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Finding Dangerous Waves—Review of Methods to Obtain Wave Impact Design Loads for Marine Structures

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Green water and slamming wave impacts can lead to severe damage or operability issues for marine structures. It is therefore essential to consider their probability and loads in design. This is difficult, as impacts are both hydrodynamically complex and relatively rare. The complexity requires high-fidelity modeling (experiments or CFD), whereas a statistically sound analysis of rare events requires long durations. High-fidelity tools are too demanding to run a Monte–Carlo simulation; low-fidelity tools do not include sufficient physical details. The use of extreme value theory and/or multi-fidelity modeling is therefore required. The present paper reviews the state-of-the-art methods to find wave impact design loads, which include response-conditioning methods, screening methods, and adaptive sampling methods. Their benefits and shortcomings are discussed, as well as challenges for the wave impact problem. One challenge is the role of wave non-linearity. Another is the validation of the different methods; it is hard to obtain long-duration high-fidelity wave impact data. [DOI: 10.1115/1.4056888]

Keywords: computational mechanics and design, design of offshore structures, dynamics of structures, fluid-structure interaction, hydrodynamics, ocean waves and associated statistics, offshore safety and reliability, probabilistic model of forces and motions, probability and spectral wave modeling, reliability based codes and guidelines, wave mechanics and wave effects

1 Introduction

Ships and other marine structures are exposed to wave impacts such as slamming, green water, and wet-deck or air-gap impacts at sea (see e.g., Fig. 1). Such wave impacts can lead to unsafe situations, severe damage, or operability issues.

1.1 Wave Impact Accidents. This has been emphasized by some regrettable accidents. Drilling platform “COSL Innovator” was struck by a steep wave in 2015 close to Norway, leading to the death of a crew member, several injuries, and extensive damage to the living quarters [2,3] (see Fig. 2). This accident was the reason for class societies to revisit their rules for wave impact design loads on offshore platforms. Interest in the topic also increased for ships when green water may have played a role in the loss of containers from “MSC Zoe” in 2019 in the shallow part of the Dutch North Sea [4]. Longer ago, containership “P&O Nedlloyd Barcelona” sustained considerable damage to its front containers due to green water in heavy weather on the North Pacific (Fig. 3). Even more serious damage was reported by Ref. [5]: a bow-quartering wave with a height around 20 m caused a big slamming event, leading to a crack in the bow flare of a containership sailing in the North Pacific in 1978. The terrible accident with the “Estonia” ferry in 1994 has also been linked to a large slamming event, that dislocated the bow visor and led to the capsizing and sinking of the vessel [6]. Another infamous fatal accident was that with the sunken “Derbyshire” in 1980 (e.g., Ref. [7]), which led to revision of the design of bulk carriers. Another, less extreme, example is the risk of wave crests hitting and damaging overhanging lifeboats on cruiseships, as happened on “Explorer of the Seas” in 2014 [8–10]. An accident with a ferry on the river Elbe in Hamburg in 2022 showed that vessels are not even safe for green water impacts on a river 50 miles inland during a storm, see Ref. [11] and Fig. 4. The Norwegian Petroleum Safety Authority reported 29 wave impact accidents on semi-submersibles in the Norwegian Continental Shelf between 2000 and 2020 [12]. A catalog of “rogue wave occurrences” based on eyewitness accounts and wave heights above the static ship freeboard was published by Refs. [13,14]. Many of these waves were probably not rogue waves under the usual definition, but the papers provide an overview of

Fig. 1 HMS Edinburgh of the UK Royal Navy in a heavy storm with 8 m waves on the South Atlantic. Courtesy: D. Rosenbaum, Royal Navy Media Archive; reproduced with permission from Ref. [1].

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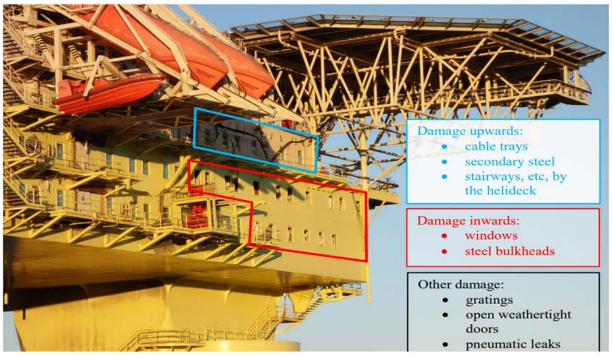

Fig. 2 Damage to semi-submersible drilling platform "COSL Innovator" after the wave impact in Dec. 2015. Reproduced with permission from Ref. [2], courtesy: Petroleum Safety Authority Norway.

wave impact accidents with mainly cruiseships and yachts. Other lists with wave impact accidents were assembled by Refs. [15] (green water on UK production ships), [16] (green water on Norwegian production ships), [17] (general green water accidents), [18] (ships in extreme sea states), [19] (ship slamming), and [20] (wave impacts on semi-submersibles).

1.2 Wave Impact Occurrence Statistics. All the above mentioned publications refer to wave impact accidents that led to significant damage, loss of life, or other serious effects. Not every wave impact has such dramatic consequences. The accident occurrence statistics are therefore not equal to the wave impact occurrence statistics. However, any study of the statistics of wave impact occurrence itself has to evaluate very long-duration model test (or full-scale monitoring) results in irregular waves; much longer than the typically applied 1 h or 3 h test durations. Such studies are rare, but a few can be found. The statistics of slamming impact occurrence on a large-volume cylinder are discussed by Refs. [23,24]. The statistics of green water and wave-in-deck impact occurrence, and their convergence with test duration, are discussed in Refs. [25,26]. Reference [27] discusses the statistics of green water occurrence on a simplified ship, and provides an overview of earlier statistical studies.

1.3 The Wave Impact Difficulty. It is clear that accidents as described in Sec. 1.1 are undesirable. Ships may be able to avoid bad weather in some cases, but critical individual wave crests are harder to predict and offshore structures can usually not avoid weather at all. So, in order to avoid hazardous situations, it is essential to consider the probability of wave impacts and the resulting loads in design.

Fig. 3 Green water damage observed in the port of Busan, South Korea on "P&O Nedlloyd Barcelona" after a heavy storm on the North Pacific. Reproduced with permission from Ref. [21], courtesy: Shipspotting admin P. Melissen / hwnautic.

Fig. 4 Snapshots from videos taken from the shore and by a passenger on inland ferry "Tollerort" on the Elbe in the harbor of Hamburg, Germany, while it was hit by a wave that smashed its front windows in storm Ylenia in Feb. 2022. Reproduced with permission from Ref. [22], courtesy: Jim Davis.

Wave impact extreme values are difficult to obtain, as impacts are both hydrodynamically complex and relatively rare. The complexity requires high-fidelity (HF) modeling (experiments or computational fluid dynamics (CFD)), whereas wave impact experiments in for instance [24–26] show that insight into the variability of these loads and a statistically sound analysis of rare events requires long-duration modeling. State-of-the-art CFD is able to quite accurately predict the wave impact load in a given wave event (see e.g., Refs. [28–33]). However, such HF tools are too computationally demanding to run a full Monte–Carlo simulation (MCS). Low-fidelity (LF) tools can be run for a long time, but do not include sufficient physical details. An important unanswered question therefore remains: how can we combine tools with different fidelity levels to efficiently obtain wave impact design loads and their variability?

1.4 Objectives and Approach. The present paper forms the start of a project that therefore aims to ***develop and validate a multi-fidelity procedure to identify short-term design loads for extreme wave loading on marine structures***. The paper contains a literature review and conclusions on areas where further study is required. First, Sec. 2 defines the most important failure modes for wave impacts. Apart from hydrodynamics, there are two statistical fields of study that play a role in wave impact design load prediction: Sec. 3 explains extreme value theory and Sec. 4 explains multi-fidelity theory. Section 5 presents an overview of applications of these theories to extreme value prediction (EVP) for non-linear response of marine structures in waves. Most of the multi-fidelity methods use LF "surrogate" models. Section 6 presents suitable surrogates for wave impacts. Next, Sec. 7 discusses the specific topic of wave non-linearity, as the statistics of wave impact phenomena are strongly related to those of the encountered waves. The non-linearity of the ship motions also plays a role, which is discussed in Sec. 8. Section 9 discusses the validation issues that are encountered for EVP methods applied to wave impacts, and Sec. 10 summarizes the identified research "gaps." Finally, Sec. 11 draws some conclusions. An earlier version of the present paper was presented at the OMAE conference [34].

2 Failure Modes

A failure mode is defined as (one of) the way(s) that a structure can fail. A wave impact load may cause the structure to fail in one or more of these modes. Structures can have different failure modes; which is the most critical depends on the exerted loads, the structural layout, possible mode combinations, manufacturing errors, fatigue, etc. Slamming-type impact phenomena are closely linked to hydro-structural interactions such as whipping (e.g., Refs. [19,35]). The relevant failure mode can therefore either be a local response (direct impact loads on sensitive structures) or a global response (global bending moments or fatigue). It was shown by Ref. [36] that direct impacts are the dominating loading process for wave-in-deck type of impacts, but that air entrapments and building jets on the front of the deck may lead to local load variations. For green water or air-gap type impacts, direct loads also seem the best choice. The present study will focus on local extreme loads due to slamming, green water, air gap, or wet deck impact events. Depending on the size and natural frequencies of the considered structure (the full ship, a panel of the hull, a breakwater, and a small vent on deck), the critical failure mode will be excited by a peak load, load impulse, or load rise time. A single load can be critical, but this can also be a combined loading. This is often considered in the form of load combination factors, where each load is normalized with its limit value and a vector of factors between zero and one indicates the simultaneous loading (see e.g., Ref. [37] and different class rules). Note that structural reliability analysis assumes that not only the loading is stochastic, but also the strength of the structure (e.g., Ref. [38]). Both need to be considered in order to find a "failure surface," where the loading exceeds the structural strength.

3 The Extreme Response Value Problem

3.1 Extreme Value Theory and De-Clustering. Waves and wave-induced responses are stochastic, so their extreme values are too (see Fig. 5). Extreme response values over a large number of realizations will follow an asymptotic generalized extreme value (GEV) distribution. The extremal types theorem [39,40] dictates that this can only take three forms: type I (Gumbel), type II (Fréchet), or type III (Weibull). This fact can be used in practical problems. The available number of response observations is often too low to be fully converged, but forms of the GEV can be fitted in order to reduce variability or to extrapolate to longer durations. See Refs. [25,26] for a discussion of the fitting quality applied to a typical wave impact dataset.

In order to use extreme value theory, it is required that the extremes in the dataset are independent and identically distributed (*iid*). Response peaks in waves have the tendency to cluster in time (due to wave grouping or memory effects). There are different ways to derive an extreme value dataset from given measurements, with different levels of de-clustering (e.g., Refs. [41,42]): using all peaks from the time traces, only the peaks over a threshold (POT, with or without a time separation constraint on consecutive peaks), the maximum value in each block of a few minutes (block maxima method), the *M* largest values in each wave realization, or only the largest value in each wave realization (ensemble maxima method). This list is ordered according to increasing de-clustering level and decreasing number of remaining peaks. Methods with a high level of de-clustering require a large number of wave realizations to obtain some statistical certainty, and de-clustering may modify important physical relations in the data (such as wave groups). There may therefore be reasons not to go to the bottom of the list. Figure 5 illustrates the differences in (cumulative) probability distributions between the elevations, peaks, and ensemble maxima for wave crests. The general idea of the peaks and ensemble maxima distributions in this figure is also representative for wave impact load distributions. For POT datasets with a sufficiently high threshold, GEV can be approximated by the generalized Pareto (GP) distribution (e.g., Ref. [43]).

3.2 Long- and Short-Term Extremes. EVP is associated with variability on the long and short term. Short-term variability is the variation in extreme response over different wave realizations or "seeds" of one wave condition, and long-term variability the variation in extreme response over all wave conditions in an operational profile or scatter diagram.

Short-term extreme response values are often presented in the form of the most probable maximum (MPM), or a "quantile" value. The 90% quantile is the value at which 90% of the ensemble maxima distribution is smaller. The MPM is the value that is most likely to occur; it is equal to the 37% quantile for a linear Gaussian signal (see Fig. 5). For offshore structures, quantiles around 85–95% [44,45] are considered a reasonable choice for design. For ships, the MPM value combined with a risk or safety factor is often used as reference value (e.g., Refs. [46,47]). The ensemble maxima distribution converges very slowly, so a large number of realizations is required to derive these quantiles. This is often not feasible in experiments. Extrapolation to longer durations based on extreme value theory fits (see Sec. 3.1) is therefore often applied.

Long-term extreme response values are often presented in the form of return periods. The environmental contour line approach [48–50] is commonly applied by the (offshore) industry to deal with short- and long-term variability for non-linear responses. This method decouples the long-term probability of a sea state from the short-term probability of a ship response, assuming that the long-term variability of the responses is equal to that of the

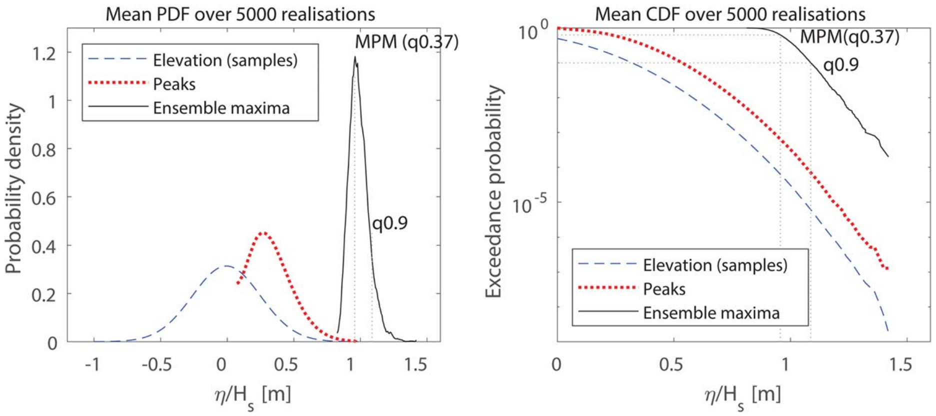

Fig. 5 Typical short-term probability density function and cumulative distribution of samples, peaks and extremes of waves, and wave-induced responses (here for 5000 realizations of 3 h linear Gaussian waves, JONSWAP spectrum, $H_s = 5$ m, $T_p = 9$ s, $\gamma = 3.3$). The elevation and peak distributions are the mean distributions over all realizations. The MPM and 90% quantile are also indicated (see Sec. 3.2).

waves. The classical approach identifies contours of equal joint sea state parameter probability (e.g., H_s and T_p). Updates of the method "inflate" these contours to account for some short-term variability. Combined with knowledge about critical or natural periods of the targeted ship response, this is a practical way to select one or more design sea states at a given probability level. The short-term probability of the response is then evaluated using many realizations of these design sea states with a certain exposure duration (e.g., 3 h) in experiments. Some of the assumptions in the environmental contour method are under debate. Different contour methods may lead to different results [51]. The approach also disregards the contribution of long exposure times in relatively mild sea states to the failure probability (it favors short exposures of severe conditions), and it does not account for combined failure modes [52]. Other limitations are the need to simplify the joint distribution of the environmental parameters (disregarding complex interactions), and the assumption that sea states are independent (disregarding the influence of groupiness due to storms). These two limitations can be avoided in a method based on hindcast data instead of a scatter diagram [42]. The balance between the short- and long-term variability is studied in Ref. [53]; it was observed that a high long-term variability is usually associated with a low short-term variability and vice versa.

4 The Multi-Fidelity Problem

Multi-fidelity modeling (MFM) combines LF and HF data in order to enhance computational efficiency. It may also enable the addition of complexity [54]. A "surrogate" in MFM is often defined as an algebraic model that approximates the response of a system by fitting to a limited set of data, which can be provided by an LF model (LF surrogate), HF model (HF surrogate), or a combination (MF surrogate) [55]. In other publications, an LF surrogate refers to the LF model itself. A function fitted to data is called a functional surrogate and an LF model a physically-based surrogate, where Ref. [56] states that the latter are usually more efficient. Alternatively, Ref. [57] categorizes three types of MFM: adaptation, fusion, and filtering. In the first category, the LF model is adapted with data from the HF model. In the second, LF and HF model outputs are combined. In the third, the HF model is only applied when indicated by an LF filter (where filter can be any selective criterion imposed on the LF results).

Low-fidelity data can be generated by lower-order models based on dimensionality reduction, simpler physics, coarser discretization, or partial convergence [55]. HF data can be generated by experiments, "real" observations, or a numerical model that includes all relevant physics (such as fine mesh CFD). MFM is considered to be beneficial only if the LF and HF results are sufficiently similar [58]. This links directly to the main difficulty of MFM: selecting and validating a suitable LF and/or surrogate model. Some techniques to generate surrogate models and to update an initial surrogate with new HF data are presented by Ref. [55].

There are many MFM methods, and developments in machine learning increase the number of options. The simplest method to construct a functional surrogate based on data points is linear or polynomial regression. Polynomial chaos expansion can also be used for uncertainty propagation problems (see below). A commonly used method is Kriging or Gaussian process regression (GPR) [59,60]. Others are fusion method Co-Kriging [61], moving or weighted least squares adaptive methods, support vector regression, and machine learning methods such as neural networks. Giselle Fernández-Godino et al. [55] and Koziel et al. [56] provide explanations and examples of each of these methods. Toal [62] evaluates when (Co-)Kriging should be used. Especially Kriging/GPR has been used widely in many fields of study. It is a stochastic technique, which provides insight in the uncertainty of the results. This uncertainty can be used to validate the selected surrogate model; Koziel et al. [56] also gives some other methods to do this (e.g., split-sample method or cross-validation).

Multi-fidelity modeling approaches can be useful to apply to three different types of problems [55,57]: optimization (where a design is optimized), uncertainty propagation (or forward uncertainty quantification, where uncertainty in input parameters is translated to uncertainty in output parameters, which is costly using MCS) and inference (where some observations of the output of a system are given, and the input needs to be inferred). The wave impact problem is an uncertainty propagation problem: the statistical variation of the input (waves) needs to be translated to that of the output (impact loads). When not only the wave loading, but also the structural strength is considered to be stochastic, this becomes a reliability problem [63]. In the maritime world, MFM strategies have mainly been used for design optimization. A brief overview of publications on this topic is provided in Appendix A. These references show that GPR methods can be useful, but recent work has shown that neural networks may be more suitable for non-linear processes (as GPR assumes relatively smooth underlying processes). This is probably also applicable to uncertainty propagation problems. Section 5 provides examples of earlier MFM work for the uncertainty propagation problem of extreme values of non-linear ship response in waves. Scholcz [64] includes a discussion of the differences between uncertainty propagation methods applied to design optimization or to prediction for a final design. Allaire and Willcox [65] provides a method to perform a sensitivity study of LF modeling by propagating input uncertainties, and a method for multi-fidelity fusion of LF and HF data for problems with Gaussian uncertainty distributions for each component.

Most literature assumes that the output of all MFM levels is the same variable, resolved at different fidelity levels (e.g., Ref. [57]). This is not possible for wave impacts: LF models can usually not resolve wave impact loads at all. In such cases, an indicator signal may be used in the surrogate model (this is further explained in Secs. 5 and 6). The indicator is then a surrogate for the statistics of the HF load, rather than for the load itself. Another assumption is that the HF data are equal to the truth. In reality, an HF model is also subject to modeling assumptions, resolution, numerical or experimental accuracy, convergence, etc. This is definitely true for the wave impact load problem: a proper experiment or CFD calculation is not straightforward to perform, and will always be associated with some uncertainty.

5 Earlier Work on Extreme Value Prediction for Non-Linear Ship Responses in Waves

The present section provides an overview of literature on EVP for non-linear wave-induced responses. Extreme value theory (Sec. 3) and MFM (Sec. 4) are used in many of these publications. The following types of methods are distinguished, where different approaches may lead to equivalent results:

- Fully experimental methods, where many realizations of a sea state are run to find the loads. The resulting wave impact load distributions can also be fitted with a GEV form to extrapolate to higher quantiles of the distribution;
- Response-conditioning methods (RCM) that "generate" critical wave events based on response functions and assumed wave properties. These events can be run with an HF tool to obtain loads;
- Screening methods (SM) that select critical wave events from time traces generated by MCS with an LF tool. These events can be run with an HF tool to obtain loads;
- Adaptive or sequential sampling methods (ASM) that iteratively update the load distribution based on many LF data points and an increasing number of HF data points.

The experimental procedure is considered state-of-the-art by some class societies and the International Towing Tank Conference (ITTC) (see the overview of guidelines in Appendix B). However, the present paper will focus on the other three methods. The similarities and differences between those methods applied to short-term

EVP are illustrated in Fig. 6, and discussed in the sections below. These methods could be useful for EVP of any rare marine structure response to waves (including wave impact events, but possibly also propeller ventilation, bending moments, parametric roll, loss of stability, broaching, etc.), but each application requires validation. LF or MF surrogates are used in all methods (see Sec. 6), and the applications include both fusion and filtering MFM methods. Adaptation seems to be used less. This may be because this is basically calibration of the LF model; this is done often, but it is not always considered to be MFM. It also seems less promising for wave impacts, as the quality of the LF models is too low.

The wave impact load rules prescribed by some class societies are explicitly based on RCM: e.g., the BV rule loads for container ships [66,67] and the LR rules for ships prone to whipping and springing [68]. The DNV guidelines for wave loads on ships [47] and offshore structures [44] as well as the ITTC guidelines for experiments of rarely occurring events on ships [69] mention the use of SM, design wave RCM, and other MFM approaches in direct assessment procedures.

5.1 Response-Conditioning Methods.

RCM deliver a wave event for a given input response value (or a given input probability of occurrence of the response), based on response transfer functions, assumptions on the wave phases at a wave crest, and usually also assumptions on the wave and response distributions. This type of method uses principles from first- and second-order reliability methods (FORM/SORM, relating a given response value to a probability) or their inverse (IFORM [48,50], relating a given probability to a response value).

In the lowest fidelity category, the equivalent design wave (EDW) method finds a linear regular wave based on a given linear response transfer function and response value. Note that the term EDW is sometimes used in a more general sense, indicating all sorts of RCM. Here, its definition is limited to methods delivering a uni-directional regular wave.

One step more complex, a group of methods is based on the “New Wave” theory [70,71]. This theory provides an irregular Gaussian wave group profile based on the auto-correlation function of the wave spectrum, conditioned on a given wave crest amplitude. Similarly, the most likely wave (MLW) method [72] delivers a new wave profile conditioned on both the wave crest amplitude and its instantaneous frequency. When this is the mean wave frequency, MLW is identical to the original New Wave. The most likely extreme response (MLER) method [73] is based on the MLW, but it uses a linear vessel response function to condition a wave profile on the response amplitude and its mean frequency instead. A directional version of this method (DMLER) was developed by Ref. [74]. Finally, the most-likely response wave (MLRW) or conditioned random response wave (CRRW) method [75–77] generates a range of New Wave profile realizations conditioned on a response amplitude and instantaneous frequency, by accounting for the random background of the sea state and response function. This means that it is no longer assumed that all wave components are in phase at the crest of the design wave, but have one of the phase realizations leading to the given response. When the given instantaneous response frequency is equal to the mean response frequency, the mean MLRW wave profile is identical to the MLER profile.

The aforementioned methods all target a specific response value, usually the MPM value for the given exposure duration. The design loads generator (DLG) [78] extends this to a probabilistic approach, finding a range of irregular linear Gaussian wave events that fit the ensemble maximum response distribution for the given exposure duration. The DLG can also be used in an NL-DLG framework, which allows for non-linear and combined responses [37]. DLG was applied to find the statistics of whipping in head sea or parametric rolling in directionally spread seaways [79,80] and to identify rare wave groups in wave buoy data [37,81]. It was also applied to slamming loads on a fixed deck box [82], but the resulting loads (calculated with CFD) were not validated against experiments or full-scale results. NL-DLG was applied to compare loads on stiffened panels of a destroyer-type hull [83]. The statistics of different bending moment combinations on a trimaran from DLG and modified versions of EDW and CRRW are compared to MCS by Ref. [84], showing that DLG provided the closest results to MCS.

All aforementioned RCM assume linear Gaussian waves and responses. Results can therefore directly be related to other exposure durations. However, this can also be a limitation, as will be discussed in Sec. 7. Maybe it would be possible to include some wave non-linearity in the RCM surrogate processes, but it will be hard to define the correct wave phases in that case. RCM use LF physical surrogates, and are filter techniques in the categorization in Sec. 4. As mentioned, Fig. 6 provides a schematic overview of the RCM steps for short-term extrema.

5.2 Screening Methods.

In the second type of method, MCS is performed with an LF screening tool to quickly “screen” many wave realizations or conditions for the occurrence of impacts or other rare ship response. HF calculations can then be performed for these identified events. It is assumed that the LF tool cannot directly calculate the critical load. Instead, it calculates a reduced-order physics indicator signal that needs to have a strong correlation to the load. The LF tool and indicator together can also be called an LF surrogate for the statistics of the load (not for the load itself). Suitable wave impact tools and indicators are discussed in Sec. 6.

The idea of screening was explicitly mentioned first in the 90s, when weakly non-linear seakeeping calculations were new and computationally demanding. Linear screening was applied to find interesting occurrences of for instance global ship bending moments, after which the weakly non-linear tools were used to determine the detailed bending moments [85]. The increase of computational power and development of CFD in recent years make screening interesting for highly non-linear (impact) phenomena. SM include the following steps:

(1) Define long-term wave information for the operational profile (e.g., scatter diagrams).
(2) Select critical sea states (LF long-term screening).
(3) Generate wave and response realization time traces.
(4) Select critical events (LF short-term screening).
(5) Generate input conditions for an HF tool for these events.
(6) Perform HF calculations for the events to obtain HF loads.
(7) Combine the LF probability from two to four with the HF loads from six to assemble the long-term load distribution.

A visual representation of both long- and short-term SM is provided in Ref. [86] (Fig. 6 only shows the short-term screening part). In step 7, the extreme value theory in Sec. 3 can be used, for instance using GEV fitting to the obtained load distributions. Screening has been applied to wave impact problems by Refs. [86–88], with promising results. These publications mainly validated indicators for wave impacts based on a few 3 h experiments (although [86] also recreated the experimental load distribution using HF CFD calculations). A proper validation of the screening approach requires longer durations and a statistical evaluation of the full procedure. SM are also recommended for the analysis of vortex induced vibrations of cables by [44]. SM use LF physical surrogates, and are filter techniques in the categorization in Sec. 4. Long-term screening is an alternative to the environmental contour method discussed in Sec. 3.2.

Figure 6 explains the main differences between SM and RCM for short-term extrema. RCM basically speed up the identification of wave events, which are otherwise expensively obtained with LF MCS. However, in order to speed up, some limiting assumptions on e.g., wave modeling are required.

5.3 Adaptive or Sequential Sampling Methods.

Sequential analysis is a branch of statistics within design of experiments that concerns itself with experiments where the sample size is adaptively adjusted instead of fixed in advance. The decision to stop assembling new observations is made based on the previous observations. The final sample size thus obtained is often lower than for predefined test conditions, which can make the experiment more efficient. Such approaches were first used by [89–91] to test statistical hypotheses. Later, it was mainly used in medical trials.

The methods called ASM here are based on this principle and MFM theory. They combine many LF and a few HF data points in a functional MF surrogate for the HF process, using regression or machine learning methods. This can either be done for a large set of HF data points at once, or in an iterative sequential analysis process that helps to decide which next HF condition will improve the surrogate most.

Adaptive or sequential sampling methods are most closely related to the MFM methods in Sec. 4; techniques such as GPR and neural networks are used. Wave impacts are an uncertainty propagation problem, which can be handled with sampling-based MFM [57]. These include MCS using fusion-type MFM estimators with control variate coefficients for different LF inputs (e.g., Ref. [92]), filtering-type importance sampling methods that can be useful for rare events (e.g. Ref. [93]), or other strategies described in Ref. [57]. Different methods to assess uncertainty propagation problems in aerospace engineering are discussed by Ref. [94], including (gradient-enhanced) Kriging. Uncertainty propagation techniques applied to ship resistance prediction are discussed by Ref. [64], including the perturbation method and (multi-fidelity) polynomial chaos expansion.

The few published ASM for EVP of periodic marine structure response use GPR to add new HF data points and to update a surrogate response probability distribution, balancing the importance of areas of the parameter space with large probability and areas of high response values (tail of the distribution). The extreme response values of a non-linear oscillator driven by stochastic noise and the hydrodynamic loads on an offshore platform were thus derived by [95]. GPR was also used to predict the long-term extreme vertical bending moments on a tanker by [96]. This publication uses a Weibull distribution as surrogate. Its parameters are updated based on new HF calculations until the distribution changes less than a specified tolerance between iterations. It relies on HF calculations for a full 3 h wave condition (which is possible with weakly non-linear tools for bending moments), and thus predicts the long-term design load based on iterative sea state selection. A similar vertical bending moment study was done by Ref. [97]. In principle, a similar procedure could be applied to event selection for a more non-linear response, but defining and updating an appropriate surrogate process may be more complicated. An interesting study in flood defense reliability analysis was published by Ref. [98], who applied a genetic algorithm that generates a data set focussed around the failure surface (see Sec. 2) and trained an artificial neural network based on this data to find the shape of this surface. A similar approach could work for reliability analysis of marine structures. Finally, Ref. [99] more generally discusses the use of data-driven strategies to obtain extreme events in fluids and waves. For problems where a full model is available (but computationally expensive), ASM approaches based on GPR are recommended. For problems where there is no accurate model available, but there is a large dataset available, data-driven (machine-learning) techniques are recommended. ASM use functional MF surrogates (see Sec. 6.2), and are fusion techniques in the categorization in Sec. 4.

Again, refer to Fig. 6 for a schematic overview of the ASM steps for short-term extrema and the differences with RCM and SM. ASM seems to offer a more efficient and statistically founded method to combine the data from different fidelity levels. However, literature related to highly non-linear ship response was not found, so the applicability of the methods to this problem needs to be evaluated.

5.4 Method Combinations. Based on the scale of the problem, it seems a good idea to apply different methods, increasing in complexity, for long- and short-term EVP. An example could be to use RCM based on linear response functions for the long-term selection of critical sea states, and SM based on coarse mesh CFD for the short-term selection of critical wave events.

6 Wave Impact Load Surrogates/Indicators

As explained in Sec. 5, most EVP methods for wave impacts use surrogate modeling. This can be a physically-based LF surrogate, consisting of a reduced-order seakeeping tool plus an indicator

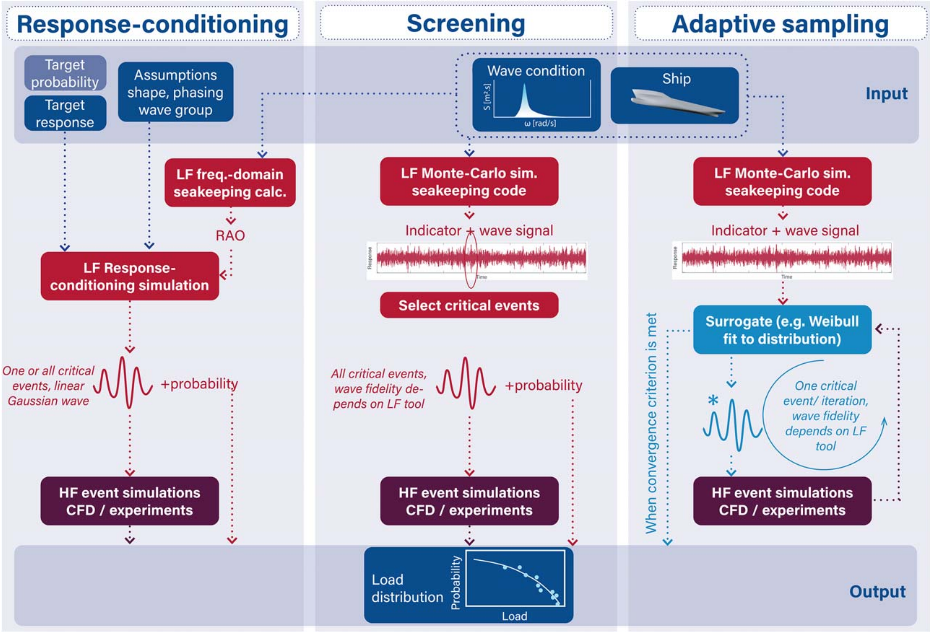

Fig. 6 **Schematic similarities and differences between RCM, SM, and ASM methods applied to short-term EVP, where the * in ASM indicates limited applicability to short-term event selection in the literature so far**

signal that is calculated with this tool (in case of RCM or SM). It can also be a functional MF surrogate, consisting of a fitting model that is updated with data from LF and HF models (in case of ASM). The ISSC [100] lists the steps required to generate surrogate models for maritime applications, emphasizing validation. The present section provides an overview of possible physically-based LF surrogates (Sec. 6.1) and functional MF surrogates (Sec. 6.2). As explained in Sec. 2, the present treatment of wave impacts focuses on local direct impact loads.

6.1 Low-Fidelity Surrogates for Extreme Wave Impact Loads. A physically-based LF surrogate model in the present context consists of a low-order seakeeping or wave tool and an indicator signal. For weakly non-linear events, the target response can directly be calculated with an LF tool, but an HF tool gives more accurate results. For such phenomena, the indicator can be a lower-order calculation of the same response. An example is the calculation of bending moments with a linear potential flow tool. For highly non-linear events, such as wave impacts, the target response can only be found with an HF tool. Fast seakeeping tools are not able to directly calculate impact loads. For wave impacts, an LF indicator needs to be defined and the LF surrogate is a surrogate for the statistics of the load rather than for the load itself. The validity of an indicator can only be assessed in combination with the considered tool; e.g., relative wave elevation (RWE) from a linear tool can be a worse indicator for green water than RWE from a non-linear tool. The present section describes possible LF seakeeping tools and indicator signals for different types of wave impacts.

6.1.1 Low-Fidelity Seakeeping Tools. Figure 7 ranks seakeeping models on the basis of their wave and response non-linearity. Their fidelity and computational cost increase from bottom left to top right.

Similar as RCM, many LF seakeeping tools assume linear Gaussian waves and linear responses (e.g., linear potential flow strip-theory or diffraction methods). However, RCM includes some additional assumptions on the shape of wave groups, so these have a lower wave fidelity. One step more complex, weakly non-linear time-domain codes can be used with Froude–Krylov response contributions. These methods are based on linear solvers, but they integrate the hydrostatic pressure and the undisturbed incident wave pressure over the instantaneous instead of the calm water-wetted hull. The waves are usually still linear. This may improve the impact identification for cases with large ship motions. It is usually also a large step in computational time, from frequency- to time-domain.

It may be necessary to include (some) wave non-linearity in the LF tool (see Sec. 7). As a first step, analytical second-order wave elevation and kinematics theory [101,102] or fully non-linear potential flow codes can be considered. This is only possible if wave impacts can be identified based on only waves, without considering the ship response. As far as known, no fully developed non-linear potential flow codes including floating bodies are presently available. One step higher in fidelity, fully non-linear volume-of-fluid or smoothed particle hydrodynamics CFD methods could be used as screening tool with a very coarse mesh or low number of particles. Reference [86] demonstrated that this is possible for green water screening on a containership, but it was ordered slower and not much better at identifying impacts than potential flow equivalents for the same indicator. However, using a coarse mesh variation of the tool that will ultimately be used in the HF analysis can have other benefits (see Sec. 7.4). A detailed overview of non-linear seakeeping code properties can be found in Ref. [47]. MFM requires an LF tool that is as fast as possible, but still includes sufficient physics to identify the critical wave conditions and events for highly non-linear response. The most suitable tool for this depends on the application.

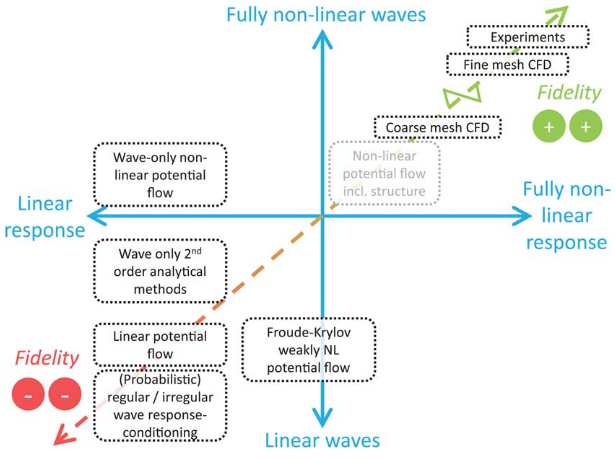

Fig. 7 Categories of seakeeping tools, on scales of wave and ship response (non-)linearity. Lowest fidelity on bottom left, highest on top right.

6.1.2 Low-Fidelity Wave Impact Load Indicators. For fixed and floating zero-speed offshore structures, horizontal and vertical wave-in-deck, airgap, or wet-deck impacts can occur. These are generally associated with steep and high waves, as the sensitive parts of most platforms are high above water. Slamming impacts on sailing ships are different because sensitive structures on ships are closer to the water surface, the ship motions are larger, and forward speed has to be considered. Bow-flare impacts are influenced by forward speed, and slamming on flat surfaces close to the water (such as the stern of a cruiseship) may happen in lower and more linear waves. For green water impacts on deck structures, forward speed of a vessel seems less important than for slamming. Green water impacts are usually associated with steep high waves, in which ships generally do not sail at high speeds (class often assumes five knots in heavy seas). For very small ships, this assumption may not be valid.

For each of these three types (impacts on zero-speed structures and slamming or green water impacts on ships), many possible indicators can be found in the literature. An overview is provided in Table 1. Summarizing, undisturbed wave crest height, steepness, or vertical rise velocity may be good indicators for wave-in-deck impacts on fixed platforms. (Non-)linear RWE crest height and steepness, local relative water velocity, or the changes in added mass around the impact area may be good indicators for slamming loads on floating platforms and sailing ships. Undisturbed wave crest height, steepness, or vertical rise velocity may also be important, but less than for fixed structures. Finally, crests or steepness of undisturbed waves or RWE, wave groups, or coarse mesh CFD results of green water loading water or fluxes on deck may be good indicators for green water loads on ships and offshore structures.

6.2 Medium-Fidelity Surrogates for Extreme Wave Impact Loads. The indicators above are all physically-based LF surrogate models. As explained, a functional MF surrogate fits a function to both LF and HF data. An example is the two-parameter Weibull distribution function used in ASM by [96] for global ship bending moments. The LF model is used both to identify interesting conditions for HF analysis and to provide the basis distribution shape. This shape is iteratively updated using new HF points. This only works if the LF and HF response surfaces are sufficiently similar. As the LF model will deliver another signal than the HF model for wave impacts (as explained in Sec. 4), this may be questionable for this type of problems. However, this has not yet been investigated.

7 Wave Modeling Considerations

7.1 Wave Non-Linearity. Historically, waves and responses have been assumed to be linear and Gaussian. This has many

Table 1 Wave impact indicators from literature (where BF = bow-flare, b.o. = based on, calc. = calculation, GW = green water, NL = non-linear, param. = parameter, RWE = relative wave elevation, steepn. = steepness, struc. = structure, UW = undisturbed wave), ordered chronologically per category

Indicator	For wave impact loads	References
Impact loads on zero-speed structures		
UW steepn. and crests	BF slamming on offshore struct.	[103]
"Impact alert param." (b.o. UW crests, heights, orbital velocity, steepn.)	BF slamming + GW on FPSO	[104]
Impact alert param. of [104] or indicator based on UW steepn.	BF slamming + GW on FPSO	[105]
Wagner model (b.o. potential flow added mass, hull flare angle)	Single vertical wave-in-deck impact	[106]
NL RWE along the side, or linear RWE modified for 2nd order UW	On aft and side of FPSOs	[107]
UW crest steepn.	On wind turbine	[108]
RWE, 3rd order UW crests & steepn. (incl. spatial effects, breaking)	Local slamming and airgap impacts	[109]
RWE and its rise time	On tension-leg & semi-sub platforms	[87]
UW crests	Wave-in-deck on jacket platform	[88]
UW steepn.	On wind turbine	[88]
Linear diffraction RWE times 1.2 (account for asymmetry NL waves)	Airgap and slamming	[44]
Particle velocities in wave crests, use of momentum theory [110]	Wave-in-deck	[44]
UW vertical rise velocity	Wave-in-deck on gravity-based struc.	[111]
RWE and especially its velocity	Horizontal impacts on semi-sub	[112]
Slamming loads on sailing ships		
Relative vertical water velocity at a ship bow	BF slamming on ships	[113]
NL RWE	BF slamming + GW on ships	[114]
Wagner model (b.o. potential flow added mass, hull flare angle)	BF slamming on cruiseship	[115]
Related to ship motions (relative vertical bow motion or velocity)	Slamming on ships due to motions	[19]
Related to UW (steepn., kinematics in the crest)	Slamming on ships due to steep waves	[19]
Momentum theory (similar to the indicator used by [44] at zero speed)	General BF slamming on ships	[19]
NL RWE along the side, or linear RWE modified for 2nd order UW	On structures on side of ships	[116]
Green water loads on sailing ships		
Static pressure of water on deck	GW on ships	[117]
RWE from strip-theory calc.,	GW on ships	[118]
RWE from strip-theory calc., corrected for dynamic swell-up	GW on ships	[119]
Local water level above the freeboard	GW on ships	[120]
NL RWE	BF slamming + GW on ships	[114]
Static pressure water on deck (amplified by forward speed)	GW on ships	[121]
Pitch motions, memory effects in wave groups	GW on ships	[16]
Empirical param. (b.o. RWE and water height and velocity on deck)	GW on FPSOs	[17]
Linear RWE	GW on ships	[122]
Linear RWE (considered sufficient for ordering)	GW on ships	[123]
"Impact alert param." (b.o. UW crests, heights, orbital velocity, steepn.)	BF slamming + GW on FPSO	[104]
Potential energy of water flowing on deck	GW on sailing yachts	[124]
UW crests & steepn., RWE crests (potential flow / coarse mesh CFD)	GW on containership	[86]
Peaks flux, force, or RWE on deck (coarse mesh CFD)	GW on containership	[86]

advantages: linear Fourier analysis, linear superposition of wave components, and the linear dispersion relation are valid, and theoretical probability distributions can be applied to predict extreme crest heights. However, real waves are non-linear and this is especially valid for the extreme crest heights of steep wave conditions. Non-linear waves have steeper crests and shallower troughs than sinusoids. The second-order wave crest distribution of Forristall [126] is often used as alternative to the linear Rayleigh distribution, but e.g., Refs. [109,125,127] show that even higher-order effects are observed in basins and at sea. Wave steepness increases the importance of higher-order effects and thus the wave crest heights, until wave breaking starts dissipating energy (see Fig. 8(*a*)). The crest distribution in the least steep wave conditions are close to Forristall, but the deviations grow with growing wave steepness. Breaking dissipates energy, which leads to the drop in distribution below Forristall for the steepest condition. Real wave crest height distributions balance these two effects. Spectral bandwidth does not play a significant role [109]. Individual freak or rogue waves (higher than predicted by this theory) may also play a role in certain wave environments. However, it is usually assumed that these are so rare that they do not represent a significant problem for offshore structures (e.g., Refs. [128,129]). Their occurrence is therefore not considered in the present study.

Figure 8(*a*) shows that higher-order effects are important for steep wave crest heights, and Sec. 6 showed that wave impact loads on marine structures are strongly related to the incoming wave crest height and steepness. This means that we have to consider wave non-linearity somewhere in the EVP process. Simplification to linear Gaussian waves is definitely not possible in HF calculations, but it is not yet clear whether this is possible in LF surrogate calculations. If the order statistics of linear and non-linear wave crests (or those of the corresponding responses) are different, this may lead to incorrect identification of the most critical events. RCM uses linear Gaussian wave modeling. Higher-order wave effects can be included in the LF models in SM or ASM, but this increases computational time considerably. In order to assess whether EVP for wave impacts using the methods in Sec. 5 is possible, the required wave order level in the surrogate modeling therefore needs to be determined.

7.2 Wave Spreading and Spatial Effects. Increased wave directional spreading reduces the importance of higher-order effects (see bottom figure in Fig. 8(*b*)). Again, this is balanced by wave breaking. The more directional spreading, the closer the distribution to second-order. The reduction of non-linear effects in short-crested waves may be attributed to the less steep wave fronts on a single line compared to long-crested waves. Using long-crested waves for design is more or less industry standard, and this is generally seen as "conservative." However, the figure shows that directional spreading has a significant influence on non-linear wave interactions, and consequently on the wave crest heights and the occurrence of wave impacts. For cases with severe breaking, impact loads may be underestimated based on long-crested

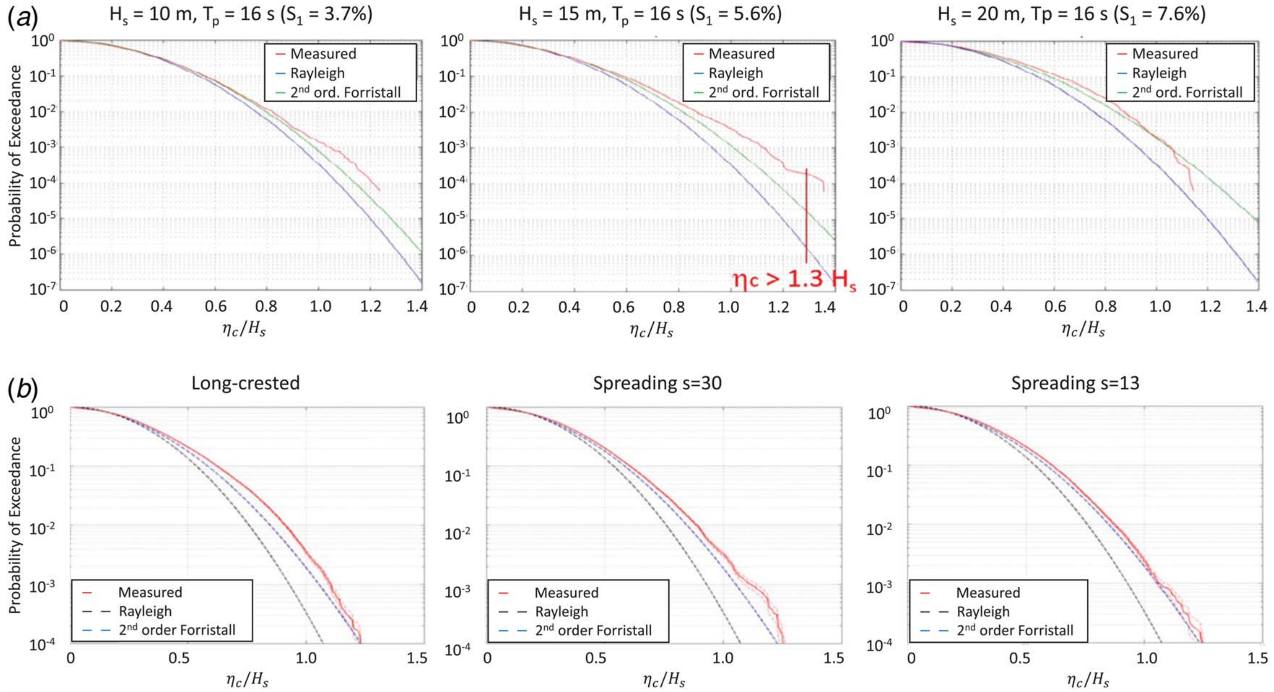

Fig. 8 Normalized crest height distributions measured in a wave basin for JONSWAP wave spectra with cos-2s directional spreading, compared to Rayleigh and Forristall (note that $s = 30$ indicates less spreading than $s = 13$). (*a*) Effect of wave steepness $S_1 = 2\pi H_s/(gT_1^2)$, all with $s = 30$ and $\gamma = 2.5$. Reproduced with permission from Ref. [125] and (*b*) effect of wave directional spreading, all with $H_s = 15$ m, $T_p = 14$ s, $\gamma = 2.5$ ($S_1 = 7.5\%$). Reproduced with permission from Ref. [109].

waves. On top of this, Fig. 9 illustrates that spatial effects may play a large role in the occurrence and details of the impact. This can probably not be fully neglected in extreme value prediction [109].

7.3 Wave Kinematics. Most indicators in Sec. 6 are related to (relative) wave elevations, but some also to (relative) wave kinematics (especially for slamming on sailing ships). Again, these can be linear or non-linear. Hennig et al. [109] recommend the use of second-order wave kinematics in design studies, possibly with an additional non-linear correction for the highest wave crests. Kinematics of waves above the free surface level can be obtained using methods such as Wheeler stretching or the second-order formulations of [102].

7.4 Wave Fidelity Level Issues. If lower-order surrogate wave modeling proves acceptable, the next issue arises for SM and RCM methods. HF non-linear inflow conditions for the identified events need to be defined based on the output of the LF model, where it is important that the LF and HF wave events are equivalent in shape and probability level. This is not necessary for ASM methods that combine the LF and HF data points in a functional surrogate model.

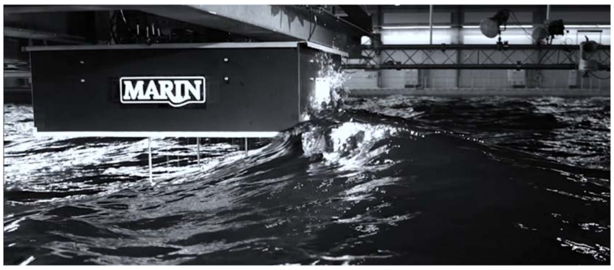

Fig. 9 Short-crested wave impact on a deck box, from a test performed within the ShorTCresT JIP [109]

One method to solve this fidelity issue is the "event matching" of [130], where identified events based on linear screening are matched to a database of fully non-linear wave events. The closest fit non-linear event is then run in HF CFD. This method enables the inclusion of higher-order wave effects and breaking in the screening process, but it is only applicable to stationary structures (no ship motions or speed). The consistency of the statistics in the linear and non-linear events also needs to be further evaluated. Another option is to use an LF model based on fully non-linear wave modeling (coarse mesh CFD or non-linear potential flow), which has the advantage that the LF and HF wave modeling order is the same. This makes it possible to directly initialize the HF fine mesh CFD calculations based on the LF results, solving the order statistics problem. In such cases, direct coupling methods such as applied in [28,131] could also be used. However, LF coarse mesh CFD is a computationally expensive surrogate. This may be another reason to use different methods for long- and short-term application (see Sec. 5.4).

When HF experiments are used, an additional issue is the reverse propagation of a wave event in the middle of the basin to the wave generator. Linear wave propagation will not do the trick in the high and steep wave conditions associated with wave impacts. Methods such as the "analytical-empirical" iterative method in [132] or a procedure based on a non-linear numerical wave tool [133] could be used to propagate a given wave event back to the wave generator in a (semi) non-linear way.

8 Ship Motion Modeling Considerations

Similar considerations as discussed in Sec. 7.1 for wave non-linearity are also valid for motion non-linearity of floating structures. Traditional seakeeping codes use linear Gaussian motion response modeling, which allows for fast frequency-domain computations. As LF tools have to be fast, it would be great if this would be sufficient to identify the right critical wave impact events. Whether second- or higher-order ship motion modeling with one of the tools in Sec. 6 is already required in the LF part of the EVP method will have to be investigated. However, it can be argued that motion non-linearity is probably less important than wave non-linearity. Wave impacts (especially green water impacts) usually occur in high and steep waves, in which typical commercial vessels and floating platforms will sail at zero or low-speed in relatively short waves. Class societies usually assume a speed of 5 kn in severe conditions (e.g., Ref. [67]). Ship motions (and thus their non-linearity) will then be small. This is valid for bottom-fixed structures, large offshore structures, and ships at low-speeds—as shown based on a comparison of linear and weakly non-linear Froude–Krylov seakeeping codes as LF surrogate for green water on a containership in Ref. [86]. Probable exceptions are smaller and more slender ships, ships at higher speeds and semi-submersible platforms; for these cases the motion non-linearity may have to be considered in the LF (surrogate) model. The inclusion of motion non-linearity in multi-fidelity EVP is probably easier than that of wave non-linearity, because it is not strictly necessary to use LF motion outcomes as input for HF calculations (as discussed in Sec. 7.4 this definitely leads to questions for the waves). The inclusion of non-linear motion response in RCM was already demonstrated by [37].

9 Validation Issues

Validation of the EVP methods in Sec. 5 for wave impacts is complex. Statistical validation requires long duration data of the "true" impact loads, and this type of data is scarce. Many studies are therefore validated against synthetic data, or data that can be generated with weakly non-linear time domain seakeeping tools. The surrogate processes are often also strongly related to the non-linear loading (which is possible using the knowledge of the synthetic HF modeling). This may have favorably influenced results. These types of validation are not suitable for wave impact problems, as the phenomena are strongly non-linear. Most surrogate validation studies for wave impacts in Sec. 6 therefore used deterministic validation against short-duration experimental data. However, this is limited to the identification of suitable surrogates, and it is associated with wave reproduction issues in the LF tools. Statistical validation of the full EVP procedure for wave impacts would be very valuable. As far as found, none of the RCM methods have been compared to measured local wave impact data. Literature on SM and ASM methods applied to wave impacts is limited, so here additional validation would also be valuable.

As explained in Sec. 5.2, the selection of a surrogate model will be different for each problem. This makes validation based on one case hard to generalize to other cases. However, if the methods are validated against a few varying cases, it is expected that more insight into the important phenomena in general will be gained.

10 Summary Research Gaps

It can be concluded that different types of MFM can be used to predict extreme values of rare events in waves, using an LF or MF surrogate model: RCM, SM, or ASM. However, it is hard to obtain a good overview of the details of the different modeling strategies and their differences based on only literature. Very few studies are available that statistically validate these methods against "real" wave impact data (model tests or ship monitoring data), see Sec. 9. This is the first identified research "gap": the application, validation, and comparison of EVP methods specifically for wave impact problems.

Second, it is known that HF assessment of extreme wave impact loads is strongly related to the incoming wave non-linearity. Many methods in Sec. 5 use linear Gaussian wave modeling, which makes them very efficient. However, the question is whether this is an acceptable simplification for the identification of critical wave events for wave impacts (see Sec. 7). The second area of study will therefore be related to the role of wave non-linearity in wave impact EVP. In a later stage, the influence of motion non-linearity may also be considered, which can be relevant for wave impacts on smaller ships.

11 Conclusions

Based on the literature review of extreme value prediction for wave impact problems on marine structures, the following can be concluded:

- The main difficulty is the complex and rare nature of wave impacts. Obtaining design loads requires long duration Monte–Carlo simulation with high-fidelity tools, which is computationally challenging.
- To mitigate computational costs, multi-fidelity methods are promising.
- Earlier multi-fidelity extreme value prediction methods for non-linear ship response to waves include response-conditioning, screening, and adaptive sampling methods.
- The validation of these methods for wave impacts is limited, mostly due to lack of "true" long-duration data.
- Wave impact loads cannot be calculated with lower-order tools, so another low-fidelity indicator signal is required. A list of possible indicators from literature (and the low-fidelity tools used to calculate them) is provided.
- The low-fidelity tool and indicator together are called an LF surrogate. Alternatively, an MF surrogate can be a load distribution that is updated based on both low- and high-fidelity data points.
- Wave non-linearity plays a large role in wave impacts; the low-fidelity modeling of most multi-fidelity approaches does not account for this. The question is whether this leads to identification of the right critical events.
- Ship motion non-linearity may also play a role. For large ships at low-speed in steep waves this role will be smaller than that of wave non-linearity, but for smaller and faster ships this may not be the case.

Based on these conclusions, two main research gaps were identified: validation of existing extreme value prediction methods for wave impacts, and the role of wave non-linearity in the wave impact surrogates.

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Conflict of Interest

There are no conflicts of interest.

Data Availability Statement

No data, models, or code were generated or used for this paper.

Nomenclature

H_s = significant wave height
T_p = peak wave period
ASM = adaptive sampling method(s)
BF = bow flare
CFD = computational fluid dynamics
CRRW = conditioned random response wave (method) = MLRW
DLG = design loads generator (method)
DMLER = directional MLER (method)

EDW = equivalent design wave
EVP = extreme value prediction
FORM = first-order reliability method
FPSO = floating production storage and offloading
GEV = generalized extreme value (distribution)
GP = generalized Pareto (distribution)
GPR = Gaussian process regression
GW = green water
HF = high-fidelity
ITTC = International Towing Tank Conference
LF = low-fidelity
MCS = Monte–Carlo simulation
MF = medium-fidelity
MFM = multi-fidelity model (ling)
MLER = most likely extreme response (method)
MLRW = most likely response wave (method) = CRRW
MLW = most likely wave (method)
MPM = most probable maximum
NL = non-linear
NL-DLG = non-linear design loads generator (method)
POT = peak over threshold
RCM = response-conditioning method(s)
RWE = relative wave elevation
SM = screening method(s)
SORM = second-order reliability method
UW = undisturbed Wave

Appendix A: Multi-Fidelity Modeling for Maritime Design Optimization

MFM can be used to optimize designs in a systematic way. A surrogate is used to quickly assess a large number of design variations, within design constraints and targeted at optimization criteria. This was demonstrated by Ref. [58] for ship hull form design, minimizing calm water resistance. Genetic algorithms available in the optimization toolbox Dakota [134] were used to quickly assess design variations within given constraints based on LF calculations. A few variations were evaluated using HF calculations. Kriging and Co-Kriging were used to estimate the HF results over the full design space, based on LF results over the full space and HF results for a few points. Other examples of MFM design optimization of ship hulls for calm water resistance were described for general ships [135], catamarans [136], sailing yachts [137], and SWATH hull forms [138]. The identification of a response surface based on a few data points is a problem for which machine learning techniques can be applied (e.g., Refs. [138,139]). Studies that also include seakeeping properties in the ship design optimization are rare: Ref. [140] included heave and pitch motions in a SWATH optimization, Ref. [141] optimized the design of a midship section for wave-induced bending moments, and Ref. [142] optimized a naval ship simultaneously for powering (full consumption) and seakeeping (operability). del Águila Ferrandis et al. [143] used different types of neural networks to predict vessels motions in extreme sea states based on the wave input only. ISSC [100] provides some other examples of studies that use MFM strategies for design optimization of ship hull structures. Examples from other fields of study include the design optimization of composite marine propellers [144] and optimization of flapping wings [145]. A more general discussion about the application of MFM to unconventional ship design is provided by Ref. [146].

Appendix B: Rules and Guidelines

Class societies and other organizations provide rules and guidelines on the assessment of wave impact design loads. The focus of the present overview is on direct assessment procedures and the background of rule loads, as we are more interested in procedures to obtain design loads than in the loads themselves.

Americal Bureau of Shipping (ABS) describes a procedure to assess slamming loads on ships in [147] and a procedure to assess air-gap and wave impact loads on semi-subs in Ref. [148]. Both use relative vertical velocity and motion from 2D potential flow tools as input for empirical load formulations. No direct assessment procedures are included; CFD and experiments are mentioned, but without further details. The Bureau Veritas (BV) rules for wave impact loads on container ships are empirical formulations based on application of EDW techniques (see Sec. 5.1) to a database of ships [66]. The BV rule note on whipping and springing assessment [67] mainly concerns global responses, but says that slamming pressures "are to be computed using either a CFD code or a boundary element method, provided that they are properly validated and coupled with the seakeeping code." No further details are provided. The Det Norske Veritas (DNV) environmental guidelines for offshore structures [44] prescribe experiments with a large number of 3 h wave realizations, or the use of deterministic single wave groups selected from longer durations (which essentially requires screening as discussed in Sec. 5.2). It also prescribes that quantiles (see Sec. 3.2) in the order of 85–95% should be chosen for the characteristic design response. If this is not possible and only one sea state realization is run (as it often is in typical seakeeping studies), it is stated that it is better to use extreme estimates based on fitting of a Gumbel distribution to the tail of the peak distribution, rather than a single sample extreme value. The use of deterministic wave groups from a screening procedure is mentioned as option, where it is better to reproduce events from a pre-calibrated full wave recording than to use numerically generated events in order to assure representative statistical response effects. The DNV class guidelines for wave loads on ships [47] state that "it is not feasible to apply the most sophisticated numerical methods or model tests to assess the complete set of lifetime load cycles corresponding to a scatter diagram." The use of screening methods, design wave methods, and other multi-fidelity approaches is discussed as alternative. In their rules for design loads on ships prone to whipping and springing [68], Lloyds Register (LR) prescribes the use of an "equivalent design sea states" approach for non-linear wave impact phenomena. It states that using an EDW approach is also possible, but not recommended. The International Association of Classification Societies (IACS) also mentions EDW as a basis for design loads in the IACS Common Structural Rules.

The International Towing Tank Conference (ITTC) guidelines for seakeeping experiments of rarely occurring events on ships [69] focus on experiments for HF assessment. They prescribe wave condition selection such that a "substantial" number of events occurs (frequency 40–60% of the wave encounters), in combination with at least 100 wave encounters (preferably 200 or 400). This approaches the problem from another angle; the wave conditions should be selected as so severe that the wave impact events are no longer rare. However, the question is whether the resulting loads are representative for operational conditions. Different loading processes may play a role. An alternative technique is mentioned, where critical parts of the wave time traces are selected and run in an experiment. This is a rudimentary form of screening, based only on the (elevation of) the undisturbed waves.

Summarizing, a large part of the present class/ITTC guidelines for wave impacts is based on RCM (see Sec. 5.1). DNV and ITTC also provide some guidance on experimental direct assessment methods. However, some class societies indicate that they are presently working on these rules.

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