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Wave loads and flexible fluid-structure interactions: current developments and future directions

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The function of a Classification Society includes the setting of standards for the design, construction and maintenance of ship hulls to ensure adequate safety throughout their service life. Fundamental to this is the determination of the design loads to support the prescriptive Rule requirements and for application in direct calculations. The current design philosophy for the prediction of motions and wave-induced loads is driven by first-principles calculation procedures based on well-proven applications such as ship motion prediction programs. In recent years, the software and computer technology available to predict design loads has improved dramatically. With the stepwise increase in ship size and complexity it is necessary to utilise the latest technologies to assess the design loads on new ship designs. This paper discusses some of the recent experiences of Lloyd's Register with regard to the current state of the art in the assessment of design loads and structural responses by reviewing recent work on the effects of flexible fluid-structure interaction for hull girder and also for sloshing applications. The paper also discusses the Lloyd's Register strategic research programme on hydrodynamics, involving the use of state-of-the-art technologies for the solution of ship dynamic response problems.

Keywords: wave loads; springing; whipping; sloshing; non-linearities; ship design

1. Introduction

The function of a classification society, such as Lloyd's Register, includes the setting of standards for the design, construction and maintenance of ship hulls to ensure adequate safety throughout their service life. Fundamental to this is the determination of the design loads to support the prescriptive rule requirements and for application in direct calculations. The current design philosophy for the prediction of motions and wave-induced loads is driven by first-principles calculation procedures based on well-proven applications such as ship motion prediction programs. In recent years, the software and computer technology available to predict design loads has improved dramatically. We have experienced a stepwise increase in ship size and complexity that has given significant momentum to the need to utilise the latest technologies to assess the design loads on new ship designs. Examples of this include studies on the whipping and springing responses of ultra-large container ships and the development of computational tools and procedures for the prediction of sloshing loads in membrane liquefied natural gas (LNG) ships.

In addition to the assessment of design loads, there is a need to demonstrate that the current standards applied to ships are acceptable. To this end, Lloyd's Register continues to monitor and assess the loads on ships in service and benchmark design procedures and software tools. In order to ensure that issues implicitly addressed in the past can be explicitly included in design assessment tools and procedures, Lloyd's Register also implements the use of advanced fluid-structure interaction models able to assess the effects of global and local loads.

The purpose of this paper is twofold. Firstly, it discusses some of the recent experiences of Lloyd's Register in the assessment of ship design loads and associated structural responses. Accordingly, the paper outlines ship motions and computational hydrodynamic applications currently developed, benchmarked and used by Lloyd's Register. It also reviews recent work on the effects of flexible fluid-structure interaction for hull girder load predictions and our research studies on sloshing applications. Secondly, the paper outlines the key directions of the Lloyd's Register strategic research programme in ship hydromechanics. This involves research studies on the use of non-linear hydromechanic interaction models, conventional computational fluid dynamics (CFD) or mesh-less fluid dynamic methods and reliability analysis methods for the improved modelling of ship dynamic response problems.

2. State of the art

Over the last 250 years, Lloyd's Register has been developing Rules for Ships that are backed up by in-service experience and account for still water and low-frequency

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wave effects. With regard to shiploads and responses the Rules for Ships primarily put emphasis on ship bending in regular waves. Accordingly, it is assumed that ship bending takes place in two distinct frequency regimes, namely (1) ultra-low frequency and (2) low frequency. Ultra-low-frequency bending occurs in still water and accounts for about 40% of the total stresses incorporated in the normal design standards. Low-frequency bending occurs at frequencies primarily associated with the natural heaving and pitching periods of ships in regular waves. It accounts for about 50% of the lifetime stress expected upon the hull girder. Today, it is understood that for the majority of ships, low-frequency bending has the most important effect both in absolute terms and in accounting for the majority of stress reversals during a ship's life, with the still water bending moment coming next in absolute terms.

In some cases the Rules for Ships are not deemed sufficient, and Lloyd's Register develops direct analysis design assessment procedures for load assessment that, wherever applicable, are implemented in the Classification standards in a notation format. These include the Ship Design Assessment (SDA) and Fatigue Design Assessment (FDA) procedures for the assessment of the structure of container ships (Lloyd's Register 2002a, 2002b, 2002c) and sloshing loads assessment procedures for membrane-type LNG carriers (Lloyd's Register 2008). As an example, in the Lloyd's Register in-house procedure for the direct assessment of global loads, the wave transfer functions are obtained through hydrodynamic analysis carried out by suitably validated wave load calculation programs. Accordingly, the transfer functions are used for stochastic analysis to identify the maximum wave loads occurring during the vessel's lifetime. Short-term analyses performed for several irregular wave conditions (with different combinations of modal period and significant wave height) are used to feed long-term analyses where the wave loads are imposed, whilst considering the probability of exposure to those waves. The standard climatic data is for the North Atlantic environment and is defined in accordance with International Association of Classification Societies (IACS) Recommendation 34, over a 25-year design life (IACS Ltd. 2001).

A reflection of these procedures, coupled with empirical rules, is also implemented in the unified IACS Common Structural Rules for Tankers and Bulk Carriers (IACS Ltd. 2007a, 2007b). In these rules the dynamic loads are represented by a series of load combination factors, which represent the linear superposition of the various dynamic load components at a given point in time when the major dynamic load component is being maximised. Dynamic loads, pressures and, wherever applicable, empirically defined internal pressures of liquid cargo, are transferred to a structural model. For fatigue life evaluations, representative characteristic loads are used to represent the large number of everyday fatigue-inducing fluctuating load ranges. Fatigue calculation results are very sensitive to load and the corresponding stress range applications; the most representative characteristic loads are calculated at a probability exceeding 10^{-4}, which is considered to give the best accuracy.

In these developments, rules and design procedures are still based on linear, rigid-body ship hydrodynamics or empirical formulations. In-service experience with new concept ship designs, such as ultra-large container ships, suggests that resonance phenomena related to global or local loads may also be important. These phenomena are associated with high-frequency bending that is vibration-oriented and occurs most strongly if any of the natural modes of vibration are excited either continuously by high-energy waves of similar frequencies (or multiples of the resonant frequency) or alternatively by wave or cargo impacts.

To ensure adequate levels of safety, Lloyd's Register's short- to medium-term marine products and research activities are focusing towards the assessment and benchmarking of phenomena related with global hull girder resonant vibration (namely springing and whipping) as well as the assessment of sloshing-induced loads in LNG tanks and their coupling with ship motions, using advanced CFD techniques. The following sections outline some of the key results of the ongoing research and development programme with emphasis on the following:

- Hydrodynamics and hydroelasticity of ships
- Full-scale measurements
- Sloshing in ship tanks

2.1. *Hydrodynamic tools*

The principal ship motion hydrodynamic tools used by Lloyd's Register are the CRS program PRECAL and the Lloyd's Register (Martec) program FD-WAVELOAD. CRS is for 'Cooperative Research Ships', which is a joint industry group. These are rigid-body frequency domain seakeeping panel codes based on linearised potential flow theory that can be applied for the prediction of loads and responses of monohulls, catamarans and trimarans. In these programs the flow potential is solved in six degrees of freedom by application of the zero-speed Green's function. Radiation and diffraction pressures are calculated and integrated over the hydrodynamic mesh of the wetted part of the ship to give the forces, and hence body motions, in regular or random waves with or without spreading.

Representation of non-linearity in the ship responses to the environment and of short-duration events, such as slamming and deck wetness, are best represented by time domain simulation. Hence, CRS (including Lloyd's Register) has been developing a non-linear time-stepping suite of programs known as PRETTI over the course of this decade. In PRETTI, the hydrostatic and wave pressures are integrated over the wetted surface of the hull at each time step. Diffraction forces are obtained from PRECAL response amplitude operators and hence remain linear. The radiation

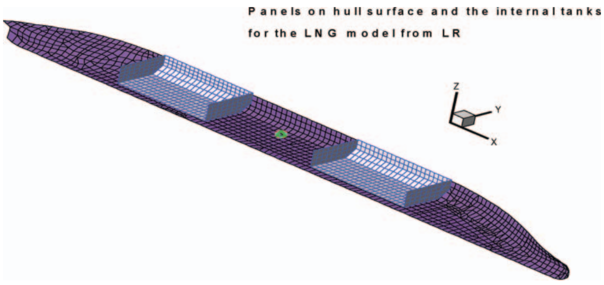


Figure 1. Hydrodynamic mesh for LNG carrier (tanks 2 and 4 partially filled). This figure is available in colour online.

forces are calculated by non-linear body velocities introduced into the linear radiation function.

In common with most ship motion codes, PRECAL and PRETTI consider only the action of the external fluid, i.e. the sea domain on the hull and its appendages. Even in more sophisticated time domain models the fluid level is assumed static at calm water level. The treatment of internal tanks is more typically limited to a nominal reduction in metacentre height due to free surfaces.

Lloyd's Register's (Martec's) latest FD-WAVELOAD software version improves the situation by considering that the fluids in tanks can be treated in a similar way as the fluid acting outside the hull, in a coupled ship motion and tank sloshing solution. The tanks are modelled with a hydrodynamic mesh (Figure 1), and the linear potential model is applied to give the forces for each panel, in a similar way as for the hull. Predictions incorporating tank fluid actions can be significantly different from those that do not account for the effects of tanks. The most dominant effects appear as the roll ship motion changes from a single-peak to a double-peak response in way of the natural frequency of the tank fluid (see Figure 2). Figure 3 shows the results of tank experiments of an LNG carrier compared with computational predictions in beam seas. The resonance in the roll motion at the tank's natural frequency is very well captured.

Roll time series data based on this advanced model are the most appropriate for studies involving sloshing; Section 2.4 discusses this area.

2.2. *Hydroelasticity of ships*

Concepts such as mode shapes, natural and resonance frequencies are not encompassed by the traditional rigid-body hydrodynamics or static analysis assumptions. Resonance phenomena may appear either in the steady state (springing) or at a transient level due to slamming of the bow (whipping) or stern of the vessel. These may produce low stress magnitudes but can have a profound effect on the number of stress reversals encountered by a ship, and certain ship types are more prone to these effects. The study of ship flexural responses requires the inclusion of hull elastic properties in the hydrodynamic model known as hydroelasticity (Hirdaris 2009a; Temarel and Hirdaris 2009). The application of hydroelasticity analysis in the design process could lead to improved predictions of global wave-induced loads, for example the torsional moments for monohull vessels with large deck openings. The combined modelling of hydrodynamics and flexibility requires consideration at a high level of complexity. Lloyd's Register is involved with research studies on hydroelastic predictions and associated model tests, as well as full-scale measurements and grid-based software development. An overview of these studies is outlined below.

2.2.1. *Hydroelastic predictions*

Hydroelasticity theory in its two- or three-dimensional form combines the principles of structural theory and marine hydrodynamics (conventional seakeeping and strength) by allowing the behaviour of a flexible body to be studied as it moves through a liquid. Hence, it can be used as a tool to determine the inherent motions, distortions and stresses under the actions of external loading arising from the seaway, as well as other dynamic sources of excitation. A typical approach for incorporating hydroelasticity in the design process of monohull vessels is shown in Figure 4 (Hirdaris and Temarel 2009c). The analysis is divided in two parts, namely 'dry' and 'wet' analysis. The relatively simpler two-dimensional analysis, comprising beam structural idealisation and strip theory for the fluid forces and fluid-structure interactions, can be used during preliminary design. On

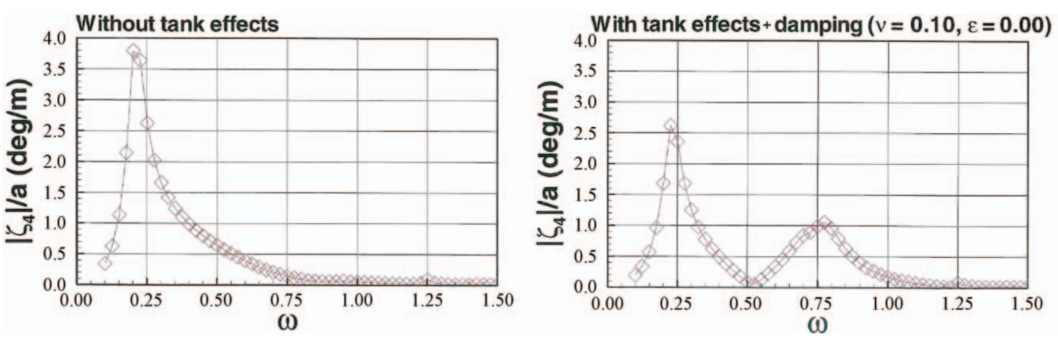


Figure 2. Roll motions of LNG carrier with and without tank effects. This figure is available in colour online.

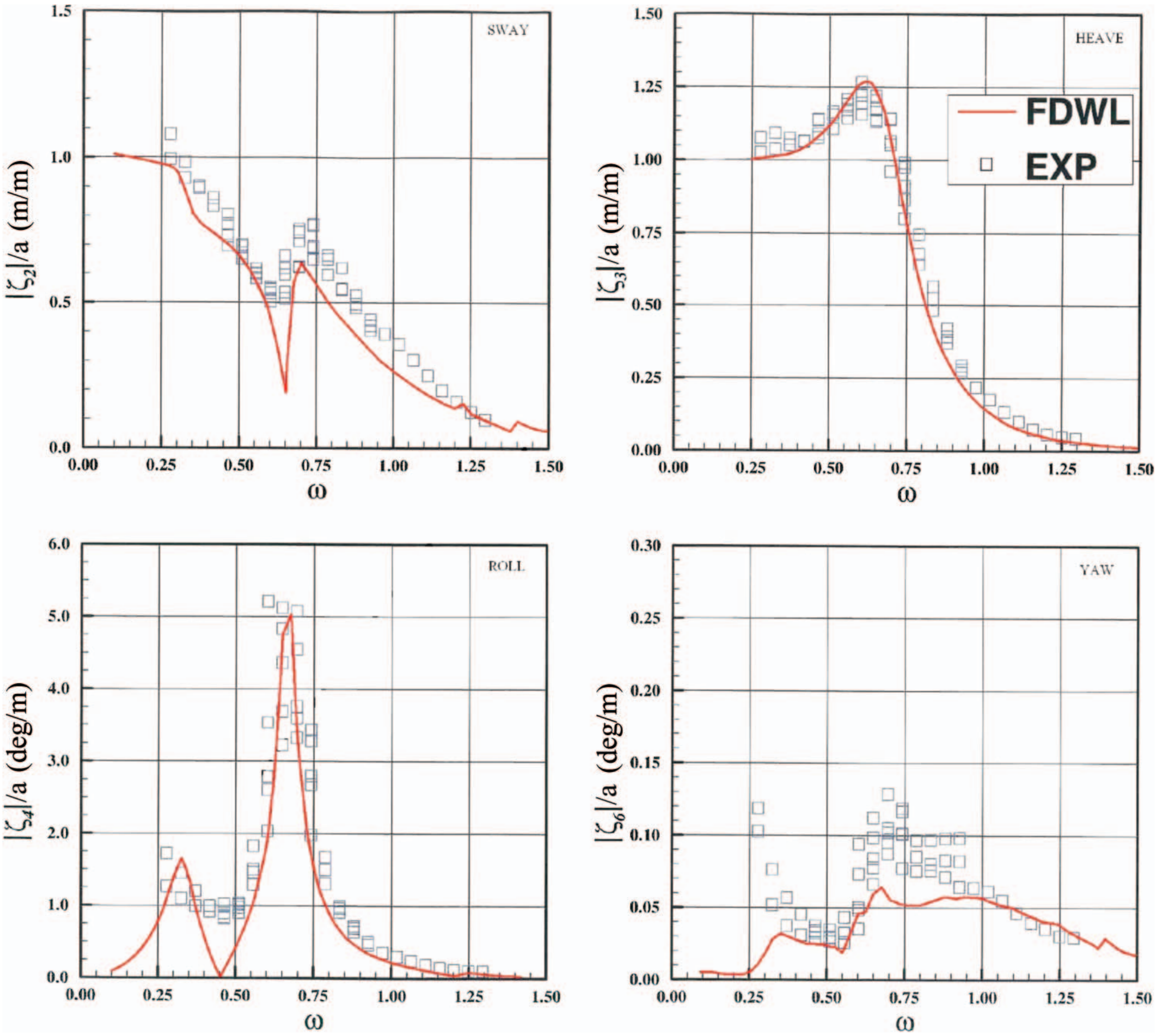


Figure 3. Comparison with model test results – motions of LNG carrier at 0 knots, beam seas (different loading conditions compared with Figure 2). This figure is available in colour online.

the other hand, a more detailed three-dimensional finite element analysis (FEA) of structural idealisation combined with source distribution over the mean wetted surface can be used for the detailed design and to account for structural discontinuities and torsional response issues.

To minimise the uncertainties related with the hydroelastic modelling assumptions and to create practical tools that can be used by designers, Lloyd's Register has been developing G-hydroflex, a Web-enabled system for hydroelastic predictions, as well as weakly non-linear hydroelastic solvers, in conjunction with the Lloyd's Register Educational Trust (LRET) University Technology Centre (UTC) at Southampton University.

In the G-hydroflex system the grid portal is at the heart of the system integrating a number of other hardware and software components (see Figure 5). Since access to the portal requires only an Internet connection and a standard Web browser, data and current job status are always available. This illustrates the built-in flexibility in terms of imported data, mesh extraction and solution and output generation for either rigid-body or unified hydroelastic analyses. The grid portal infrastructure provides workflow and user and job management by incorporating object-oriented programming facilities and hydroelastic and rigid-body hydrodynamic programmes, as well as suitable visualisation software (see Figure 6).

Recent Lloyd's Register studies carried out using the modelling assumptions and procedures incorporated within the G-hydroflex software have been focused on modelling the springing analysis of a container ship and the service factor assessment of a Great Lakes bulk carrier (Hirdaris and Temarel 2009c, Hirdaris et al. 2009b). Whereas the

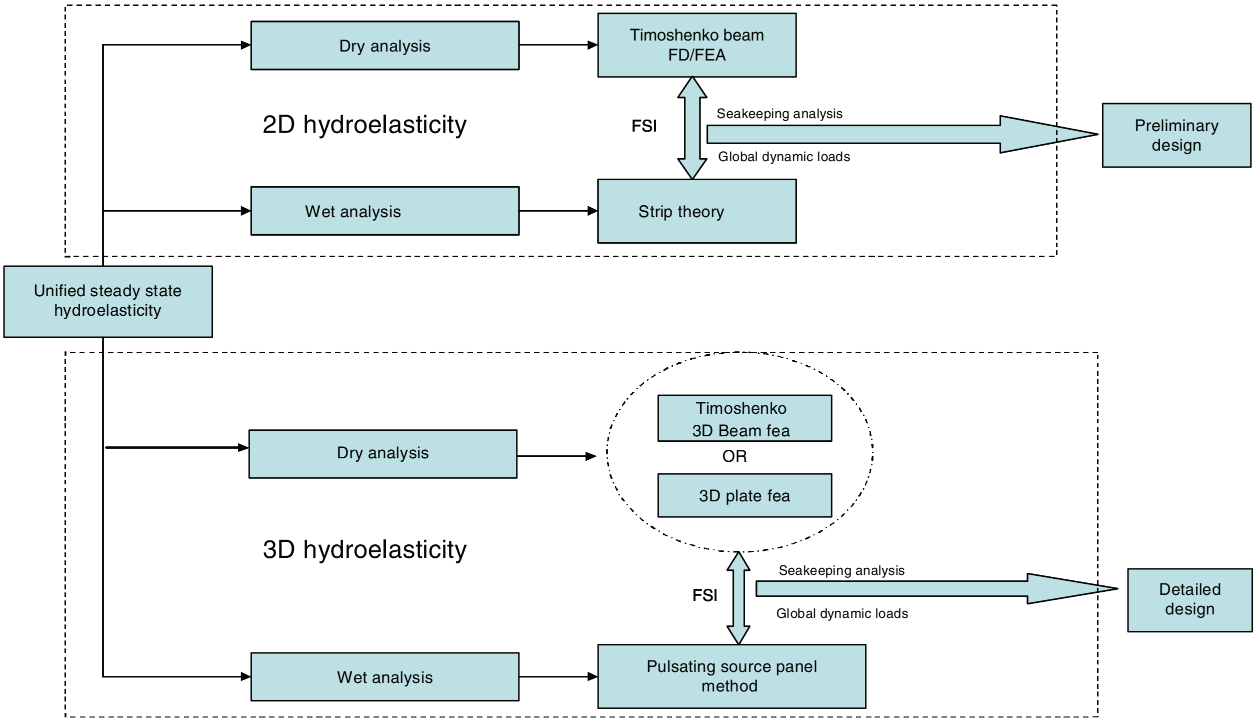


Figure 4. Example illustrating the use of hydroelasticity theory in the design process of monohull vessels. This figure is available in colour online.

former application contributed towards building up of hydroelastic modelling capabilities, the latter contributed towards enhancing the Lloyd's Register technology investigation capabilities.

For the container ship study a NASTRAN-generated three-dimensional finite element model (FEM) was used to determine the global mode shapes of the vessel and the associated modal internal actions (see Figure 7). The mean wetted surface mesh, required for the wet analysis, was

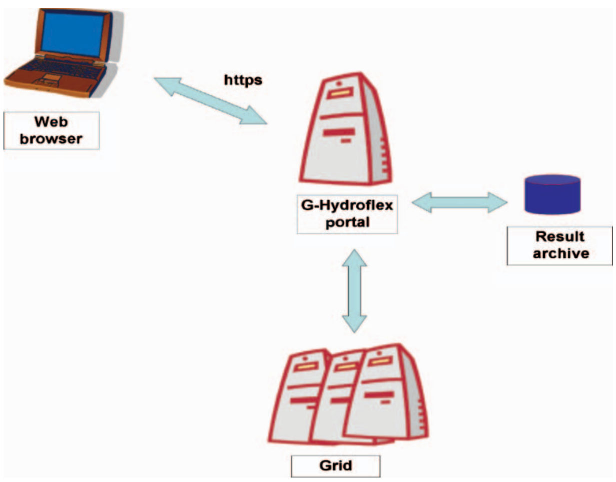


Figure 5. G-hydroflex web portal architecture. This figure is available in colour online.

extracted from the imported finite element (FE) data file, using the shell elements on the hull surface (see Figure 8). Through the use of grid-based computation, the wet analysis for a refined mesh was carried out in a time frame acceptable for practical engineering analysis. Steady state vertical and horizontal bending moments, associated shear forces and torsion moments were evaluated in regular waves.

The assessment procedure followed for the derivation of the service factor assessment of the Great Lakes bulk carrier is outlined in Figure 9. In hydroelastic analysis, four distortion modes were included and predictions were obtained in both regular and long-crested irregular waves. To determine the effects of fore-body slamming on the hydroelastic response, maximum forefoot emergence of 0.25 Lpp was assumed. The transient hydroelastic analysis (whipping) loads were derived in the time domain. A three-dimensional frequency domain hydrodynamic (rigid-body) analysis was carried out in regular and irregular waves, the latter using spectral analysis. In this case the vertical wave bending moment and wave shear force response amplitude operators were obtained by applying the hydrodynamic and inertia loads to a beam model, equivalent to that used in the two-dimensional hydroelasticity analysis.

The flexible fluid-structure interaction analysis results were correlated with full-scale measurements that are available for this ship in irregular seas and were found to be in good agreement in both the ship-wave matching region and the two-node wet resonance (3.84 rad/s) associated with

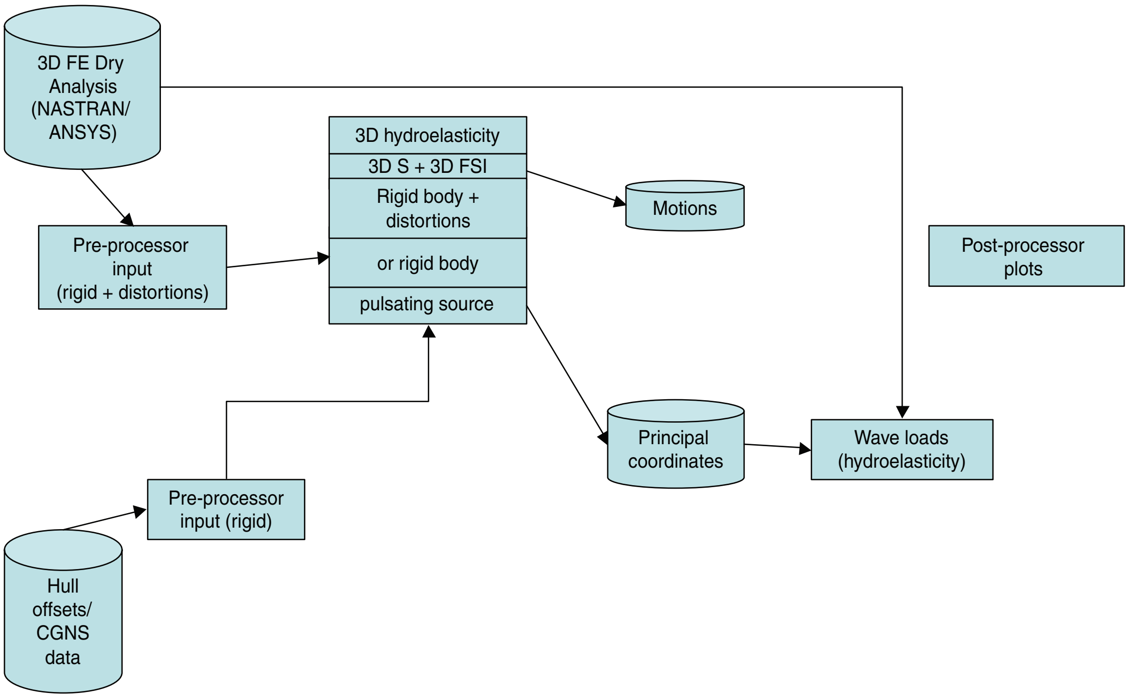


Figure 6. G-hydroflex sample workflow functionality of underlying algorithms. This figure is available in colour online.

springing (see Figure 10). These comparisons showed that achieving good agreement between hydroelastic predictions and measurements, for both ship-wave matching and springing, depends on the parameters of the wave spectra as well as the estimation of structural damping for the latter and any uncertainties involved in measuring such data. A maximum difference of 37.7%, due to springing and whipping, was obtained for the vertical wave bending moment by way of amidships at head seas in irregular seaways of significant wave height 7.1 m and characteristic wave period 7.0 s. For the transit voyage loading condition, and for the sea states considered, whipping due to bottom slamming was found to be of similar importance as springing.

As part of the work of correlation with full-scale measurements (see also Section 2.3), Lloyd's Register has underway a non-linear hydrodynamic study to predict springing and whipping for the case of an 8100-TEU container ship. The analysis was based on an equivalent design wave height of 14.5 m (peak–peak) and a period 14.3 s corresponding to a wavelength of about 0.9 L_{BP}. Linear and non-linear time domain calculations were carried out for a forward speed of 5 knots into head seas. In non-linear hydrodynamics the hydrostatic and wave pressures were integrated over the wetted surface of the hull for each defined panel at each time step. Hence, the simulation accounted for the changing waterline, which is of particular interest in the bow region.

For this regular wave, the results predict that ship-hogging wave-induced bending moments increase by about

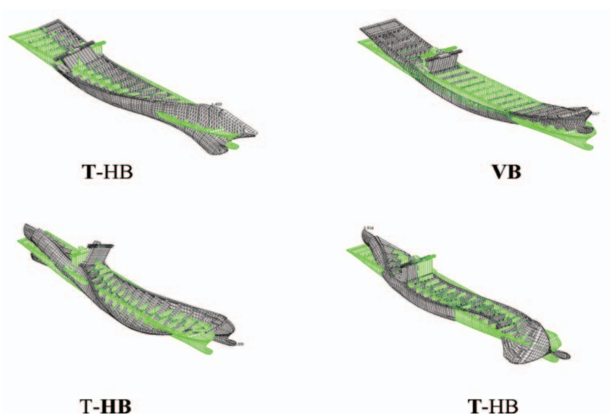


Figure 7. NASTRAN illustration of flexible modes of the container ship (T = torsion, H = horizontal bending driven, VB = vertical bending; bold letters denote dominant effects). This figure is available in colour online.

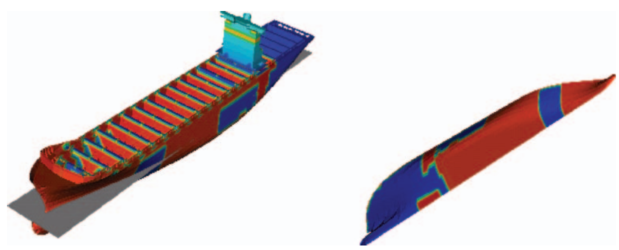


Figure 8. Container ship CAD idealisations (three-dimensional geometry and wetted surface). This figure is available in colour online.

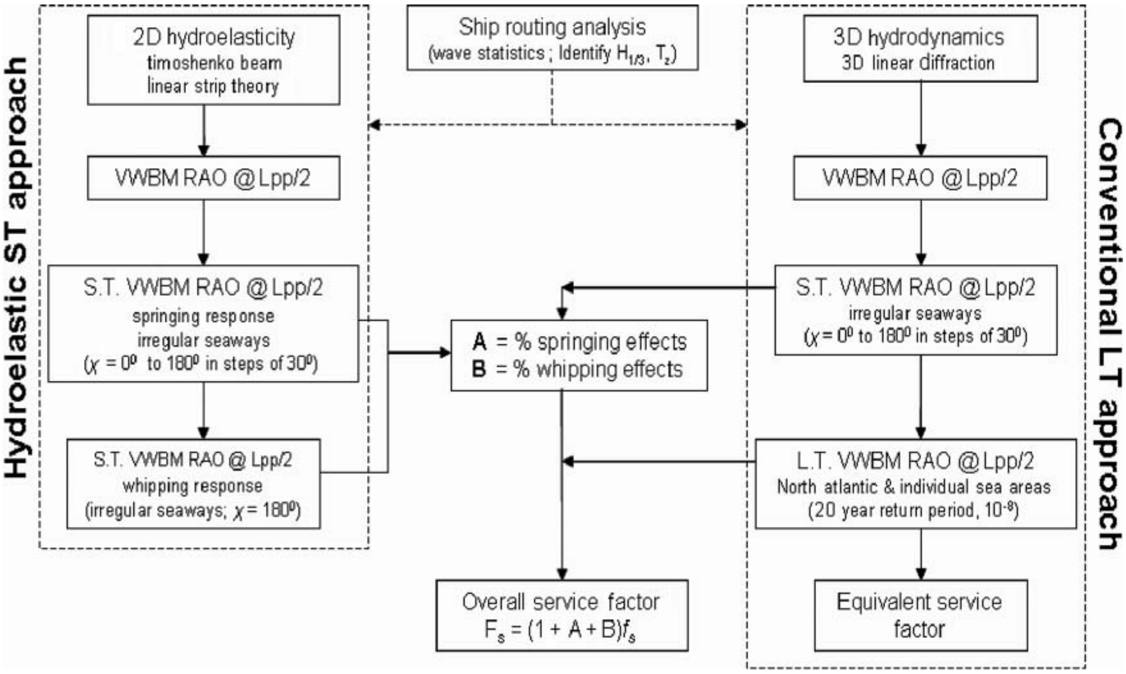


Figure 9. Service factor assessment procedure (S.T. = short-term probabilistic approach, L.T.= long-term probabilistic approach, $H_{1/3}$ = significant wave height, T_z = zero crossing wave period, χ = wave heading).

11% compared with linear rigid-body hydrodynamic predictions when whipping/springing are included. However, the sagging wave-induced vertical bending moment (VBM) increases by 42% when non-linear hydrodynamic effects are considered and by 71% when whipping is included. Calculated results (Figure 11) are similar in trend to full-scale results (Figure 18). Calculations have also been made in a rather steeper wave (wave height 16 m, period 10 s). In this case, high-frequency slam events are more visible, as are the springing vibrations of the ship (Figure 12). Higher-frequency vibrations are present when the whipping effect is included, though they do not show the damped very high-frequency vibration classically associated with slamming.

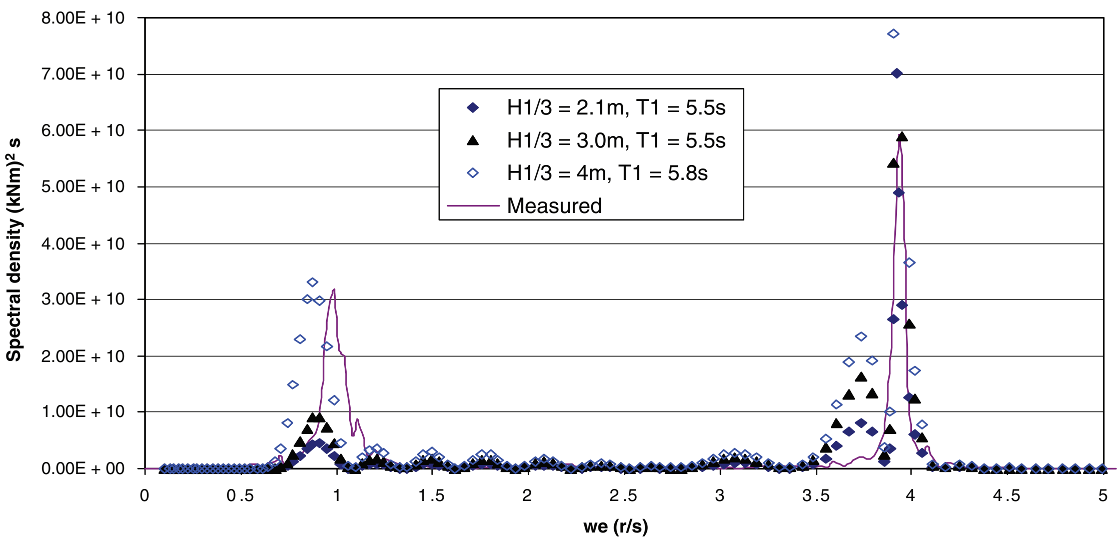


Figure 10. Comparison of amidships' VBM response spectra $(kNm)^2$ s predicted by two-dimensional hydroelasticity analysis against full-scale measurements. This figure is available in colour online.

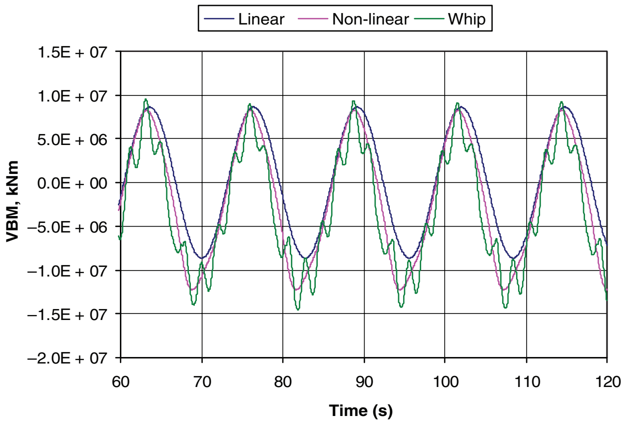


Figure 11. Time history of amidships VBM of container ship in equivalent design wave. This figure is available in colour online.

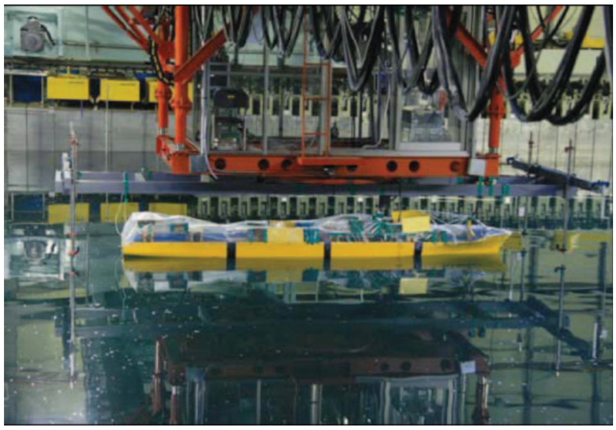


Figure 13. Four-segmented 6250-TEU container ship model used for WILS I model tests. This figure is available in colour online.

2.2.2. *Model tests*

Since 2006, as part of the efforts to understand the mechanics of flexible fluid-structure interactions and validate in-house software capabilities, Lloyd's Register has participated in the joint industry project Wave-Induced Loads on Ships (WILS), managed by the Korean Maritime and Ocean Engineering Research Institute (MOERI). The project consortium comprises major Korean ship builders and class societies. The overall objective of the project is to provide model-scale measurement data for wave-induced ship motions and loads, as well as to benchmark with measurement data and numerical results calculated by Class Rules and software applications. In the first phase of the project (WILS I, 2006–2008), the hydroelastic model tests that have been carried out involved experiments with a 1:55 scale model of a 6250-TEU ($L_{pp} = 286.3$ m, $B = 40.3$ m) container ship with bilge keels and four segments (see Figure 13). Experiments were undertaken in regular and irregular waves over a variety of forward speeds and headings (Hong et al. 2008). Comparisons between experimental and numerical results have shown satisfactory agreement for ship symmetric responses (i.e. vertical shear forces and bending moments) as shown in Figure 14. However, measurements and predictions of horizontal shear forces and torsional moments for both non-linear and design wave cases showed less satisfactory agreement.

The ongoing second phase of the project was initiated in 2008. It involves further comparisons of experimental measurements against linear and weakly non-linear hydroelastic computer programs. Currently, numerical predictions are compared against model tests of a 1:60 scale six-segmented 10,000-TEU container ship model. The experiment set-up used six-component load cells and pressure gauges in the measurement system. The test conditions considered the effects of irregular waves over a variety of seakeeping conditions (three speeds and five headings) and estimated loading conditions. Figure 15 shows an example of non-linear springing events measured during the tests.

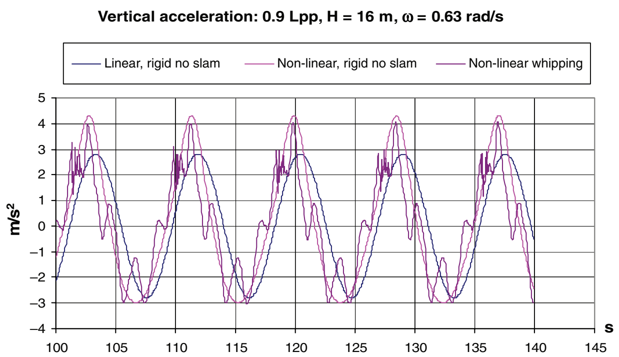


Figure 12. Vertical acceleration near bow. This figure is available in colour online.

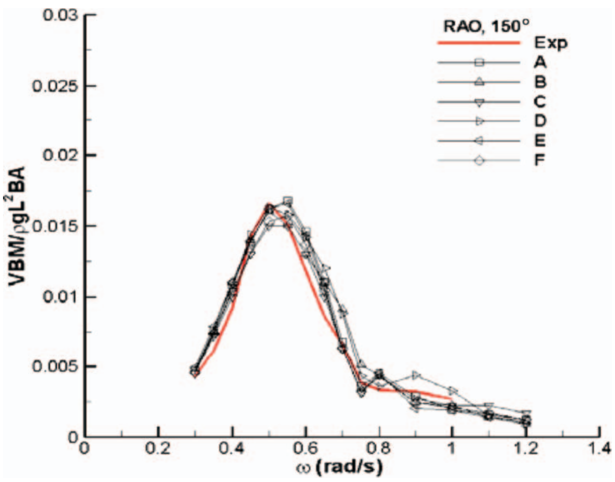


Figure 14. VBM comparisons between measurements and predictions of the WILS container ship; $V_s = 5$ knots, $\chi = 120°$ (Exp = experimental; and A, B, C, etc. = predictions). This figure is available in colour online.

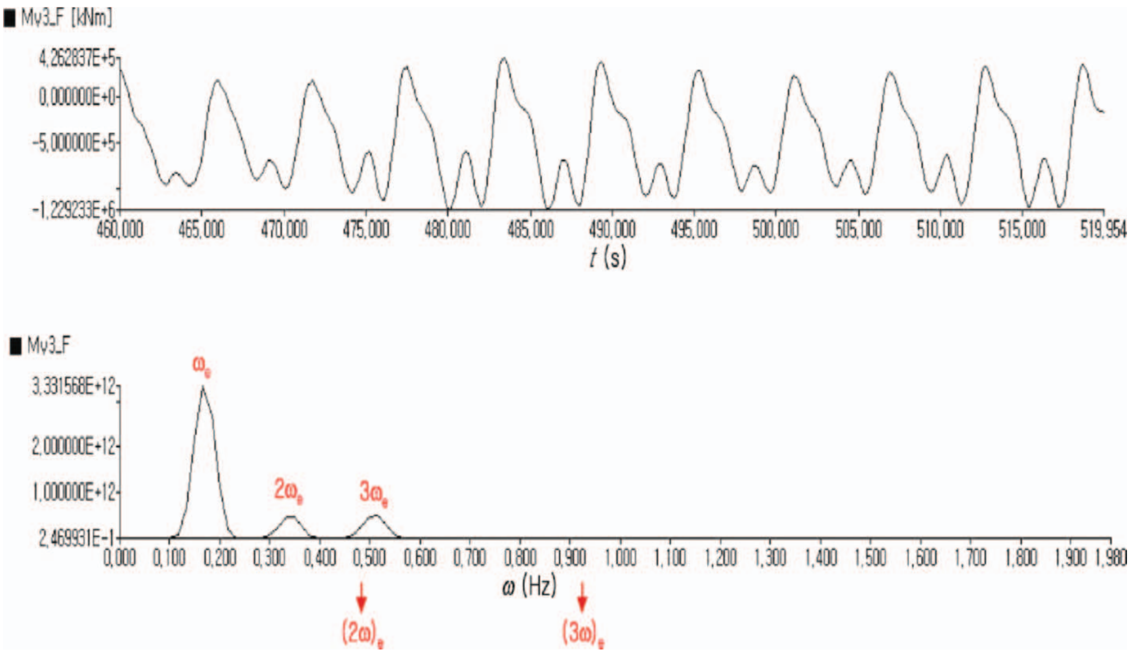


Figure 15. An example of non-linear vertical bending springing investigated during the tests; $V_s = 20$ knots, $\chi = 180^\circ$, $H_s = 5$ m, $t =$ 9.812 s. This figure is available in colour online.

The results from this joint industry project will enhance the understanding on the combined effects of non-linear wave actions and antisymmetric (i.e. horizontal-bending-and torsion-driven) wave-induced loads on global and local dynamic response (MOERI 2009) and assist with the verification of Lloyd's Register hydrodynamic and hydroelastic ship motion tools.

2.3. Full-scale measurements

Since 2005, Lloyd's Register has been conducting long-term full-scale measurements on board an 8100-TEU ($L_{OA} =$ 334 m) container ship. One result of this programme is that the measurements have improved our understanding of the contribution of hull flexibility to the cumulative fatigue damage index.

During an 18-month measurement campaign, the vessel was operating on a Europe–Far East route. The ship was instrumented with six long-base strain gauges to measure the stresses, a WAVEX-type wave measurement system, six-degrees-of-freedom motion measurement unit and a global positioning system (GPS) receiver. Four long-base strain gauges have been arranged as a ring at the engine room forward bulkhead, and two long-base strain gauges have been installed on under-deck longitudinal amidships (see Figure 16).

The hull girder stresses on the transverse section in way of the engine forward location have been correlated to the applied global loads by a set of linear simultaneous equations in matrix form. The matrix coefficients were determined using a full-ship FEM and applying unit values of each global load to the structural model. As a result, longitudinal distortions, vertical and horizontal bending moments and the torsion moment were determined in way of critical locations (Figure 17).

The same matrix coefficients have also been used to convert the individual global loads into local stresses at the sensor locations in way of the engine room forward bulkhead location. Using a simple beam theory and the torsion distribution from the FE results, the stresses at critical locations were calculated (Lloyd's Register 2002b). The highest stresses were measured at the top of the hatch coaming, where both the VBM-induced stress and the warping stress are maximum.

The contribution of global loads on the total fatigue damage index was obtained by removing individual global load stresses from the total stress time traces. The total fatigue damage index for the stress history with and without the global load components can then be calculated. Then the difference is the contribution of that global load to the total fatigue damage. It was concluded that for the section forward of the engine room, the contribution to the fatigue damage index from torsional loads is significant, up to 50% for the longitudinal stiffener in way of the deck passageway and 75% for the longitudinal stiffener in way of inner hull bottom. The analysis also revealed that vertical hull girder bending moment (as opposed to horizontal or torsional components) can contribute more than 99% of the total fatigue damage index in way of the deck locations amidships.

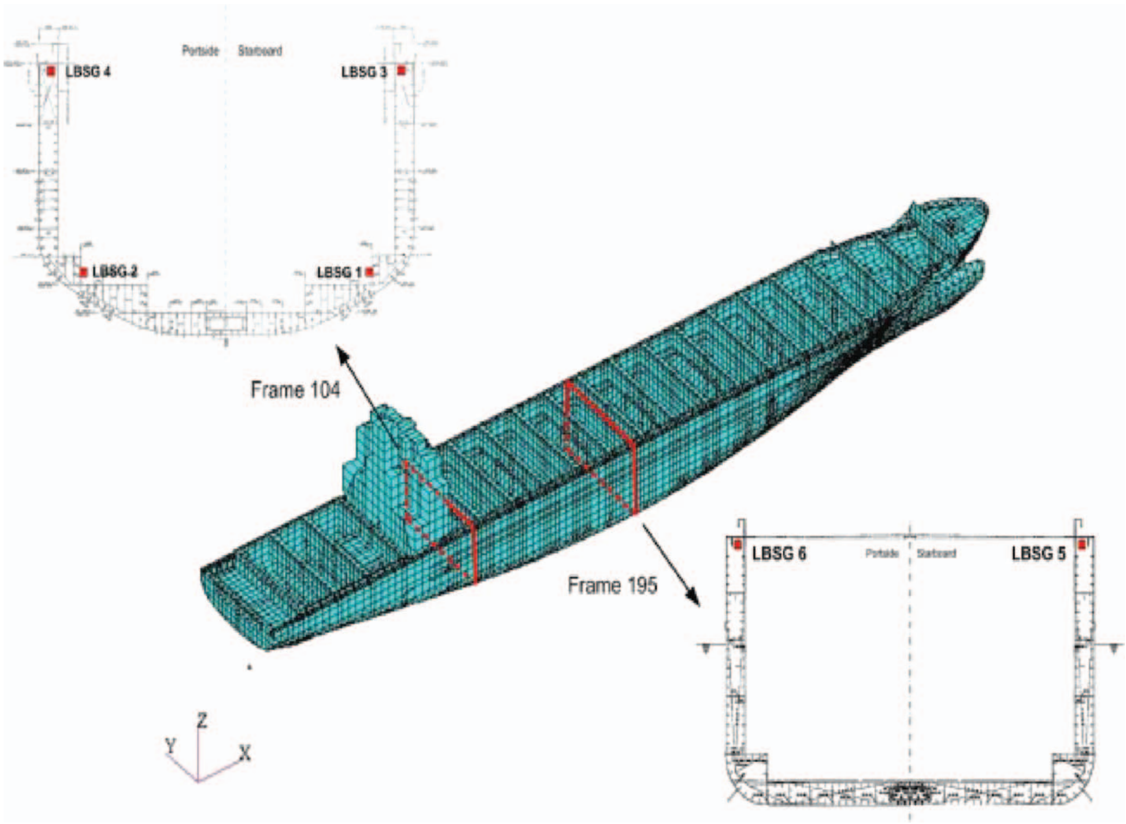


Figure 16. Location of the long-base strain gauges. This figure is available in colour online.

Although slamming-induced whipping has a relatively low probability of occurrence, the resulting VBM-induced stresses are often significant and, even with low structural damping, last for only a few cycles. In contrast, for springing, the VBM amplitude is much lower than a slamming-induced whipping event, but due to possible extended periods of oscillation, it may have a significant effect on the expected fatigue life of the ship structure. By applying a frequency filter over all the measured data it is possible to isolate the natural frequency response of the structure and compare it with the response which includes all information. An example of a measurement time trace with a slamming impact superimposed over a fairly constant springing effect is shown in Figure 18.

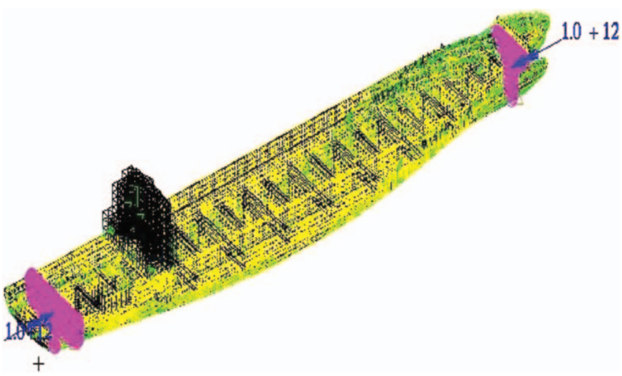


Figure 17. Torsion moment applied to the FE model. This figure is available in colour online.

Figure 19 shows the effect of applying a filter to extract only the high-frequency part of the time trace. The effect of hull flexibility on fatigue was calculated by comparing the fatigue damage index using the unfiltered data with the index calculated by data after the high-frequency data, i.e. the hull natural frequency response, has been removed so that only the low-frequency wave response is present. Results have been calculated for 14 starboard locations at the engine room forward bulkhead location and in way of the two midship sensors (Figure 20).

The results clearly indicate the importance of the springing and whipping contribution towards the total fatigue damage. Whereas the fatigue life is 65 years when the effect of natural hull girder vibration is not taken into account, the projected fatigue life at the hatch coaming top based on the sea condition encountered in the first 14 months of operation was estimated as 49.5 years (based on design S-N curve corresponding to 97.25% survival).

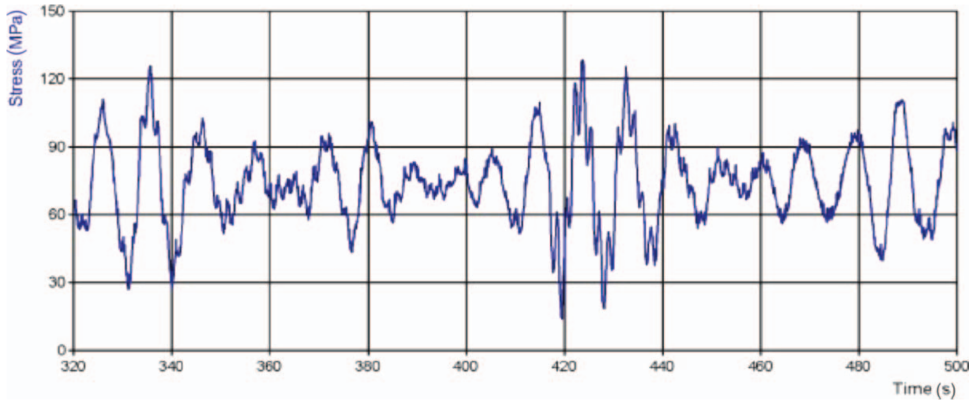


Figure 18. Typical whipping event at about 415 s. This figure is available in colour online.

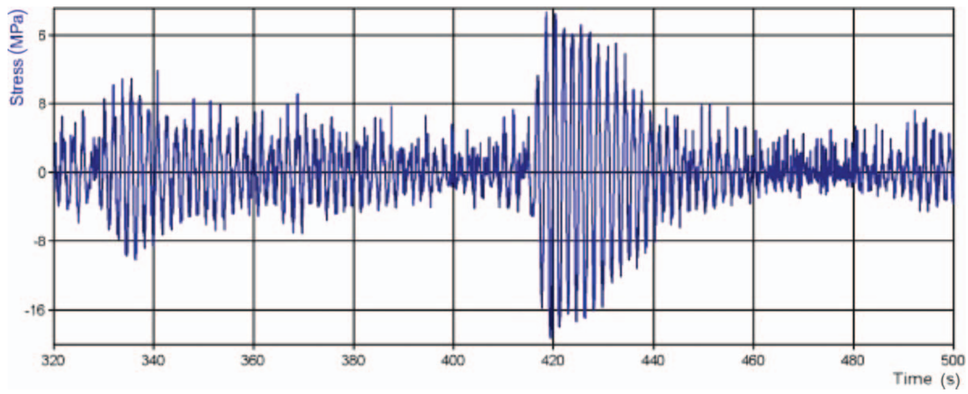
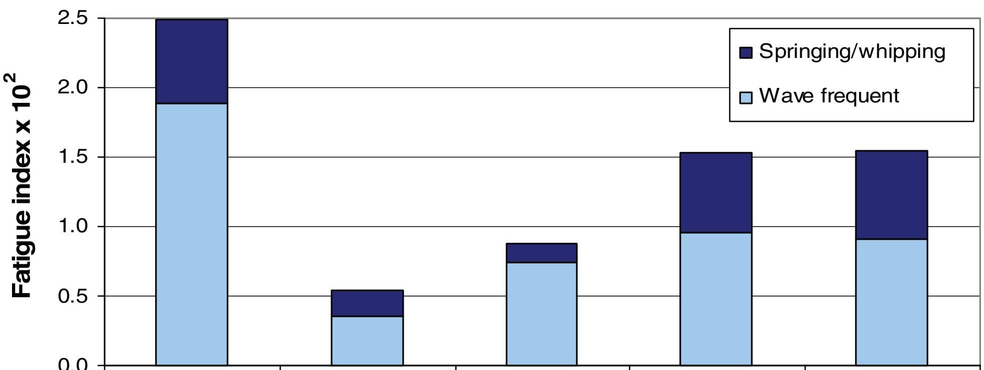


Figure 19. Filtered data showing only natural hull response frequencies. This figure is available in colour online.



	1	2	3	4	5
Springing/whipping	0.594	0.187	0.125	0.577	0.639
Wave frequent	1.890	0.361	0.748	0.9561	0.9079
All data	2.483	0.548	0.873	1.53337	1.54728
Increase [%]	31.4	51.9	16.7	60.4	70.4

Location

Figure 20. Fatigue damages caused by wave-induced rigid-body motions and hull vibrations (1 = hatch coaming top; 2 = underdeck longitudinal; 3 = bilge location; 4 = midship underdeck longitudinal port side; 5 = midship underdeck longitudinal starboard side). This figure is available in colour online.

2.4. *Sloshing in ship tanks*

Lloyd's Register has been heavily involved with sloshing-related studies since 2000 and has developed a state-of-the-art methodology for assessing the integrity of LNG containment systems (Lloyd's Register 2009). Apart from the main research and development programme, additional studies have been undertaken following a major incident that resulted in severely deformed primary membrane boxes of a ship fitted with the GTT NO96 system. A review of the voyage history showed that the ship had not experienced any really severe storms, and hence the deformations were totally unexpected. Studies confirmed that the maximum sloshing loads may be encountered in moderate sea states and not in the severest sea states as previously thought.

In this Lloyd's Register procedure, guidance is given for deriving the sloshing loads from the model tests, the additional processing necessary to review the type of impact and the most appropriate scaling laws to derive the full-scale impact pressure. It is also necessary to derive the rise and decay times for the critical sloshing impact events to ensure the structural dynamic effects are handled correctly. On the load capacity side, the procedure gives guidance on the evaluation of the strength issues, taking into account dynamic loads and their application, dynamic strain rate effects, temperature effects, containment system and hull interaction issues.

In view of the recent sloshing-related problems being encountered, the document recommends that a simplified absolute approach be adopted, which effectively applies a load resistance factor-design approach. This is linked with a hazard identification risk assessment process, which is used to identify the possible failure modes and consequences. The intention is that the designers undertake as thorough an analysis as is possible, with the support of Lloyd's Register, by taking into account as many factors as possible. Factors which are practically impossible to derive are addressed by the application of partial factors that build conservatism into the design. These partial factors can be refined in due course when better analysis or modelling techniques become available. The novelty of the materials being used by the cargo containment system designers means that the experience base that Lloyd's Register has with steel structures is no longer applicable, and hence it is the designers who are responsible for setting the acceptance criteria for their design. At a later stage, Lloyd's Register will appraise the designers' documentation and calculations as is usually recommended in safety case approaches.

Due to the complexity of the underlying physics of the sloshing impact pressures and structural dynamic response of the containment systems, it is the Lloyd's Register view that in the short term a practical and reliable method for predicting sloshing impact pressures for design assessment is the use of scale-model sloshing tests. However, as part of our ongoing research programme, we also focus on methods related with the prediction and correlation of the loads due to sloshing impacts, the calculation and prediction of the structural response and ultimate and fatigue capacities of the insulation. Studies related with this research programme follow.

2.4.1. *Assessment of sloshing loads*

Modern LNG carrier ships have very large LNG tanks which may span a significant portion of the beam of the vessel, as tank sizes have reached a length, width and height of 46, 48 and 29 m, respectively. Due to the motion of the ship in waves, the LNG sloshes around the tank and in the process can generate very high-impact pressures on the containment system and the supporting hull structure.

Historically, sloshing loads have been assessed using model tests with water. Lloyd's Register undertook a series of model tank tests in the early 2000s to review the possibility of allowing unrestricted fill levels in LNG membrane tank ships. The results of this assessment allowed for a reduction in the barred fill range from 80% to 70% of the internal height of the tank. Further model tests were carried out to review the loads on pump towers and to calibrate CFD tools against model tests (Lloyd's Register 2008). These early studies also revealed that there are several issues related to the application of loads derived from model tests, namely

- scaling issues due to the use of water and air (or some other ullage gas) and
- suitable representation of the near-boiling LNG liquid and vapour in the ullage space.

Correlation with full-scale measurements is also complex. To reflect this, Lloyd's Register is currently involved in a joint industry project with another Class Society, GTT, owners and a shipyard to measure loads and strains acting on the cargo containment system and hull structure of an LNG membrane ship fitted with GTT's NO96 containment system.

With the increase in computer power, the practical application of the latest generation of CFD codes for design assessment is becoming more realistic. Hence, Lloyd's Register also concentrates on the development of expertise in the modelling of sloshing phenomena using CFD programs such as OpenFOAM and Star-CD. The CFD-based sloshing analyses being carried out by Lloyd's Register use three-dimensional time domain ship motions. Processing of the time histories of the sloshing pressures on the boundary of the tank is assessed using proprietary software. This determines the occurrence of impacts, assesses the mean rise/decay times of the pressure pulse and statistically processes the impact events. A similar technique is also used for results from model tests. As noted earlier, recent in-service experience has revealed that the maximum sloshing

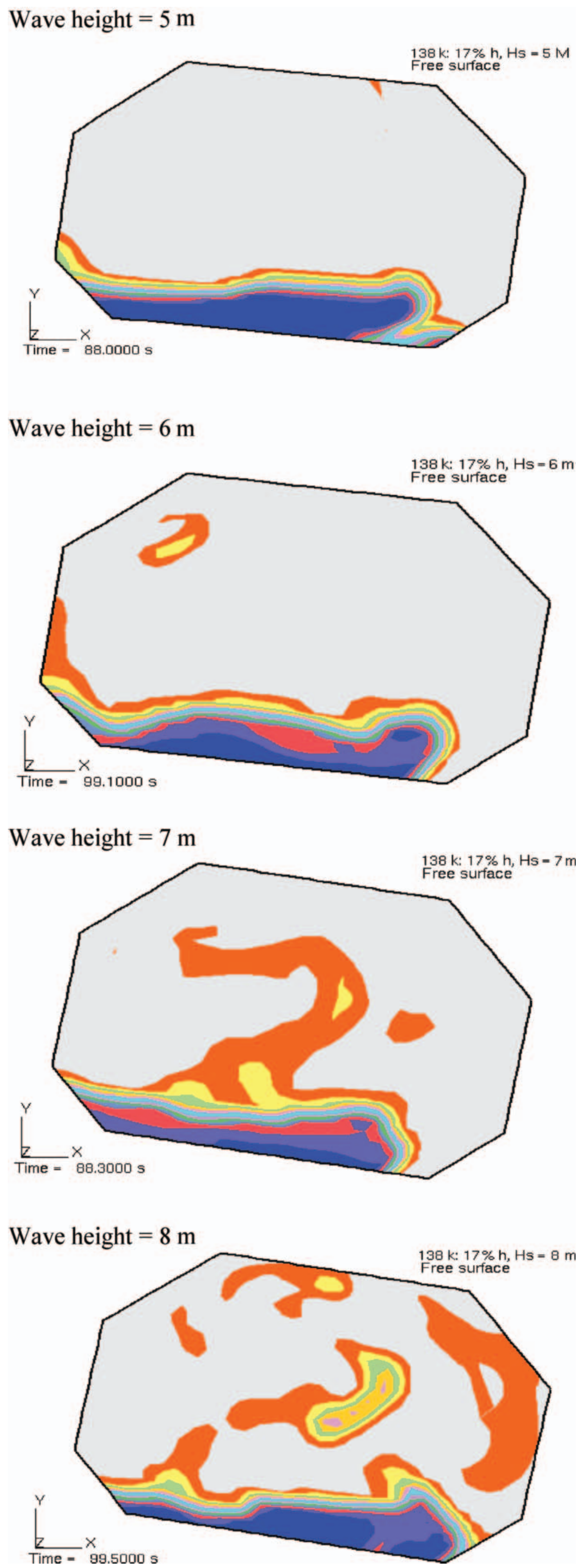


Figure 21. CFD simulation illustrating the effect of increasing sea state on the liquid motion. Maximum predicted sloshing load occurs at 6 m and then gradually reduces for increasing wave heights. This figure is available in colour online.

loads are encountered in moderate sea states rather than the severest sea states. Figure 21 illustrates this point with results of a simple CFD study. In each case the sea state wave period is the same, but the significant wave height is altered. The sloshing bore wave is most strongly pronounced for an intermediate wave height of 6 m. In higher sea states, the liquid motion becomes more violent and dispersed and the bore wave is not so clearly defined.

CFD offers the capability to look at many issues, which is not possible using model tests. For instance, it can provide important insights into local flow phenomena and address general flow characteristics. However, application is not straightforward. A number of issues related to engineering physics and the ‘economy’ of the simulation need to be resolved. These are as follows:

- Scaling of results, associated with the use of water/air or other fluid mixture used in model tests compared with LNG/gas mixture at full scale.
- Compressibility of gas during violent events both in the fluid and at the walls.
- Turbulence modelling, particularly during wall impacts and wave breaking.
- Local hydroelastic effects during impacts, as tank walls may be considered flexible.

Additionally, it is appropriate to consider the coupling of ship motions and the sloshing loads, as mentioned in Section 2.1.

2.4.2. *Strength assessment*

Lloyd’s Register has undertaken an extensive series of large-scale dynamic FEAs, which include the hull structure and portions of the containment system for both GTT NO96 and Mark III containment system designs (see Figures 22, 23 and 24). The aim was to improve our understanding of the effect that sloshing impact loads have on the containment system, taking into account local hull flexibility effects. The review included studying the sensitivity of the dynamic response to effects such as load area size, rise time and impulse duration of impact loads. Other FE studies looked at non-linear dynamic analyses of parts of the containment system. This included looking at methods to assess the effects of LNG in contact with the containment system after the impact and the effect this wetting has on the dynamic response and simple ways of handling this fluid-structure interaction effect. In order to better understand fluid-structure interactions and to integrate the use of FEA with CFD, Lloyd’s Register has undertaken an additional research programme that includes one-way transfer of pressures from the CFD code to the structural dynamics analysis FE code at each time step. In addition, the effects of the transfer of pressures from the fluid code to the dynamic FEA and the resulting instantaneous deformation response

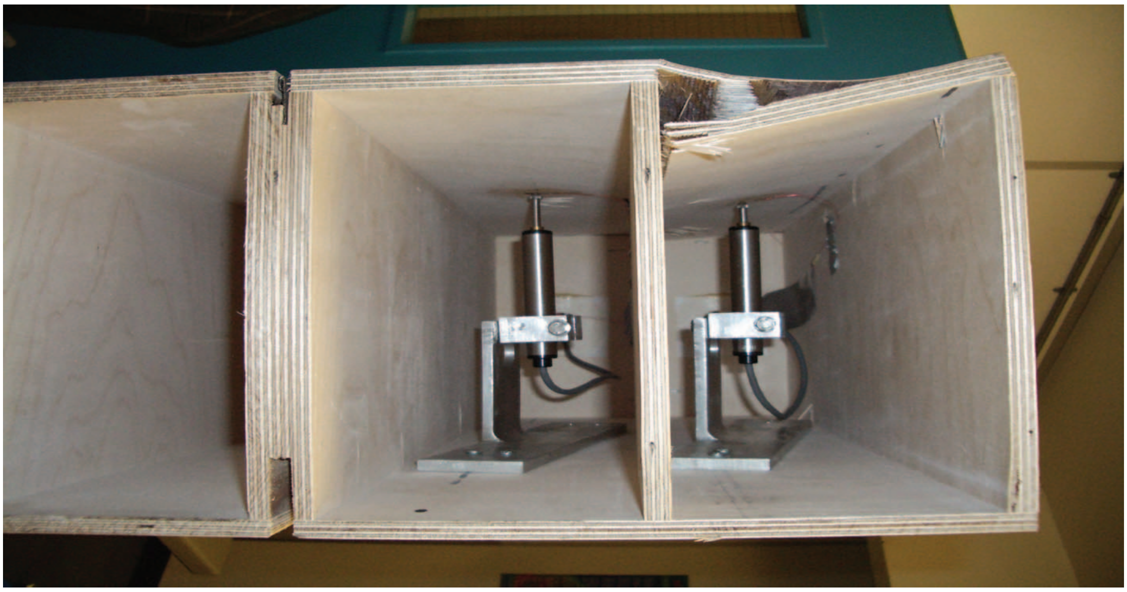


Figure 22. Failure of NO96 primary box due to repetitive cyclic loads. This figure is available in colour online.

of the containment system boundary being transferred back to the CFD program has been investigated. This allows the use of the instantaneous deformed tank shape to evaluate the pressure at the next time step. This work will assist in the understanding of the sloshing pressures experienced by the containment system in response to sloshing events and also the response of the containment system.

3. Future research

3.1. Motivation

In the development of a modern maritime industry, ship classification has emerged as an essential contributor to the safeguarding of life, property and the environment. Today the maritime industry faces heightened challenges. Major forces among those shaping the topography of the

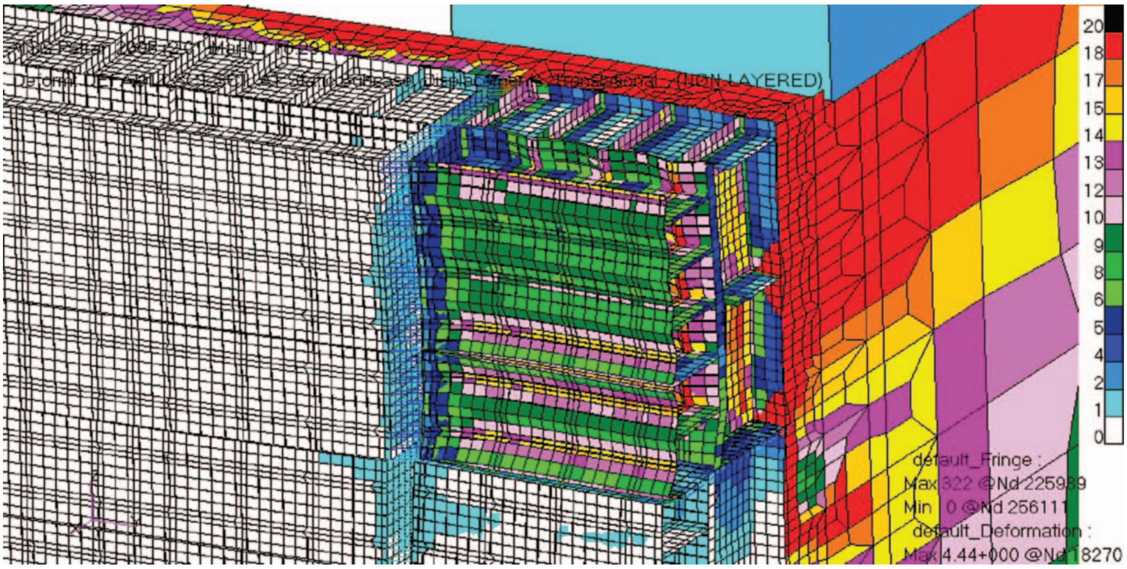


Figure 23. FEA of a set of NO96 boxes (slice through the containment system and hull structure). This figure is available in colour online.

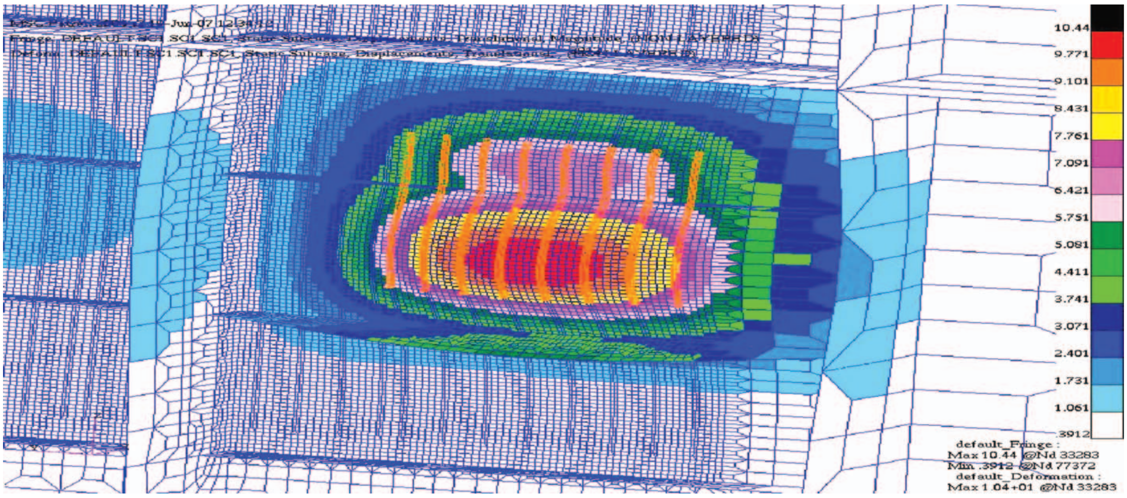


Figure 24. Bending of the hull plating due to a sloshing load applied to a single NO96 box. The orange lines denote the location of the mastic ropes between the NO96 boxes and the hull plating. This figure is available in colour online.

technology landscape are the increasing globalisation of markets, the need for enhanced safety and environmental performance standards, the need for transparency and uniformity in standardisation via updated regulatory frameworks and even the changing workforce requirements.

The completion of Common Structural Rules for Tankers and Bulk Carriers (IACS Ltd. 2007a, 2007b), the IMO Goal-Based Standards initiative (Lloyd's Register 2008), the continuous technology advances in information technology and naval architecture, the shipbuilding market demands with reference to the economies of scale and the opening of new routes for shipping operations (e.g. Arctic route), as well as the increasing need for collaborative work between maritime industry stakeholders, are some of the top-level drivers that in the future will affect hull design assessment services. These in turn will drive technologies that will affect the rationale behind research and development directions for the assessment of shiploads and responses.

In order to reflect future industry demands, the Lloyd's Register strategic research programme on shiploads and hydrodynamics has been tasked with the aim of establishing Lloyd's Register as the 'leading provider of technological solutions by considering risk contributions applicable to contemporary and novel ship designs through open innovation'.

Accordingly, the medium- to long-term research in ship hydrodynamics is driven by the Lloyd's Register's longer-term vision to build up its intellectual infrastructure so as to

- lead in the development of risk-based regulatory framework for shiploads and responses;
- develop improved ship design procedures for robust strength assessment under extreme conditions; and
- provide training courses to educate ship designers, consultants and operators.

3.2. Streams of innovation

The Lloyd's Register's medium- to long-term streams of innovation on technologies for hydrodynamics and wave load assessment are driven by research initiatives with specific focus on

- risk assessment,
- emergency preparedness,
- extreme wave modelling,
- advanced prediction methods and
- operational monitoring.

The long-term research streams outlined above are directed towards enabling an optimal approach to design under extreme wave environments and the development of accepted analysis. The following paragraphs expand on relevant research topics.

3.2.1. Risk assessment

According to the IMO Goal-Based Standards initiative (Hoppe 2005), in the future, top-level compliance to safety standards associated with wave loads and responses will be based on a comprehensive assessment of the risks involved and their prevention and mitigation measures accounting for information on cost and benefits. Irrespective of the detailed theoretical or practical advances, neither the loads on a structure nor its resistance to load (strength) can be exactly determined. Within this context, it would not be a surprise that the specialist area of hydrostructural analysis will require the development of qualitative and epistemic methods that would provide more extensive detailed knowledge of shiploads during the operational lifetime of various ships of interest. The use of such risk-based assessment procedures would then allow the rational assessment of the design of ships which are outside the historical database. They will also provide a more efficient approach to the designing of conventional vessels. To this end, the future research studies focus on the following:

- Qualitative risk-based approaches for the prediction of the long-term effects of loads and responses from a life cycle cost and operational performance perspectives.
- Probabilistic reliability analysis methodologies and associated criteria incorporating a rational treatment of uncertainties of extreme hydrodynamic actions in stochastic seaways (see Sections 3.2.3 and 3.2.4).

3.2.2. Emergency preparedness

Loss of structural integrity due to collision and grounding are perhaps the most important contributors to accidental pollution at sea. Today, a relatively simple post-accident load assessment can be performed using simplified methods for the prediction of the collapse strength of the hull girder. When these methods are used, the ability of the damaged ship to survive is assessed by comparing the calculated strength with the environmental loads, the latter normally calculated without considering the effect of the damage on the motions and loads acting on the ship. The Lloyd's Register future research programme, therefore, aims to improve the ship dynamic response modelling and load assessment criteria with the ultimate objective of reducing significantly the extent of damage for specific incident scenarios and the consequential risks. This will involve research on modelling the effects of wave loads on collision/grounding of ship hulls with particular emphasis on the following:

- Reliability analysis for the assessment of loads via combination of non-linear hydrodynamic methods and advanced structural dynamics (see Section 3.2.4).
- FE methods for the prediction of fluid impact loads due to explosion and shock.
- Assessment of loads in ice-infected waters with particular emphasis upon developing ship–ice interaction models and methods that simulate the combination of load-level effects with operational scenarios.

3.2.3. Extreme wave modelling

'Extreme' or 'rogue' or 'freak' waves described as 'walls of water' and 'holes in the ocean' by mariners are characterised by sharp wave crests and deep wave troughs. Real seas are chaotic, although there is increasing evidence to suggest that cumulative wave non-linearities cause multi-directional seas to become more unidirectional during the formation of extremes. These non-linearities also cause rogue waves to occur more often than predicted by standard statistical models (i.e. Rayleigh distribution), which assume that the ocean wave components are independent. This dimensional simplification, which in some respects is in alignment with observations by mariners, is an issue that needs to be addressed with the aim to assess the effects of extreme waves on ship response. Our preliminary studies have shown that higher-order wave formulations or the so-called new wave concept may offer a way forward, particularly if they can be incorporated into methods evaluating motions and loads (Denchfield et al. 2009; Temarel et al. 2009). This may also be important in assessing performance and survivability of damaged marine structures (see Section 3.2.2). However, conventional statistical approaches are not capable of properly accounting for the occurrence of rogue waves. Hence, future work will concentrate on models for realistic extreme waves and design methodologies for the loading and response of ships by

- analysis of satellite observations;
- wave generation models that determine the effects of hurricane wind speed, size, duration and translation speed on extreme wave generation;
- extreme fully non-linear wave models;
- statistical analysis models for extreme wave statistics with emphasis on the effects of short-crestedness on extreme wave statistics, non-co-linearity of wind, waves and current;
- design procedures for the analysis of the effects of wave-structure interaction on the distribution of the extremes; and
- limit states and accidental limit states analysis methods for the prediction of failure modes as a result of loads due to extreme waves.

3.2.4. Advanced prediction methods

In the wider field of theoretical predictions of shiploads and responses, computational numerical hydrodynamics remain a challenge. Current analyses are, by and large, based on linear or partially linearised flexible fluid-structure interaction models (Hirdaris and Temarel 2009c; Temarel and Hirdaris 2009; Temarel et al. 2009). Accordingly, the transient terms of the equations describing the fluid flow around ships are omitted, in both the fluid and solid domain models, and convergence is checked based on quasi-equilibrium. For impact problems (e.g. slamming), convolution integrals are still used to obtain the effects of the transient dynamic response in regular and irregular waves. There are additional difficulties that, to date, have prevented widespread innovation. The fundamentals of the problem depend on the development and efficient use of transient formulations and FE structure solvers to iteratively solve the flexible fluid-structure interaction problem (Matthies and Steindorf 2003; Figueroa et al. 2006; Torii et al. 2006).

It is expected that with the improvements of computational efficiency and the demands of the economies of scale in the future, procedures for the prediction of wave-induced loads and responses will accommodate advanced numerical analysis techniques. Particular emphasis on the effects of ship hull flexibility, water entry and exit problems including slamming, green water, violent fluid flow and free surface hydrodynamics will probably be at the top in this agenda (Hoppe 2005; Hirdaris et al. 2009b). Hence, the medium- to long-term programme of Lloyd's Register involves research on the following:

- Non-linear hydroelasticity theories where structural dynamics are coupled with three-dimensional body non-linear hydrodynamic or three-dimensional body exact methods, where the wetted hull surface is defined by the instantaneous position of the hull surface, in relation to the incident wave surface.
- Hydroplasticity analysis by combining non-linear structural dynamics with three-dimensional weakly or fully non-linear hydrodynamics.
- Reynolds Average Navier–Stokes (RANS) CFD incorporating the effects of hydroelasticity.
- Mesh-less particle numerical methods, such as smoothed particle hydrodynamics (SPH), that may be suitable for violent fluid flows encountered in slamming problems.
- Numerical uncertainty (see Sections 3.2.1–3.2.3) by higher-order probabilistic methods (e.g. Monte Carlo simulations) and advanced benchmarking techniques for long-term load distributions.
- Multi-body hydrodynamic interactions involving the assessment of the dynamics of modular vessels and mooring loads (e.g. LNG to terminal interaction).
- Shallow water hydrodynamics for the prediction of loads due to high-speed wash (e.g. air gap) effects and the assessment of the effects of variable bathymetry.

3.2.5. Operational monitoring

To date, operational monitoring has been used in a limited and voluntary way. The wider use of Class Society-approved in-service analysis methodologies could lead operational criteria being derived in the medium to long term, and these criteria could be incorporated in the Rules for Classification of Ships in the form of additional notations. Research will involve the following:

- Hull condition monitoring studies with emphasis on FEM updating, emerging sensor technology (e.g. fibre optics, thermoelasticity sensors) and acoustic emissions technologies.
- Methodologies allowing the assessment of the severity of the sea state from the measured ship motions, thus avoiding the use of radar-based monitoring systems, which are costly and operationally demanding to use.
- Operational guidance systems that will predict the near-term motions and structural loads due to both weather changes and possible changes in course and speed by the shipmaster.
- Data acquisition systems for signal manipulation and conditioning.

3.3. Future design assessment tools

In the future the use of direct calculation methods that account simultaneously for the effects of dynamic wave environment using fully non-linear hydrodynamics, CFD and non-linear static and dynamic FEA are expected to evolve further. To reflect this trend, the Lloyd's Register products for design assessment are being developed to include the following:

- Three-dimensional full-ship detailed linear and, wherever applicable, non-linear FEA to support coupling with hydroelasticity analyses.
- Three-dimensional fully non-linear springing and whipping analysis, where the three-dimensional bow flare and stern slamming analysis should incorporate the effects of hull flexibility, green water and, wherever applicable, air trapping, jet flow formation, etc.
- Three-dimensional spectral fatigue analysis accounting for the effects of hydroelasticity, e.g. springing and whipping.
- CFD approaches are expected to become increasingly useful in the future. The use of RANS methods as part of or coupled with hydroelastic solutions is a realistic goal. The finite volume method and particle-based methods (SPH, MPS, etc.) may offer further capability.

3.4. Implementing the vision

The diversity of the streams of innovation outlined in Sections 3.2 and 3.3 show that the future demands for research are very much dependant on the need to combine the efforts of Lloyd's Register with other companies and institutions. The globalisation of research and innovation raises opportunities for developing international, interregional and global research and innovation networks. How to manage them from a scientific, administrative and human capital point of view remains a challenge. To achieve the vision of leading maritime Classification Society, Lloyd's Register has been developing a research strategy that

- explores the critical changes taking place in today's research structures and functions;

- tracks the key drivers behind the changes in maritime technology and looks for their causes and effects;
- understands how and whether competitor companies and governments are adapting to the changes;
- forecasts the future of a more international, global and interregional research and development patterns;
- analyses the implications of these forecasts to our long-term research; and
- employs, develops, utilises and motivates human capital in the most effective manner.

Our approach to research and innovation brings together ideas, people and strategies to develop future products and services with the view of making Lloyd's Register the leading classification technology provider. As part of our open innovation research strategy, and in order to start implementing our forward-looking programme of research on loads and hydrodynamics, we have initiated a forward-looking programme of scientific research with leading UK maritime universities, namely Southampton, Strathclyde and Newcastle upon Tyne. We also take part in international joint industry research projects, and we lead various national research initiatives.

4. Conclusions

This paper has discussed some of the recent experiences of Lloyd's Register with regard to the current state of the art in the assessment of wave-induced loads and ship responses. The paper reviewed recent research studies on hydrodynamics, hydroelasticity, full-scale measurement and sloshing applications. It also outlined the basic streams of innovation of the Lloyd's Register strategic research programme on hydrodynamics.

The incorporation of the combined effects of springing and whipping induced loads in the design process in a sensible and quantifiable manner are technical challenges that impact research over the short to medium term. However, as ships change in terms of scale and type, and operational, economic and environmental requirements become more stringent, it is possible that the use of a more realistic 'first-principles' approaches for the assessment of wave-induced loads, either on its own or in combination with the latest generation of prescriptive classification rules and procedures, could become more prevalent. This may be in particular enforced by future design developments, such as the Goal-Based Ship Construction Standards, that would present a challenge in bringing together codes of design practice and performance-based design.

Consequently, the use of reliability-based technologies, risk assessment tools, non-linear hydroelastic and non-linear structural behaviour of intact or damaged ship structures subject to violent or extreme phenomena (e.g. ice loads, extreme waves) is part of the research framework over the medium to long term. Additional demands will probably arise due to the demand for life cycle operational monitoring of ships and the need for systematic validation of sophisticated computational tools and design procedures.

Within this context, the Lloyd's Register is working towards the further development of technologies that will assist in the current and future development of rules and design assessment procedures and regulatory requirements for design assessment. Acknowledgement of the latter enforces our commitment to enhance engineering knowledge on the prediction, occurrence and life cycle effects of wave-induced loads. In this new era of innovation, Lloyd's Register follows an open innovation strategy that is committed in leading the maritime industry by

- introducing a change culture fostered by the need of interaction between the academic community and the industry for improved technological solutions;
- promoting a new school of thinking towards assessing and validating novel engineering problems from a fundamental perspective rather than from empirical or traditional routes;
- stirring technology differentiation as a tool of raising awareness in industrial maritime organisations to strategically develop technologies, products and services that raise the standards of safety at sea and protection of the environment.

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