Adán Vega Sáenz · Newton Narciso Pereira
Luis Manuel Carral Couce
José Angel Fraguela Formoso *Editors*

Proceedings of the 25th Pan-American Conference of Naval Engineering—COPINAVAL

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To all those visionaries who, more than 50 years ago, founded the Pan-American Institute of Naval Engineering (IPIN). They are the source of our inspiration to continue working to keep alive the flame of naval engineering through the continuous generation of knowledge.

Adán Vega Sáenz
Newton Narciso Pereira
Luis Manuel Carral Couce
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Foreword I

The Pan American Conference of Naval Engineering, Maritime Transport and Port Engineering (COPINAVAL) is a long-standing prestigious conference. It has been held in practically every American country, from the United States in the north, to Chile and Argentina in the south of the continent. Strangely enough, until 2017, it was never before held in Panama, a bioceanic country whose importance to world maritime activities is simply too great to need an explanation.

It is only fair to acknowledge that COPINAVAL 2017 put things right. The conference was outstanding in organization, venue, and scientific quality of the papers. The outcome, in the form of this book, shows that a small resolute team can achieve results second to none.

Valdivia, Chile

Dr. Marcos Salas,
Universidad Austral de Chile

The publication of XXV COPINAVAL papers by SPRINGER shows the progress and academic success of the Congress and rewards the authors and the organization of the event for the excellent work developed. The 40 selected papers in the areas of ship design, ship maintenance, sustainability, maritime transportation, corrosion, legal aspects, and education, demonstrate high quality and the ability to produce good research with interesting themes that was achieved by the Pan-American countries.

Sao Paulo, Brazil

Dr. Rui Carlos Botter
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The Pan-American Conference of Naval Engineering, Maritime Transportation and Ports Engineering (COPINAVAL) has been an excellent opportunity for the meeting of researchers, professors, and users related to the maritime sector. The importance of the exchange of experiences of different technological centers and universities is of crucial importance in the new era of this fourth revolution, also called Industry 4.0, in which we are immersed. The observation of reality shows that R&D investment generates economic return, quality employment, and great benefits for society. Reference institutions such as the United Nations or the OECD confirm that sustainable growth in research is the engine for social improvement.

The papers presented are a good example of research and represent an excellent manual to learn about innovation in different aspects in shipbuilding, maritime transport, and naval engineering. In this new era of the optimization of processes, whose characteristics are to make intensive use of process simulation and to use other cutting-edge technologies, the primary goal is to develop industrial plants with much better interconnected production chains and obviously much more competiveness. The naval field is not outside this practice and the presentations, like those included in this book, are good evidence that innovation in this field produces benefits that sooner or later will reach the desired social improvement.

A Coruña, Spain

Salvador Naya
Vicerector for Science Policy, Research and Transfer
Universidade da Coruña, Spain

Foreword II

Over the years the Pan-American Conference of Naval Engineering, Maritime Transportation and Port Engineering—COPINAVAL, has been constituted in the ideal space for the development and strengthening of technological and scientific capabilities of academics and professionals of the area, those who with huge effort, discipline, perseverance, and motivation have worked for the progress of our brotherly nations.

The XXV COPINAVAL, followed with a five-decade trajectory, has been developed in a week that allowed the assistants, speakers, and master lecturers, to share experiences, good practices, and new knowledge that surely will generate impact in the solving of today's problems linked to the tasks of naval engineers and related professionals, people who with hard work and determination assume the responsibility of generating development and social welfare, taking the great ocean as the referent of new opportunities.

Panama, with commitment and dedication, was the manager of all intercultural and scientific exchange in October of 2017. Proof of this was shown through the excellent academic agenda that considered a wide range of issues that considered aspects regarding the 4.0 industry, corrosion, maritime trade, legal aspects of the naval world, offshore, and ship recycling as an opportunity to shipyard crises, among other topics of no less importance.

This book is an acknowledgment of all the authors who contributed to the continued enrichment of the naval profession in the last COPINAVAL. All the works considered here, that were elaborated with excellent quality, are the reflection of the innovative and creative spirit of the professionals in Pan-American nations, all committed to the consolidation of naval engineering. Surely for our authors, the ocean has pointed to the horizon as a life project for self-realization.

With this motivation, and recognizing the success of the XXV COPINAVAL Congress, we invite all authors, professionals, and related researchers to continue in the generation of knowledge and development, using science and technology as the main tools for continuous improvement of our nations.

Colombia accepts with great enthusiasm and happiness assuming the challenge that the Pan-American Institute of Naval Engineering—IPEN has given to us. Our Panamanian kin and their labor will be a reference point for accomplishing the assigned duty, so that in the next March of 2019 the XXVI COPINAVAL Congress in union with the VI International Ship Design and Naval Engineering Congress (ISDNEC) and the VIII International Fair of Naval Industry—Colombiamar, all the Pan-American countries and invited nations will continue to contribute to the development of society through knowledge.

To all of you, thank you for the effort. We will be waiting for you in Cartagena in order to continue with this noble purpose.

Bogota, Colombia

Vice Admiral Jorge Enrique Carreño Moreno
President
Pan-American Institute of Naval Engineering

Acknowledgements

This book would not have been possible without the support received from each of the authors who cordially accepted our invitation. The great success achieved in the XXV COPINAVAL was based on the hard work of the organizing committee, the editors, the reviewers, and of course, thanks to each of the organizations that believed in the project. To the Maritime Authority of Panama, Asmar Shipyard, Bureau Veritas, IBS Class, Copa Airlines, COTECMAR, International Marine Expert, MEC Shipyard, Marine Jet Power, OMCS Class, SENACYT, CILIP, International MarConsult, Talleres Industriales, and the International Maritime University of Panama, our special gratitude.

Special thanks also to the students of the School of Mechanical Engineering of the Technological University of Panama, to the students and professors of the International Maritime University of Panama, and to Barcelo Congress, for all their support.

Last but not least important, we want to thank the board of directors of the Pan-American Institute of Naval Engineers for giving us the opportunity to organize the XXV COPINAVAL in Panama.

Dr. Adán Vega Sáenz
President
Pan-American Institute of Naval Engineers (2015–2017)

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About the Editors

Dr. Adán Vega Sáenz is a mechanical engineer with a Master's degree in materials science and another in plant engineering from the Technological University of Panama. He holds a Ph.D. in marine engineering from Osaka University, Japan. The author of more than 50 scientific articles and a textbook, Dr. Vega's professional experience includes, among others, being a university professor for 15 years at the Technological University of Panama, and visiting professor at the Technological University of Bolivar and UNINORTE, both in Colombia. He is also academic vice president and research vice president at the International Maritime University of Panama and a consultant to several national and international companies.

Dr. Newton Narciso Pereira joined the Fluminense Federal University (UFF), Rio de Janeiro—Brazil, School of Metallurgical Industrial Engineering of Volta Redonda (EEIMVR) in 2016. In 2014 he completed his postdoctorate in Naval Architecture and Ocean Engineering focusing on ballast water management and control in Brazilian ports. He holds a Ph.D. and Master's degree in Naval Architecture and Ocean Engineering from the Polytechnic School of University of São Paulo. He is a graduate in Naval Technology from the Faculdade de Tecnologia de Jahu—UNESP and Production Engineering from Guarulhos University. Dr. Pereira is the general coordinator of the Center for Sustainable System Studies (CESS-UFF) and the graduate coordinator of the Production Engineering course at (EEIMVR).

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Dr. José Angel Fraguela Formoso holding a Ph.D. in Naval Architecture and Marine Engineering, Dr. Fraguela is a professor at the University of A Coruña (Spain) and the director, organizer, and speaker in numerous masters', expert courses, specialization courses, and technical conferences in Europe and Latin America and the director of numerous Ph.D. and Final Degree projects. He is a member of scientific committees, and peer reviewer and editor in international and national congresses as well as president of the IPIN-SPAIN (Pan-American Institute of Naval Engineering) and a member of the Consultative Council of IPIN-AMERICA. Dr. Fraguela is also the author of many books and technical articles in JCR journals and other databases.

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Part I
Naval Engineering

Structural Parametric Model of an Ecological and Efficient Shuttle Tanker for Operations at the Brazilian Pre-salt Region

Rodrigo A. Schiller, Rubens C. da Silva and Kazuo Nishimoto

Abstract The aim of this paper is to present the development of an ecological and efficient shuttle tanker structural parametric model with optimized capacity that was designed to operate at the Brazilian pre-salt region. Such a model estimates the weights and centers of the bare hull, as well as the structural weight, the center of gravity of the ship, and the moments of inertia at different dimensional, geometric, and capacity features of the ship from structural elements of the parallel middle body. These elements were automatically dimensioned at a MATLAB® environment. After an exhaustive search method through several dimensioning cases of these elements, the lowest structural weight was obtained, which satisfies the rules of classification societies. Finally, the results are shown as a response surface, which was built by means of artificial neural networks. These allow assessing the behavior of weights and centers characteristics of the ship, based on the variation of design parameters.

Keywords Pre-salt region · Shuttle tanker · Structural parametric model
Weights and centers

1 Introduction

Structural weight reductions are quite important in design and construction cost savings and have a reasonable effect on decreasing fuel consumption and gas emissions. For large cargo vessels (displacement hulls) a lower structural weight increases the available deadweight for a ship of the same size, thereby improving transport efficiency.

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To gain an understanding of the impact of decreased light ship steel weight on fuel consumption, according to [2], a 1% reduction in hull steel weight for each ship in a set of standard designs leads to decreasing fuel consumption by 0.16% for Suezmax tankers (approximately 0.11 ton/day fuel savings).

The discoveries made in the Brazilian pre-salt are among the world's most important in the past decade. The pre-salt region comprises large accumulations of excellent quality, high commercial value light oil, a reality that puts Brazil in a strategic position to meet the great global demand for energy. Daily oil output at the pre-salt progressed from the average of approximately 41,000 barrels per day in 2010, to 1 million barrels per day in mid-2016 [3]. This overall growth of Brazilian oil production generates a demand for a more modern tanker fleet, capable of efficiently transporting the whole production of offshore oil rigs to terminals and following international environmental regulations. Such vessels may present unique design features that can lead to a hull with unconventional dimensions, specific to operate at certain areas with a desirable efficiency.

The purpose of this paper is to present a numerical methodology to estimate the weights and centers of a shuttle tanker hull based on a midsection whose structural components have the lighter possible weight and are in accordance with the International Association of Classification Societies (IACS) Common Structural Rules (CSR) for Double Hull Oil Tankers.

2 Methodology

2.1 General Considerations

The structural model can estimate the weights and centers of a double hull shuttle tanker with a payload (Δ_{load}) greater than 100,000 ton, for different combinations of length overall (L_{OA}), breadth (B), block coefficient (C_B), depth (D), and draft (T). The structural arrangement of the ship's parallel middle body is sized in accordance with the International Association of Classification Societies (IACS) Common Structural Rules (CSR) for Double Hull Oil Tankers with Length 150 m and Above and by comparisons with existing similar ships.

As shown in Fig. 1a, the obtained midship section has a typical double hull oil tanker layout, with a double side structure and one cargo tank symmetrically arranged on each board. The tank arrangement and D were parameterized with L_{OA} and B from existing ships, particularly the NORDIC Rio Shuttle Tanker (Fig. 1b).

The structural model can be used, as demonstrated in the results section, as an analysis tool of variation of weights and centers of the bare hull in preliminary stages design, in which different combinations of main dimensions of the ship are evaluated.

In the specific case of the application example presented, a vessel with a fixed Δ_{load} = 170,000 ton that will operate at the Brazilian pre-salt region was

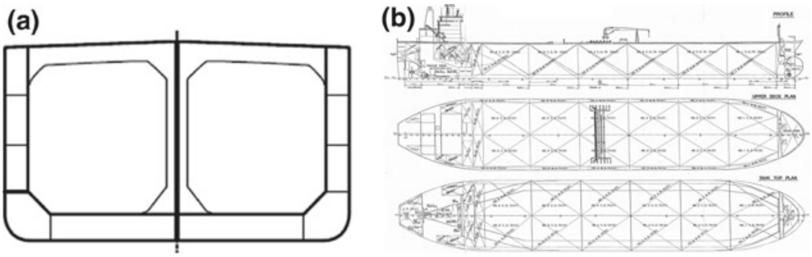

Fig. 1 **a** Typical midship section for double hull tankers [1], **b** NORDIC Rio general arrangement [4]

considered. The results were evaluated by means of a response surface that allowed observing the weights and centers variations in function of a combination of L_{OA} and B.

2.2 *Sequence of Structural Model Operations*

The sequence of the structural synthesis model operations (steps A to I) is shown in Fig. 2. Each step is explained below.

- **Step A**: The model establishes for each (L_{OA}, B) combination the possible values of spacing among primary support members (S), stiffeners (r), and frames (l) (Fig. 3a), based on IACS requirements, and the variation of plating and stiffener thickness. As a simplification, C_B and Δ_{load} were considered constant, and D was estimated by cargo tank height of similar ships. In addition, r, S, and l remained constant around the whole midship section in each case. However,

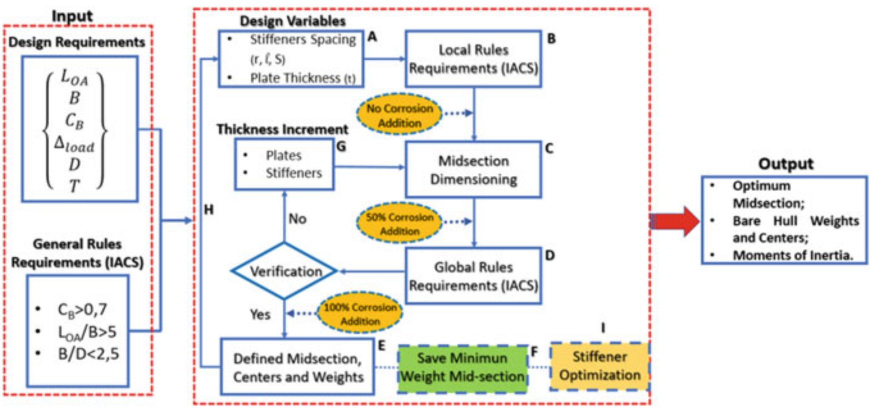

Fig. 2 Structural model flowchart

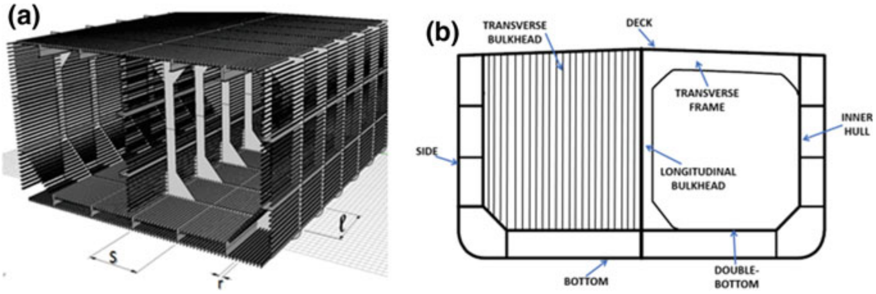

Fig. 3 **a** Spacings considered in the model; **b** different element thickness regions

based on IACS requirements, the plating and stiffeners thickness vary according to their location (Fig. 3b).

- **Step B**: For a given combination of (r, S, l) the minimum thickness and dimensions of plating and stiffeners are calculated according to the IACS local loads and dimensioning criteria, considering the position of each structural element and the static and dynamic pressure combinations on each region for different conditions of draft, loads, and damage. Moreover, thickness values were obtained from manufacturers' tables.
- **Steps C, D**: After meeting the local requirements, the structural elements are placed and the midship section is defined. Hereafter, the section modulus and hull girder inertia are calculated and compared with the minimum global requirements.
- **Steps E, F**: If the midship section meets the global requirements, the weights and centers are calculated. At each cycle defined by a given combination of (r, S, l), the data (longitudinal and transversal elements) of the midsection with the minimum structural weight (considering the linear weight of the parallel middle body) are stored.
- **Step G**: If the global requirements are not met, the structural elements undergo a new thickness increment and a new midship section is defined for further evaluation. The thickness increment is performed to maximize the increase of the section modulus and the hull girder inertia with the smallest possible increasing weight.
- **Step H**: The process is repeated for all (r, S, l) combinations.
- **Step I**: Each midship section stored in **Step F** initially has flat bars as stiffeners. In this step, the stiffener profile is optimized to an equivalent T-bar profile with lower weight and the structural requirements are compared. Finally, the weights and centers of the new midship section are calculated.
- **Corrosion Additions**: The IACS Local Corrosion Additions (LCA) were implemented in the model. The LCA consider the environment that the plates and stiffeners are immersed in and the adjacent ones to increment the thickness due to corrosion. For dimensioning the structural elements, IACS defines three different conditions for the application of the corrosion additions:

- **No Corrosion Addition** (For dimensioning the local elements, corrosion additions are not considered and the local requirements are met for the most critical situation of a lower thickness).
- **50% Corrosion Addition** (The calculation of the section modulus and hull girder inertia is made considering half the corrosion addition and then, the global requirements are assessed).
- **100% Corrosion Addition** (For the final arrangement of the structural elements and for the calculation of the structural weight, the full corrosion addition is considered).

2.3 *Geometric Optimization of Stiffeners*

For each minimum weight midship section stored in Step F, a series of T-bar stiffeners with different flange and web length ratios ($L_{\text{flange}}/L_{\text{web}}$) were dimensioned (flange and web have the same thickness). T-Profile was chosen because of its symmetry and it will not be prone to skew bending and is favorable for fatigue strength. The main constraints in this case are the minimum section modulus, inertia, and thickness defined by IACS in a certain position and previously calculated for the flat-bar stiffeners. T-bar stiffeners with $L_{\text{flange}}/L_{\text{web}}$ around 35–40% were chosen because they presented the higher sectional area reduction (A_T/A_I) if compared with the flat-bar at the same position. Particularly, Fig. 4 shows a result of a stiffener located at the double-bottom region that presented a sectional area reduction of almost 24%.

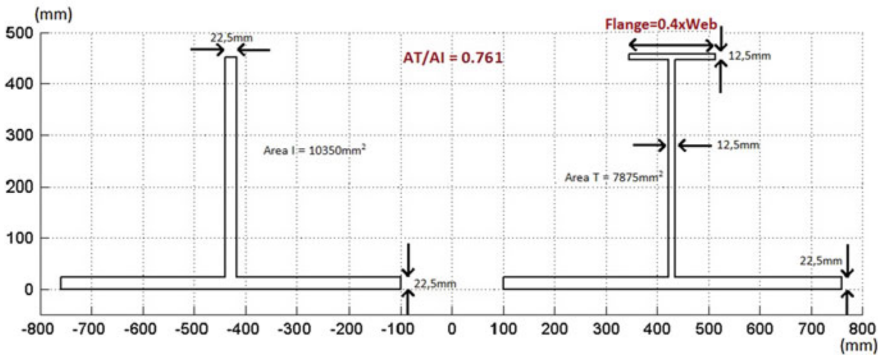

Fig. 4 Sectional area reduction (A_T/A_I) of a stiffener located at double-bottom

2.4 Bare Hull and Lightship Weight and Centers Estimation

The estimation was based on the method of Watson [5], which uses a bare hull steel-weight distribution curve along the length between perpendiculars obtained by analyzing existing vessels with parallel middle body and displacement hull (Fig. 5). This curve is determined by three parameters (r, p, e), where r is the distance between the after perpendicular and the parallel middle body, p is the length of the parallel middle body, and e is the distance between the parallel middle body and the forward perpendicular.

At this preliminary stage in which the hull geometry is not yet defined, the three parameters were determined by the arrangement of the similar vessel NORDIC Rio (Fig. 1b). The distribution of the frames' weight is simple, because its geometry and spacing (l) are defined in the structural model. The number and spacing of transverse bulkheads were also defined by the tank arrangement of the similar vessel. The linear weight of the midship section was defined as the sum of the linear weights of the longitudinal and transverse structural elements. Therefore, by the presented methodology the bare hull weight was estimated by adding a margin of 5% referring to welding and painting material.

The longitudinal position of the center of gravity (LCG) was based on the longitudinal position of the center mass of the steel-weight distribution curve (Fig. 5). The vertical position of the center of gravity (VCG) was approached by the VCG of the parallel middle body, neglecting the stern and bow regions.

For bare hull moments of inertia estimation, the moments of inertia of each structural element "i" of the midship section was calculated according to equations:

$$I_{xx}(i) = \iiint \left(y^2 + z^2\right) \rho_{\mathrm{eq}} \mathrm{d}v(i) \tag{1}$$

$$I_{yy}(i) = \iiint \left(x^2 + z^2\right) \rho_{\mathrm{eq}} \mathrm{d}v(i) \tag{2}$$

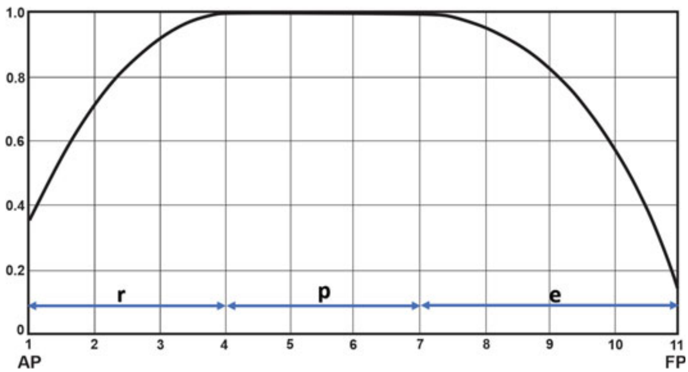

Fig. 5 Steel-weight distribution for ships with parallel middle body [5]

$$I_{zz}(i) = \iiint \left(x^2 + y^2\right)\rho_{\mathrm{eq}}\mathrm{d}v(i) \tag{3}$$

where $\rho_{\mathrm{eq}} = f(x)\rho_{\mathrm{steel}}$ is the equivalent density and $f(x)$ is associated with the steel-weight distribution curve (Fig. 5) to estimate the mass properties of the stern and bow regions. This approach can present significant errors by not considering the geometry of the stern and bow of the ship, especially for the I_{xx}. However, it is satisfactory for the preliminary stages of the project. Furthermore, the parallel axis theorem was applied to calculate the moment of inertia of the whole midship section considering the position of the bare hull center of gravity.

The lightship (W_{LS}) was considered to consist of four components: bare hull (W_{Hull}), superstructure (W_{SS}), machinery (W_{M}), and outfit (W_{O}). The weight of each component, except W_{Hull} (calculated by the structural model) was estimated from formulations that consider parameters such as L_{OA}, B, D, and C_{B}. Such formulations, which are not detailed, were based on the studies of [6–8].

3 Results

In this section, the results of the structural model for a specific case of preliminary stage design of a shuttle tanker made to operate at the Brazilian pre-salt region are presented. The following design requirements were considered.

- Maximum draft ($T_{\mathrm{máx}}$) = 18 m.
- Lightship limited to $0.22\Delta_{\mathrm{load.}}$
- Δ_{load} = 170,000 ton and C_{B} = 0.82.
- $L_{\mathrm{OA}}/B > 5$ and $B/D < 2.5$ (IACS).

As previously explained, the input variables are the main dimensions of the ship, of which just L_{OA} and B vary, and for each combination (L_{OA}, B) also the spacings (r, S, l) of the midship section components vary.

The range of values (r, S, l) were based on the analysis of similar Suezmax tankers, with a small margin on the lower and upper values. Table 1 shows the values of the variables, and it is possible to evaluate the number of simulated cases.

Table 1 Range of values assumed by the variables

Variable	Range	Number of cases
L_{OA}	263:2:357	48
B	44:1:56	13
S	$\frac{B}{[4:2:12]}$	5
r	$\frac{S}{[5:1:20]}$	16
l	$\frac{L_{\mathrm{OA}}}{[50:10:150]}$	11
Total number of cases		549,120

3.1 Midship Section and Parallel Middle Body

From the presented variables, the structural model establishes the elements of the midship section, such as the side plating, double hull, main deck, longitudinal and transverse bulkheads, frames, and longitudinal stiffeners.

The mechanism chosen to define the lower weight midship section for each combination of structural variables was the exhaustive search. This is a simple method that will always define a result. However, the computational time in this case is much higher than using optimization algorithms.

As a result, Fig. 6 shows examples of a lower structural weight midship section and frame (Fig. 6a) for a specific case of L_{OA} = 297 m and B = 53 m and the three-dimensional model of the parallel middle body (Fig. 6b).

3.2 Response Surface

The response surface for each estimated parameter was constructed with artificial neural networks (ANN) because they can present accurate results for simple meshes (with a few simulated cases), depending on the parameter variation. The ANN topology that best fits the characteristics of the response surface with fast convergence and high precision was the one with a 10-neuron layer and back propagation training algorithm (Fig. 7a). According to [9], back propagation is the most widely used ANN algorithm for general engineering applications.

The ANN inputs were L_{OA} and B values and the desired outputs were the estimated parameters from the structural model (one per ANN). The training subset, composed of 60–90% of random samples from the complete set, were used essentially in the ANN learning (training) process. The ANN results and the values obtained by simulations of the structural model were compared. The obtained mean error was almost 2%, and the number of simulated cases was considered sufficient to obtain a good response surface. Figure 7a shows the comparison of the results for the lightship (W_{LS}).

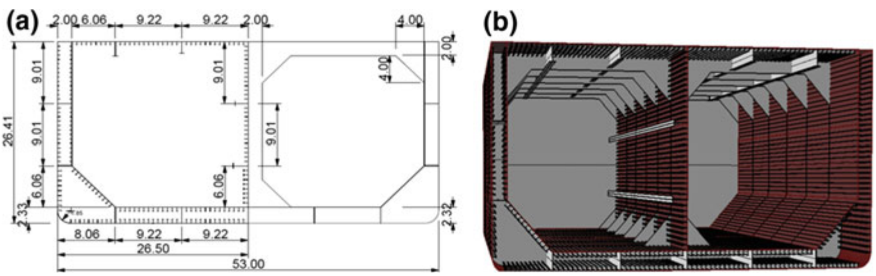

Fig. 6 Lower structural weight midship section (a) and parallel middle body (b)

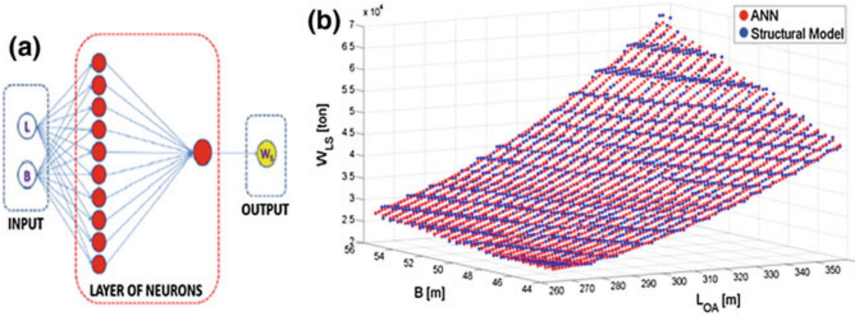

Fig. 7 ANN topology (**a**) and comparison between the W_{LS} results and ANN (**b**)

3.3 General Results

This section presents the results of weights and centers of the lightship according to the variation of L_{OA} and B. Figures 8, 9 and 10 show some of the main results obtained from the structural model to a constant Δ_{load} = 170,000 ton.

Applying the design constraints relative to lightweight (limited to $0.22\Delta_{load}$) and maximum draft ($T_{máx}$ = 18 m) to the results, a region with the feasible cases was defined (Fig. 11).

To validate the model results, the range of W_{LS} values was compared with the IHS–Fairplay data for Suezmax tankers with 160,000 ton $\leq \Delta_{load} \leq$ 170,000 ton and the same range values of L_{OA} and B from [10], through the lightweight coefficient ($C_{WLS} = W_{LS}/L_{PP}xBxD$). Table 2 shows the comparison between the results from the structural model and the IHS–Fairplay data, and the adherence among the values can be noticed.

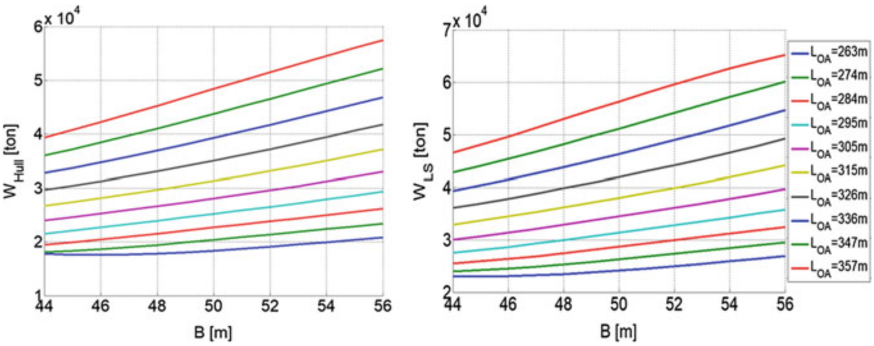

Fig. 8 W_{Hull} and W_{LS} results

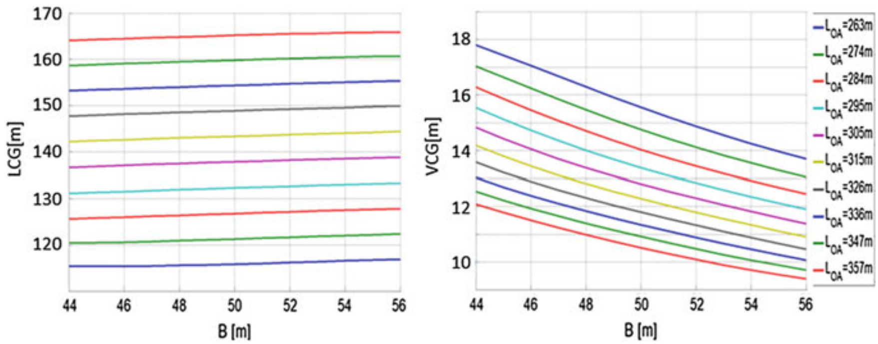

Fig. 9 LCG and VCG results

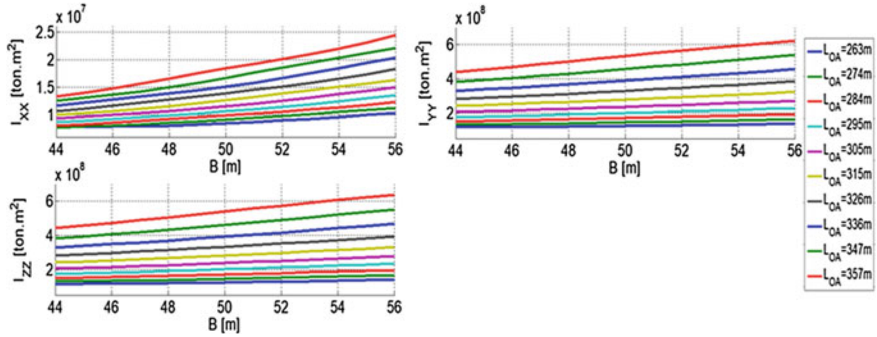

Fig. 10 Inertia results

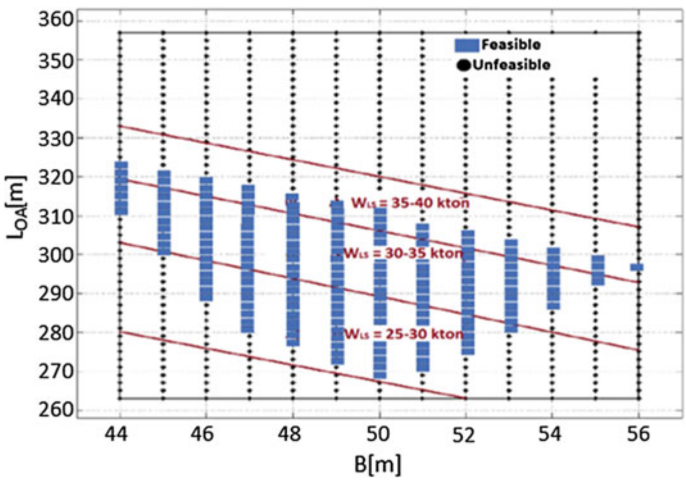

Fig. 11 Feasible region defined by the design constraints

Table 2 Values of C_{WLS} from structural model and IHS–fairplay data

	C_{WLS} [ton/m^3]
IHS–fairplay	0.078–0.09
Structural model	0.079–0.091

4 Conclusion

The structural model generated results that can be quite important at the early stages of the design of a vessel with specific dimensions and requirements as an assistance to decision making. The behavior of the output parameters according to the variation of some variables (in this case, L_{OA} and B) has a great value as a sensitivity analysis of the design requirements. However, an optimization algorithm must be added to the model to make it more efficient, mainly regarding computational time. Moreover, the bow and stern geometry must be considered in more detail to increase the accuracy of the inertia and weights results. These aspects will be improved in the next works.

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Effect of Encountered Wave Condition on Fatigue Life Prediction of Ship Structures

Luis De Gracia, Hitoi Tamaru, Naoki Osawa and Toichi Fukasawa

Abstract Ship weather routing develops an optimum track for ocean voyages based on a forecast of weather, sea conditions, and a ship's individual characteristics for a particular transit. In these days, most ships follow weather routing, and those ships never experience extremely severe seas. In classification society rules, ship structure fatigue assessment is performed without consideration of weather routing. In these assessments, the occurrence probability of severe seas is overestimated and their recurrence interval is underestimated. This might lead to deterioration in fatigue assessment precision. In this study, S–N-based fatigue assessments of a welded joint in a container ship that follows weather routing are performed. This ship sails on a North Atlantic Ocean route. Fatigue lives are evaluated assuming different encountered wave conditions: for a planned route, "Great Circle Route," and a weather routing, "Minimum Time Route." Short sea sequences are generated by a storm model using hindcast data. The storm profiles are determined by using the cumulative frequency of shot seas which is experienced on the MTR routes. Based on these results, the effect of encountered wave conditions on cumulative fatigue damage is discussed.

Keywords Fatigue · Cumulative fatigue damage · Routing · Storm model
Wave load

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1 Introduction

A fatigue assessment is a mandatory assessment in major Classification Society Rules. The fatigue assessment is performed based on the S–N approach (Palmgren–Miners rule). The fatigue damage is caused primarily by the variation of the wave loading acting on ships, resulting in the variation of the stress amplitude [1]. The effectiveness of the S–N-based assessment falls in the reliable description of the encounter wave conditions experienced by ocean-going ships. Tomita et al. [2–4] proposed a “storm model” that can simulate the wave load sequence experienced by ocean-going ships. Kawabe [5] and Prasetyo [6] modified Tomita’s model to improve the emulation capability of a real sea state sequence. Recently, De Gracia et al. [7] proposed a modified model that considered the stochastic nature of the wave direction.

In this paper, fatigue assessments of a 6000 TEU (Twenty-foot Equivalent Unit) container ship’s welded joint were performed. The target ship is assumed to face two different encountered wave conditions in a North Atlantic Ocean route, following a weather routing, called minimum time route (MTR), and a planned route, great circle route (GCR). Short sea sequences are generated by using Japan Weather Association (JWA) hindcast data, and those for MTR are simulated by adopting Tamaru’s weather routing algorithm [8]. SN-based fatigue assessments are performed for MTR and GCR sequences, and the effect of the encountered wave condition on fatigue damage is examined.

2 Encountered Wave Conditions

2.1 Weather Routing Algorithm

The benefits of ship weather routing are primarily in time and cost reductions and increased crew and structural safety. The reduction in transit time, fuel consumption, extreme weather encounters, and hull damage is directly related to saving in operating cost reductions. A weather routing algorithm that can judge the minimum time route from a spatiotemporal distribution of sea states (significant wave height and wave direction) was proposed by Tamaru [8]. The relationship between significant wave height, ship speed loss, and the relative heading angle is considered in the analysis. The ship route is optimized by analysis of the isochrones and the spatiotemporal sea state data was generated from JWA’s hindcast data.

2.2 Sea State Data

A North Atlantic route between Boston and Bishop is chosen as the shipping route. The weather routing algorithm explained in Sect. 2.1 is adopted in this study, and the GCRs and MTRs are determined by Tamaru. Figure 1 shows an example of the MTR for the assumed route.

The target ship is a 6000 TEU container ship. It is considered that she sailed on the North Atlantic Ocean for a period of 10 years. The ship experiences the sea state (significant wave height H_S, mean period T_S, and wave direction θ) sequence determined by those at the nearest JWA hindcast data grid point.

2.3 Real Headings Model and Wave Statistics

Consider θ, α, and χ as the wave direction, ship's heading angle, and relative heading angle. The stress in the conventional fatigue design procedure is evaluated assuming that χ is given by a uniform random number. However, throughout the ship's service life, she meets each new wave at a particular relative angle. In this paper, let "real headings model" be the model in which the stress response is calculated by considering the χ's occurrence probability f_χ. θ is determined by random number selection considering θ's occurrence probability f_θ, and χ is calculated by Eq. 1 each time.

$$\chi = \alpha - \theta \tag{1}$$

The averaged f_θ for the North Atlantic Ocean is determined from JWA hindcast data. Figure 2 shows the determined f_θ. It is shown that θ is predominant between 240° and 330°.

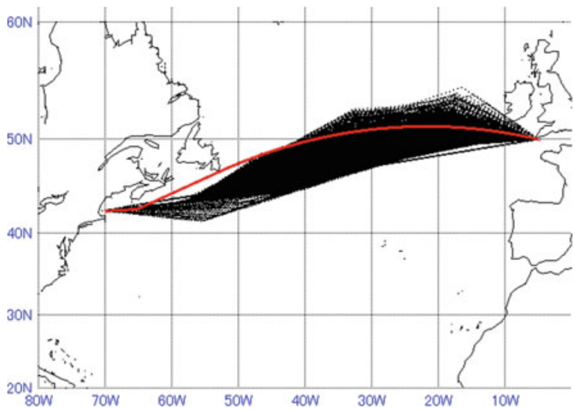
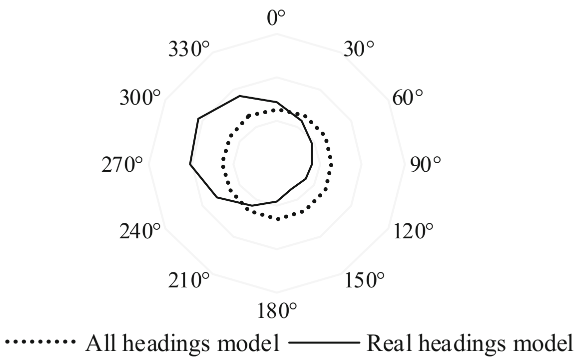


Fig. 1 An example of minimum time routes (MTR) for the United States/ United Kingdom

Fig. 2 Wave direction's occurrence probability distribution f_θ, determined from JWA hindcast data in the North Atlantic Ocean



The time history of individual wave height is generated assuming that the individual wave height obeys the Rayleigh distribution, whose energy spectrum can be defined by the ISSC (International Ship and Offshore Structures Congress) spectrum as Eq. (2).

$$\frac{S(\omega)}{H_S^2} = 0.11\left(\frac{\omega T_S}{2\pi}\right)^{-5} \exp\left\{-0.44\left(\frac{\omega T_S}{2\pi}\right)^{-4}\right\} \tag{2}$$

where ω is the wave frequency (rad/s), $S(\omega)$ the specified wave spectrum (m^2/s), and T_S the peak period (s). Let "as-simulated sea sequence" be the sea state sequence directly determined from the GCR or MTR ship position sequence and JWA hindcast data's spatiotemporal wave data, and the "storm sea sequence" be that generated from a storm model simulation. These spatiotemporal wave data are fitted by the log-normal distribution proposed by Wan and Shinkai [9] due to rounding errors that might be found in the histograms. Figure 3 shows the comparison of H_S exceedance probability P_{EX,H_S}, of an as-simulated sea sequence for GCR and MTR routes. It is observed that the difference becomes larger for waves larger than 5 m, whereas the difference increases with H_S. Additionally, differences

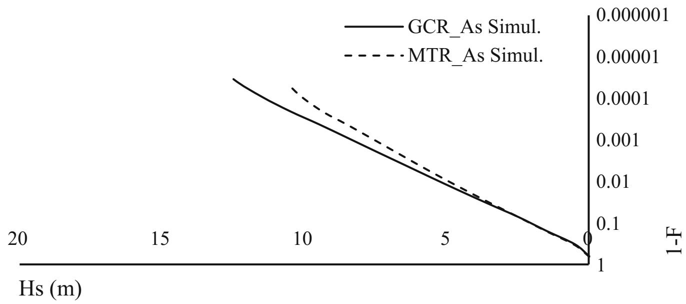


Fig. 3 The comparison of significant wave height's exceedance probability $P_{EX,Hs}$, for as-simulated sea sequence for MTR and GCR routes

in the maximum significant wave height $H_{S,max}$ with MTR having less severe encounter wave conditions than those found in the GCR route are observed.

3 Stress Response

3.1 Stress Statistics

In the as-simulated sea sequences, sequences of (H_S,T_S,θ) are given. The ship course α, is determined by drawing a line segment joining previous and current ship positions. The relative heading angle χ can be determined from θ and α. In this way, the sequence of (H_S, T_S, θ) is determined. ΔS denotes the hotspot stress range. Once (H_S, T_S, θ) is given, the ΔS sequence can be generated by following linear spectrum analysis. In these analyses, ISSC's wave spectrum is adopted as the R parameter. Let this ΔS sequence be the "as-simulated stress sequence." Let $P_{EX,\Delta S}$ be ΔS's exceedance probability. Let $P_{EX,\Delta S|GCR}$ and $P_{EX,\Delta S|MTR}$ be $P_{EX,\Delta S}$ of as-simulated stress sequences for GCR and MTR routes. A comparison of $P_{EX,\Delta S|GCR}$ and $P_{EX,\Delta S|MTR}$ is presented in Fig. 4. In the as-simulated sequence, the difference in the encountered wave condition shows that the difference in the stress exceedance probability becomes evident for $\Delta S > 100$ MPa, and the difference becomes slightly larger with the increase in ΔS. It is considered that these differences are due to χ's randomness and the variation in stress response amplitude operator (RAO) associated with χ. Additionally, the differences in the stress exceedance probability is associated with the encountered wave condition differences between the two routes.

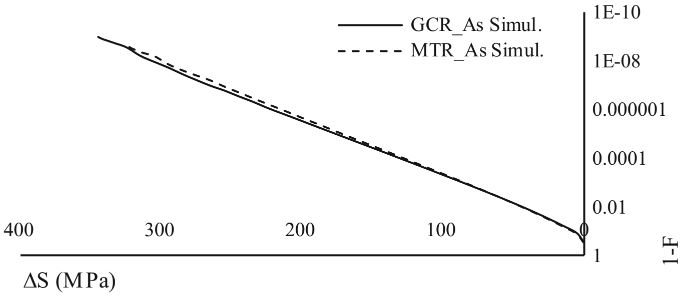


Fig. 4 Comparison of the stress range's exceedance probability $P_{EX,\Delta S}$ for as-simulated stress sequence for MTR and GCR routes

4 Storm Model

4.1 Wave Scatter Diagrams

The joint frequency distributions of (H_S,T_S), known as a wave scatter diagram, are generated by counting sea states recorded in as-simulated sea sequences for both encountered wave conditions: GCR and MTR routes. It is considered that these sea histograms include round errors. These errors are corrected by using the correcting method proposed by Wan and Shinkai [9]. In this method, histograms are fitted with the conditional log-normal distribution $p(T_S|H_S)$ given by Eq. (3).

$$\begin{aligned} p(T_S|H_S) &= \exp\left\{-\frac{[\ln(T_S-\mu)]^2}{2\sigma^2}\right\}\alpha(T_S,H_S), \\ \alpha(T_S,H_S) &= \frac{\sqrt{2\pi}}{2\pi T_S\sigma}, \mu = E\{\ln(T_S(H_S))\}, \\ &\sigma^2 = \mathrm{var}\{\ln(T_S(H_S))\} \end{aligned} \tag{3}$$

H_S's marginal probability distribution $p(H_S)$ is determined in Sect. 2.3. The joint probability distribution $p(T_S,H_S)$ is calculated by Eq. (4).

$$p(H_S,T_S) = p(H_S)p(T_S|H_S) \tag{4}$$

Furthermore, it is recognized that the long-term probability distribution of H_S can be approximated by the Weibull distribution [10]. The characteristic of the Weibull distribution is described as that of $F(H_S)$ in Eq. 5:

$$F(H_S) = 1-\exp\left[-\left(\frac{H_S}{\lambda}\right)^k\right] \tag{5}$$

and, its p.d.f. is given as

$$\left(\frac{kH_S^{k-1}}{\lambda^k}\right)\exp\left[-\left(\frac{H_S}{\lambda}\right)^k\right] \tag{6}$$

where k and λ are the Weibull's shape and its scale parameters.

In Figs. 5 and 6 are presented the Weibull plot of $F(H_S)$ considering all seasons on the North Atlantic wave scatter diagram for the GCR and MTR cases. The relation between $\ln(H_S)$ and $\ln(\ln(1/1-F(H_S)))$ can be represented by a straight line. The shape and scale of the Weibull parameters can be identified by using the least square method in conjunction with the correlation of natural logarithms on the

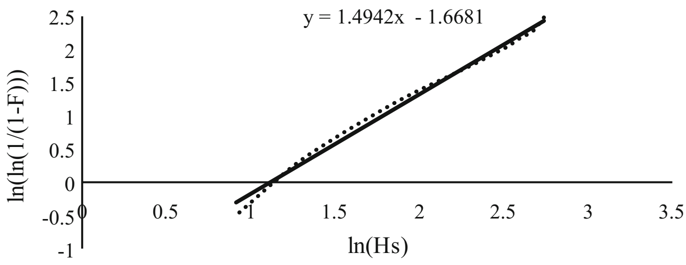


Fig. 5 Weibull plot considering all seasons in the North Atlantic Ocean for GCR cases

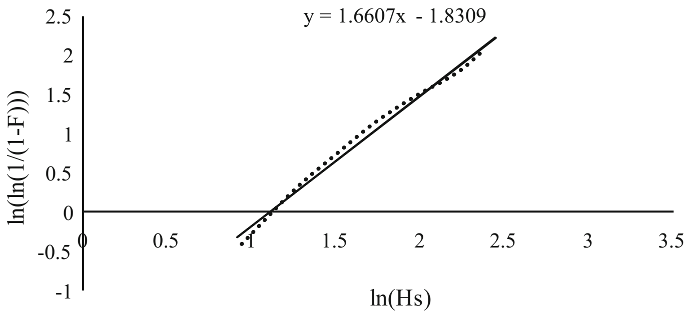


Fig. 6 Weibull plot considering all seasons in the North Atlantic Ocean for MTR cases

left- and right-hand sides of Eq. (5). In this case, for the North Atlantic wave scatter diagram, $F(H_S)$ are determined by performing Weibull fitting from all H_S ranges.

4.2 Storm Models

Tomita et al. [2] studied the time history of wave occurrence experienced by a ship during voyages on the North Pacific Ocean, and demonstrated that the wave-induced load in a ship hull can be divided into two groups: calm sea condition and storm condition. The wave histories are described in calm conditions as time-independent waveforms, whereas in the storm condition the waves can be modeled as time-dependent crescendo–decrescendo waveforms, and they appear randomly. Figure 7 shows an example of wave history generated by the storm model. The "storm model" consists of a "storm profile" and H_S's probability distribution in calm seas. The storm profile consists of a series of storm waveforms and the occurrence probability of storms. In this paper, storm profiles are determined by adopting the "3G storm model" proposed in [6], which can take into account variation of storm duration.

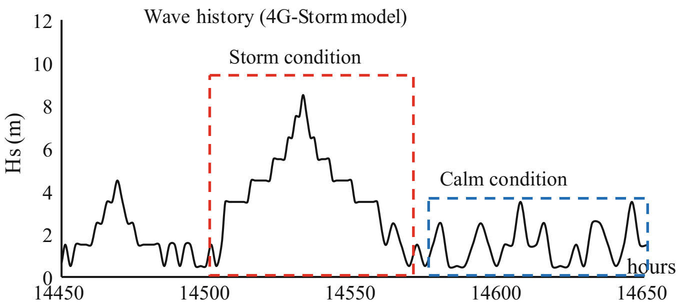


Fig. 7 An example of wave load history generated by the storm model

Once the storm model is established, sea sequences (H_S, T_S, θ) are generated from the storm model. After these sea sequences are generated, stress sequences are generated by adopting real headings or all-headings models. Let $P_{EX,\Delta S,\text{storm}}$ be ΔS's exceedance probability of a storm model's stress sequence. $P_{EX,\Delta S,\text{storm,RH}}$ represent $P_{EX,\Delta S,\text{storm}}$ calculated for a real headings model. A storm sea sequence generated by a storm model with a real heading model emulates the occurrence probability of sea state and relative heading angle.

Figures 8 and 9 show comparisons of $P_{EX,\Delta S,\text{storm,RH}}$ and as-simulated $P_{EX,\Delta S}$ for GCR and MTR routes. It is shown that the differences in $P_{EX,\Delta S}$ are satisfactorily small for both routes. Furthermore, these results demonstrate that the storm models have the emulation capability of generating stress sequences experienced by ocean-going ships. These results are presented for cases where ships follow a weather routing or not, under the conditions chosen.

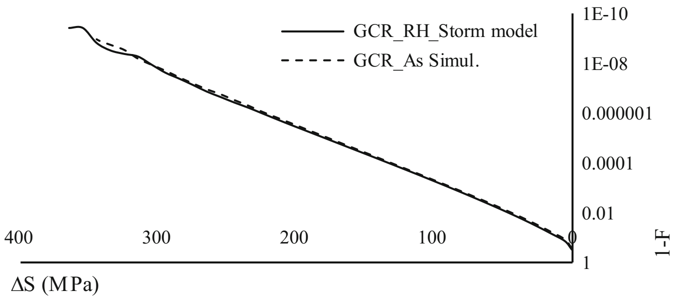


Fig. 8 The comparison of the storm model and as-simulated for GCR route

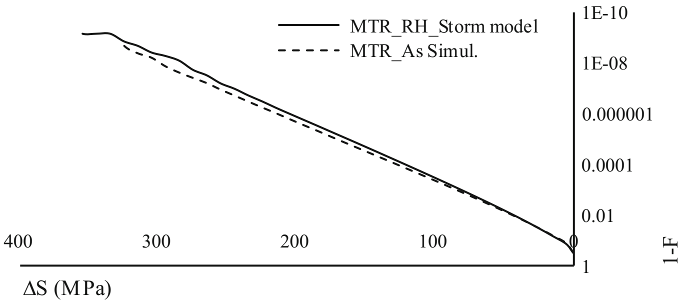


Fig. 9 The comparison of the storm model and as-simulated for MTR route

5 Fatigue Assessment

5.1 Cumulative Fatigue Damage

The cumulative fatigue damage is evaluated by the Palmgren–Miner rule for all classification society rules. It says that the total damage experienced by the structure may be expressed by the accumulated damage from individual load cycles at different stress levels. In this paper, the cumulative damage is calculated over 10 years $D_{10\text{years}}$. The cumulative fatigue damages of the target welded joint $D_{10\text{years}}$ for a given ΔS sequence is calculated by Eq. (7):

$$D_{10\text{years}} = \sum \frac{n_i}{N_i} \tag{7}$$

where n_i is the number of stress cycles in ith stress range block ΔS_i, and N_i the number of cycles to failure for ΔS_i, which is determined using DnV CN.30.7's curve I (for welded joints) [11]. The thickness effect is not considered and the mean stress is assumed to be zero.

5.2 Fatigue Damage Results

In this section, the comparison of the fatigue damage due to differences in the encountered wave conditions is presented. It is assumed that the ship sails in the North Atlantic Ocean. Additionally, the effectiveness of the storm model is examined, comparing the fatigue damage results with those obtained in the as-simulated sequences for both routes, the GCR and MTR. Table 1 shows the cumulative fatigue damage results over 10 years $D_{10\text{years}}$. It is observed that the differences in statistical properties of $D_{10\text{years}}$ are about 15% smaller for ships that encountered wave conditions following the minimum time route, compared to those that sail in the great circle route. These results clearly suggest the effect of the

Table 1 Comparison of the statistic L_f calculated by DnV CN. 30.7

Sequence model	Storm model		As simulated	
Route	GCR	MTR	GCR	MTR
$D_{10\mathrm{YR}}$	0.3694	0.3223	0.3408	0.3402
L_f (year)	27.07	31.03	29.345	29.399

encounter wave condition for vessels that follow a weather routing, is to extend the service life of the structure. These results are expected due to less severe wave conditions encountered in a weather routing compared to those structures experiencing wave loadings in a great circle route (see Figs. 3 and 4).

Moreover, it is recognized that the storm model for weather routing can successfully emulate the (H_S, T_m, χ) sequences experienced by a vessel in the GCR and MTR routes. Under the condition chosen, the storm model results tend to be slightly conservative compared to those obtained in the as-simulated sequence. The differences in statistical properties of $D_{10\mathrm{years}}$ are at most about 8% larger than those obtained in the as-simulated sequence. However, the effects of the high-frequency loading (whipping/springing vibrations) were not considered in this paper, and additional studies are needed to clarify their effect on the statistical properties of the fatigue damage of ship structural members.

6 Conclusions

In this paper, fatigue assessments of the welded joint in the 6000 TEU container ship are performed. Two different encounter wave conditions in the North Atlantic Ocean are considered: great circle (GCR) and minimum time (MTR) routes. Stress sequences are generated by the storm model, with a real heading model that emulates the occurrence probability of sea state and relative heading angle. SN analyses are based on DnV CN 30.7. The following points are obtained from the results.

- To generate the stress sequence of wave random loading, the storm model can be adapted. The storm model leads to slightly conservative estimations compared to those obtained in the as-simulated sequence, under the condition chosen.
- The weather routing affects the fatigue assessment results. The difference in the cumulative fatigue damage between GCR and MTR is at least about 15% under the conditions chosen.
- Additional studies on the development of an advanced wave load sequence model that can consider the effect of whipping/springing vibration are needed.

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Numerical Model to Analyze a SNCR System to Reduce NO_x

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Abstract Taking into account the importance of NO_x (nitrogen oxides) emissions from marine engines and the current increasingly restrictive legislation, this work aims to develop a numerical model to study NO_x reduction. Particularly, a selective non-catalatytic reduction system was designed. A numerical model was developed to analyze several performance parameters. The pressure, velocity, temperature, and NO_x concentration fields were characterized. This numerical model was compared with experimental measurements. The satisfactory results obtained validated the work.

Keywords CFD · SNCR · NO_x · Emissions

1 Introduction

Due to the lean combustion that takes place in diesel engines, these emit low values of carbon monoxide and hydrocarbons. However, their emissions of nitric oxides and particles are considerable [1]. The current environmental situation requires new technologies to control nitrogen oxides, and recently new techniques are being developed. The oxides of nitrogen formed in combustion processes are mainly caused by the reaction of nitrogen present in atmospheric air. For this reason, it is very difficult to avoid their formation. Nitrogen oxides are generated from nitrogen and oxygen at high combustion temperatures. The formation of NO_x increases with the combustion temperature, the residence time of the gas burned at high temperature, and the amount of oxygen present [2, 3].

In the marine field, pollution is controlled by agencies such as the European Protection Agency, European Commission, and the International Maritime Organization, among others. In this regard, the United States Environmental Protection Agency (EPA or USEPA), which belongs to the federal government of

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the United States, was created to regulate the environment and its influence on human health. The European Commission also regulates the environment and developed limitations aimed at pollution from ships. The International Maritime Organization (IMO) focuses on marine pollution and other fields such as safety, technical issues, legislation, and so on. According to this legislation, it is extremely important to reduce NO_x in marine engines.

Many NO_x reduction methods have been proposed in the literature [4]. Basically, these can be classified into primary and secondary methods. The difference is that primary methods reduce NO_x while combustion takes place and secondary methods reduce NO_x at the flue gases. The main goal of primary methods is to reduce the combustion temperature due to its importance in the NO_x formation process.

Regarding secondary methods, two procedures are widely employed in the marine field: SCR and SNCR. SCR (selective catalytic reduction) eliminates NO_x contained in the exhaust gas employing catalytic substances to accelerate the chemical reactions that take place. On the other hand, SNCR (selective noncatalytic reduction) does not employ catalytic substances. The main limitation of SNCR is that the temperature must be high if catalytic substances are not employed. According to this, the present work analyzes measures to get a reasonable NO_x reduction. Particularly, ammonia was chosen to reduce NO_x.

2 Kinetic Model

NO is the main species of NO_x [5]. For this reason, the present work focuses on reducing NO. The first research about NO reduction using ammonia was realized in the 1970s and after that several models were proposed in the literature. The most relevant kinetic models are indicated in Table 1.

The present work compares the models of Miller and Bowman [6], Glarborg et al. [7], and Miler and Glarborg [8].

Despite the discrepancies between these models, the main differences can be explained in terms of the branching ratio of the sequence, α. This parameter is defined by the expression:

Table 1 Kinetic models for NO reduction using ammonia

Authors	Number of reactions	Number of species
Miller and Bowman [6]	73	19
Glargorg et al. [7]	104	22
Miller and Glarborg [8]	134	24
Brouwer et al. [9]	2	2
Duo et al. [10]	2	2