1 INTRODUCTION

Small high-speed craft normally operate at a wide range of speeds and in different sea conditions. There are nevertheless restrictions to speed when operating in waves. Installed propulsive power, crew endurance, equipment functionality and structural integrity are all factors that set boundaries to the safe operation of the vessel defining its ‘operational envelope’.

In calm seas the maximum speed is typically limited by the installed propulsive power. As the sea becomes more severe it is often the crew comfort, the on-board equipment and the structural strength that become of concern. As suggested by (Riley and Marshall 2013), the maximum allowable speed can be limited by either accelerations, which have a negative effect on personnel and equipment, or by large loads that lead to excessive structural stresses. Which of these operating limits is reached first partially depends on the size and weight of the craft and on the seat vibration damping systems installed (Cripps, Cain, et al. 2004).

This paper presents a conceptual overview of the method adopted to construct a structural limit curve as a function of speed and sea state severity. This curve contributes to defining the ‘operational envelope’ of the craft, which informs design teams and crews of the speed limits for the safe operation in waves. The paper does not present explicit results, which are referenced throughout the paper.

2 RATIONALE

The Royal National Lifeboat Institution (RNLI) operates a number of lifeboat classes, all designed with a specified service life. The Severn Class (Figure 1 & Table 1), consisting of a fleet of 45 vessels, first entered service in 1995.

Figure 1. RNLI Severn Class lifeboat.

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<th>Table 1. Severn Class main particulars.</th>
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<td>Length overall</td>
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These lifeboats would now be approaching the end of their original operational life, but due to their exceptional in-service performance the RNLI has started a life extension programme to extend the operational life of the fleet to 50 years (Roberton 2015).

For the Severn Class, as for the other lifeboats designed and operated by the RNLI, crew’s endurance has traditionally been one of the main limitations to speed during operation in rough seas. Excessive motions and accelerations can reduce the crew’s operational effectiveness and raise the risk of personal injury. In those situations the coxswain in command of the vessel is aware of the shocks experienced and will usually adapt the speed, and/or the heading, with respect to the prevailing weather and sea conditions. The structural limit of the lifeboat is assumed to be far beyond the crew safety limit since structural failures have proved to be extremely rare, although do occasionally occur (Phillips et al. 2009).

Many lifeboats in the Severn fleet have already been fitted with more modern replacement engines. New technologies to improve the ride quality are also available that, if adopted, would reduce the crew’s exposure to accelerations and provide the possibility to operate at higher speeds. Whilst this is beneficial for the response to emergency call-outs, it also implies the potential for operating closer to the structural limit of the vessel. Furthermore, improved seat damping system, and thus the ride quality, could limit the ability of the coxswain to appreciate the loads being sustained by the structure. This has the potential to push the operation of the vessel close to or even beyond the structural limit. Such a scenario is graphically illustrated in Figure 2, an adaptation from the original plot presented by Riley & Marshall (2013).

The Severn life extension programme highlighted the need to gain a better understanding of the structural strength of the RNLI’s all-weather lifeboats. This could only be achieved by predicting with confidence the loads sustained by the structure during operation. A study undertaken by Newcastle University, the RNLI and Lloyd’s Register set out to investigate the loads and the consequential structural response. Work is ongoing to produce a set of structural response curves that will provide the RNLI’s design, maintenance, training and operational teams with an enhanced insight into the operational envelope of the Severn.

3 SEAKEEPING LOAD PREDICTION METHODS

3.1 Numerical methods

Hydrostatic loads, due to self-weight and buoyancy forces, can be determined with an acceptable degree of accuracy (Phelps 1997). Differently, there is less guidance for the prediction of hydrodynamic loads on a small high-speed craft. There is also no standard approach to the inclusion and treatment of hydroelastic effects.

With regard to the latter the American Bureau of Shipping (2011) suggests that for small craft only in some cases is there significant interaction between loads and response, for which a fully hydroelastic approach should be adopted. Examples of this are springing of multi-hulls and the dynamic response of panels to slamming impacts. Also designs optimised for low structural weight that result in a higher flexibility of the hull could require a hydroelastic approach.

In the majority of cases, and especially for small stiff hulls, rigid body motions are dominant and therefore wave loads are not significantly influenced by dynamic effects. The prediction of hydrodynamic loads can be carried out by treating wave and dynamic loads independently. Wave loads are computed on the assumption that the body is rigid. Highly dynamic effects, such as those induced by slamming, are computed separately and superimposed.

The majority of seakeeping predictions are carried out within the framework of potential flow theory, assuming an incompressible, inviscid and irrotational fluid. The problem can be further simplified if the ship-wave system is idealised as linear, as first suggested by St. Denis & Pierson (1953). This is usually the case for conventional displacement vessels travelling in light or moderate seaways, for which motion and wave amplitudes are small. The sea surface can be modelled as a linear superposition of regular sinusoidal waves of all frequencies. Motions and wave-induced loads can then be studied in elemen-
tary regular waves and the principle of superposition applied to determine the overall response in an irregular seaway. Under these assumptions seakeeping predictions can be made even more efficient by solving the problem in the frequency domain. Several linear potential flow methods such as 2D strip theories and 3D panel methods have been developed and are incorporated into commercially available software packages.

In rough seas and at high speed the potential flow approximations cannot be made as the ship-wave interaction becomes nonlinear. A number of approaches have been developed of which a review is given in Prini et al. (2015).

Semi-empirical methods are usually used for practical design and are implemented in the scantling rules of most Classification Societies (Det Norske Veritas 2012, American Bureau of Shipping 2014, Lloyd’s Register 2014). The assumption underpinning these methods is that transient non-uniform pressures can be modelled as ‘equivalent’ quasi-static uniform pressures that, if applied to the structural component, will produce the same maximum deflection and peak stress as those produced by the actual loading (Heller & Jasper 1960).

Theoretical approaches to investigate water impact pressures have been developed since the 1920s (Von Kármán 1929, Wagner 1932), later implemented and extended by others (Stavovy and Chuan 1976, Zhao and Faltinsen 1993, Zhao et al. 1997). Advanced methods based on solving the Reynolds Averaged Navier-Stokes (RANS) and Euler equations have been applied to a range of problems and their use is also being investigated for seakeeping predictions on the Severn Class (Aktas et al. 2017).

3.2 Experimental methods

Experimental measurements of seakeeping responses of a vessel are an alternative to numerical methods and provide a way of validating their predictions.

Most of the tests at model scale are conducted in towing tanks or wave basins, which provide ease of taking measurements and good control of the wave environment (Lloyd 1989). Regular and irregular wave patterns can be generated and repeated during subsequent runs. Seakeeping motion tests have been carried out extensively in the past and the choice of the measurement apparatus often depends on the facility’s practice, the test objectives and on whether the model is towed by a carriage or equipped with its own propulsion system.

External pressures are usually measured with pressure transducers. Since they provide point-measurements, the complete pressure field on the hull bottom can only be reconstructed from arrays of transducers, as proposed by Rosén (2005). The use of slamming patches to measure the hydrodynamic force exerted on a cut-out of a bottom panel has also been investigated (Manganelli et al. 2003).

Seakeeping experiments are also conducted to measure hull girder load effects. Ideally a ‘hydro-structural’ scaled model would be used to measure loads at any longitudinal position, however, due to the practical complexities in satisfying the structural similarity at model scale, the use of a segmented model is most common (ITTC 2011). The segmentation consists in cutting the hull shell into a number of segments so that the hull does not provide any continuous structural support. The hull girder stiffness is given by an internal backbone structure. Load measurements are taken at the segmentation cuts by means of strain gauges on the backbone beam or load cells connecting the segments. Two types of segmented model exist depending on the stiffness of the connecting structure: rigid or elastic. A rigid segmented model has a much higher stiffness than the actual vessel and greater natural frequency than the wave encounter frequency (ITTC 2011). Wave loads can be measured and compared with numerical computations. However, dynamic and impact load effects, such as whipping and springing, require the stiffness of the hull girder to be appropriately reproduced at scale. For these loads an elastic segmented model that represents the rigidity of the prototype hull should be used.

In spite of the numerous advantages of model testing it should be recognised that scaling is problematic. The towing force only resembles the thrust of an actual propulsion system and the wave environment tends to lack the confused nature of the sea.

To investigate the seakeeping of a vessel in real operational conditions, sea trials are necessary. They are nevertheless expensive and time consuming, which is why they are not carried out on a regular basis. If conducted for design purposes they also require a prototype vessel to be built first.

An example of full-scale tests conducted on an instrumented small high-speed naval craft (LWL=9.5m, V=+40kn) was presented by Rosén & Garme (1999). At a larger scale, other examples are the sea trials conducted by the US Navy with a wave-piercer catamaran (Jacobi et al. 2014) and those conducted with the research vessel Triton (Grassman and Hildstrom 2003, Renilson et al. 2004), a joint program between the United Kingdom and the United States to assess the trimaran hull form for implementation in future warship designs.

3.3 The RNLI load curve

Due to the extreme conditions in which the RNLI’s lifeboats operate and their challenging structural requirements, the methods adopted for other high-speed craft presented limitations (Cripps et al. 2005). Consequently a load prediction method de-
developed in-house has been used by the RNLI design team for some time (Cripps, Phillips, et al. 2004, Cripps et al. 2005).

This approach treats the design loads in terms of equivalent static ultimate pressures. The maximum ultimate pressure for the design of a new lifeboat is determined as a function of load displacement and operational speed. This pressure value is modified according to the longitudinal position along the hull and for the topsides, which carry only a percentage of the pressure applied over the hull bottom. For each panel a pressure value is then found, which can be applied uniformly over the whole of the respective panel.

4 A DIRECT CALCULATION METHOD

Semi-empirical methods, as implemented by most Classification Societies, and the RNLI’s load prediction method have been successfully employed for design purposes. However, because of their nature, they cannot be used for direct calculations of the structural response to the numerous load cases of different combinations of speed, heading and sea.

RANS and Euler equation solvers are increasingly more popular and have successfully been used for single case studies. Yet two aspects limit their use in seakeeping. Firstly, if the non-linear behaviour is dominant, simulations should be carried out in the time domain as nonlinearities are history-dependent. The principle of superposition, applied by linear codes, does not hold anymore. Each combination of heading, speed, displacement, regular and irregular wave pattern has to be investigated. The second drawback is the significant computational resource still required for these methods. This, together with the large number of scenarios to investigate, made these codes unsuitable for this study.

It was concluded that a single reliable method to predict the whole loading scenario during operation in waves was not available. As a result a systematic approach combining different methods was adopted, as shown in Figure 3. This consists of a numerical hydrodynamic model based on linear potential theory (CFD Model), a global finite element model for the computation of the structural response (FE Model), and experimental tests at both model scale (Small-Scale Tests) and full scale (Full-Scale Tests).

The principle underlying this approach is that rigid body motions are dominant and wave loads are not significantly affected by high frequency dynamic effects induced by slamming, which can be accounted for independently. Loads of different natures that act on the structure at the same time (hydrostatic, wave and slamming-induced) are calculated separately and superimposed in the generation of a load case for the structural analysis (Figure 3). Hydrostatic and wave loads are predicted numerically with a CFD model. Slamming-induced loads are predicted based on experimental data from sea trials.

Because of the different operational modes of the Severn, from displacement to planing, it was still necessary to validate the wave loads predicted with the seakeeping simulation model. This was done by comparing the results from the seakeeping simulations against experimental data. This process is represented in Figure 3 as ‘validation’. A detailed explanation of the tasks undertaken and of the methods adopted to compare the results and assess the accuracy of the wave loads predicted numerically is given in the following sections.

5 NUMERICAL MODEL

A global finite element model of the Severn Class was developed with the marine design software MAESTRO. Details of the first model under construction are given in Prini et al. (2015). This model was further updated and refined to improve its accuracy. The refined model is shown in Figure 4.

The entire vessel with its main structural components were represented through a combination of shell, beam and rod elements. The laminate properties were embedded into each element as layered orthotropic for shells; uniform orthotropic for beams; and isotropic for rods.

The structural mass was automatically computed by the software, based on the elements and the material properties used. Other masses were represented, according to their nature, as: volume masses, scaled-up structural mass, point masses and large solid masses whose centre of gravity lies at a distance from the supporting nodes. The computed centre of
gravity position was checked against the target value calculated from an analysis of the inclining test data of the fleet.

MAESTRO integrates hydrostatic, hydrodynamic and structural analysis through a hydrostatic balance tool, a potential flow solver MAESTRO-Wave and a linear finite element solver (Ma et al. 2012, Zhao et al. 2013, MAESTRO Version 11.5.0 2017).

5.1 Hydrostatic and hydrodynamic analysis

Static equilibrium on the waterline is reached by applying hydrostatic balance and inertia relief methods embedded into MAESTRO (Ma et al. 2012, Zhao et al. 2013, MAESTRO Version 11.5.0 2017). The first provides equilibrium in heave, pitch and roll by iteratively adjusting draught, trim and heel of the vessel. The latter adjusts additional accelerations to reach equilibrium in surge, sway and yaw. Static equilibrium balance is used in two circumstances. Before running any hydrodynamic analysis, equilibrium on the still waterline is sought to define the attitude of the vessel and the wetted elements to be used by the hydrodynamic solver. The second purpose of the static equilibrium balance is to compute the hydrostatic pressures that will form part of the load case for the structural analysis. For this purpose, the vessel is re-balanced on a sinusoidal wave rather than on the still waterline.

The computational tool MAESTRO-Wave was used to predict the hydrostatic and wave loads of the vessel. Figure 5 shows the steps undertaken and the output from the analysis. Two linear potential flow codes, based on the theory proposed by Salvesen et al. (1970), were used: at speeds up to Froude numbers of 0.4 (10 knots for the Severn Class) a 2D strip theory using a zero-speed Green function was used; at speeds above Froude numbers of 0.4 a 2.5D strip theory using a Rankine Source method and a forward speed correction term in the free surface computation was employed. The equations of motions are formulated based on the structural mesh (Zhao et al. 2013). This overcomes the challenge of transferring the pressure mapping from the hydrodynamic model to the corresponding structural model.

The simulations were run in the frequency domain, at a range of speeds, headings and wavelengths. Panel pressures, motions and hull girder load RAOs (Response Amplitude Operators) were calculated. It should be noted that in this paper the convention is followed whereby the Response Amplitude Operator is the same as its transfer function and used in its unsquared form.

The accuracy of the predictions was assessed by comparing motions and global loads RAOs against those measured experimentally. This is shown in Figure 5 as ‘validation’.

5.2 Structural analysis

The MAESTRO linear finite element solver is used to run the structural analysis. The sequence of the tasks undertaken is shown in Figure 6. One of the first steps is the definition of a load case, which consists of all those loads that act on the structure simultaneously. What is often of interest, especially for design purposes, is the response to loads that are experienced in severe waves, or sea states, that characterise the extreme environmental and operating conditions of the craft (American Bureau of Shipping 2011). The limits of numerical methods, as discussed in the previous sections, make these loads challenging to estimate and experimental data cannot always be produced for each scenario. A common approach is to define an equivalent wave (often referred to as equivalent ‘extreme’ or ‘design’ wave) through its amplitude and frequency. The loads that

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Figure 4. Finite Element (FE) global model of the Severn Class lifeboat.

Figure 5. Direct calculation approach. Numerical simulation model for the prediction of hydrostatic and wave loads.
would be experienced in such a wave, for a given vessel’s loading condition, heading and speed, are then predicted through scaling and extrapolation of loads known for other scenarios.

For the present study, the load components forming the load cases are: hydrostatic, wave and slamming loads. This last term includes the slamming load effects on the hull girder (whipping) and the slamming impact pressures acting at a local level on the bottom and bow panels.

Once the extreme wave is defined, the hydrostatic pressure is computed through the static equilibrium balance method explained earlier.

Wave loads obtained from the hydrodynamic simulations are known in terms of their RAOs, hence for regular waves of unit amplitude. These loads, and their related pressures, are scaled linearly according to the amplitude of the extreme wave. This process is at the basis of linear theory and is related to the very notion of transfer function (St. Denis and Pierson 1953).

It is also necessary to define the extreme value of the global and local load effects induced by slamming. A measure of these loads was obtained from tests conducted at full scale. The information consists of a number of short-term data sets. Extreme values can therefore be calculated by extrapolation of measured data. The nonlinear nature of slamming also implies that linear extrapolation by means of a transfer function may not be possible. Instead suitable statistics can be applied, as explained for example by Ochi (1981), Hughes (1983) and Clarke (1986). Once the extreme value of the response is found, it must be applied as a load to the structural model. Two different methods were adopted.

The whipping response caused by slamming can be thought of as an addition to the vertical bending moment induced by waves. The extreme value of both these components is now known, so the dynamic response can be accounted for through a scaling factor applied to the linear response. Wave-induced pressures are scaled up so that the magnitude of the resulting bending moment includes both the wave and the slamming terms.

Slamming loads reacted upon by the local structure are modelled as additional pressures. Although these pressures would be transient in nature, they are applied as equivalent static uniform pressures to the structural panels of the bottom shell. The procedure adopted to recover a static uniform pressure from experimental measurements will be outlined later. For now it suffices to consider that the measurements were taken on a number of panels along the length, from near amidships to the bow. From these measurements it is possible to calculate a maximum equivalent static pressure value and a longitudinal distribution factor to take into account that the slamming pressure varies in magnitude along the hull length and that not the entire hull may be subject to slamming impacts. From these it is possible to construct a static pressure field to apply to the structural model.

Once the load case is defined the inertia relief method is applied to restrain the model. This supersedes the application of rigid restraints to prevent unlimited rigid body motions, which often results in unrealistic deformation patterns and artificial stress concentrations.

The finite element analysis is performed as linear elastic, with stresses, strains and displacements output for evaluation. An example is shown in Figure 7.
SMALL-SCALE TESTS

Motions and hull girder loads were also predicted through seakeeping experiments conducted in a towing tank. Figure 8 outlines the experimental process.

Two scale models of the Severn lifeboat were tested: a ‘solid’ and a ‘segmented’ model. The first is a conventional model for measuring rigid body motions. The latter is a rigid segmented model that, in addition to body motions, allowed the measurement of hull girder loads at three segmentation cuts (Figure 9). The backbone structure holding the hull segments together consisted of three aluminium beams of square hollow section instrumented with strain gauges. The strain gauge layout was devised to measure vertical and horizontal bending moments and vertical shear force. The beams were calibrated with a test rig through 3 and 4 point bending tests.

The segmentation and sealing of the hull shell and the presence of the backbone structure introduced further complexities in the model design, building and testing process. Furthermore, it was necessary to ensure that the two models showed similar seakeeping characteristics. The segmented model was therefore built with a solid hull shell. Preliminary tests in calm water and in waves were run and results compared with those from the solid model. The hull shell was later segmented and the same tests run again. Motion results, from the first and second set of tests were compared to ensure that the segmentation had not altered the seakeeping behaviour of the model.

Details of the two models, the facility, the test apparatus and setup are given in (Prini et al. 2016). Two groups of seakeeping tests were completed: at forward speed in head waves and at zero speed with different headings.

Tests at forward speed were conducted with the model attached to a standard free-to-heave-and-pitch dynamometer. Motion data was therefore collected for heave and pitch only and load data for vertical bending moment and vertical shear force.

Tests at zero speed were performed with the model positioned at the centre of the tank. A set of mooring lines constrained the model in yaw, surge and sway. Motion data was collected through an optical tracking system for heave, pitch and roll. Hull girder loads were measured for vertical and horizontal bending moments and vertical shear force. Figure 10 shows the setups for the two groups of tests.

The experiments were conducted in regular waves generated by a wavemaker. For each speed, or heading, a range of wavelengths was tested and the wave elevation measured. This allowed reconstruction, through a peak-to-trough analysis, of the RAOs of the responses from their respective time histories.

The motions and load RAOs were then compared against those obtained from the seakeeping simulations. Figure 11 shows an example for heave and amidships vertical bending moment at 20 knots in head waves. Results are presented in terms of RAOs. The magnitude of the response is plotted per metre of wave height against the ratio wavelength/ship length. The comparison between the small-scale test data and the numerical results is represented in Figure 8 as ‘validation’.

![Figure 8. Direct calculation approach. Small-scale tests with a ‘solid’ and a ‘segmented’ model for the prediction of rigid body motions and global wave loads.](image1)

![Figure 9. Segmented model of the Severn Class lifeboat with three segmentation cuts. The hull segments are held together by an internal backbone beam. Load measurements are taken at the segmentations by means of strain gauges on the beam.](image2)
7 FULL-SCALE TESTS

Tests at full scale were conducted on an instrumented Severn Class lifeboat to determine her seakeeping behaviour and the wave and slamming loads experienced in real operational conditions. Details of the trials procedure, instrumentation layout and data collected can be found in Prini et al. (2018).

The tests took place in the North Sea offshore from Tynemouth (UK) and consisted of 11 trials conducted at speeds ranging from 5 to 25 knots and in different sea states, with a significant wave height from 0.3 to 4.6 metres. The route followed during each of the trial was a ‘star pattern’ devised to include headings from head to following seas, both port and starboard, at 45-degree increments. The length of each leg of the star was set to allow a minimum of 100 wave encounters to occur, based on the expected mean period of the sea spectrum. An example of star pattern and actual route followed during one of the trials is shown in Figure 12. Details of different types of trial trajectories can be found in Johnson (2004).

The lifeboat had been fitted with 1 triaxial accelerometer, 1 triaxial rate gyro, 58 linear strain gauges and 2 thermocouples for the temperature compensation of the strain signals. The sensors were positioned and oriented to measure: accelerations and angular velocities at the centre of gravity of the vessel; vertical and horizontal bending strains of the hull girder at five longitudinal locations; local panel deflection due to pressure loads, slamming and green water on six bottom panels, two bow panels and two panels on the fore deck.

All the sensors were wired into one data acquisition unit and their signals sampled at different frequencies depending on their nature: acceleration and strain signals recording local pressure loads were sampled at 2048Hz; angular velocities and strain signals measuring hull girder loads at 256Hz.

A measure of the sea state was also necessary to correlate motions and structural response to the wave environment. In addition to visual observations, a directional Waverider buoy was used. The buoy was deployed central to the trial area and left free to float for the whole duration of each trial. Forward (North), transverse (West) and vertical (heave) displacements were generated through a GPS-based motion sensor at 1.28Hz. Additional wave data was also obtained from two wave buoys moored approximately 10 nautical miles N and 23 nautical miles ESE from Tynemouth, operated by the Channel Coastal Observatory (CCO) and the Centre for Environment, Fisheries and Aquaculture Science (Cefas) in the UK.

The analysis of data from sea trials is typically more challenging than for tests conducted in a controlled environment: the vessel’s response to a random sea state is irregular; signals are often affected...
by noise and drift; and quasi-static and dynamic effects are superimposed. The data post-processing was based on the principle that these components tend to occur at different and distinct frequencies: drift is a very low frequency component or even a slowly moving trend; wave-induced responses are related to the wave encounter frequency; and slamming-induced responses tend to occur at higher frequencies. It was therefore possible to isolate the response of interest by applying the appropriate frequency-based filters. An example of how the response of a panel due to slamming is isolated by applying a high-pass filter to the raw signal is shown in Figure 13.

Another aspect driving the data analysis was the type of data describing the sea state. A wave buoy provides an effective measure of the wave environment in the trial area, but this measure is still relative to the buoy’s location. It is impossible to relate a particular event in the response to the wave that has generated it. Figure 14 outlines the analysis of the data obtained from the full-scale tests.

The RAOs of motions and hull girder loads were computed through a spectral analysis. The response spectrum and the wave encounter spectrum were first calculated. The transfer functions were found from the ratio of the spectral ordinates at each encounter frequency defining the wave encounter spectrum. This analysis was conducted for headings from head to beam seas for which no negative encounter frequencies occur. The RAOs were compared against those obtained numerically with a loading condition representative of the full load departure of the lifeboat used for the trials. This step is shown in Figure 14 as ‘validation’ and an example of RAO plot with both numerical and full-scale data is shown in Figure 15.

Figure 13. Strain recorded at the centre of hull bottom panel during a slamming event. A high-pass filter is applied to the raw signal to isolate the strain due to slamming.

Figure 14. Direct calculation approach. Full-scale tests on an instrumented lifeboat for the calculation of rigid body motions, global wave loads and slamming-induced load effects: whipping of the hull girder and local slamming pressures.
8 NONLINEAR AND DYNAMIC ASPECTS

8.1 Numerical model

Strip theory introduces several simplifications to solve the ship-wave interaction problem for which a detailed explanation is given by many authors including Salvesen et al. (1970), Hughes (1983) and Lloyd (1989). The main simplification is that the underwater part of the hull is approximated by a number of prismatic segments, or strips. Forces are calculated independently for each strip using two-dimensional flow theory and the vessel’s response is obtained by integration over the various segments (Hughes 1983).

Moreover, because the analysis is based on potential theory, fluid viscosity is neglected. This implies that hydrodynamic lift is not present and that the wetted surface does not change with speed. It also implies that motion damping can only be attributed to wave radiation (Lloyd 1989). This is generally adequate for most motions with the exception of roll, for which viscous damping is important. As a consequence potential flow solvers tend to underestimate roll damping. A correction factor, in terms of a critical roll damping ratio, was therefore defined for the hydrodynamic analysis.

In order to linearise the problem, further simplifications are introduced, which imply that: the hull is wall-sided; and the amplitudes of waves and motions are small (Hughes 1983). The assumption of ‘wallsidedness’, in particular, means that linear strip theories predict the same value of wave-induced bending moment for both sagging and hogging.

8.2 Small-scale tests

One of the advantages of conducting tests in regular waves is that it is possible to observe, from the time histories of the responses, occurrence of some nonlinearities. Nonlinear motion responses could be captured with either of the two models tested, whilst load nonlinearities are only observable with the segmented model. However, these are limited to some aspects of the response at a global level only.

The differences between sagging and hogging bending moments arising from the hull shape and from the hydrodynamic differences between the entry and the exit of the hull at the waterplane are captured. The hog-to-sag ratio could be calculated from a peak-to-mean and trough-to-mean value analysis.

Slamming-induced dynamic responses, such as whipping, require the hull girder stiffness to be reproduced at model scale. Since the primary strength of the segmented model was provided by a ‘rigid’ backbone beam, assessment of these load effects was not possible at model scale. Nonlinearities due to irregular seas or scaling effects were also neglected.

8.3 Full-scale tests

Work is being conducted to calculate the effect of slamming at a global and local level. These are whipping of the hull girder and the local response of the hull bottom panels, the bow and the deck reacting to the applied pressures (Figure 14). The nonlinearity and the highly dynamic nature of these loads makes it impossible to solve the problem in the frequency domain, hence a time-domain analysis has to be performed to find the peak values of the response. Suitable statistical approaches and probability distributions, such as the Gumbel, Weibull or Generalized Extreme Value, can be applied to linearise and extrapolate the load magnitude to find extreme values with a given probability of exceedance (or return period). An example of how a Gumbel distribution can be fitted to measured data to predict the magnitude of extreme values with a given return period is shown in Figure 16.

As detailed in the previous sections, the whipping response can be accounted for through a scaling factor applied to the linear response. The magnitude of the resulting bending moment will include both the wave and the slamming terms. Slamming loads reacted upon by the local structure are instead modelled as additional pressures. To achieve this, one more step is necessary, which is the conversion from a strain value to a pressure load that can be applied to the structural model.

A slamming impact is typically characterised by a pressure front that travels rapidly. Attempting to recover a dynamic pressure field from strain readings and applying it dynamically to the finite element
model was not practical for this study. Instead an equivalent static uniform pressure can be found. This is the pressure that, if applied to the whole panel, produces at its centre the same strains as those produced by the actual pressure field. This correlation can be found from a local finite element model of the panel under consideration through a linear static structural analysis.

9 THE STRUCTURAL RESPONSE CURVE

The previous sections concerned the prediction of the loads caused by a given extreme wave and the computation of the vessel’s response. It is left to define what is an ‘extreme wave’ and to define an approach to assess the results of the structural analysis to identify a ‘structural limit’.

An extreme wave is taken to be a wave that causes an extreme value of a ship’s response, such as vertical bending moment or vertical acceleration. In order to relate a wave to a ship’s response, it is often assumed that the response is linearly proportional to the wave amplitude, even when extrapolated to higher sea states, and hence that the highest seaway will produce the largest response (Lewis 1988). It is then possible, from an examination of the response in elementary regular waves (or RAOs), to find the combination of heading and wave frequency that causes that response to reach its maximum. With the wave frequency found, then the amplitude of the highest wave that the vessel is likely to encounter over a period of time should be estimated. Given the stochastic nature of the sea and the many possible operating conditions of a vessel, this procedure is inevitably related to the concept of probability.

Only within a limited period of time, typically 1 to 4 hours, can the sea be considered to remain nearly uniform and statistically stationary (Lewis 1988). Hence, idealised wave spectra (ITTC 2002) are commonly employed to formulate short-term descriptions of the sea. For long-term predictions the use of wave scatter diagrams is most common. These are constructed based on visual observations and/or measured data and are therefore relative to particular sea areas. Atlases of this type were published for example by Hogben and Lumb (1967), Bales et al. (1981) and Hogben et al. (1986). A more recent collection of wind and wave frequency distributions for sites around the British Isles was edited by the Southampton Oceanography Centre (2001). From these descriptions of the sea state it is possible to find the probability of a wave of being exceeded by a higher wave over a given period of time.

Set the return period, an equivalent regular wave (described by its heading, frequency and amplitude), which simulates the magnitude and location of an extreme value of a ship’s response, can be determined (American Bureau of Shipping 2011).

The purpose of this study was to determine a structural limit curve as a function of speed and sea state severity. The procedure to achieve this is presented here for a return period of three hours (Figure 17). Speed on the abscissa can be conveniently expressed in terms of speed-over-ground in knots. A suitable description of the sea can be obtained from an idealised spectrum together with a measure of wave height and period. The significant wave height is used on the ordinate.

In order to work with two axes only, a number of parameters must be fixed. These are: loading condition, heading, spectral shape and associated period. Multiple plots can be created for different combinations of these parameters, or one can be created for the most severe. Within any plot, the structural response curve is constructed from specific points with coordinates given by speed and significant wave height. Each point on the plot represents the structural response of the vessel to a load case consisting of the extreme loads that are likely to be experienced in that combination of speed and significant wave height. The extreme loads are the most probable maximum loads, computed through the definition of an equivalent extreme wave, expected to occur once within the return period.

The response of the structure to the loads imparted by an extreme wave can then be assessed. Depending on the probability level used to determine the extreme wave, and on the operational profile of the vessel, the designer can be satisfied with different levels of adequacy. For design loads a linear dynamic response is often sought. For investigations of

![Figure 16. Example of Gumbel plot to predict extreme slamming strains on a panel based on observed slamming events. The extreme values are computed for a return period of 3 hours based on 19 minutes of data recording. The peak positive and negative strain values recorded over every minute are shown.](image-url)
the ultimate strength to a wave representative of survival condition, the designer could accept damage of local structural members, as long as the overall integrity of the ship is not compromised. Ultimately more than one structural response curve can be produced, according to the chosen level of adequacy of the structure and/or the deemed urgency of a particular operation. For example, a curve could be created for a non-urgent, standard passage or transit and an alternative curve for urgent or time-critical services. The latter would require clear operating procedures and training as it means the boat would be working closer to or may even cross the structural limit bringing with it the increased likelihood of some structural damage to the secondary structure (e.g. stiffeners).

Because of the statistical nature of the approach and of the dependence on the return period, structural response lines should be read as lines with an associated risk of structural failures rather than hard lines with exact numbers.

The same procedure outlined here can be adopted for predicting the extreme lifetime loads and the associated structural response. This can be done by using a long-term description of the sea combined with information on the operational profile of the vessel to account for the time spent at each combination of speed and sea state.

10 CONCLUSIONS

The structural design of small high-speed craft has traditionally relied on semi-empirical methods. Whilst successfully employed for design purposes, these methods are less suitable for the direct calculation of seakeeping loads. A study has been undertaken to investigate the loads sustained by the RNLI’s lifeboats during operation and the consequential structural response.

Numerical simulations, towing tank experiments and sea trials were conducted to predict the major loads sustained when in operation. The numerical model was validated through comparison against experimental data.

Hydrostatic, wave and slamming loads are accounted for through a combination of seakeeping simulations and experimental data collected during the sea trials. The loads experienced during operation in rough seas are computed through an ‘equivalent regular extreme wave’ approach. Wave and slamming loads are linearised and scaled in the generation of a load case that represents the extreme loads experienced in given operating conditions.

The response of the structure to a load case is studied with a global finite element model of the vessel. A structural limit curve (Figure 2), as a function of speed and sea state severity, can then be defined from an analysis of the response of the structure to a range of load cases. Once the work is completed structural response curves will be constructed for different stress (or strain) thresholds and it will be possible to comment on their accuracy. Theories to determine the possible modes of failure of composite structures could also be employed.

11 OUTCOMES

Work is now being conducted by the RNLI to obtain empirical confirmation of the limits to speed in waves imposed by the installed propulsive power and crew endurance – the ‘Ride Quality’ and ‘Power Limit’ curves of Figure 2. Together with the work on the structural limit described in detail in this paper, the outcome will make it possible to gain a better insight into the operational envelope of the Severn Class.

This new knowledge will inform the design teams on areas of possible improvements in view of the life extension programme. The outcome will also have wider applicability to the design of future all-weather lifeboat classes and small high-speed craft in general.

This study also sets the basis for the development of a structural monitoring system to support the operation of search and rescue craft. By informing the crews of the loads being sustained by the structure, it is possible to optimise the on-board comfort whilst minimizing the risk of structural damage.

Ultimately, it is expected that this approach to the design and operation of lifeboats will result in improved performance, better response to emergency call-outs and increased safety for the on-board crews.
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