Towards component reliability testing for Marine Energy Converters

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Abstract

The dearth of generally available, failure data that can be directly applied to marine energy converters (MECs) has been commented on for some years. The advancement of the industry will be fundamentally linked to proven reliability assessments, which is difficult on an industry wide basis.

This paper describes how targeted component reliability testing could enable the establishment of relevant failure rate data for the marine renewable energy industry. The necessity for dedicated component testing is briefly reviewed with examples from the wave energy sector. The experience of testing in other industries is discussed and adapted for the marine sector. A generic procedure used in other test intensive industries to obtain standardised load-time histories for service simulation testing is outlined and applied to mooring tests that have been carried out in a wave tank. By means of a rainflow analysis procedure and the Palmgren-Miner rule the most

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severe load cycles, largely contributing to the fatigue damage are identified and reproduced for a possible component test signal.

The application of the suggested generic test approach will assist marine energy stakeholders in obtaining evidence of component reliability under simulated operational conditions much more rapidly than can be achieved with prototypes under normal service conditions. Importantly, this would also allow a more accurate estimate of field failure rates and could reveal possible failure modes/design weaknesses ahead of field deployments.

Key words: Reliability, Marine energy converter, Mooring, Component testing, Service simulation testing

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1. Introduction

In the UK, marine energy projects with a total capacity of 57.5MW are under development (Entec UK, 2009). Although the planning consent has been granted for 27 MW, less than 2 MW of marine energy converters (MECs), i.e. wave and tidal energy devices are installed. The recent commercial showcase project with 2.5MW installed capacity off the coast of Portugal came to a halt due to technical and financial issues (Blum, 2009).

The history of development of many important technologies are characterised in their early stages by frequent breakdowns, unanticipated failure modes, low reliability and high unavailability. This is true for the early motor cars, aeroplanes and computers. Unfortunately it has also been true for many of the early marine renewable energy devices. Survivability and reliability of devices have been identified as major challenges for the marine renewable sector to successfully emerge from the research/testing/prototype stages to economic and commercial deployment (UKERC, 2007; DECC, 2010). Consequently, reliability assessment and demonstration for MECs is essential. In particular the characterization of appropriate component failure rates is recognized as a key requirement for the deployment of commercial-scale MECs. This is the case for new components along with non-marine components being used in a marine environment and for marine components being used under different operating conditions (Ricci et al., 2009). For both cases the available reliability information is often scarce and/or not directly applicable. The challenge is to establish, accurately, failure modes and associated reliability data for the components and subsystems of marine renewable devices and, when reliability is unsatisfactory, to develop components that are fit for their purpose in a hostile marine environment. All this needs to be done as rapidly as possible to pave the way for MECs that have sufficiently high reliability to ensure the confidence of investors and the public alike.

The main body of this paper is concerned with the question as to how appropriate failure rates can be established and consequently how to improve reliability. It is organised in four parts whilst focussing on marine renewable components. The first part discusses the need for dedicated component testing. This is followed by a description of reliability test approaches commonly applied in other industries. In the third part, a generic procedure to provide evidence of component reliability under operational conditions is proposed. This is subsequently applied in part four, based on a case study for a mooring assembly of wave energy converters (WECs).

It must be highlighted whilst this paper is focusing on the mooring system for WECs, the proposed method of establishing component reliability information can be generically applied to a range of structural, mechanical, hydraulic and electrical component of MECs.

2. Component reliability testing

Reliability testing and demonstration are an integral part of the overall reliability programme of product development. While reliability testing aims to reveal any design weaknesses and tries to establish if the component/equipment under test meets the operational requirements, the demonstration of reliability will also provide evidence that the component meets a specified reliability target under stated conditions (Santhamma et al., 1988).

2.1. Component testing in other industries

Reliability testing is widely used in numerous industries to provide assurance that components and products are fit for purpose. The general requirements and procedures are described e.g. in the British Standard 5760-4:2003 (BSI, 2003).

Electronic components have been systematically tested for decades, providing information about failure modes, mean time to failure (MTTF) and stressors (Meuleau, 1965). Other industries that make extensive use of reliability testing are for example the automotive, aviation, offshore oil and gas, mining and astronautic industry. In all such cases the reliability of systems has to be assured before operational deployment/product launch, or long term specifications (e.g. operational safety, fatigue life) had to be established with limited operational experiences. A bibliographic list of reliability test applications was compiled by Dhillon (1992, 2007).

Recent examples from the automotive industry include the fatigue life testing of a rear tow hook assembly (Petracconi et al., 2010) and the validation of fatigue life predictions for a fusion welded suspension arm to realise weight reductions (Fourlaris et al., 2007). Both examples physically simulate in-service operational loadings to verify and/or improve component reliability and design.

Cardenas et al. (2007) used accelerated testing to achieve a more rapid degradation process of umbilical cables in order to investigate the combined environmental effects of cyclic loading, marine environment and ultraviolet radiation.

2.2. Test types

Having decided that a component reliability programme should be developed, a decision has to be made upon the type(s) of test. A large variety of tests is described in the literature, but a broad distinction can be made in terms of the phase of product development. At an early stage the focus lies on accurate reliability prediction whereas later stages are more concerned with reliability growth considerations. In general the type of tests can be classified by their purpose (Schijve, 1985):

- Testing of full-scale structures - Indicate fatigue critical items of a structure, obtain crack growth data to schedule service inspections, validation of damage tolerance requirements;

- Testing of specimens - Obtaining data on crack growth and specimen life to support and optimise structural design;

- Comparative tests - Investigation of design parameters and variables;
- Model validation testing - verifying model predictions e.g. for fatigue life and crack growth.

The type of test can be further distinguished, depending on how accurate the field loads are replicated and to what extent they are accelerated (Klyatis and Klyatis, 2006).

- Field testing of the actual system under accelerated operating conditions
- Laboratory testing of actual system through physical simulation of field loads
- Virtual (computer-aided) simulation of system and field loads

Raath (1997) investigated the relationship between test type, acceleration and required safety factors. He argues that the test type determines the necessary safety factor. For example, in-service testing applies the actual loadings to the component, so lower safety factors can be applied with confidence, whereas a series of single axis tests necessitate a higher safety factor to compensate for the simplified load assumptions. However, if tests are highly accelerated, they implicitly assume failures mechanisms are independent of cycle frequency, which is not always the case (e.g. corrosion fatigue).

As a result of these interdependencies, accurate service load simulation can contribute to reduce costly safety factors of components and obtain reliability information at the same time.

Position of Table 1.

3. Component testing procedure

The process of providing evidence of system/component reliability under operational conditions can generally be divided into four successive steps (Weltin, 2009):

- Measuring of realistic load data,
- Identification of representative loading regimes,
- Testing of a (representative) sample on a laboratory test rig under the representative loads,
- Root cause analysis and statistical evaluation of test results.

Heuler and Klätscke (2005) describe a more specific process to generate and use standardised load spectra and load-time histories. Such test regimes have been applied to test aircrafts (TWIST, FALSTAFF), helicopters (HELIX), cars (CARLOS), wind turbine blades (WISPER/WISPERX) and offshore structures (WASH). They aim to assess the fatigue behaviour of structures and components when simple constant amplitude assumptions/data do not provide a sufficient level of confidence. This is particular the case if the load spectra significantly differs in amplitude and mean-stress variations compared to assumed constant amplitude loading or in the case of multiaxial, complex loading.

To generate a representative and meaningful test regime an iterative five stage process has been applied in industrial applications (Heuler and Klätscke, 2005; Kam, 1992; Etube et al., 2001) and that has been adopted here towards MECs (Figure 1):

1. Define an operating period and conditions (e.g. operating time, environmental conditions, wave climate) resulting in an expected operating profile;
2. Undertake field load measurements under operational conditions (or alternatively calculations/assumptions);
3. Process the measured load samples to establish a "load library" for different operating conditions;
4. Implement the operational profile for the planned test regime;
5. Finally, generate the test load sequence through the combination of operating profile and load library segments.

Steps 1 and 2 would represent data input related to a specific MEC device and site conditions. Ideally, the operating conditions and load data would be defined and measured directly in the field, e.g. the wave climate and loads experienced by the components of a prototype device or sub-system under full scale sea conditions. Steps 3 to 5 are based on established theoretical methods that can be applied, which will be discussed in the following. To close the loop for comprehensive component reliability testing a root cause analysis of occurring failures would need to be implemented additionally.

Position of Figure 1.

3.1. Identifying representative loading regimes

To obtain a load library for different operating conditions, the load cycles are extracted from the load signal to derive a representative loading regime. Measured loads for different operational conditions would present distinct entries to establish a load library.

There are different methods to characterise load signals. When the load cycles are of randomly varying amplitude the so-called rainflow count method is commonly used to evaluate fatigue damage, as it realistically considers the fatigue damage caused by each, individual load cycle. It identifies and counts the stress ranges corresponding to individual hysteresis loop (Schijve, 2009).

The rainflow algorithm is based on a definition of a rainflow cycle (Rychlik, 1987). Starting from a local load maximum Max_K (Figure 2) the region to the left and the right, which are characterised by lower load levels than Max_K are determined. Two minima are identified before and after Max_K, i.e. Min_{K+} and Min_{K-}. That minimum having the smaller deviation from Max_K is chosen as the rainflow minimum $Min_{K,RFC}$, giving the k:th rainflow cycle $(Min_{K,RFC}, Max_K)$. This algorithm is then repeated over the entire time series t.

Position of Figure 2.

Further, with t_K as the time of the k:th local maximum and the rainflow amplitude characterising the amplitude of the hysteresis loop the total damage $D(t)$ can be calculated by the Palmgren-Miner rule. It assumes that the each cycle causes a damage of $1/N(S_{K,RFC})$:

$$D(t) = \sum_{t_k \leq t} \frac{1}{N(S_{K,RFC})} = K \sum_{t_k \leq t} (S_{k,RFC})^{\beta} \tag{1}$$

Where $N(S_{K,RFC})$ is the number of cycles during the time t. K represents a material dependent random variable and β is usually taken to be a fixed constant, both describing the shape of the material's S-N curve:

$$N(S) = \begin{cases} K^{-1}S^{-\beta} & S > S_{\infty} \\ \infty & S \leq S_{\infty} \end{cases} \tag{2}$$

With N(S) number of load cycles; S stress amplitudes

It is worth noting that β is usually in the range from 3 to 5 for many components and thus, from equation 1, when the amplitude of a load cycle doubles the amount of fatigue damage increase by a factor of between 8 and 32. Therefore the fatigue damage caused by small load cycles is negligible compared with those by the largest load cycles. So the smallest load cycles can be ignored in a test programme as they have a negligible effect on the result.

3.2. Accelerated testing

In order to complete the physical testing within justifiable time and cost budgets, component reliability tests usually have to be accelerated, implementing steps 4 and 5 described above. Escobar and Meeker (2006) distinguish four general possibilities that can be applied to accelerate reliability tests, by increasing the following characteristics either one by one or simultaneously:

- Use rate of the component , e.g. increased load cycle frequency;

- Test stress levels, e.g. increased load force ranges compared to normal operating conditions;
- Radiation exposure intensity, e.g. increased UV radiation;
- Aging rate of the component, e.g. increasing the chemical degradation process through higher levels of humidity.

This can be achieved by cycling the items under more severe stresses compared to the expected normal operation, which leads to earlier failures and hence reduced testing periods. It is thereby important, that the failure mode of normal operation and accelerated conditions stays the same (Lydersen and Rausand, 1987). An example where the test regime influences the failure mode is corrosion fatigue, as the crack growth is heavily dependent on cycle frequency. If this failure mechanism is accelerated through high cycle frequencies (e.g. 10Hz test frequency instead of 1Hz operational cycle frequency) the fatigue life of the component would be overestimated since the effect of corrosion is decreased over the shorter test times, by the higher cycle frequencies (Uhlig, 2000). For a detailed description of accelerated test methods the reader may refer to (Nelson, 1990, 2005; Escobar and Meeker, 2006).

3.3. Root cause analysis and statistical evaluation

In order to gain comprehensive information from any component test an analysis of the root cause and statistical significance of occurring failures needs to be conducted. While the component failure is identified through the failure mode (e.g. corrosion, rupture, crack, etc.) the root cause analysis investigates the reason for component failure. Once the failure cause is established measures need to be taken to improve the component reliability. The improved component should be retested (O'Connor, 2008). As a result the establishment of more reliable component for specific applications becomes an iterative process. The numbers of iterations during system development have to be limited due to cost and time constraints. This should prevent early catastrophic in-service failures as it reveals possible failure modes and associated causes. The root cause analysis also has its application during the operational life of a system, as occurring failures need to be investigated and subsequently resolved.

Both parametric and non-parametric models can be used to derive a statistical model from the test results which will give an indication of component failure rates and lifetimes under normal operational use. Rausand and Høyland (2004) describe a range of models for the three acceleration designs mentioned above. However, for statistically significant results numerous components need to be tested, so in early design stages it is more cost efficient to test one component under accelerated conditions, investigate the root cause of the failure and aim for a design improvement.

4. Component testing for marine renewables

Reliability testing is essential for any product development programme, in particular if the development risks are high (O'Connor, 2008). This is certainly the case for the marine renewable energy sector which is now emerging from a research and development phase to the deployment of full-scale prototypes and even small commercial projects. Reliability test programmes are crucial in order to prove that the design is reliable under the harsh marine operating environment and the dynamic loads experienced by most marine energy systems.

The necessity to engage in component testing at this stage of development is mainly due to the three following aspects:

- The need to reduce costly safety factors in the design of MECs.
- The current development of marine energy towards commercial deployments, necessitating reliable estimates of plant-performance indicators, i.e. reliability, availability and maintainability (RAM).
- Both investors and insurance companies require assurances of reliability for safety and economic reasons. Reliability test results are a key component of this assurance.

The implementation of proven technologies and components in the design of MECs is confronted by the different environmental and operational conditions which lead to uncertainty as to how previous knowledge should be applied. Component testing in truly representative conditions will allow the establishment of the necessary specific information about component performance and failures.

A component test facility to collect reliability data especially for wave energy converters was proposed by Salter (2003a) and described later in more detail (Salter, 2003b). The suggested design of a floating raft included test beds to operate rams, seals, belts and cables at their operational use conditions; conduct cavitation testing and expose components to marine fouling conditions to assess the effectiveness of coatings. The initiative was not pursued further principally due to the cost and practicality of such a platform.

Wolfram (2006) suggested the application of accelerated testing for critical components to assess if the environment alters known failure rates. Any test results should be collected in a collaborative failure rate database.

The Carbon Trust (Callaghan and Boud, 2006) proposed both knowledge transfer from established offshore industries (e.g. engineering standards, risk assessment methods) and rigorous testing of components, sub-assemblies and device prototypes to mitigate technical risks. And indeed many companies have had their devices assessed in this way by consultants such as WS Atkins or by certifying authorities such as Det Norsk Veritas (DnV).

Mueller and Wallace (2008) called for extensive testing to improve reliability and establish a statistical database of component reliability in the marine renewable environment. The failure rate data currently available is scarce and often generic, making crude adjustments necessary that lead to necessarily conservative and highly uncertain results (Thies et al., 2009).

Marine component test efforts

Although extensive component testing in representative conditions is considered suitable to mitigate technical risk and to build up confidence of stakeholders, results from specific tests are so far sparsely publicised for the marine energy application.

One of the few examples is the full-scale rig that was constructed to test the hydraulic power take-off of the Pelamis MEC (Henderson, 2006;

Yemm, 2003). The power module of the Pelamis device was exercised by an externally mounted 1MW hydraulic actuation system that replicated the heave and sway wave force and motions experienced at sea. The main objectives of this test effort were:

- Providing evidence of the power conversion efficiency,
- verifying the PTO control algorithms,
- functional testing of the power module components, particularly seal performance,
- gaining experience to assemble and operate the power take-off.

The intention of the three month cycle test was not to provoke failures by accelerated testing, but rather "...to increase confidence in reliability before the first offshore test"(Yemm, 2003). It is further stated that the rig will be further used to assess new components, control algorithms and to simulate any field failures of the full-scale prototype.

Another, more recent test example is a performance test for a new device concept called Aegir Dynamo (Al-Habaibeh et al., 2010). The power take-off system is tested under realistic, simulated wave force conditions in one degree of freedom. The test rig is a hydraulic linear piston, rated at 55kW hydraulic power with a maximum force of 63.8kN, aiming to replicate random wave profiles up to 3m (Ocean Navitas, 2007).

From these two examples and the lack of other published failure-induced testing, it appears that testing efforts are mainly concerned with the functionality and performance of the power take-off system. Furthermore a tendency to demonstrate the reliability of systems and components is apparent in the testing approach undertaken, rather than accelerating the reliability test and inducing failures. While this is a suitable approach to convey confidence, it does not investigate the physical limits of the components (i.e. reliability limits). This important disparity is highlighted by O'Connor (2008), who states that in order to come to meaningful results in a cost- and time-effective way ". . . we must test to cause failures, not test to demonstrate successful achievement".

5. Outline of a case study for a moored WEC installation

The traditional approach in the offshore oil and gas industry is to minimise resonant response conditions to achieve an acceptable stability which allows the reduction of critical loadings, that otherwise could lead to failure. Contrary to this, many WECs operate close to the resonant frequency in at least one degree of freedom, within the most energetic wave conditions, in order to maximise power conversion (Bates and Hill, 2005). This dynamic behaviour could add to accumulated loads, leading to component and/or system failure.

5.1. Extreme and operational loads

For moored WECs it has to be identified if the weighting of the "N-year" return extreme waves, responsible for survivability, or specific average sea state conditions, such as groupiness, governing reliability, are driving the main design consideration. Clearly, extreme waves need to be applied in the analysis to predict survivability that can be based most likely on offshore oil and gas station keeping standards, such as DNV-OS-E301

(Det Norske Veritas [DNV], 2008). However, to prevent fatigue failure of components due to accumulated loading, which could have important implications for reliability, in service loads need to be considered.

Consequently with regard to component reliability, both design dimensions have to be satisfied:

1. Testing for survivability where a device/component is required to withstand the maximum force/load.
2. Testing for reliability where a device/component is required to withstand the operational (mean) loads and forces.

While those considerations can be applied to the range of structural, mechanical, hydraulic and electrical components of WECs, this paper will focus on the operational implications for mooring systems, as they are likely to be a major technical risk for WECs due to the large dynamic response characteristics of motion dependant devices (Wolfram, 2006). During the mooring design process, both cases mentioned above need to be assessed i) the extreme environmental conditions, i.e. the Ultimate Limit State (ULS) and the Accidental Limit State (ALS); as well as ii) the expected accumulated fatigue damage for discrete reference conditions (Johanning et al., 2005; Det Norske Veritas [DNV], 2005). In particular fatigue reliability is likely to be a major concern, because during a 20 year lifetime, load cycles are expected to reach the order of 10^9 for wind offshore installations (Schaumann et al., 2004). Depending on their operational principle and site of installation WECs are likely to experience a similar or more serious cyclic loading regime. The actual wave loading for each device has to be determined through numerical simulation, tank tests and field measurements.

5.2. Safety factors

The established practice in the offshore hydrocarbons industry to overcome the environmental loading uncertainties is to apply larger design safety factor. However, increased safety factors incur higher capital costs which are justified and accepted in safety-critical applications and are also more easily accommodated in the high-value product form the hydrocarbon industry. If any system failure or downtime occurs, costs of safety factors need to be outweighed by the consequence of failure in order to be justified (Ayyub and McCuen, 2003). In the case of marine renewable energy it can be argued, that the actual product - electricity - does, currently, not have the monetary value which would justify largely over-engineered structures and devices. A large part of a safety factor is often a 'factor of ignorance', either about the loading on a system or its response to that loading. Reliability testing under realistic loading conditions reduces that ignorance and allows a lower safety factor.

As higher levels of reliability in principle relate to higher construction and design costs, maximum reliability is not in itself the goal, but it should be maximised under prevailing cost-constraints, i.e. minimising the overall risk. A minimum required (target) reliability is often governed by the severity of failure consequence. Loss of human life is the most severe failure consequence and often determines acceptable levels of failure probability and safety levels. Maintenance operations during high seas may put lives at risk, but as WECs are usually unmanned, the maximum (catastrophic) consequence would be usually loss of capital equipment or production income. The possible loss of reputation might be even more severe for the industry. Another possible indirect consequence to risk of life and/or environment could be the result of mooring failure that could lead to collisions between the drifting devices and other marine users. A reduction of safety factors must be balanced for every individual component, assessing the potential cost reductions against the additional risk of failure. Component tests are a key tool to assess this balance as the failure rate probability under representative load conditions can be assessed for different design alternatives.

5.3. Experience from device developers

Two published examples document the specific requirements of WECs with regard to design and reliability considerations of moorings.

Retzler (2006) reports the experimental measurement of the slow drift forces of a 20^{th} scale model that replicated the dynamics of the full-scale prototype. The measured mooring forces and power absorption have each been presented as capture width ratios, i.e. dividing the mean mooring force by the mean wave force:

$$F_{CW} = \overline{F_{Moor}} \,/\, \overline{F_{Wave}} = \overline{F_{Moor}} \,/\, \frac{1}{4}\rho g a_i^2 \tag{3}$$

Where F_{CW} = Force capture width, $\overline{F_{Moor}}$ = Mean mooring force, $\overline{F_{Wave}}$ = Mean wave force, a_i= incident wave amplitude.

Figure 3 shows the capture width ratios for mooring force and absorbed power of the device, reaching a peak capture width in excess of 12m (about four times its beam). As a result the drift forces are much higher than for a vessel of similar dimensions that does not aim to absorb the wave power.

Kofoed et al. (2006) compare the measured mooring forces of the scaled wave tank testing with field loads experienced by the Wavedragon prototype. The prototype trials showed the occurrence of high snap loads (Figure 4) which could lead to mooring failures, but may be mitigated by an elastic mooring configuration.

These specific mooring load characteristics underline the importance of dedicated component testing to ensure the mooring arrangement meets an acceptable level of reliability, both in terms of extreme loads and possible fatigue failures.

Position of Figure 3.

Position of Figure 4.

6. Case study

To illustrate the component test approach described above, a case study for a moored WEC is presented in the following.

In the context of this paper a test regime for a mooring assembly is derived using data that was obtained during tank tests conducted at the MARINTEK institute in Trondheim, Norway as part of a HYDRALAB III test, carried out during a SuperGen Marine project (Bryden and Linfoot, 2009; Ashton et al., 2009). Generic floating Oscillating Water Column (OWC) devices have been tested at 1:20th scale. The device was instrumented with mooring line load cells, optical motion tracker and accelerometers. Different wave and current test conditions were applied to the device, while motion (6 dof) and mooring forces were monitored. Figure 5 shows the experimental setup and mooring dimensions of the generic OWC in plan and elevation view. The mooring attachment points have been welded to the tank floor, so there is no consideration of bed effects.

Position of Figure 5.

6.1. Defining operating conditions

The operational conditions for MECs are site-specific, so an assessment of these is essential for prospective component reliability. The operating conditions would give an indication of the expected wave climate, and subsequent loads. Neither the seasonal and annual variations nor the spectral variations are considered in this paper, but should be in a full analysis.

The tank test conditions covered a range of wave heights $Hs = 2m - 6m$, wave periods $Tp = 5s - 13s$ and current flows (at 1:20^{th} scale). Although the test tank data does only roughly replicate field conditions, it allows high sample frequencies and lends itself to illustrate the procedure of deriving a representative test regime.

6.2. Load measurement

The time series in Figure 6 shows an excerpt of the measured load signal for the mooring line that was collinear with the wave direction. This specific test run simulated a wave climate with a significant wave height HS =3.5m and wave period $T = 8.0s$. The test was run for 120min, with a data sample frequency $f = 20Hz$. All values are presented for full scale conditions.

The signal shows a fluctuating tension force with occasional spikes. These spikes are due to the occurrence of snap loads on the mooring line, caused by a sudden acceleration of the OWC. While most of the load fluctuates around $F = 200kN$, the snapping induces much higher loads of $F > 1000kN$.

Position of Figure 6.

6.3. Identifying critical loads

The critical loads cycles for a possible fatigue failure have been obtained through a rainflow analysis procedure (described in 3.1) carried out with the WAFO Matlab toolbox (WAFO-group, 2000).

To calculate the Palmgren-Miner damage for the conducted mooring test (see equation (1), (2) above), K was set to K=1 (assuming no material variation) and the material parameter $\beta = 13.46$ for polyester moorings was obtained from (Banfield et al., 2000).

Figure 7 shows the Rainflow matrix for the full test length with $H_S = 3.5m$ and $T_p = 8.0s$. The matrix counts each range in the interval the cycle started (Min) and the value where the cycle is completed (Max). The number of occurrence indicates the number of observed load cycles in the specific range. It can be seen, that in the unfiltered case a) the majority of cycles have a very small range of less than 200kN.

In order to reduce the effect of potential signal noise and to exclude the load cycles that are too small to induce any fatigue damage, a threshold value was introduced. Load cycles with a range below a value of $F_{TH} = 50kN$ are not considered which significantly reduces the load counted cycles, as shown in Figure 7, case b).

Position of Figure 7.

The normalised fatigue damage is calculated by dividing the fatigue damage of each matrix cell by the computed total fatigue damage. The corresponding, normalised fatigue damage matrix is shown in Figure 8 and indicates the percentage contribution, from each load cycle, to the total fatigue damage caused during the duration of the test. While the small amplitude loads are not numerous enough to show an effect (due to the limited test length) the significant effect of the snap loads can be clearly identified and account for more than 95% of the fatigue damage caused during the test.

Position of Figure 8.

6.4. Accelerated testing

Once the most critical loads are identified, they can be used to generate a load test signal for physical testing. In the present case study an example is presented for a possible accelerated test signal by increasing the use rate of the mooring assembly. This is achieved by distilling the original load signal to the most severe cycles (tensile load force range in excess of 600kN) which have shown to cause most of the fatigue damage. This distilled line tension force signal, the corresponding turning points and a possible (simplified) test rig signal (interpolation between turning points) are shown in Figure 9. The use of such a test signal could replicate the most severe loads of a 2h test in less than a minute of laboratory test time and could in turn simulate one year operational loads under the assumed conditions in approx. 60h of continuous testing.

Position of Figure 9.

A second way to accelerate the reliability test is to increase the mean tensile force compared to the original load signal. The mean tension force of the presented load signal (Figure 6) is = 90kN. The mean load could be increased in a step-stress testing procedure as proposed in (Rausand and Høyland, 2004), where the mean load level is increased after defined time intervals, until the component fails. A possible regime would be to increase the mean stress level by 100kN after a defined test time interval while maintaining the force frequency. This regime is graphically illustrated in Figure 10, where the mean stress levels are subsequently increased from $s^0 = 600kN$ to $s^3 = 900kN$. A third possible acceleration design would be to continuously test a number of components at different but constant stress levels, or to increase the stress continuously.

Position of Figure 10.

The results of such accelerated testing would assist to reveal early failures and would provide information on component failure rates and expected lifetime under operational conditions.

7. Conclusions

For the marine renewable energy sector to emerge successfully from the research and development phase toward commercial-scale deployment, marine components need to be extensively tested and proven for two main reasons:

- The cost of field failures is high, in particular in the case of array configuration with numerous devices.
- There is a real need for independent validated data for components used in the marine renewable. This is true both for engineering verification but also to increase confidence of investors and insurers.

This paper has given an account of the operational characteristics of MECs and the corresponding need of component testing to establish applicable failure rate estimates and consequently to develop reliability growth for devices. It has been further shown, how a generic reliability test approach employed in other industries could be used to provide evidence of component reliability under specific operational (test) conditions.

The case study for a mooring component test applied a rainflow analysis procedure to available tank test data in order to establish a possible accelerated component test regime. The most severe load cycles, largely contributing to the fatigue damage were identified and reproduced in the test signal. In this way one year operational loads under the assumed wave tank conditions could be simulated in approx. 60h of testing. Although this technique has been demonstrated using mooring line dynamics as an example, the approach will be suitable for many of the component subsystems.

8. Further work

It is intended to apply the presented approach in conjunction with the facilities of Peninsula Research Institute for Marine Renewable Enegy (PRIMaRE) (2010) research group:

1. The operational conditions will be measured using wave buoys and acoustic Doppler current profileometers (ADCPs),
2. Real time load data of various mooring configurations will be measured using the South Western Mooring Test Facility (SWMTF) (Johanning et al., 2008).
3. The Dynamic Marine Component Test facility (DMaC) will be used for specimen and accelerated component testing (see also Figure 1).

Adopting a service-simulation testing approach might be capital expensive but it will enable device developers and component manufacturers to reveal possible failure modes/design weaknesses and to estimate component failure rates. This allows an early assessment, to improve and to demonstrate the component reliability of MECs before they are deployed in the field. Further, component testing will provide information regarding operation and maintenance (O&M) issues. These include operational planning of maintenance/replacement schedules. The results would also contribute to an understanding of how condition monitoring can be applied in an effective way. It is certainly true that the cost-effective deployment of larger arrays will be heavily dependent on issues arising from reliability and maintenance that should be investigated prior to mass deployment.

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10. Figures and Tables

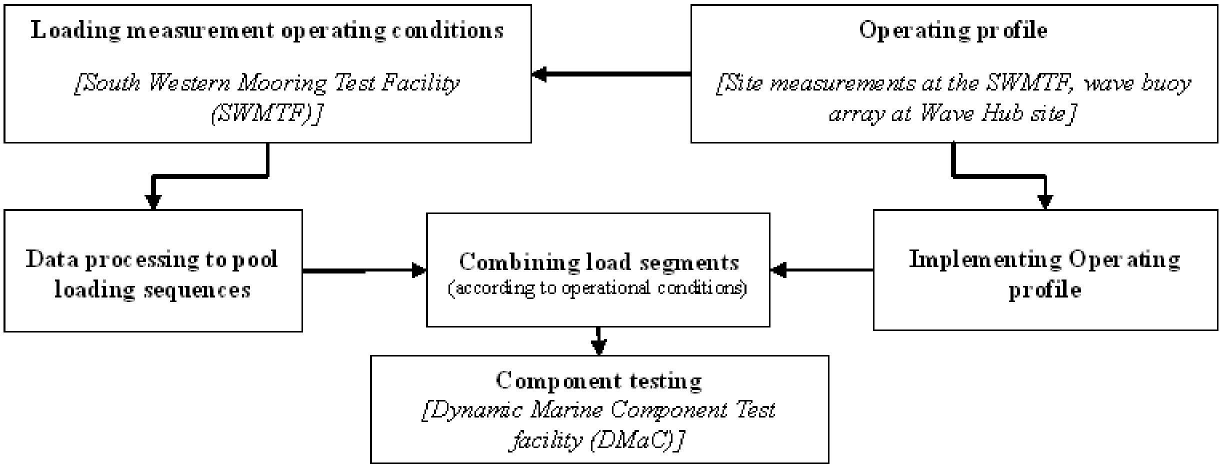


Figure 1: General simplified approach for the generation of standardised load-time history [based on (Heuler and Klätscke, 2005)] and facilities within the PRIMaRE research group

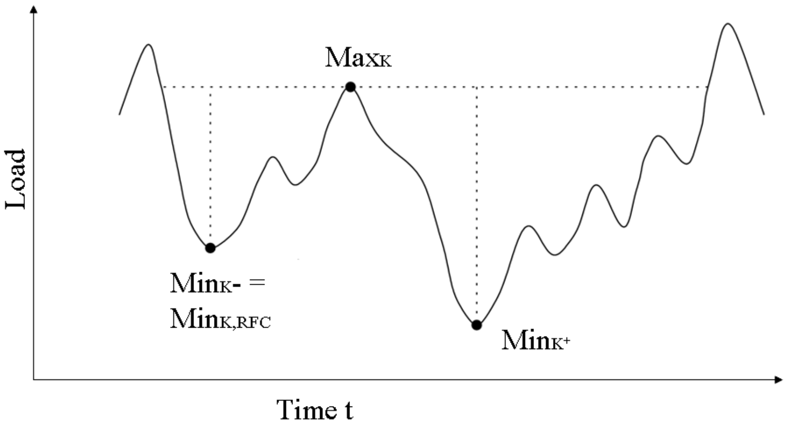


Figure 2: Rainflow cycle definition, after (Rychlik, 1987)

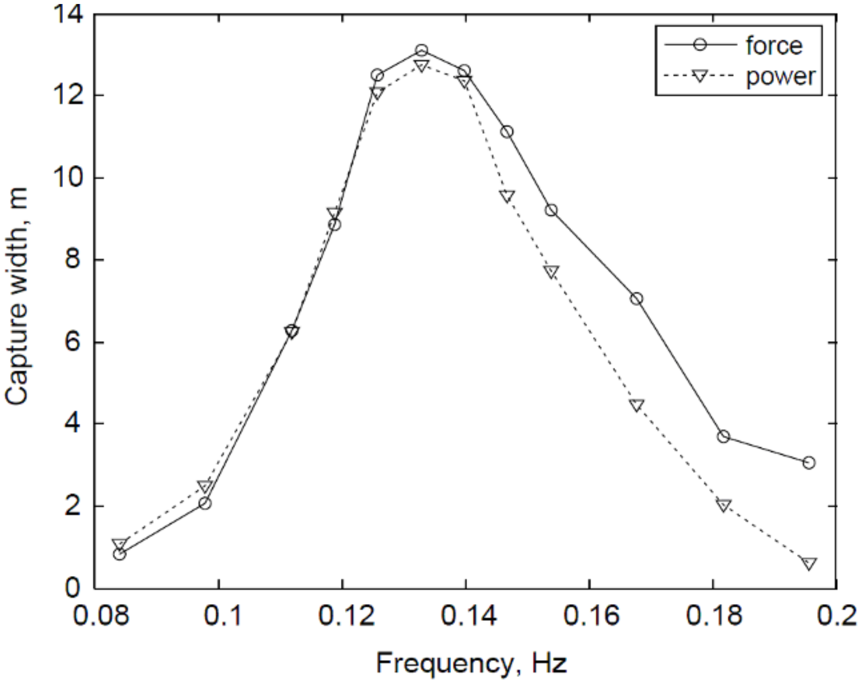


Figure 3: Capture width ratios for mooring force - and power absorption for Pelamis experiment (Retzler, 2006)

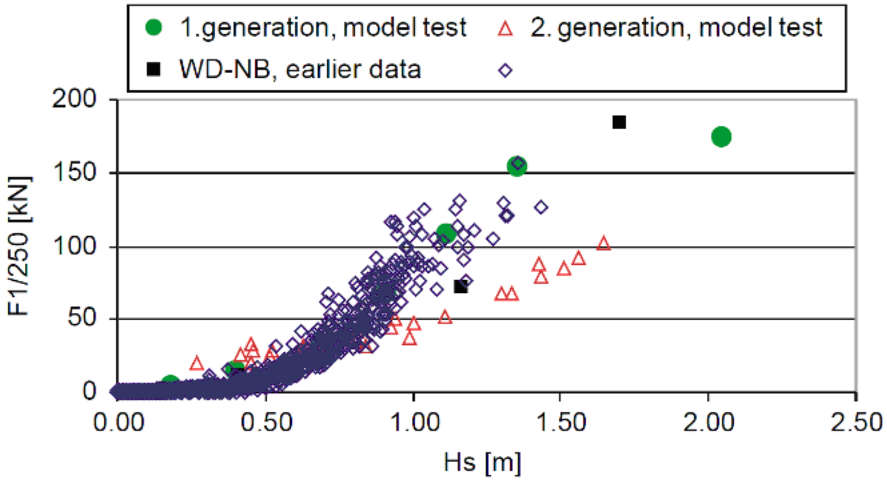
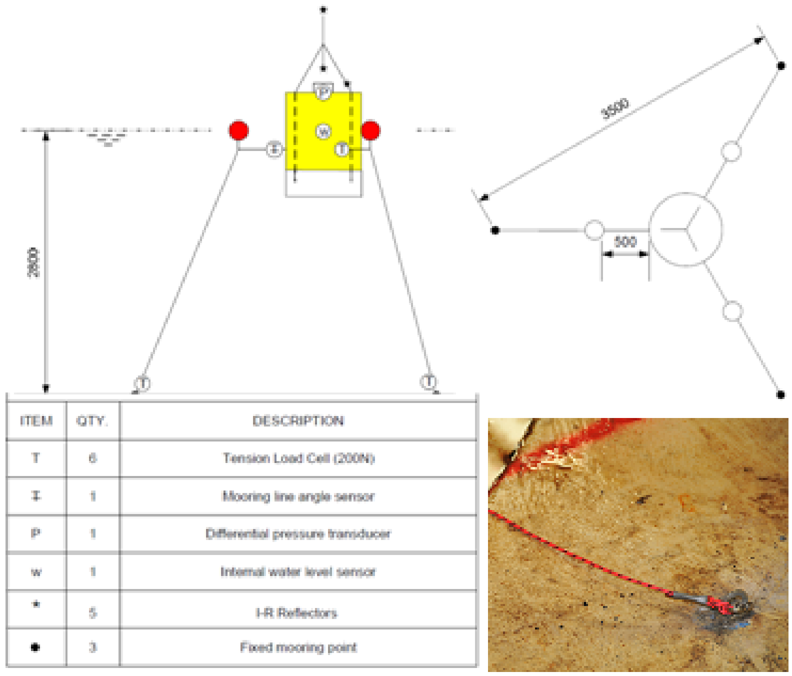


Figure 4: Wavedragon mooring forces (prototype scale) in terms of F1/250 (average of the 1/250 largest peaks), measured during model tests and prototype measurements (Kofoed et al., 2006)

Test type	**Acceleration**	**Loading**	**Safety factor**
In service	None	Actual loading	Low
Service load simulation	Low	Selections of true loading	Low
Cyclic single axis	Medium	Multiple level	Medium
Cyclic multi axis	High	Single level	High

Table 1: Type of test and required safety factors, based on (Raath, 1997)



ITEM	QTY.	DESCRIPTION
T	6	Tension Load Cell (200N)
T̶	1	Mooring line angle sensor
P	1	Differential pressure transducer
w	1	Internal water level sensor
*	5	I-R Reflectors
●	3	Fixed mooring point

Figure 5: Experimental setup and mooring dimensions [mm] of generic floating OWC used in tank test. Left: plan view; Top right: elevated view; Bottom right: welded anchor point

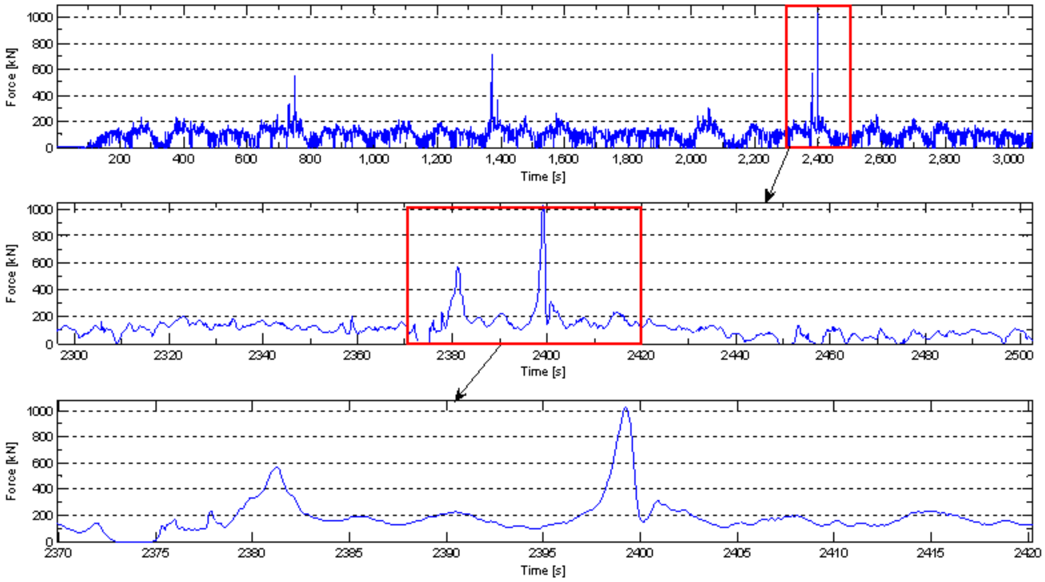


Figure 6: Raw signal of line tension force F [kN] for full scale dimensions

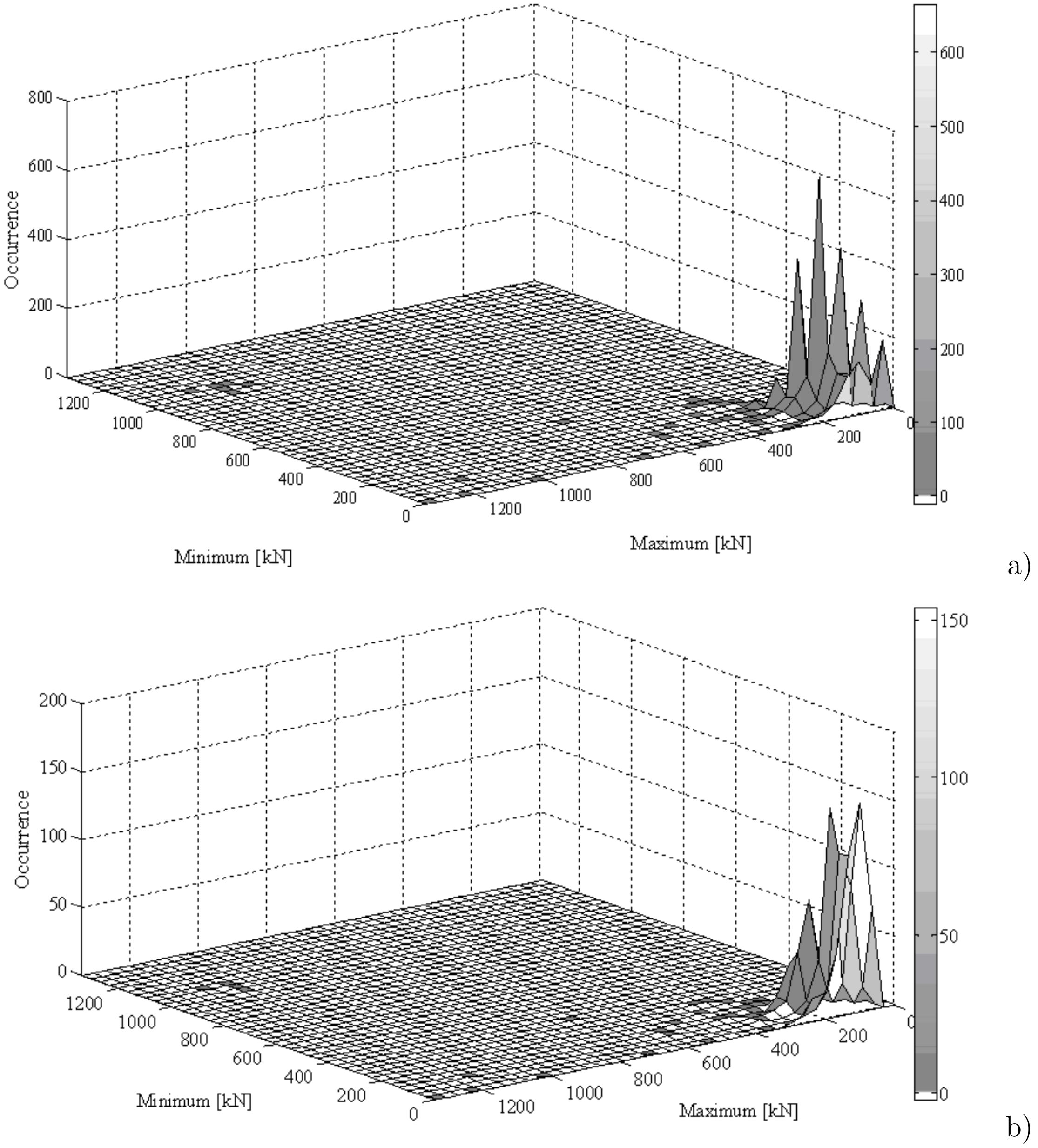


Figure 7: Rainflow cycle matrix indicating the occurrence of mooring line tension load cycles ranges [kN] a) Unfiltered Rainflow matrix b) Filtered Rainflow matrix with threshold value $F_{TH} = 50kN$

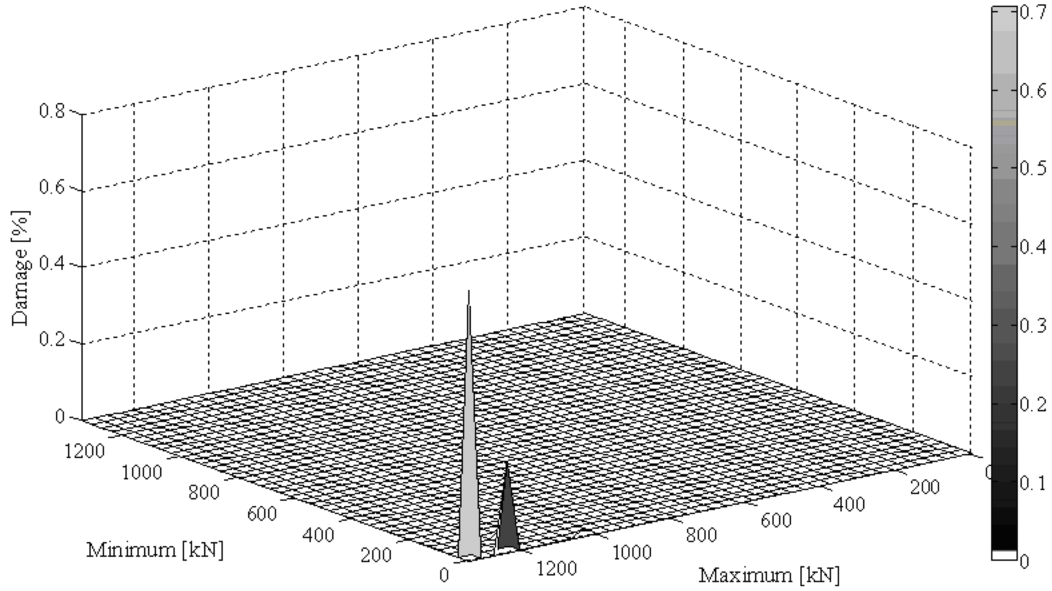


Figure 8: Normalised fatigue damage matrix indicating the damage contribution of different rainflow cycles during the tank test

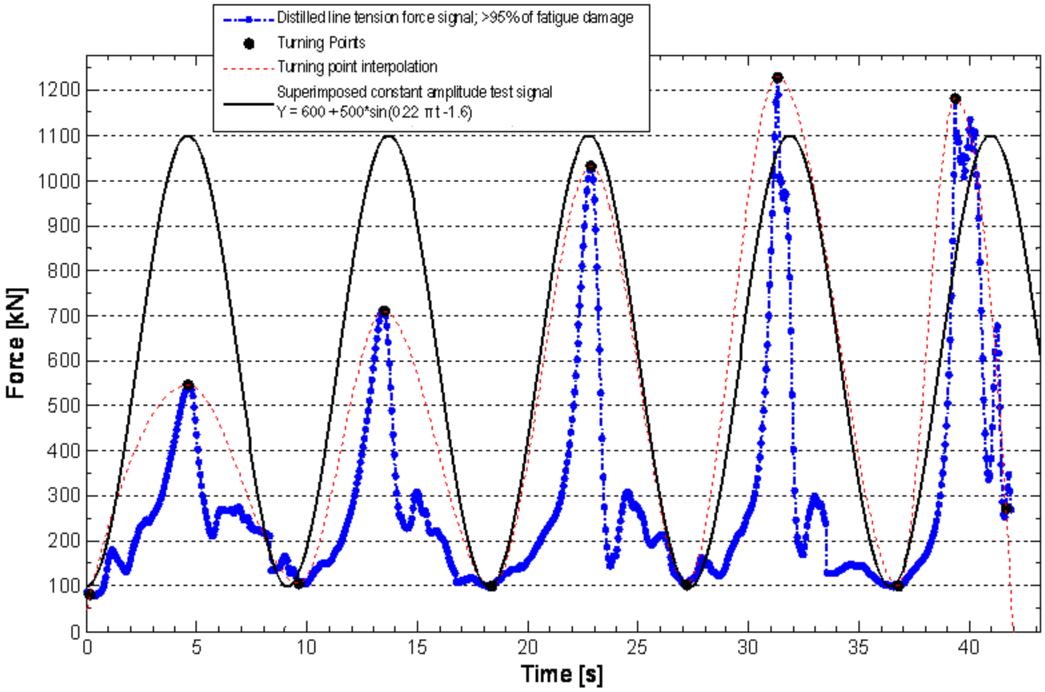


Figure 9: Distilled mooring tension load signal [kN], turning points and indicative test cycle regime

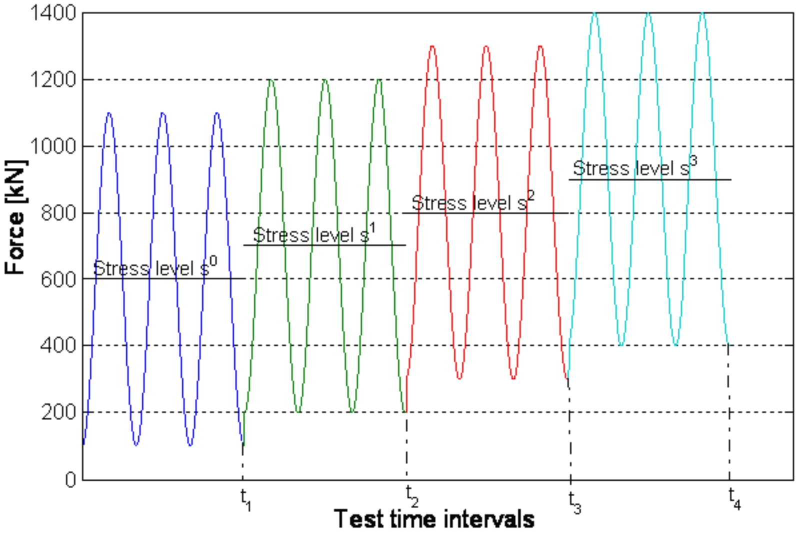


Figure 10: Step stress accelerated test regime