures ranging from 19,380 cycles to 109,470 cycles and a variety of failure locations including on both the pin and bow (Figure 2).

Figure 2: Examples of failed shackles

New and pre-aged shackles were deployed at the SWMTF for a period approaching 6 months, with maximum loads reaching just over 10kN. Failures were not anticipated at this load range and none were observed. Dye penetrant testing was used to investigate damage; no damage was observed. Following the sea trials, the shackles were subject to further fatigue testing at DMaC.

The numerical modelling correctly identified areas of weakness in the shackle, but significantly underestimated the strength of both the pin and the bow. The physical testing showed that large safety factors are present in static loading situations with the shackle being substantially stronger than the supplier specification or that predicted by the numerical models. Safety factors are significantly reduced in fatigue loading with failures occurring from 20,000 cycles when the 90kN load was applied cyclically; this loading level is below the MBL specified by the supplier. Further analysis is required regarding sea trial data.

In this case study the physical testing allowed accurate figures to be established for failure modes predicted by the numerical modelling. The ability to perform accelerated testing at 2Hz allowed a large number of cycles to be applied to the shackles for a detailed assessment of fatigue performance. The mean stress applied during these trials was found to have a significant effect on the rate of failure when comparing data to DNV recommended guidance [14]. Further details of the study can be found in [15].

3.3 SYNTHETIC ROPE PERFOMANCE AND DURABILITY ASSESSMENT (TRL4)

With a proven track record in the offshore industry, synthetic ropes have the potential to be an enabling technology for the MRE sector in terms of the specification of economic and durable mooring components. The response of synthetic ropes is complex, because they display viscoelastic and viscoplastic behaviour which is dependent on time and prior load history [16,17]. Significant effort over the past two decades has been made into characterising this behaviour through testing (e.g. [18]) and the development of numerical models (e.g. [16,19]). However, the loading regimes used during testing have reflected the main application of synthetic ropes to-date (large equipment, such as oil and gas exploration drilling platforms or support vessels), for example tests involving low frequency sinusoidal loading. The loading regimes experienced by dynamically responsive MRE devices such as WECs are clearly different and may indeed be sensitive to mooring characteristics such as damping [20]. Therefore a new approach to performance testing and analysis is required for MRE applications.

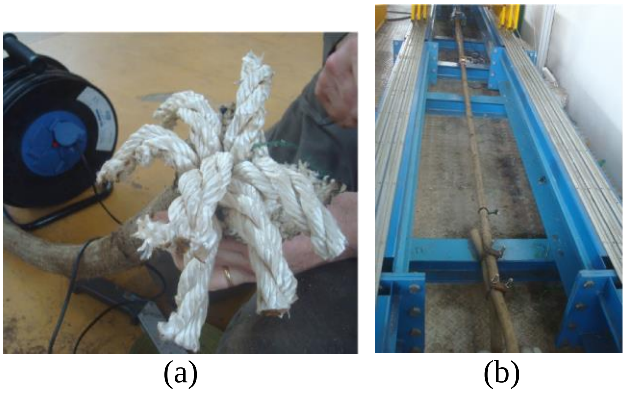

(a) (b)

Figure 3: (a) Rope sample with outer jacket removed showing construction (parallel-stranded). (b) IFREMER 100 Tonne test machine [21]

As part of the MERiFIC (Marine Energy in Far Peripheral and Island Communities: http://www.merific.eu/) project, tests were conducted at the University of Exeter and L’Institut français de recherche pour l'exploitation de la mer (IFREMER) to ascertain the performance of nylon ropes subjected to loading conditions relevant to MRE devices. In the first part of the study [17] several new rope samples (Figure 3a) were subjected to harmonic and irregular loading regimes using the DMaC test rig based on tension measurements recorded by the SWMTF. Tests were also carried out using the 100 Tonne test machine at IFREMER, partly to compare the performance of both test machines (Figure 3b). The focus of the study was to determine the influence of load history on response, characterised through three performance metrics which are important to MRE mooring system design: rope strain, axial stiffness and axial damping.

In agreement with published studies it was found that the time-averaged axial stiffness of the samples was dependent on the applied mean load. This trend was also observed for axial damping. Whilst an inverse relationship between axial damping and load oscillation period was demonstrated, the trend between axial stiffness

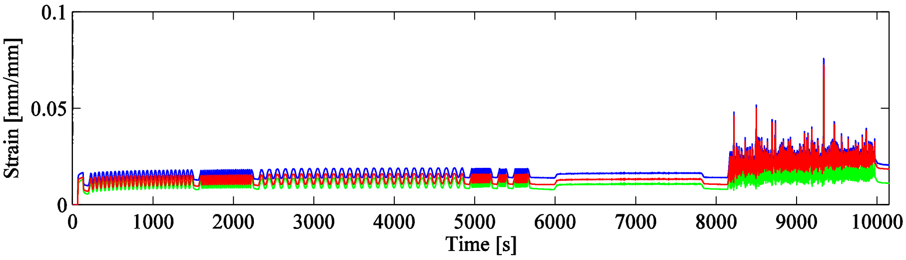


Figure 4: Calculated time-varying strain values for three samples subjected to different initial loading conditions. Further details can be found in [16]

and period was less obvious and appeared to be influenced by the non-monotonic order of applied oscillation periods. Further investigation into the harmonic and irregular response time-series revealed that the operational performance of the rope samples was strongly influenced by the instantaneous load-strain characteristic (e.g. Figure 4). This clearly has implications for mooring system design, because although non-linear load-strain curves can be implemented in most commercially available mooring system software, the time-dependency of component response is not accounted for. The findings of the study also have implications for the installation of a mooring system, including the need to 'bed-in' the ropes to avoid having to re-tension the lines in service.

The second part of the study looked into the performance of aged samples [21,22] after 18 months use as part of the SWMTF mooring system. Whilst it is important for a device developer to know the short-term performance of mooring components, it is also crucial that the long-term durability is well understood. After subjecting the aged sample to the same loading conditions as the new samples in the first part of the study, the investigation revealed small changes to the properties of the rope. Closer inspection of yarn and fibre samples using tension testing and scanning electron micron equipment at IFREMER showed that this was likely to be due to mild fatigue wear sustained during deployment. The results of this study will appear in a forthcoming publication [21].

3.4 NOVEL MOORING COMPONENT PERFOMANCE TESTS: THE EXETER TETHER AND TFI TETHER (TRL4)

In addition to commercially available mooring components, the DMaC has also been used to test novel designs. The Exeter Tether is one such design which has been developed and patented by the University of Exeter [23]. The prime motivation behind the Exeter Tether is to overcome the limitation of existing mooring options by decoupling the minimum breaking load of the tether from the axial stiffness.

The Tether is unique and utilises an elastomeric core element to resist the diametric contraction of a hollow fibre rope, which in turn limits axial extension. By adjusting the material properties of the core and the geometries of the core and the hollow rope, the design can be tailored to satisfy the application (i.e. the specification of axial stiffness values in one or two stages of extension whilst achieving the required minimum breaking load). The tension load path is uncompromised with the hollow rope acting as primary load carrier. Decoupling the axial stiffness from the minimum breaking load allows the specification of lower axial stiffness for a given MBL. The primary components of the tether are detailed in Figure 5. The development of the tether involved a proof of concept study which included performance testing at DMaC and durability testing in representative environmental conditions at the SWMTF. Details of preliminary results established during these tests can be found in [24].

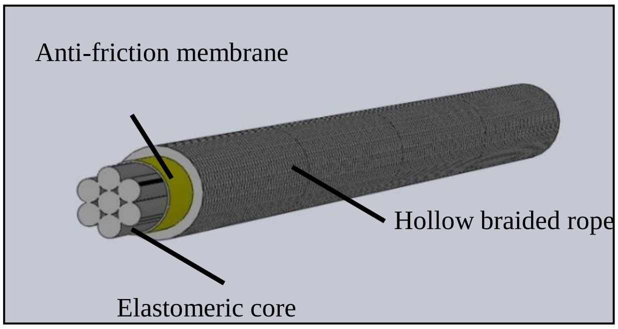


Figure 5: Representation of the Exeter Tether assembly

Another novel mooring tether concept has been developed by Technology for Innovation. The tether offers an elastic, 'soft' load response using an elastomeric rubber material together with a region of soft response, utilising the properties of thermoplastic compression elements (see Figure 6) and is described in more detail in [25]. The main objective of testing using the DMaC was to validate the working principle and the performance characteristics of the TfI tether in a wave energy application as well as indicate expected levels of reliability.

Figure 6: Technology for Innovation (TfI) mooring tether during performance and service simulation test at DMaC.

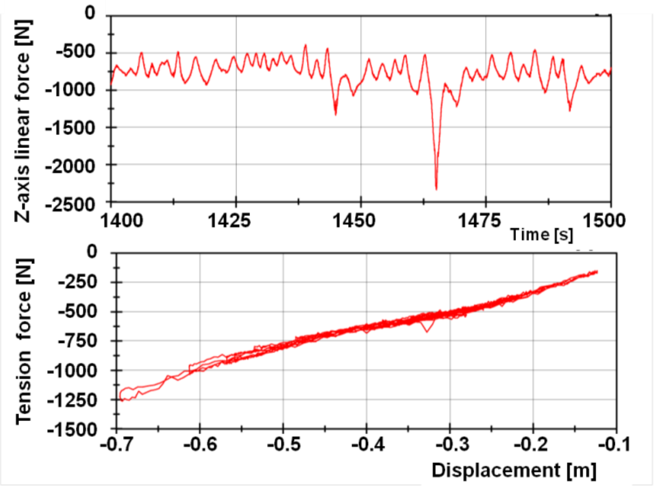


Figure 7: Replication of (scaled) force signal for storm conditions (upper plot) and associated load extension curve (lower plot) for the TfI mooring tether during service simulation test DMaC. Please note, due to test rig convention tensile forces are denoted as negative.

One of the service simulation tests was to replicate the force time series of a 100-year storm condition computed by a numerical model of the wave energy device. The time-series was scaled assuming Froude scaling to account for the 1:3.45 scale of the tested component and the maximum available stroke of 1m. A snap shot of the time-series and the associated load response of the mooring tether can be seen in Figure 7.

The storm test was run for 45min, equivalent to 3 hours at full-scale. The load extension curve largely followed previously established behaviour. Indeed the compressive elements engaged for the largest of force peaks which demonstrated the working principle of the tether under realistic, non-linear load conditions. The tests were also able to reveal a design issue of the connectors used for the prototype which could then easily be avoided.

3.5 DYNAMIC MARINE POWER CABLE TEST (TRL6)

Another critical offshore component are umbilical cables or pipelines which are used to transmit electrical or hydraulic power from the floating installation down to the cable or pipeline on the seabed. The mechanical load conditions for marine renewable energy are likely to be highly dynamic and well outside the load envelope that umbilical cables have been previously designed to [26].

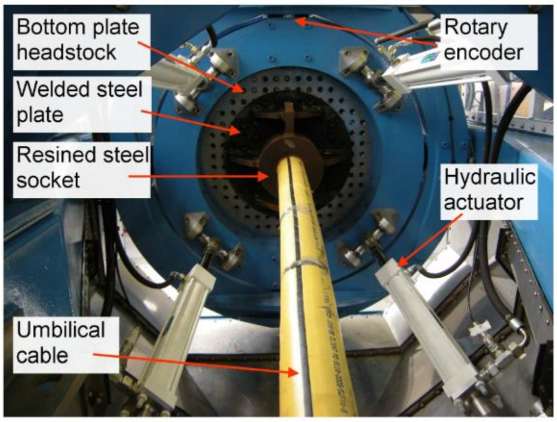
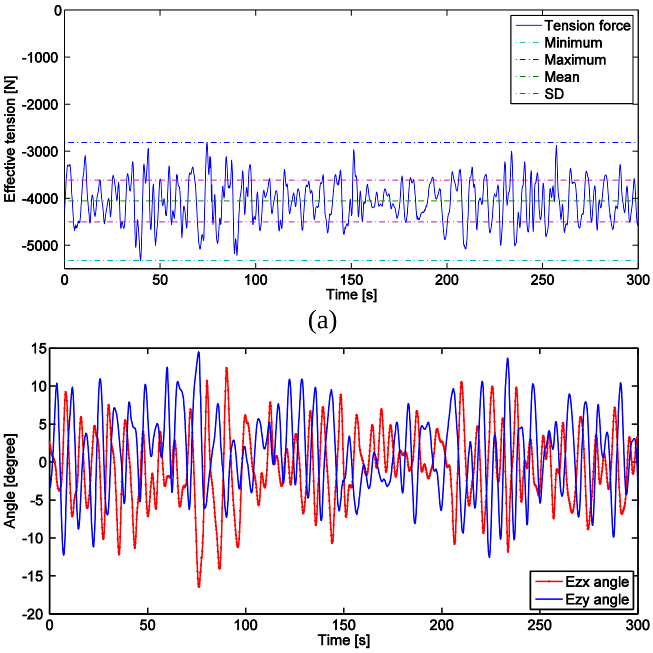


Figure 8: Service simulation testing for a marine power cable [26]. Experimental setup in DMaC, cable courtesy of JDR cable systems.



(a)

(b)

Figure 9: Umbilical service simulation test signals, showing the effective tension force (a) and the coincident headstock angles (b). Please note, due to test rig convention tensile forces are denoted as negative [26].

Only a short load signal lasting 5 minutes was employed during initial tests. The main purpose is to demonstrate the feasibility of the test approach to simultaneously apply dynamic tensile and bending loads [26].

An extract of the effective tension signal is plotted in Figure 9a. The negative values denote the tensile force experienced by the cable section which varies between -2.8kN and -5.3kN. The tension force is highly cyclic, with a total of 122 load cycles. This effective tension is combined with bending angles at the headstock which are depicted in Figure 9b. The angles are also highly cyclic and follow the five incident wave groups with a range between −16.4° and 14.5°.

Similar tests will have to be carried out over substantially longer durations in order to verify the long-term integrity of the power cables deployed in such conditions.

These tests will not only help cable manufacturers to redesign their cables according to the expected load envelopes (adapting stiffness, levels of armouring or allowable bending radii), but would also increase the confidence levels for long-term installations.

4. DISCUSSION AND PROPOSED APPROACH FOR THE DTOCEAN DESIGN TOOL

Marine Renewable Energy has the potential to make a significant contribution to the supply of electricity for countries with sufficient resource. In order for it to be financially competitive with other forms of electricity generation, significant, but not insurmountable barriers must be overcome before large scale array deployments are realised. Whilst the MRE sector is currently seen as high-risk investment option, the rewards are potentially large. In order to encourage continued investment in the sector confidence in the long-term operating availability and long-term durability of designs is required for a range of stakeholders including certification agencies, insurers and investors. Indeed given the choice of investing in one of several technologies, the ability to operate almost continuously (apart from during scheduled maintenance intervals or when resource is too low) may be more important than device performance rating.

For devices which have reached TRL 4, efforts within the sector are currently focused on de-risking technologies through incremental development work with the aim of achieving designs which are both cost effective and reliable. This involves laboratory testing, numerical modelling and prototype testing at benign sites in order to ‘iron-out’ issues before full-scale prototypes are deployed (where the consequence of failure could range from inconvenient and costly to catastrophic). De-risking not only includes scrutinising novel designs but also COTS equipment used in different applications. Component testing has a key role to play in this process. By subjecting components to representative conditions that are likely to be seen in service greater confidence can be gained about failure rates, marking a departure from using generic (and perhaps unsuitable) database values. Testing also enables the causes and effects of failure to be investigated in great detail further contributing to risk mitigation.

The aim of the DTOcean project is to develop a design tool which will provide a number of solutions for array design. Currently there is a lack of detailed operational data in the MRE sector (particular

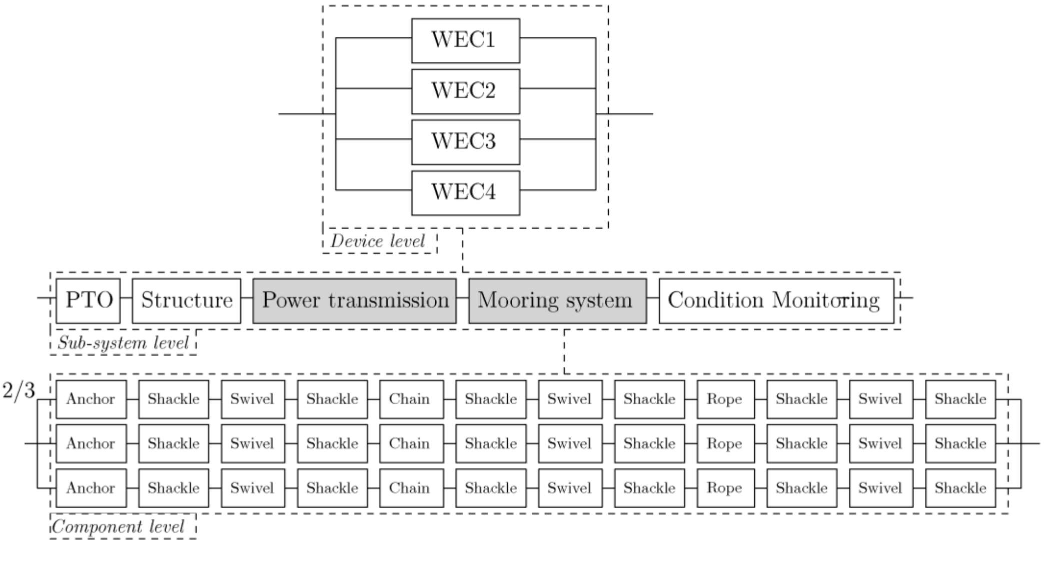


Figure 9: Reliability Block Diagram for an array of four generic wave energy converters each with three mooring lines

ly shared data) and hence it is proposed that reliability of each solution will be assessed in the tool using the widely used bottom-up statistical method, which will draw upon failure rates for each component in addition to relevant influence factors from a centralised database. These values will be sourced from appropriate failure rate databases, including those identified in this paper.

There are two sub-modules in the tool which will generate technical solutions at a sub-system level: i) power transmission and ii) mooring and foundation system. The components which make up each sub-system will be displayed graphically to the user in a reliability block diagram. These diagrams are a powerful method to calculate system reliability when sub-systems exist which have inter-dependencies or where provision has been made for redundancy. For the example shown in Figure 9 it can be seen that each device in the array has three mooring lines comprising a number of components. The reliability of each line is dependent on all of the components contained therein. However, the mooring system is dependent on 2 of the 3 lines remaining intact in order for the device to be kept on station in the event of a single line failure (referred to as accident limit state in [14]). By default the other parts of the system (i.e. power take-off, structure and condition-monitoring) will be represented by a generic block named ‘device’ and assigned a failure rate by the user, perhaps based on sea-trials of a single device.

To reduce the complexity of the tool, constant failure rates from the ‘bottom of the bathtub’ portion of component life (Figure 1) will be used. The proposed tool will therefore provide basic functionalities as well as the option to include more sophisticated failure distributions and adjustment mechanisms If the user has conducted their own analysis, the tool will have the functionality to accept failure rates, overwriting the default values held in the database.

Table 2: Technology assessment classification according to DNV-OSS-213 [27]

Application area	**Technology status**		
	1 (proven)	**2 (limited field history)**	**3 (new or unproven)**
1 (known)	1	2	3
2 (new)	2	3	4

Uncertainty in the reliability calculation will be addressed by the application of uncertainty ranges which will be dependent on the status of the technology and application area (e.g. Table 2). This approach will be based on technology classification assessment procedures outlined in [27]. For example a proven technology in a known application will be assigned a much smaller uncertainty range than a new or unproven technology used in a new application.

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