THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Direct Calculation of Wave-Induced Loads and Fatigue Damage of Container Vessels

ZHIYUAN LI

Department of Shipping and Marine Technology
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden

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Department of Shipping and Marine Technology
Division of Ship Design
Chalmers University of Technology
SE-412 96, Gothenburg
Sweden
Telephone: + 46 (0)31-772 1000

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Abstract

Container ships and their rules for fatigue design are in several ways different compared with other types of commercial ships such as tankers and bulk carriers. For example, most modern container ships have a pronounced bow flare and an overhang stern. This unique hull form, in combination with high service speed, gives rise to large ship motions that require nonlinearity in wave loads must be taken into account. Another important characteristic of container ships is that the U-shaped cross sections due to the large deck openings make the ship structure sensitive to wave-induced torsion, especially in high waves. A consequence of the open cross section is low torsion rigidity of the ship hull, which, together with the high service speed and large ship motions, demands new stricter requirements for fatigue design of the future container ships.

The objective of the current thesis was to review the design methodology in current ship design regarding wave-induced structural loads and fatigue strength assessment. The outcome and contribution to both industrial and scientific relevance of the research work is a novel and comprehensive calculation procedure on the direct calculation of wave-induced loads and fatigue damage assessment with the target application of container ships. It comprises hydrodynamic analysis, finite element (FE) analysis followed by fatigue assessments.

A 4400TEU Panamax container ship is used for case study in the thesis. The wave loads and ship structural responses are based on the nonlinear time-domain hydrodynamic analysis, with particular attention to wave-induced torsion. Together with full-scale measurement data, the nonlinear vertical bending moments from hydrodynamic simulations are employed for the extreme hogging and sagging prediction. Global and local FE models of the ship are designed and used in the structural analysis. A procedure for calculation of the stress concentration factor (SCF) for local details is proposed which compares the ranges of the hot spot stress and the nominal stress. The results from the FE analysis are used in a fatigue assessment procedure. Fatigue damages in two structure details are calculated using the rainflow counting approach. Additionally, a designed wave scatter diagram for the North Atlantic was introduced for the computation of a long-term fatigue damage accumulation.

The approach and models presented in the thesis have been validated against full-scale measurements of ship motions and stress responses. In addition, a numerical code for fatigue route planning and monitoring is presented, which will be further developed in future work. Finally, it is believed that the numerical procedure proposed contributes to enhanced accuracy in the estimation of fatigue damage of container ships.

Keywords: Container ship, direct calculation, extreme loading, fatigue, fatigue routing, nonlinear wave loads, stress concentration factor, wave-induced torsion.

Preface

This thesis is comprised of work carried out during the years 2008-2011 at the Division of Ship Design at the Department of Shipping and Marine Technology at Chalmers University of Technology. The work was carried out as part of the EU project SEAMOCS (http://www.maths.lth.se/seamocs) in collaboration with Det Norske Veritas (DNV) in Høvik, Norway, and the Department of Mathematical Sciences at Chalmers. It was funded by the Swedish Governmental Agency of Innovation Systems, VINNOVA, and by the Swedish Competence Centre in Maritime Education and Research, LIGHTHOUSE (www.lighthouse.nu).

First and foremost, I would like to thank my supervisor Professor Jonas Ringsberg for his deeply dedicated support and infectious enthusiasm. I would also like to thank my colleagues in the project, Dr. Wengang Mao, Professor Igor Rychlik and Adjunct Professor Erland Johnson for our fruitful discussions. Grateful acknowledgements are due to Dr. Gaute Storhaug and Ms. Louise Ulstein at DNV in Høvik for providing me with the measurement data and for much valuable advice from their industrial experience. Special thanks to Dr. Junbo Jia, Dr. Kaijia Han and Professor Emeritus Anders Ulfvarson for their encouragement and friendly care.

In addition, I would like to express my thanks to all of my colleagues at the Department of Shipping and Marine Technology.

This thesis is dedicated to my parents.

Gothenburg, March 2011.
Zhiyuan Li

Contents

List of appended papers

Paper I Li, Z., Ringsberg, J. W., (2010). *Fatigue routing of container ships – assessment of contributions to fatigue damage from wave-induced torsion and horizontal and vertical bending*. Accepted for publication in the international journal of Ships and Offshore Structures (in press).

The author of this thesis contributed to the ideas presented, took part in the planning of the paper, developed the methodology with the co-author, carried out the numerical simulations and wrote most of the manuscript.

Paper II Li, Z., Ringsberg, J. W., (2011). *Direct calculation of fatigue damage of ship structure details*. To be presented at and appear in the Proceedings of the ASME 2011 30th International Conference on Ocean, Offshore and Arctic Engineering (OMAE2011) in June 19-24, 2011, Rotterdam, The Netherlands: OMAE2011-49758.

The author of this thesis contributed to the ideas presented, was responsible for the planning of the paper, performed the numerical simulations and wrote most of the manuscript.

Paper III Mao, W., Li, Z., Ringsberg, J. W., Rychlik, I., (2011). *Assessment of full-scale measurements with regard to extreme hogging and sagging condition of container ships*. To be presented at and appear in the Proceedings of the ASME 2011 30th International Conference on Ocean, Offshore and Arctic Engineering (OMAE2011) in June 19-24, 2011, Rotterdam, The Netherlands: OMAE2011-49456.

The author of this thesis contributed to some of the ideas presented, took part in the planning of the paper, performed the hydrodynamic analyses and wrote parts of the manuscript.

"Ships being delivered today are basically 20 year-old technology, by and large."

Tor E. Svensen (2010), President of DNV

1. Introduction

Generally speaking, the shipbuilding industry is relatively conservative compared to many other branches, for instance the automotive industry, which more or less annually launches new cars with the latest technology in many perspectives. However, most of today's newly built ships are minor revised versions of ageing old ship designs. Even though the production processes in modern shipyards become more and more automated, there is still a need and potential for improvements in the methodology and tools used in the ship design phase. The current thesis deals with this issue with regard to wave loads assessment and fatigue design of container ships.

1.1 Assessment of ship strength

Traditionally, a ship hull structure is often approximated by a two-dimensional beam in the ship strength assessment. The longitudinal strength is the most important strength and the only strength required in the Unified Requirement Concerning Strength of Ships adopted by the International Association of Classification Societies (IACS), see IACS (2010). In this context, the loads that act on the ship hull are normally divided into static loads, which are the loads acting upon a ship floating in still water; and dynamic loads, which implies the loads induced by waves. Accordingly, vertical bending moments (VBM) from still water and wave are design criteria for ship strength. The extreme bending moment is believed to occur amidships when the ship hull is balanced on the wave crest (hogging) or in the wave trough (sagging) of a trochoidal wave profile, see Fig. 1. This approach has not considered the randomness and irregularity of waves, and the dynamic effects of wave loads and ship motions are disregarded as well. Nevertheless, it offers a simple way for evaluating the wave-induced loads on ship structures and is therefore well accepted for ship strength assessment. In fact, the design philosophy, namely, taking the ship/wave system as a beam placed in a two-dimensional wave, is taught in the textbooks for naval architects of all generations and therefore has a profound influence on ship design practice.

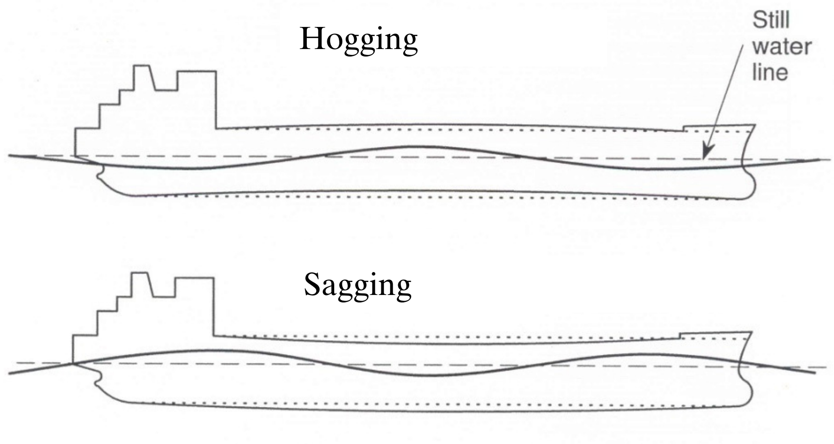

Figure 1. Illustration of hogging and sagging ship responses.

However, modern seagoing ships are among the most complex mobile structures built by human beings and should be treated with more rational design procedures. In addition to the VBM and shear force, other types of forces, such as the horizontal bending moment (HBM) and a torsion moment (TM) should also be considered in ship structural strength analysis. Actually, in their new rules or recommendations major classification societies have established criteria for specific type of vessels for taking into account transverse and torsion strength; see for instance ABS (2011), DNV (2009), GL (2007) and IACS (2008; 2009). Nevertheless, the correlation between various types of forces and moments in the evaluation of ultimate strength and fatigue strength is vaguely specified.

1.2 Container ships

International container shipping has been one of the most dynamic economic sections during the last half century. According to Lloyd's (2005) the container trade has expanded annually at a rate of 10% between 1990 and 2005, which has greatly surpassed the seaborne trade overall and also the international air transportation.

Accordingly, in contrast to the conservative shipbuilding industry, the development of container ship design has changed dramatically. Since the emergency of the first container ship in the mid-1950's, there has already existed six generations, and the capacity of container ships has increased from less than 1000TEU (TEU = the twenty-foot equivalent unit) to today's 11000-14500TEU, and the trend in the increase of the size of container ships is expected to continue thanks to the driving force of scale economics. The fast change of container ship design brings us great technical challenge. Traditional experience-based rule design has become less applicable. Consequently, direct calculations of wave loads as well as a detailed structural analysis like extreme strength and fatigue strength assessments seem inevitable in the future.

The new Panama Canal is expected to change the container ship design significantly. In ship design practice, a large amount of cargo ships is limited by the capacity of the Panama Canal that is currently under reconstruction. The expansion work is scheduled to be completed by 2015. By then, the maximum beam of the new "Panamax" ship will increase from today's 32.3 m to 49 m. The limitations of the length and the draught will increase considerably as well. This change is expected to trigger an evolution within shipping and shipbuilding industries. Numerous unconventional designs of ship structures might come into being, which will offer naval architects greater technical challenges.

Container ships are in several ways different compared with other types of commercial ships such as tankers and bulk carriers. For example, most modern container ships have a pronounced bow flare and an overhang stern. This unique hull form, in combination with high service speed, gives rise to large ship motions that require that nonlinearity in wave loads must be taken into account. Another important characteristic of container ships is the U-shaped cross sections due to the large deck openings that makes the hull structure sensitive to wave-induced torsion, especially in high waves; see Fig. 2 for a typical deformation mode caused by a wave-induced load that gives rise to torsion. The wave-induced torsion moment of the ship hull becomes more pertinent with increased wave height. Note that the wave-induced torsion can give rise to a larger magnitude of longitudinal stresses in several locations of the ship other than the deck amidships. A consequence of the open cross section is low torsion rigidity of the ship hull, which, together with the high service speed and large ship motions, demands new stricter requirements for fatigue design of the future container ships.

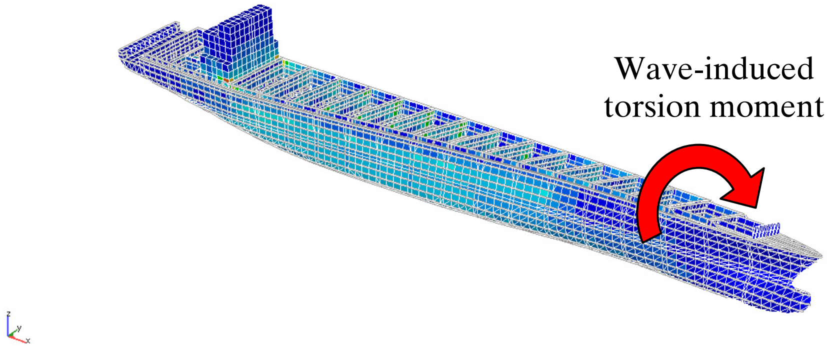

Figure 2. An example of a container ship hull under wave-induced torsion load.

2. Objective and motivation

The objective of the current research work was to review the design methodology in current ship design regarding wave-induced structural loads and fatigue strength assessment of container ships.

There are examples of accidents with container vessels during the last decade, which reveals that the development of rational design methods seems to have stagnated. For example, on January 18, 2007, MSC Napoli encountered heavy seas when passing the English Channel and suffered a catastrophic failure of her hull in way of her engine room. Figure 3 shows a picture taken shortly after the accident. The MSC Napoli was one of the first Post-Panamax container ships built in the early 1990's. The accident investigation showed that fatigue together with a lot of other factors contributed to the failure of the hull structure, and that the analysis procedure of wave loads in combination with structural response should be improved; see MAIB (2008). The Napoli accident was a wake-up-call for the container shipping industry. Suddenly, new revised methods for strength analysis and fatigue assessment were called for, especially by the classifications societies. The current work started in 2008 in collaboration with DNV and it was also part of the EU project SEAMOCS.

Figure 3. The MSC Napoli during rescue operation in the morning of January 18, 2007; see MAIB (2008).

Another motivation to the current thesis work comes from the early detection of fatigue cracks in "young" ship structures. The normal fatigue design life of a ship operating in the North Atlantic is usually more than 20 years. It is, however, reported by Storhaug et al. (2007b) that fatigue cracks were found in a container vessel after less than eight years of service. Similar observations for an ore carrier after only one year of service were reported by Moe et al. (2005). It is noteworthy that both of the vessels were operating in the North Atlantic. These two examples justify the need to investigate the fatigue strength of individual vessels under actual operation conditions, using more accurate approaches with respect to wave loading representation followed by fatigue assessment.

3. Overview of methodology

3.1 Wave-induced ship structural loads

Seagoing ships undertake various types of loads. A correct evaluation of those loads is the key element in the design of ship structures. The methods of ship structural design have undergone far-reaching change during the past few decades, partly because of the rapid development of computation capability. Nevertheless, design procedure based on empirical formulas is still specified in classification rules and is followed in assessments of wave-induced ship structural loads and related ship strength and fatigue problems.

3.1.1 Description of waves

In the scope of seakeeping, the mathematical foundation of hydrodynamics analysis is the potential flow theory, which assumes "ideal fluid", i.e. the flow is inviscid, incompressible and irrotational. A further simplification is called Airy wave or linear wave theory that assumes small wave amplitude as compared to the wavelength and water depth. In the application of ship structural strength assessment, the linear wave theory is widely used for describing waves.

The sea surface is irregular and changes constantly. Therefore, the application of statistical methods is necessary to quantify the characteristics of waves. A stationary sea condition is usually defined by the significant wave height H_s, which denotes the average of the highest one thirds of measured wave heights, and various measures of the average wave period, for instance, the zero-crossing period T_z. By means of Fourier analysis, the irregular wave time history is decomposed into a series of component regular waves, and the relative importance of the component wave is expressed in the wave amplitude energy density spectrum, or in short, the wave spectrum $S_i(\omega)$, as shown in Eq. (1), where a_i is the amplitude of the component wave, and $\Delta\omega$ is the frequency increment. The statistical descriptions of wave height and wave period can then be expressed by the spectral moments of the wave energy spectrum. In practice, idealized wave spectra are used instead of the wave spectra derived at a particular time and place. Examples of these idealized wave spectra are the Pierson-Moskowitz (P-M) spectrum that describes fully developed seas, and the JONSWAP spectrum that describes developing seas; see among others DNV (2007a) for description of the spectra.

$$S_i(\omega) = \frac{a_i^{\,2}}{2\Delta\omega} \tag{1}$$

Usually, the wave is considered as "long-crested" which implies that all component waves propagate in the same direction. This is of course an idealized situation because in realistic seas the wave is almost always spread in other directions and thereby called "short-crested". In the practice of ship design, the assumption of long crested sea may result in a too conservative analysis in assumed head seas or following seas. On the other hand, the directional wave components have a strong influence on the ship's roll motion, and therefore, should not be neglected if oblique waves are concerned. A short-crested sea can be modelled by including some spreading functions into the wave energy spectrum. In practice, a spreading function of ‘‘cosine square’’ is often assumed.

Obviously, the severity of waves in sea areas worldwide varies from one situation to another. For the purpose of ship deign, an appropriate estimation of encountered wave environment is preferred. The comprehensive “Global Wave Statistics” written by Hogben et al. (1986) is a useful tool in this case. In this book, based on long time observations, the global ocean surface is divided into different areas where the severity of wave environment varies. For each area, a general wave scatter diagram describes the probabilities of occurrence of significant wave heights and zero-crossing period. For certain areas, detailed wave scatter diagrams are available, in which other parameters like the wave direction and the time of a year are included as well.

3.1.2 Spectral method

The direct calculation of wave loads started with the emergency of the strip theory which was first established by Korvin-Kroukovsky (1955) and Jacobs (1958). In general, the strip theory divides the ship hull into a number of separate slices; the underwater part of the ship hull can be considered as a section of an infinite long cylinder. In contrast to putting the ship hull in an empirical static wave, the strip theory-based direct calculation computes the hydrodynamic forces caused by the waves and the ship motions in response to those waves.

An important advantage of the strip theory comes from the assumption of linearity that makes it possible to utilize the spectral method, i.e., analysis in the frequency domain. Using the spectral method, all relevant ship structural responses, such as the ship motions, the bending and torsion moments, strains and even the fatigue damage can be expressed by the response spectrum $S_{response}(\omega)$ which can be directly derived by means of a transfer function, $H(\omega)$, multiplied by the spectrum of the encountered wave, $S_{wave}(\omega)$, see Eq. (2). In other words, the universal success of the strip theory in seakeeping codes is largely grounded on the low requirement of computation resources, which in turn relies on the assumption of linearity in wave-induced loads and ship responses.

$$S_{response}(\omega) = \left|H(\omega)\right|^2 S_{wave}(\omega) \qquad (2)$$

However, despite its computational advantages, the linear strip theory has some limitations. First, the linear strip theory assumes small wave amplitude as well as small ship motions relative to the water surface, which are violated in high sea states. In high waves, the shape difference between cross sections along the hull plays an important role. Consequently, the hogging and sagging moments are not symmetric any more. The linear assumption in this makes the evaluation of longitudinal strength questionable. Secondly, the linear strip theory gives a less accurate prediction for ship motions and wave loading in planes other than the vertical plane. In other words, the calculation from the linear strip theory is only satisfactory in predicting heave and pitch motions as well as the related vertical bending and shear force. Furthermore, because each strip of the hull is treated separately, the three-dimensional (3D) effects, such as the mutual interference between the strips, flow leakage in the bow and stern areas are overlooked. In general, the linear strip theory gives relative accurate predictions for conventional “box-shape” ships, but its shortcomings might lead to inaccuracy in predicting loadings such as the wave-induced torsion of modern cargo ships where, for example, the flare angle has increased significantly compared with old-fashioned designs.

In the past half century, significant efforts have been devoted to the modification of the linear strip theory in order to take into account the nonlinear effects in wave-induced loads. Those methods are solved either in the frequency domain, see, for instance, Jensen and Pedersen (1979); or in the time-domain, see for example Wu and Hermundstad (2002). Both give agreeable results in evaluating the nonlinearity of VBM in head seas. Nevertheless, because of the two-dimensional nature of the strip theory, less improvement has been achieved in the calculation of ship motions and related structural loads in oblique waves.

3.1.3 Nonlinear time-domain approach

The emergency of the 3D time-domain approach is a big step in the direct calculation of hydrodynamic loads. In general, solutions to these methods are based either on the Rankine panel method, or on a Green function method. Compared to the Green function method, the elementary solution in the Rankine panel method does not satisfy the free surface boundary condition. Consequently, the integral equation to be solved will have unknowns on both the hull and on the free surface. As a result, the equation system to be solved of the Rankine panel method is larger. On the other hand, the computation of the matrices in this equation system is easier. The main advantage of the Rankine panel method is that different free surface conditions can be handled. Detailed discussions can be found in, for example, Kring et al. (1996), and Lin and Yue (1991).

The nonlinear effects can be solved in different levels with corresponding computation costs. The most important nonlinear effect comes from the Froude-Krylov force of the incoming wave. If the mean waterline is taken as the wetted surface for all time steps in the integration, the algorithm is termed as linear. Then, the wave-induced hogging and sagging moments have the same amplitudes but opposite signs. In contrast, a nonlinear effect is addressed when the hydrostatic restoring and Froude-Krylov forces are integrated on the instantaneous wetted surface, which gives more realistic values of the wave-induced hogging and sagging moments. Compared with the strip theory method, 3D effects due to shape change of the ship hull are addressed; reasonable ship motions and structural loads can be obtained also in oblique waves.

3.2 Full-scale measurement

The numerical results obtained from hydrodynamic codes need to be validated by model tests or full-scale measurements. The model test is a necessary step in new ship design before the ship is built. Compared to full-scale measurement, model tests cost less and are more time-efficient. The main disadvantage, in addition to the scaling problems that can never be solved completely, is due to the limitation of laboratory facilities. For instance, most model tests are performed in head seas as a consequence of limited space in the towing tank. In fact, few seakeeping basins around the world have the capacity to generate short crested waves, which is more desirable when studying ship motions in oblique waves.

Despite the high expense and time cost, a full-scale measurement gives us the most realistic ship responses. Reliable ship motions and structural behaviours can be obtained by various types of sensors onboard. The challenge of a full-scale measurement, however, is the measurement of environmental loads such as the encountered waves. The correlated wave height, modal wave period, the shape of the wave spectrum and the wave spreading must all be measured with a high degree of accuracy. With the advent of technology, novel measurement tools such as the onboard wave radar become available and their accuracy is improving. Nevertheless, wave data from onboard measurements must be calibrated by other means such as the measured wind speed or the satellite wave data.

For an individual vessel, it is particularly beneficial if the numerical analysis results can be compared with a full-scale measurement carried out on a similar vessel in service. Since 1999, Storhaug at DNV and co-authors have collected and published comprehensive measurement data from onboard measurements on several vessels; see Storhaug et al. (2007a; 2007b; 2007c; 2009). Although the original purpose of these full-scale measurements was to investigate the wave-induced vibration of the hull, the measurement data of the container vessels are utilized in the current research and reported in the appended Papers I-III.

3.3 Extreme responses of ship structures

In the discipline of ship design, extreme response prediction is a key step in evaluating the safety level of ship structures. The corresponding stress under extreme wave loads must not exceed the structural ultimate strength. During a life of 20 to 30 years, a seagoing ship is expected to encounter a wide range of sea state conditions. This time span can be regarded as a large number of short intervals or sea states from 20 minutes to 3 hours, during which the wave statistics are considered stationary. By this means, the long-term ship responses such as the extreme stress can be calculated based on short-term ship responses.

Statistical data such as a stress record for an extreme response evaluation are either from full-scale measurement or from numerical simulation. When the short-term ship response data are available, certain statistical methods for predicting the extreme responses could be employed; see DNV (2007a). The most common method is to fit the long-term cumulative distribution function (cdf) of the local response maxima. A suitable quantile of the fitted cdf determines the design extreme value. Normally, a two-parameter Weibull distribution is assumed. However, if the short-term responses are low or moderate, using the corresponding peaks to extrapolate the tails of extreme value will result in large errors, according to Mao (2010). An alternative approach proposed by Mao et al. (2010) implies using the long-term uncrossing spectrum to predict the extreme ship response. This method applies to both Gaussian and non-Gaussian ship responses, which make it particularly useful given the fact that ship responses are in reality a non-Gaussian process in severe seas. More discussion can be found in Mao (2010).

3.4 Fatigue assessment of ship structures

Fatigue is a common failure issue of ship structures subjected to wave loads and it is one of the limit state design criteria. Fatigue cracks are not generally responsible for the total failure or loss of ships, but the costly inspection and repair greatly influence the serviceability and operational economy. Moreover, short and visible fatigue cracks, if not detected and repaired in time, may continue to grow to a critical length that affects the structural integrity. This can lead to other failure modes of the structure, such as buckling, and ultimately total collapse of the ship hull.

Fatigue strength must be treated differently compared to ultimate strength. The ultimate failure is caused by static extreme stress or exceedance of a design-limit value, while fatigue is caused by cyclic loading (stresses) which degrades the material by accumulation of damage for every load cycle. Ultimate strength in the midship section is often taken as the design criterion given the fact that in most cases the extreme bending occurs amidships. Fatigue, in contrast, is a local problem determined by the cyclic history of local stresses. It is thereby not self-evident that a sufficient fatigue resistance of the midship section can be used as the governing design criterion of fatigue strength, even though structural details of the same configuration are used along the hull; see Paper II.

Fatigue design principles which are based on phenomenological models are divided into stress-based (high-cycle fatigue) and strain-based (low-cycle fatigue) approaches. In these approaches, there is no need to know the size of a fatigue crack at the outset of the analysis. Instead, these approaches are used to calculate the number of cycles to (initiate) grow a crack to a length determined by testing or by ocular inspection. In the stress-based approach, the cyclic stresses are assumed as being less than the yield stress of the material (or, they have shaken down to an elastic steady state by elastic shakedown), while in the strain-based approach, the stresses may be beyond the yield stress limit and the material deforms plastically. In most cases, the stress in ship structures remains at low levels below the yield stress with only occasional periods of very high stress levels when storms are encountered. This justifies the selection of a stress-based approach that by Hooke's law gives a linear relationship between stress and strain.

If a crack is discovered in a component or in a structural detail of a ship structure, a fracture mechanics-based fatigue approach should be used to study the further growth of the crack. By means of this approach, the crack growth rate is calculated in order to judge when repair and maintenance is needed before the crack reaches a critical length that affects the functionality or becomes a safety issue. The fatigue research work presented in this thesis is therefore limited to and based on the assumptions of the validity of using the stress-based approach.

The fatigue problem has been investigated by numerous researchers over a long period. Various terms have been used under different circumstances and some of them need to be clarified to avoid confusion. The following nomenclature is according to DNV (2005; 2010b):

- **Nominal stress, σ_n:** a general stress disregarding the stress raising effects due to geometry discontinuity and the presence of welds; can be calculated by engineering beam theory or by coarse mesh finite element (FE) analysis.
- **Hot spot:** originally means the weld toe, but it also refers to any critical point in the structure where a fatigue crack may initiate.
- **Hot spot stress, σ_{hs}:** a stress taking into account the effects of a structural discontinuity but exclusive of the stress raising effect due to the weld itself; also referred to as *geometric stress* or *structural stress*. For a plate, the hot spot should be calculated at the surface of the shell element, by a combination of the membrane stress and the bending stress through the plate thickness.
- **Geometrical stress concentration factor, K_g:** a stress concentration factor due to general structural discontinuity; if standard workmanship and welding procedures are assumed:

$$K_g = \frac{\sigma_{hs}}{\sigma_n} \tag{3}$$

- **Additional stress concentration factor, K_m:** additional stress concentration factor due to fabrication such as eccentricity tolerance, angular mismatch, or due to un-symmetrical stiffeners on laterally loaded panels. K_m is exclusive from standard S-N curves.
- **Local notch:** a notch such as the local geometry of the weld toe, including the toe radius and the angle between the base plate surface and weld reinforcement. The local notch does not alter the structural stress but generates nonlinear stress peaks.
- **Weld stress concentration factor, K_w:** a stress concentration factor due to the presence of the weld, depending on the weld configuration and the weld toe angle.
- **Local notch stress, σ_l:** a total stress at the root of a local notch taking into account the stress concentrations caused by both geometric discontinuity and weld, when other stress raisings have been disregarded, $\sigma_l = K_w K_g \sigma_n$.
- **Total stress concentration factor, SCF:** the ratio of *local notch stress* to *nominal stress*, i.e.:

$$SCF = \frac{\sigma_l}{\sigma_n} \tag{4}$$

3.4.1 S-N curves

The stress-based approach is also called the “S-N methodology” and it is the most common way to evaluate the fatigue capacity of ship structures. In a diagram, S-N curves for the relationship between the load cycles to failure, N, for the applied stress range, S, are plotted using results obtained by fatigue testing of a material, see for example Dowling (1972). The relationship between fatigue life (load cycles) and applied loading (stress) is presented in Eq. (5) where m and α are constants affected by among others type of material, mode of loading and geometry tested.

$$N = \alpha \cdot S^{-m} \tag{5}$$

Fatigue testing of a material follows a standard for materials testing and it is normally carried out in a laboratory environment. Some examples of characteristics of such tests are presented below.

- The specimen size is generally smaller compared with the actual structural detail in a ship structure.
- Weld joints are sometimes included in the specimen.
- Constant amplitude loading and in most cases in the uniaxial direction.
- Standard workmanship assumed, which means additional fabrication tolerance may need to be considered.

Standard S-N curves for a selection of materials etc. are available among classification societies and other organizations. The usage of S-N curves is not straightforward, as they might seem. An S-N curve shall be selected according to the application environment, the weld type and the structural configuration, as well as the stress type. It is particularly important to distinguish between different stress types in the S-N curves. For instance, for a hot spot S-N curve, the influence of the weld is already included in the S-N curve, thus these S-N data are compatible with calculated hot spot stress instead of the nominal stress.

3.4.2 Linear fatigue damage accumulation

In the stress-based approach, fatigue damage caused by each cyclic load can be treated independently and simply superposed. This assumption allows for the application of standard S-N data derived from constant amplitude tests to fatigue analysis of which the loads are seldom regular. This method is known as the Palmgren-Miner cumulative damage rule, or in short, Miner’s rule. The basic idea is that if the damage contributed by one cycle of the stress range S_i is $1/N_i$, where N_i is the mean fatigue life under a constant amplitude stress range S_i, by superposition the cumulative damage D caused by i different stress ranges equals to:

$$D = \sum \frac{n_i}{N_i} \tag{6}$$

Various methods exist for counting the cycles of a variable amplitude stress record, among which the rainflow counting approach is most frequently used. This approach is based on the hysteresis properties of material where the cyclic stress-strain curves form loops. The rainflow counting approach identifies the local maxima that should be paired with the local minimum to form a hysteresis loop, which is believed to give the most accurate fatigue life prediction. More details about the rainflow counting approach and its development can be found in the literature on the subject, for example, by Dowling (1972), and by Rychlik (1987).

3.4.3 Stress concentration

Fatigue strength is reduced by the introduction of a "stress concentration". In general, for ship structures, stress concentration is caused either by geometrical irregularities, or by the presence of a weld; the latter is discussed in Section 3.4.4. Since actual hull structure elements invariably contain stress raisers like stiffeners, brackets, cut-outs, holes, etc., to avoid stress concentration from these geometrical discontinuities at all is unrealistic. It is therefore more pertinent to establish methods for the correct evaluation of the geometrical stress concentration factor K_g.

The derivation of K_g involves the use of FE analysis. The hot spot stress can be determined by fine FE mesh (usually in the level of plate thickness) and compared with the nominal stress. It should be pointed out that K_g is not only determined by the geometric configuration, but also by the loading conditions. Paper II gives more discussion.

3.4.4 Welding-induced fatigue of ship structures

Ship structures are built and characterized by welded plating. With respect to fatigue, the ship structures are strongly affected by the welding process so that fatigue failures in most cases appear at the welds rather than in the base material even though the latter contains other types of notch such as cut-outs and corners. Below are some issues that affect the fatigue characteristics of welded structures:

- The heating and cooling process of welding introduces inhomogeneous material microstructure within the material.
- The additional filler material introduces inconsistence between different materials.
- A weld usually contains defects like inclusions, pores, cavities etc. that may act as sites for crack initiation.
- The shape of the weld profile causes geometrical stress concentration.
- The notch at the weld toe introduces notch stress concentration.
- Welding induces residual stress.

Compared to the fatigue strength reduction introduced by geometrical stress concentration, K_g, it is more difficult to evaluate a weld-related fatigue problem with numerical tools such as the FE method. In reality, the weld-induced fatigue can be estimated by some empirical formulas. For instance, according to Cramer et al. (1995), a weld stress concentration factor $K_w = 1.5$ is often assumed for a typical ship structural detail.

3.4.5 High strength steel

High strength steel (HST), also termed as high tensile steel, refers to steel that has yield stress considerably higher than that of a mild steel (235 MPa). Examples of commonly used high strength steels are HT32 and HT36, with a minimum yielding stress of 315 MPa and 355 MPa, respectively.

According to Løseth et al. (1994), HST was first used in ship structures in the early 1970's, In the beginning, the HST was only included in deck and bottom, and in the longitudinal members in order to increase hull girder strength, but lately it has also been used in side-structure and transverse elements. Until the mid of the 1980's, HST of different grades had been massively used in all ship structural members. This has given more optimised ships, in terms of both reduced steel weight costs and increased earning potential by increased deadweight.

However, accompanying the benefits of reduction in the scantlings, the fatigue problem due to HST became imminent. Since the 1990's, fatigue damage in a ship hull has become a major concern among classification societies. Now, it is well reckoned that fatigue properties of welded structures are not improved compared to mild steel, which explains why structures made of HST are more prone to fatigue damage than those of mild steel. This means additional measures must be taken in the design phase with special attention given to the fatigue risk associated with HST.

3.4.6 Uncertainties in fatigue life prediction

Fatigue life prediction is always associated with large uncertainties. This is because fatigue damage is a stochastic accumulation process influenced by a large range of factors. Some of the factors rely on the geometrical configuration of the structural detail, for example, the shape, size and thickness, which can be evaluated by the stress concentration. The other group of factors is associated with the material properties such as grain size and corrosion that are often addressed in S-N curves. Weld as well as the welding process, however, is hard to evaluate and therefore introduce particular uncertainties. Other factors, for example the mean stress and residual stress, are often ignored. This without doubt introduces uncertainties in fatigue life prediction.

The tests of S-N curves are fundamental of fatigue assessment. It should be highlighted that large uncertainties are associated with the derivation of S-N curves. As regard to the scatter of the test results, it is commonly accepted that the mean S-N curve implies minus two standard deviations. Besides, when transferring the S-N data from idealized laboratory specimens to complex structural details, some uncertainties are expected.

From the viewpoint of ship designers, a correctly calculated cyclic stress in fatigue assessment is of the greatest importance. For this purpose, realistic loading due to wave and ship responses must be modelled. Further, stress concentration within the structural details needs to be evaluated as accurately as possible. Finally, we should take into account the direction of principle stress with regard to the weld joints with the aim of achieving improved accuracy of fatigue life prediction.

4. Summary of the work in the appended papers

The previous Sections 1 and 2 presented an introduction and motivation of the work in this thesis. Section 3 aimed at presenting an overview of the evolution of and commonly used design methods for analysis of wave-induced ship structural loads and fatigue damage, respectively. The current section is a summary of the work presented and achievements made in the appended Papers I-III. The selection of methods used is motivated and discussed with reference to the previous sections of the thesis.

4.1 Overview of the analysis procedure

The appended Papers I-III present a methodology developed for the direct calculation of wave-induced loads and the fatigue damage of container vessels. The methodology comprises several sequential steps of numerical analyses such as hydrodynamic analysis, FE analyses followed by a fatigue assessment. Figure 4 presents the flowchart of the developed models, numerical codes and analyses that have been used in Paper I to III. In the case studies presented in Papers I to III, the same 4400TEU container ship is used; note that in Paper III, also a 2800TEU container ship is used for comparison in some of the analyses.

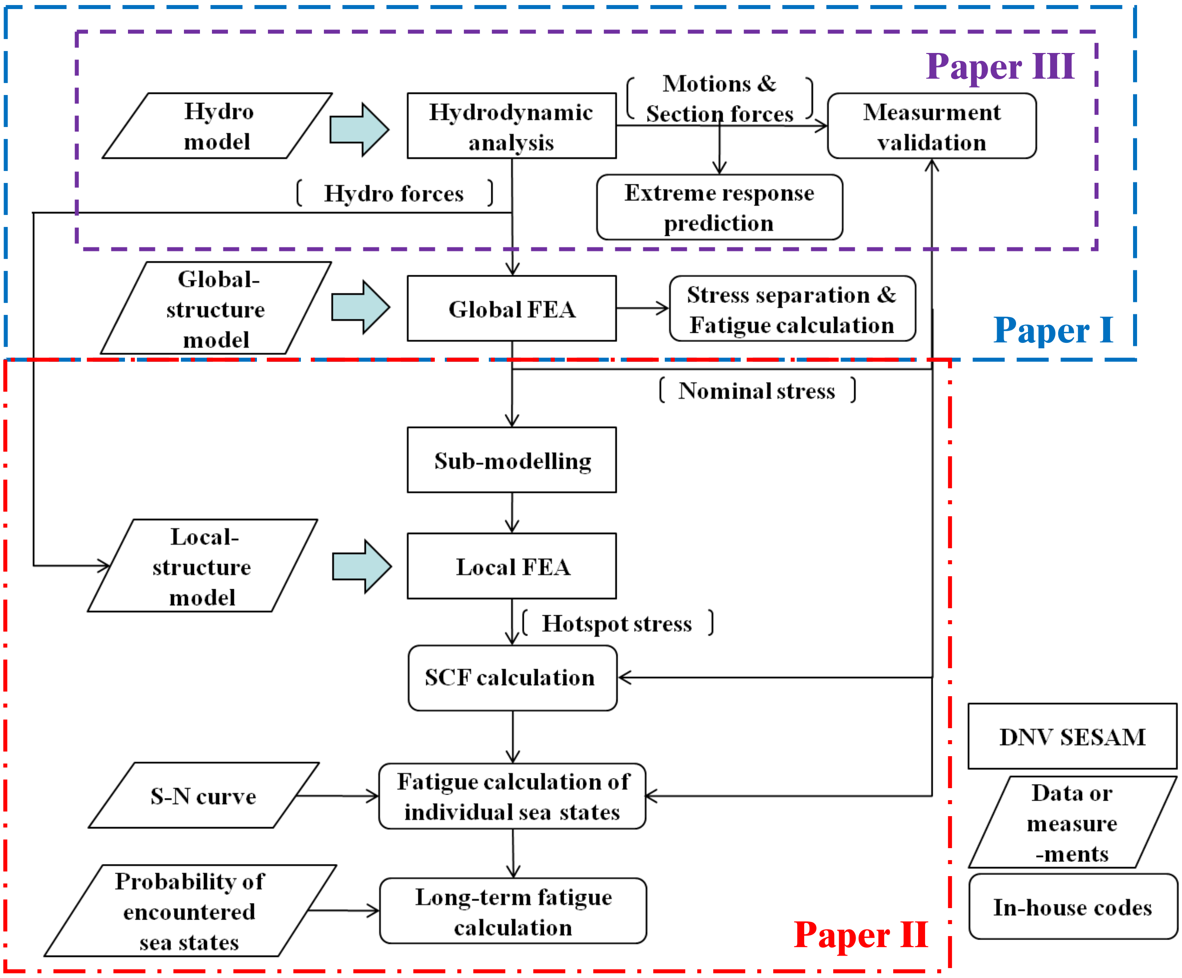

Figure 4. Flowchart of the developed models, numerical codes and analyses that have been used in Papers I to III.

The main scientific and industrial contributions presented in this thesis represent the analysis procedure in the flowchart in Fig. 4. The design and creation of the numerical models, which should transfer results between sub-programs of a commercial software (such as SESAM; WASIM-SESTRA-SUBMOD), is not an easy task since it requires accuracy in the modelling phase and also a good understanding of the theoretical background behind each module; see DNV (2004; 2006; 2007b) for details about the SESAM software and its modules.

The analysis procedure presented in Fig. 4 comprises a chain of analyses of load analysis and strength assessment followed by a fatigue evaluation (globally or locally) with regard to short- or long-term fatigue characteristics. Instead of employing the often used spectral method, the time-domain approach was selected because its advantages of, for example, taking into full consideration the nonlinearities in loads and responses throughout the analysis procedure. The midship bending moments from the hydrodynamic simulations were used for extreme hogging/sagging prediction, as stated in Paper III. The results from the hydrodynamic and structure analyses have been validated by full-scale measurement presented in Papers I and II.

Moreover, a fatigue routing code is under development and its objective is to indicate if it is possible to benefit from fatigue route planning leading to an extension of the fatigue or service life of the container vessel under study. In the development of code, a novel method for calculation of the SCF was proposed in order to improve the accuracy in the fatigue damage estimations, see Paper II.

4.2 Hydrodynamic analysis

The normal procedure in a numerical analysis of fatigue characteristics is that the hydrodynamic analysis is performed for several individual stationary sea states that are characterized by the significant wave height and the average wave period of a standard wave spectrum; a sea state is considered stationary within the time period 20 minutes to 3 hours.

The 3D nonlinear hydrodynamic code WASIM carries out the numerical simulations in the time domain. Two important nonlinear effects are addressed in WASIM. First, the integration of the hydrostatic restoring and Froude-Krylov forces on the instantaneous wetted surface, which gives realistic values of the wave-induced hogging and sagging moments. Secondly, quadratic roll damping is accounted for which must be incorporated in the numerical analyses of the oblique waves that are encountered. In addition, an arbitrary forward speed can be assigned and the forward speed effect is taken into account, which is particularly important for fatigue analysis. Waves can come from an arbitrary direction and ship motions are calculated in all six degrees-of-freedom. In this thesis, various ship speeds and wave headings are compared and their effects on fatigue damage are discussed, see Papers I and II.

In WASIM, the hydrodynamic model is based on the Rankine panel method where both the hull and the free surface are represented by panels, see Fig. 5. The dimensions of the panels can be large in the main hull where the hull shape and geometry changes only slightly, while smaller panels should be used in the bow and the stern areas. Accordingly, the hull shape can be modelled accurately following the geometry of the hull. This ensures that 3D effects are sufficiently accounted for in the hydrodynamic analysis. It also results in efficient and consistent mapping of the hydrodynamic pressures from the hydrodynamic model into the FE mesh that forms the ship's structure model.

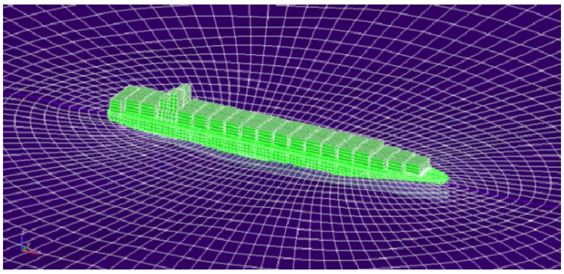

Figure 5. Illustration of the hydrodynamic model of the container ship in Paper I-III.

4.3 FE analysis

The time-varying hydrostatic forces, or pressure distributions, from the hydrodynamic analysis are transferred to the FE structural model; see Fig. 2 for an example of the full global FE model. The global FE model was represented by a coarse mesh model of the vessel where the element size was determined by the dimensions of the girder spacing. The development of the global model is presented in Paper I, while the design of two sets of local models is presented in Paper II. In addition, an intermediate model is created to ensure a smooth loading transfer from the global FE model to the local FE model; see Fig. 6 for an illustration of the models. Often, the global FE model is used for screening to identify local areas where a more detailed FE model is required for further detailed investigation; cf. Paper II. Then, using SUBMOD, displacements of the nodes are transferred from the global model to the local models.

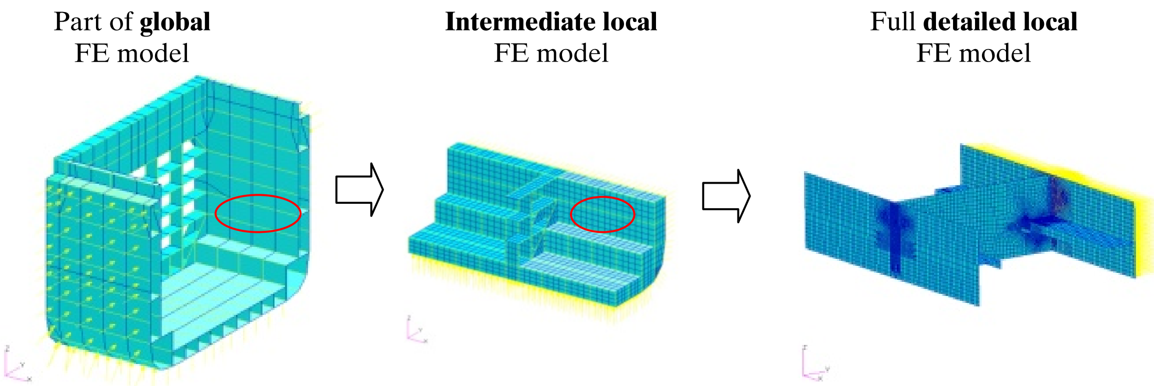

Figure 6. Illustration of the global, intermediate local and detailed local FE models.

From a global FE model analysis, the nominal stress in an arbitrary location of the ship can be calculated. In Paper I, the ship's longitudinal normal stress was recorded in a position amidships where strain gauges in full-scale measurements of a similar-sized container vessel were mounted. Figure 7 presents the results from a case study which validated the combination of hydrodynamic and FE models followed by a stress component analysis procedure. In the study, the wave environment and ship operational parameters were set similar to the set of parameters recorded during the full-scale measurement campaign. The results in Fig. 7 show that there is good resemblance between the numerical analyses and measured stress with respect to both amplitude and phase; see Paper I for details.

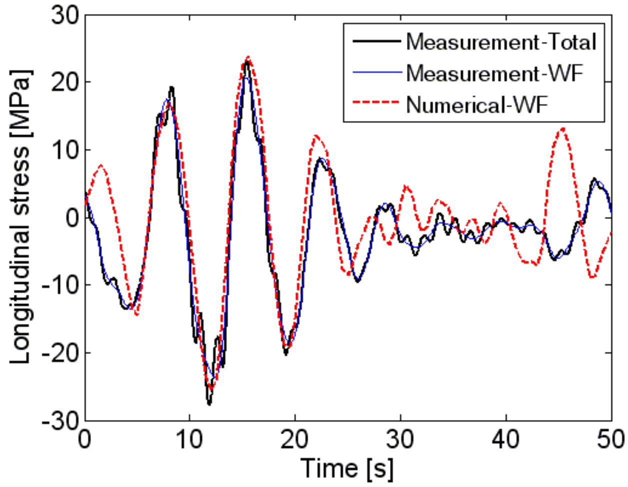

Figure 7. Stress response from full-scale measurements and from numerical analysis.

4.4 Derivation of SCF

In Paper II, two alternatives how to compute the SCF are compared: a method proposed by DNV (2010a), and another method proposed by the authors of Paper II with the motivation to increase the accuracy of the SCF. The method proposed by DNV (2010a) is carried out by means of FE analysis following a procedure where the hot spot stress and the nominal stress under certain identical loadings are compared. These loadings have no connection to hydrodynamic analysis; instead, they are empirically determined. The approach considers the actual structure configurations. However, the deviation from true loading scenarios can lead to underestimation of the SCF, see Table 2 in Paper II. Therefore, another method for calculation of the SCF has been proposed. In the approach, the dynamic loads from the hydrodynamic analysis are directly transferred to the global and local FE models for a representative period of simulation time. The stress concentration factor is computed as the fraction of stress ranges between local and global FE models in the location of interest; see Eq. (7) where SCF_2 is the notation in Paper II for the new proposed SCF computation. The results show that this way of calculating the SCF seems to be more conservative and also realistic.

$$SCF_2 = \frac{\Delta\sigma_{\text{local}}}{\Delta\sigma_{\text{nominal}}} \tag{7}$$

4.5 Stress separation and fatigue routing

In Paper I, a simple method was presented for the calculation of longitudinal stresses caused by VBM, HM and TM. The main objective was to estimate how much the wave-induced torsion moment (TM) contributes to the total longitudinal stress, since often only the longitudinal stresses from the VBM and HBM are incorporated in the fatigue analysis. That is, the contribution from warping behaviour in the Vlasov torsion theory is often disregarded. By means of the WASIM analysis followed by the

SESTRA analysis of the global FE container model, the longitudinal stress was recorded in six locations, *i* to *vi* in Fig. 8. According to engineering beam theory, relationships for the longitudinal stress component in these locations could be defined also in terms of the stress response obtained from applied VBM, HBM and/or TM loading conditions; see Paper I for details.

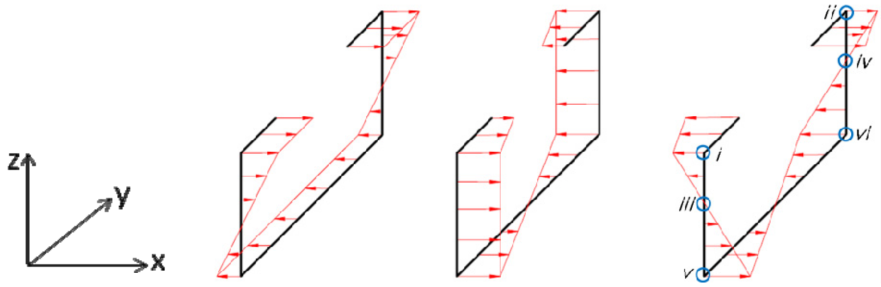

Figure 8. Illustration of longitudinal stress distributions in a transverse cross section of a container vessel: (left) vertical bending stress, σ_{VB}, (middle) horizontal bending stress, σ_{HB}, and (right) warping stress, σ_{W}.

The method proposed in Paper I is simple and accurate enough to form the basis for a fatigue routing code. The rainflow counting method was used to study the contribution to the short-term fatigue damage accumulation from the individual, and total, longitudinal stress components. A series of ship speeds and wave heading angles were studied under a relatively high sea state (H_s = 5 m), and the fatigue damages as functions of ship speed and wave heading were plotted in two polar diagrams, in the deck and bilge area amidships, see Fig. 17 and Fig. 18 in Paper I. It was found that for the selected midship section, the largest contribution to fatigue damage in the deck is caused by the vertical bending of the ship beam, and that head seas give the highest fatigue damage. In the bilge area, oblique seas will cause higher fatigue damage than head seas, and in the oblique waves, the warping stress largely determines the resultant longitudinal stress.

4.6 Long-term fatigue assessment

Similar to extreme response prediction, standard statistical methods are employed for long-term fatigue assessment. Two approaches are commonly used by classification societies; see for example ABS (2004). In addition to the spectral method, an alternative simplified method is available that requires no direct calculation. Instead, it relies on the design loads specified in the rule formulas that assume different levels of probability of exceedance. The resultant long-term distribution of the hull stress as well as the fatigue damage is assumed to follow a two-factor Weibull distribution, of which a general shape factor can be derived directly from the ship type and length. The classification societies have also developed tables of shape factors for different configuration of structural details along with the S-N curves; see for example DNV (2005).

However, both the spectral method and the simplified method are based on the linearity assumption of wave loads and ship structure responses. From this assumption, it concludes that most of the fatigue damage occurs in the long-time fatigue life range of an S-N curve. In other words, the fatigue damage is mainly caused by small waves, which has been proved questionable when the ship sails in a harsh environment such as in the North Atlantic where nonlinear wave effects on fatigue damages should not be disregarded; see Paper I and II for more discussions and references.

In Paper II, a long-term fatigue analysis method is proposed. A wave scatter diagram modified on the standard wave scatter diagram for the North Atlantic is designed, and the long-term wave environment is represented by 20 sea states and their respective probabilities of occurrence. The long-term fatigue damage is then a summation of individual short-term fatigue damages of each sea state multiplied by the respective probability of occurrence. This method is based on the nonlinear hydrodynamic analysis and is expected to give a more accurate fatigue assessment compared to the conventional methods. Using this approach instead, it is found that the fatigue life of the studied structural details is much shorter than their design values.

4.7 Extreme hogging and sagging prediction

In Paper III, an analysis of the extreme stress response in the deck in the midship cross section from hogging and sagging conditions is presented. It is assumed that the stress peaks are caused by vertical bending when the ship sails in head seas. The 4400TEU container ship was used in the study using the numerical results from WASIM analyses. The stress peaks were calculated by using the hogging and sagging moments divided by the midship section modulus, respectively. The numerical stress responses exhibit obvious nonlinearity and are skewed to the sagging side; see Fig. 4, and Fig. 5 in Paper III.

In addition to the numerical analysis, full-scale measurement data of the 4400TEU vessel and another 2800TEU container ship for the study of extreme hogging and sagging conditions were used. In these measurement data, one has both wave frequency stress and high frequency stress. The latter comes from wave-induced vibration responses that cannot be obtained by current numerical simulation. It is found that the high frequency responses significantly increase the value of extreme stresses, particularly in the sagging condition.

5. Summary and conclusions

A comprehensive numerical procedure for the direct calculation of wave-induced loads and fatigue damage of a 4400TEU container vessel has been established. Parts of the numerical procedure and the models were validated against full-scale measurements made on a similar container ship. A practical fatigue routing tool is proposed with the aim to reduce fatigue damage under real ship operation conditions. The summary and major conclusions of the thesis, divided into the contributions from each of the appended Papers I to III, are given below.

PAPER I

Nonlinear three-dimensional hydrodynamic time-domain simulations of a 4400TEU container ship are presented using WASIM for five heading angles and at various ship speeds. The structural responses to these simulation conditions are calculated using the FE-software SESTRA. The stress histories calculated by finite element analyses were used in the rainflow counting approach in order to assess the fatigue strength in various locations in the amidships cross section and in a cross section near the engine room.

- A fatigue assessment procedure based on the direct calculation of stress history was established. Equations for the stress components related to vertical bending, σ_{VB}, horizontal bending, σ_{HB}, and warping, σ_{W}, were derived using the Euler-Bernoulli beam theory. It was found that the σ_{HB} and σ_{W} stress components are coupled but with different relationships, depending on the location in the ship. In general, the combined stress σ_{HB+W} is small in the deck compared with the bilge of the ship.
- For deck structures of container ships, the greatest fatigue damage usually occurs in head seas, especially when the speed is relatively high. In contrast, for bilge areas, the greatest fatigue damage is related to bow seas. In both positions, only considering vertical bending stress in fatigue assessment may lead to non-conservative results.
- The speed reduction effect was studied by comparing the accumulated fatigue damages under the service speed with that of below half service speed conditions. The results show that ship speed has a strong impact on fatigue damage accumulation. It confirmed that speed reduction is beneficial with regard to fatigue damage.

PAPER II

Fatigue of ship structural details is a problem that is influenced by many factors. Depending on different requirements of accuracy in results and computational resources, various levels of simplification are made by engineers and researchers. The current investigation demonstrates the need for improved accuracy in the fatigue life assessment of container vessels. As a result, most of the early fatigue problems which are reported today among container vessels sailing in harsh waves might be avoided.

- A procedure of direct calculation of fatigue damage of ship structure details is presented. This novel approach accounts for realistic and relevant loadings and it is believed to give more accurate predictions in fatigue assessments.

- In contrast to the conventional approaches, the hydrodynamic analysis is performed in a time domain by means of a potential flow theory code. The nonlinearities in wave-induced loads as well as ship responses are hence incorporated.
- A sub-modelling technique in the FE analysis is employed to transfer loadings from global structure model to local structure models, and the hydrodynamic pressure for the hull structure under water is also taken into account in both global and local models.
- Hot spot stresses are employed together with relevant S-N curves in the bilge region. Stress concentration factors at welded joints and non-welded hot spots are calculated using a novel approach that is based on stress ranges of local and nominal stresses. The results highlight the importance of loading types in the calculation of SCFs.
- Short-term fatigue damage is calculated using the rainflow counting method based on time-domain hydrodynamic and following FE analyses. Long-term fatigue assessment is obtained from accumulated short-term fatigue damages of all encountered sea states during the ship's lifetime. It is found that the fatigue life calculated by means of the proposed calculation procedure is significantly shorter than the target fatigue life.

PAPER III

In the design of a vessel's ultimate strength the extreme hogging condition is of great concern. Due to special properties of container ship structures, such as large bow flare and overhanging stern, wave-induced slamming makes the ship responses more skewed to sagging conditions. In particular in large sea states, the ratio between maximum sagging and hogging can be quite high. Hence, the sagging condition might be very crucial with respect to a ship's ultimate strength.

- Through investigation of full-scale measurements made on two different container ships, one 2800TEU and one 4400TEU ship, it is found that the high frequency (HF) responses can significantly increase the extreme ship response due to both sagging and hogging.
- For the 2800TEU vessel, the HF response can lead to a 40% and 10% increase of extreme sagging and hogging responses, respectively. The HF response also contributes with about 43% to the extreme response for the 4400TEU container ship.
- Although ship responses are known to be non-Gaussian, the wave-induced response can be well approximated by Gaussian processes. In particular for the hogging response, the Gaussian assumption may give a conservative estimation of extreme responses, which can be accurately computed by the upcrossing spectrum of ship responses.
- For the 2800TEU ship, the hogging responses are approximated using upcrossings of Gaussian processes and this works well with the observations. This approach can be treated as a special case of transformed Gaussian methods, i.e. linear transformation for positive values x (hogging condition).

6. Future work

Hydroelastic analysis
The ship hull in WASIM has, in the current thesis, been represented as a rigid body. In future work, it is planned to carry out a hydroelastic analysis instead in order to: (a) obtain more realistic pressure variations (wave-induced loads) on the hull, and thereby (b) more accurately be able to calculate the ship structure response and fatigue damage caused to the container ship.

Estimation of fatigue damage from springing
The wave-induced loads discussed in this thesis have been limited to waves whose wave frequencies are far lower than the natural frequency of the ship hull. It means that the assumption of a rigid body of the ship hull in WASIM does not interfere with the conclusions made, since these wave loads do not excite or induce vibratory response of the ship hull. However, high-frequency wave loads that come from waves of very short periods do exist, and they might trigger resonance of the ship hull called "springing". In future work, once the hydroelastic analysis part is implemented, the contribution to fatigue damage accumulation from springing will be investigated in more detail.

Estimation of fatigue damage from slamming and whipping
The transient impact load "slamming" is the impact of the bottom structure of a ship onto the sea surface. It induces extremely high loads to ship structures and is taken under consideration when designing ships. Slamming can also induce "whipping" response of the ship structure and it is a hull vibration with a fundamental two-noded frequency. Whipping can produce stresses similar in magnitude to the quasi-static wave-bending stresses and it can also produce very high local stresses which contribute significantly to fatigue damage.

In the data collection of ship hull responses, whipping is detectable as a transient vibration due to wave impact. In Fig. 9, a typical record of stress history is presented where the "WF" curve represents the wave frequency response while the "WF+HF" curve represents total response, where the contribution from high frequency or whipping response is clearly shown. It is obvious that whipping contributes significantly to the peak of the stress range. Note in this context, as well as that in the appended papers, that the ''HF'' responses are referred to high-frequency responses caused by wave-induced vibration, of which both springing and whipping are enveloped.

There are different views on how much whipping contributes to the total wave-induced fatigue damage, see among others Drummen et al. (2008), Gu and Moan (2002), Mao (2010), and Storhaug et al. (2007c). The investigation of whipping involves a number of factors such as the encountered sea state, wave encounter direction, ship speed and the hull structural properties. A correct evaluation of the whipping effects and their contribution to fatigue requires good mathematical modelling of wave and hull structure. This will be one of the challenges in future work.

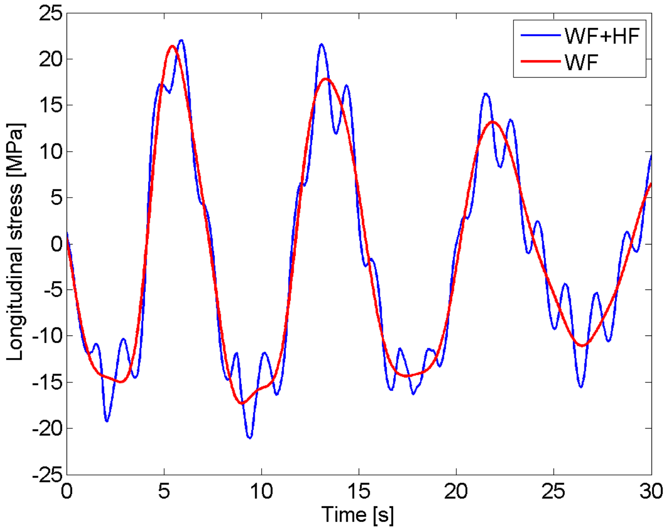

Figure 9. A comparison of stress responses from wave frequency (WF) and high frequency (WF+HF) wave loads.

A practical tool/code for fatigue route planning and monitoring

The long-term ideas of the current research project are to contribute to the development of a practical tool or code for fatigue route planning and monitoring. The current thesis has only given the foundation to such a code, but, together with the statistical models and approaches presented in Mao (2010), at least a simplistic tool or code can be achieved in the near future. Finally, in the continued work with the partners already involved in the project, the aim should be to consolidate knowledge gained this far and add the future work issues of this section to the fatigue routing code which will then make it more complete.

7. References

ABS [American Bureau of Shipping] (2004). “Guidance Notes on Spectral-Based Fatigue Analysis for Vessels”. January 2004. American Bureau of Shipping, ed.

ABS [American Bureau of Shipping] (2011). “Rules for Building and Classing Steel Vessels, Part 5C”. February 2011. American Bureau of Shipping, ed.

Cramer, E. H., Løseth, R. and Olaisen, K. (1995). “Fatigue Assessment of Ship Structures”. Marine Structures **8**(4): 359-383.

DNV [Det Norske Veritas] (2004). “SESAM User Manual Submod: Transfer Displacements from Global Model to Sub-Model”. Version 3.0, November 2004. Det Norske Veritas, ed.

DNV [Det Norske Veritas] (2005). “Classification Note No. 30.7: Fatigue Assessment of Ship Structure”. July 2005. Det Norske Veritas, ed.

DNV [Det Norske Veritas] (2006). “SESAM User Manual Wasim: Wave Loads on Vessels With Forward Speed”. Version 3.4, September 2006. Det Norske Veritas, ed.

DNV [Det Norske Veritas] (2007a). “Recommended Practice DNV-RP-C205: Environmental Conditions and Environmental Loads”. April 2007. Det Norske Veritas, ed.

DNV [Det Norske Veritas] (2007b). “SESAM User Manual Sestra: Superelement Structure Analysis”. Version 8.3, March 2007. Det Norske Veritas, ed.

DNV [Det Norske Veritas] (2009). “Classification Notes - No. 31.7: Strength Analysis of Hull Structures in Container Ships”. October 2009. Det Norske Veritas, ed.

DNV [Det Norske Veritas] (2010a). “Classification Note No. 34.2: Plus - Extended Fatigue Analysis of Ship Details”. June 2010. Det Norske Veritas, ed.

DNV [Det Norske Veritas] (2010b). “Recommended Practice DNV-RP-C203: Fatigue Design for Offshore Steel Structures”. April 2010. Det Norske Veritas, ed.

Dowling, N. E. (1972). “Fatigue Life Predictions for Complicated Stress-Strain Histories”. American Society for Testing and Materials, Journal of Materials **7**(1): 71-87.

Drummen, I., Storhaug, G. and Moan, T. (2008). “Experimental and Numerical Investigation of Fatigue Damage due to Wave-Induced Vibrations in a Containership in Head Seas”. Journal of Marine Science and Technology **13**(4): 428-445.

GL [Germanischer Lloyd Aktiengesellschaft] (2007). “Rules for Classification and Construction Chapter V-1-1: Guidelines for Global Strength Analysis of Container Ships”. Germanischer Lloyd Aktiengesellschaft, ed.

Gu, X. K. and Moan, T. (2002). “Long-Term Fatigue Damage of Ship Structures under Nonlinear Wave Loads”. Marine Technology **39**(2): 95-104.

Hogben, N., Dacunha, N. M. C. and Olliver, G. F. (1986). “Global Wave Statistics”. British Maritime Technology Ltd, ed.

IACS [International Association of Classification Societies] (2008). “Common Structural Rules for Double Hull Oil Tankers”. July 2008. International Association of Classification Societies, ed.

IACS [International Association of Classification Societies] (2009). “Common Structural Rules for Bulk Carriers”. July 2009. International Association of Classification Societies, ed.

IACS [International Association of Classification Societies] (2010). “Unified Requirements Concerning Strength of Ships, Rev. 7”. May 2010. International Association of Classification Societies, ed.

Jacobs, W. (1958). “The Analytical Calculation of Ship Bending Moments in Regular Waves”. Journal of Ship Research **2**(2): 20-29.

Jensen, J. J. and Pedersen, P. T. (1979). “Wave-Induced Bending Moments in Ships – a Quadratic Theory”. Transactions of RINA **121**: 151-165.

Korvin-Kroukovsky, B. (1955). “Investigation of Ship Motions in Regular Waves”. SNAME Transactions **63**: 386-435.

Kring, D., Huang, Y-F., Sclavounos, P. D., Vada, T. and Braathan, A. (1996). “Nonlinear Ship Motions and Wave Induced Loads by a Rankine Method”. In: Proceedings of the 21st Symposium on Naval Hydrodynamics, Trondheim, Norway, June 24-28, 1996, pp. 16-33.

Lin, W-M. and Yue, D. K. P. (1991). “Numerical Solutions for Large Amplitude Ship Motions in the Time Domain”. In: Proceedings of the 18th Symposium on Naval Hydrodynamics, Ann Arbor, Michigan, USA, August 19-24, 1990. Published 1991 by National Acddemy Press in Washington, D.C., USA, pp. 41-66.

Lloyd’s [Lloyd’s Register] (2005). “Classification News - Technical News and Information on Container Ships”. August 2005. Lloyd’s Register, ed.

Løseth, R., Sekkesæter, G. and Valsgård, S. (1994). “Economics of High-Tensile Steel in Ship Hulls”. Marine Structures **7**(1): 31-50.

MAIB [Marine Accident Investigation Branch] (2008). “Report No 9/2008: Report on the Investigation of the Structural Failure of MSC Napoli English Channel on 18 January 2007”. April 2008. Marine Accident Investigation Branch, ed.

Mao, W. (2010). “Fatigue Assessment and Extreme Response Prediction of Ship Structures”. Doctoral Thesis, Department of Mathematical Sciences, Chalmers University of Technology, Gothenburg, Sweden.

Mao, W., Li, Z., Galtier, T., Ringsberg, J. W. and Rychlik, I. (2010). “Estimation of Wave Loading Induced Fatigue Accumulation and Extreme Response of a Container Ship in Severe Seas”. In: Proceedings of the 29th International Conference on Ocean, Offshore and Arctic Engineering (OMAE2010) in Shanghai, China, June 6-11, 2010, OMAE2010-20125.

Moe, E., Holtsmark, G. and Storhaug, G. (2005). “Full Scale Measurements of the Wave Induced Hull Girder Vibrations of an Ore Carrier Trading in the North Atlantic”. In: Proceedings of the International Conference “Design and Operation of Bulk Carriers”, RINA, London, UK, October 18-19, 2005, pp. 57-84.

Rychlik, I. (1987). “A New Definition of the Rainflow Cycle Counting Method”. International Journal of Fatigue **9**(2): 119-121.

Storhaug, G., Mathisen, J. and Heggelund, S. E. (2009). “Model Test and Full Scale Measurements of Whipping on Container Vessels in the North Atlantic”. In: Proceedings of the 28th International Conference on Ocean, Offshore and Arctic Engineering (OMAE2009), on Hawaii, USA, May 31 - June 5, 2009, OMAE2009-79797.

Storhaug, G., and Heggelund, S. E. (2007a). “Measurement of Wave Induced Vibrations and Fatigue Loading Onboard Two Container Vessels Operation in Harsh Wave Environment”. In: Proceedings of the International Conference on “Design and Operation of Container Ships”, RINA, London, UK, July 3-4, 2008, pp. 81-100.

Storhaug, G., Moe, E. and Holtsmark, G. (2007b). “Measurements of Wave Induced Hull Girder Vibrations of an Ore Carrier in Different Trades”. Journal of Offshore Mechanics and Arctic Engineering **129**(4): 279-289.

Storhaug, G., Moe, E. and Piedras Lopes, T. A. (2007c). “Whipping Measurements Onboard a Midsize Container Vessel Operating in the North Atlantic”. International Symposium on Ship Design and Construction in Shanghai, China, November 28-29, 2007, pp. 55-70.

Wu, M. and Hermundstad, O. A. (2002). “Time-Domain Simulation of Wave-Induced Nonlinear Motions and Loads and its Applications in Ship Design”, Marine Structures **15**(6): 561-597.

Paper I

Paper II

Paper III