ISSN: 2754-4982

Journal of Civil Engineering Research & Technology

SCIENTIFIC Research and Community

Review Article

Open Access

On the Fatigue of Ship-Structures under Wave Loads

P Corigliano and F Frisone*

Department of Engineering, University of Messina, Messina, Italy

ABSTRACT

Background: Fatigue damage is one of the main failure modes in ship structures. This type of damage usually starts from weak point of the structure as welded joints, sites of stress concentrations and cracks, whose propagation can lead to the failure of the ship structures. Cyclic loadings that ships encounter during their service life are one of the main causes that can produce fatigue damage, especially loads due to wave, mainly analyzed in this work. Once the crack is started, also lower stress cycles, which would have negligible effects on intact components, can propagate the crack.

Objective: This paper wants to resume the most used fatigue strength assessment approaches, in order to analyze drawbacks and advantages and to provide the necessary background knowledge for the development of a future and reliable theoretical/numerical models for predicting the fatigue life of ship structures subjected to collision events and different sea states.

Methods: This scientific work will thus consider the main theoretical approaches in time and frequency domain by using energy spectral methods. Collision rules are also assessed to check the hull girder ultimate bending capacity in the damaged state.

Results: Cyclic stresses determination in specific structural details of the hull girder and welded joints is discussed, in order to evaluate the relevant maximum stress range useful for the subsequent fatigue studies, performed by finite element analysis. In a collision scenario, also in minor damages, fatigue cracks may appear and propagate, reducing structural strength and structures fatigue life.

Conclusion: Structural loads determination can be categorized in different methods, but the frequency-domain method is the most extensively used methods in fatigue analysis procedure, because it requires significantly less computational efforts than the time-domain method. Once determined the stress distribution, in most cases fatigue damage is calculated using the Palmgren–Miner cumulative damage rule in combination with the S–N curves of materials, structural details and welded joints. In a scenario where a damaged ship encounters large wave amplitudes, the damage accumulation could lead to low-cycle fatigue.

***Corresponding author**

F Frisone, Department of Engineering, University of Messina, Messina, Italy.

Received: April 23, 2024; **Accepted:** April 25, 2024; **Published:** May 06, 2024

Keywords: Ship Structures, Fatigue Assessment, Wave Cyclic Loads, Spectral Methods, Welded Joints

Introduction

During their service life, ships and offshore structures are constantly subjected to cyclic loads. These cyclic loads can propagate fatigue cracks existing in the hull structure components, leading to fatigue failure after some years of service and damaging the integrity of the structures. Once the crack is started, also lower stress cycles, which would have negligible effects on intact components, can propagate the crack and produce fracture. The most sensitive spots of these structures, where crack can initiate and propagate, are welded joints, widely used in shipbuilding industry [1]. The aim of this work is to present the most used approaches to define the resultant loads distribution and the structural response prediction caused by different sea states encountered by the ships, in order to evaluate the fatigue behaviour of ship structures, with particular regard to welded joints, the most critical areas regarding fatigue damage, due to the presence of possible crack-like defects. The state-of-the-art of the topics addressed in this work will be used to lay the foundation for the development of a future theoretical/numerical model for predicting fatigue life of ship structures by finite element fatigue analysis.

The second paragraph introduces the different cyclic loads, with a focus on wave-induced loads, the main cause of fatigue failures for ship structures. This paragraph will treat the concepts of wave system spectral energy, wave modelling in frequency and time domain and calculation of wave induced loads. The third paragraph presents theoretical fatigue strength assessment methods to estimate loads distribution and to predict fatigue life of structural components and welded joints. The fourth paragraph presents material properties that affect fatigue behaviour of ship structures, with particular attention to welded joints features.

Finally, the fifth paragraph reviews the issue of collision damage in extreme sea states, introducing concepts as leak structural integrity and environmental pollution.

Cyclic Loads

Cyclic loads are the main cause that can produce fatigue damage on ship structures. The residual structural capacity after several continuous cyclical loads can be significantly lower than the instantaneous collapse strength under a single load excursion, due to the accumulation of plastic deformation that permanently degraded the structural resistance. Cyclic loads are, consequently, the crucial input factor for any fatigue analysis. For ship structures, the cyclic loads can be divided into three categories according to their frequency or period:

– Hydrodynamic loads, induced by propulsion equipment on the hull:
Higher-frequency loads caused by engines and propellers, result in forced vibrations with high number of load cycles, typically 10^{10} or more;
– Loads due to varying loading conditions, loading and unloading of the cargo:
Low frequency loads with very long periods, resulting in hundreds to thousands of load cycles during the operational lifetime;
– Cyclic waves load:
Low frequency loads, usually in the order of 0.1 Hz. For an operational lifetime of 25 years, the total number can be between 10^7 and 10^8 load cycles [2-4].

Wave-Induced Cyclic Loads

It has been shown that the main cause of fatigue failures can be attributed to wave-induced loads [2]. Motion of waves induces variable and complex loadings in the structure. Low/medium frequency stresses caused by oscillating wave loads and wave impacts (slamming) are critical for fatigue life of structural components. The fatigue life of ship structures is closely related to waves characteristics, such as wave height, period, and steepness. As shown in several numerical and experimental studies, these factors affect the frequency and amplitude of cyclic loads, leading to varying levels of fatigue damage [5,6].

The random nature of wave-induced fatigue loads makes it difficult to be numerically estimated and described. The sea surface is irregular and changes constantly, therefore, the application of statistical methods is necessary to quantify the characteristics of waves and define wave loads to which ships are subjected. The structural response predictions of ship structures strictly depend on the wave energy [4]. Waves energy can be directly measured by instruments like wave buoys and radars, and post-processed to obtain the wave spectrum at the desired location. In situations where measurements of the actual wave conditions are not available, standardized wave spectra derived from experimental data are used to approximate the sea state using statistical parameters like the significant wave height and peak wave period, predicted by numerical models, weather forecasts or hindcasts [7]. By means of Fourier analysis, the irregular waves are decomposed into a series of harmonic regular waves components, whose frequency, time and amplitude define the wave energy density spectrum of the system [8]. The wave spectrum can then be modelled as one of different idealized wave spectra derived from experimental studies, used to describe different characteristics that tend to be closer to the real sea conditions.

Frequency-Domain Spectra

Frequency-domain spectra describe the energy of a short-term sea state and represent the energy density of each harmonic regular component of the system as function of frequency. The energy spectral density of a sea state is the crucial source of information for any frequency domain calculation method to define loading history [1]. The total area subtended by the spectrum is proportional to the total energy per surface unit of the irregular wave system. The energy spectrum can be obtained empirically from a recording of irregular waves, but in ship design it is preferable to use theoretical spectra defined by theoretical formulas, valid for different sea states.

Of all theoretical spectra, the most widely used spectrum for engineering purposes is the Bretschneider spectrum (Figure 1). It's the most applied spectrum in the wave analysis because it has the advantage to be valid for both fully developed sea and developing or endangered sea, for this reason is recommended for open-ocean wave conditions and usually employed to describe tropical storm waves, for example, in the Gulf of Mexico or typhoons in the South China Sea. This spectrum is mathematically expressed by the following equation (1) [8].

$$S_\zeta^B(\omega) = \frac{A}{\omega^5} e^{-\frac{B}{\omega^4}} \tag{1}$$

Where A and B are two defining parameters, functions of the characteristics of the wave system, dependent on significant wave height $H\ 1/3$ and zero-cross period Tz and wind speed, measured at a standard height of 19.5 m above sea level.

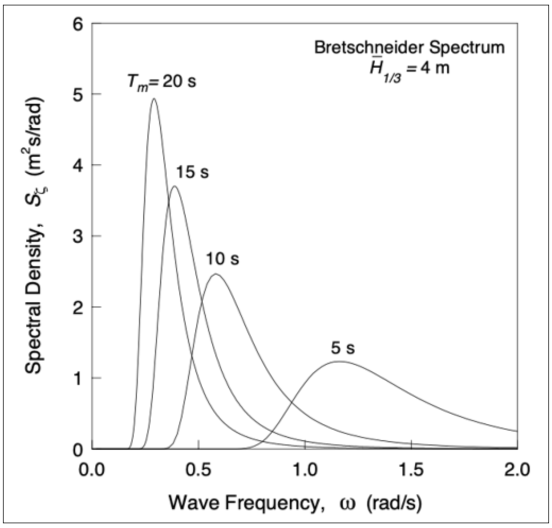

Figure 1: Bretschneider Spectrum for Different Values of the Peak Period [8].

There are two other important types of wave spectrum in frequency domain, even if they are less frequently used for engineering purposes because of their futures and restrictions:
The Pierson-Moskowitz spectrum is a two-parameter spectrum used in simulation of random sea surface and valid just for fully developed sea, result of long-term action of a constant wind, a rather rare condition to achieve spectral stability (Figure 2) [9]. It follows that it is not very suitable for design purposes. Note that the Pierson-Moskowitz spectrum can be obtained as a particular case of the Bretschneider spectrum, mathematically expressed by the following equation (2):

$$S_\zeta(\omega) = \frac{\alpha g^2}{\omega^5} e^{-\beta(g/V_W\omega)^4} \tag{2}$$

Where the VW is wind speed, measured at a standard height of 19.5 m above sea level, α and β are two parameters dependent on significant wave height $H\ 1/3$ and zero-cross period Tz.

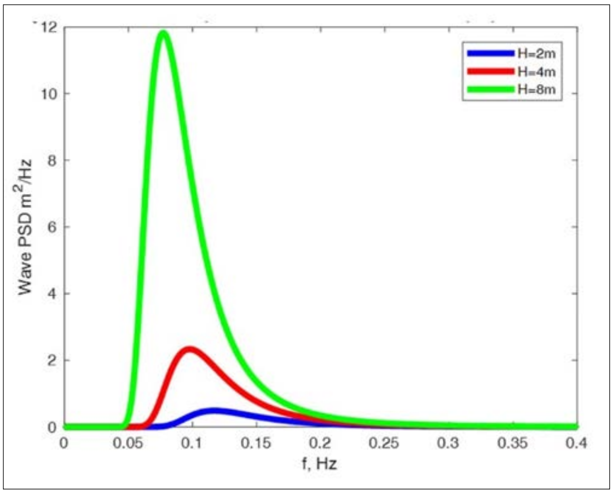

Figure 2: Pierson-Moskowitz Spectrum for Three Wave Heights [1].

The JONSWAP spectrum is also a Bretschneider spectrum integration, used to reproduce the highest peaks and frequency shifts that occur in a limited-fetch storm, that Bretschneider and Pierson-Moskowitz spectra can not to represent, for the same energy (Figure 3). For this reason, JONSWAP spectrum is able to take into account a storm situation under development much more accurately than the Bretschneider spectrum [10]. It's mathematically expressed by the following equation (3):

$$S_\zeta^J(\omega) = 0.658 S_\zeta^B(\omega)\gamma^{\exp[-(\omega-\omega_m)^2/2\sigma^2\omega_m^2]} \qquad (3)$$

Where $S_\zeta^B(\omega)$ is the spectral density of Bretschneider spectrum,

ω_m is the frequency of the corresponding maximum, γ is the overshoot parameter that expresses the ratio between the maxima of the JONSWAP spectrum and the Bretschneider spectrum.

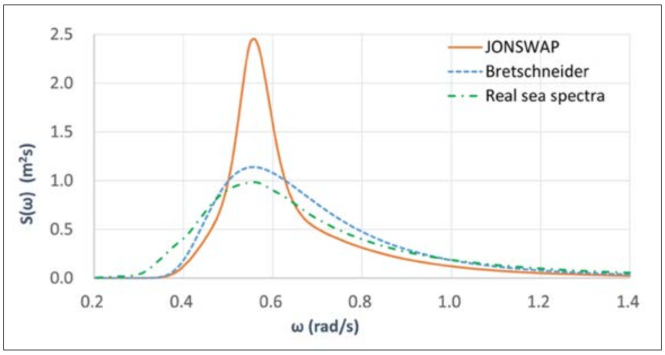

Figure 3: JONSWAP and Bretschneider Spectra Comparison [10].

Despite their application restrictions, Pierson-Moskowitz and JONSWAP spectra still play a great oceanographic importance because they represent in a very detailed manner the characterized sea states and its application validity can also be extended to include cases other than those initially envisaged.

How is it possible to note, spectra mathematical equations are quite simple and all of them depend on two specific wave characteristics: significant wave height *H* 1⁄3 and zero-crossing period Tz. These waves features have been catalogued over time in the wave atlas "Global Wave Statistics" (Figure 4), based on more than 55 million observations from 1854 to 1984. It covers the entire planet using a global grid of 104 sea areas, showing the probability of occurrence of height and period. Thanks to this atlas, every sea region in the world can be described with a very good approximation by one of the theoretical spectra mentioned above [11].

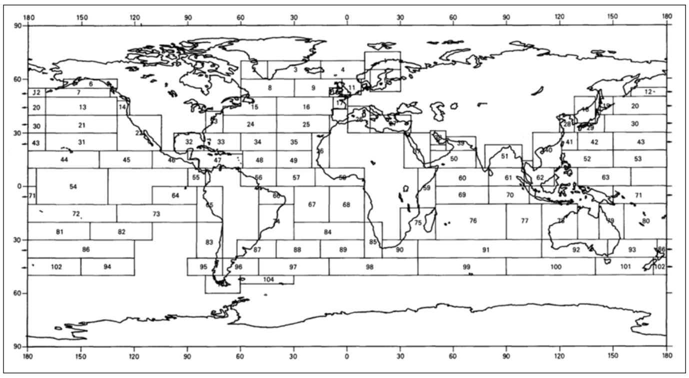

Figure 4: "Global Wave Statistics" Sea Areas [11].

Fatigue Strength Assessment Approaches

The fatigue strength of ship structures is an highly uncertain and complex phenomenon. The random nature of wave-induced fatigue loads makes it difficult to be numerically estimated and described. identified the sources of uncertainty in the spectral description of wave elevation in a stationary short-term sea state [4]. Theoretical models were formulated to quantify the uncertainty of stress response variance due to different waves charateristics and spectrum shape. Therefore, an accurate description of these loads is an essential prerequisite for performing fatigue damage and crack growth analyses. Loads determination can be categorized in two main methods: simplified-deterministic method and direct calculation method. All these methods include four main steps: determination of fatigue loads, calculation of the long-term distribution of stress range, determination of the fatigue capacity of structure, assessment of the fatigue damage.

Simplified-Deterministic Method

Simplified procedures for fatigue assessment differ among classification societies. They apply the two-parameter Weibull probability distribution to describe the long-term stress range distribution of ship structural components. This type of fatigue assessment procedure is also defined 'deterministic' due to analysis of a large number of specified (deterministic) load cases. Deterministic method is some sort of a simplified version of spectral-based method, using deterministic wave height and period to characterize a seastate rather than using short-term wave spectrum. presented a comparison of simplified procedures for fatigue assessment of ship structural details, used by classification societies [12]. Fatigue damage is calculated for longitudinals and transverse structural connetions in the hopper tank, topside tank and double bottom of the bulk carrier. The study shows that fatigue life of the structural component is highly sensitive to small changes of shape parameter of stress Weibull distribution. On the basis of the above observations, these two simplified methods are used for local details, and suit for urgent cases.

Direct Calculation Method

Direct calculation method is the most extensively used approach in fatigue analysis procedure. It's divided into time domain (TD) method and frequency domain (FD) method.

The time-domain method can consider nonlinearities like slamming and whipping effect and can obtain the fatigue stress time history of structure under real seastates by simulating a series of seastates and using hydrodynamic calculations. The frequency-domain method it's a statistical fatigue analysis technique based on the dynamic loading approach, known as spectral fatigue analysis. Fatigue damage is predicted based on an irregular sea state and estimated by applying a statistical function to the stress distribution on a structural component using a stress range that follows a narrow band-based Rayleigh distribution, calculated by assuming a rigid-body ship. The advantage of using the frequency-domain method is that it requires significantly less computational efforts than the time-domain method. On the other hand, in a long-term fatigue assessment, the time-domain method could be preferable because the pressure loads are more realistically computed [13]. In fact, different from FD analysis, in TD analysis wave loads are directly calculated in hydrodynamic calculations. These loads are then transferred into FE analysis to obtain the stress time histories for each hotspot. also proposed a hybrid frequency-time domain method, that combines FD and TD analysis [14]. This method avoids the imprecise narrow-band approximation in spectral-based method and adopts rainflow counting instead. Results shows that the hybrid method provide a fatigue damage prediction very close to time domain analysis, except in some midship areas where the hybrid method understimate the fatigue life of strucural components. Thus, the hybrid method is not applied extensively on ship fatigue assessment because relevant research is insufficient.

Frequency-Domain Analysis

For conventional ship fatigue design, the direct calculation method is often used to obtain the wave loads for different loading and operating conditions. Most often, the response is calculated by linear analysis in the frequency domain [15]. In the frequency-domain spectral-based method, three main assumptions are considered:

- Linear wave theory: the irregular wave can be considered as a superposition of a series of component regular waves, and its energy can be characterized by short-term wave spectrum;
- A linear relationship occurred between waves and ship structural response. This assumption introduces transfer functions to describe the dynamic properties of the ship structure;
- Narrow band approximation: stress range within each short-term sea state is considered as Rayleigh distribution and cycle count is according to zero up-crossing period of short-term structural stress responses. While in the hybrid method, this assumption is avoided [14].

Based on the first linear wave theory, an irregular wave time history A(t) can be considered as a superposition of a series of regular waves using Fourier analysis (4). The stationary sea state is then described by one of the wave spectra previously analyzed.

$$A(t) = \sum_{i=1}^{N} A_i \cos\left(k_i x - \omega_i t + \varepsilon_i\right) \qquad (4)$$

Another important assumption in frequency domain is the linear relationship between waves and ship structural response. Ship motions and wave loads can be computed by a linear hydrodynamic analysis through strip theory, followed by structural analysis. The structural response under irregular waves can be considered as a superposition of structural responses under regular wave components. This approximation is introduced by the transfer function of structural stress, as the ratio between structural response (output) and wave load (input).

The modulus of the transfer function, the Response Amplitude Operators (RAO), is thus the scale factor between the wave spectrum S (ω) and the stress power spectral density (PSD), as indicated in the following equation (5):

$$S_\sigma(\omega|H_s,T_z,\theta) = |RAO(\omega|\theta)|^2 \cdot S(\omega|H_s,T_z) \quad (5)$$

For any arbitrary sea state characterized by the significant wave height Hs, wave period Tz, and wave spectrum S(ω), the short term stress response in frequency-domain (stress power spectral density) can be determined by the combination of the wave spectrum and the transfer function RAOs [14,15]. Transfer function calculation of wave spectra has always been complicated. developed a mathematical modeling with wich is possible to define the spectra transfer function and, consequently, wave power spectrum, rapidly and efficiently [9]. Also presented a simple and practical method which can be used to tune and improve the transfer function prediction capability [16].

Figure 5 represents schematically every step of the frequency-domain analysis procedure just described.

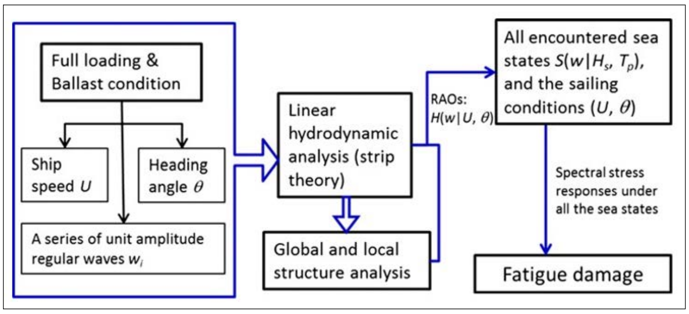

Figure 5: Spectral Calculation Procedure for Ship Fatigue Assessment [15].

Fatigue Damage Analysis

Once determined the stress distribution through the above-mentioned methods, fatigue assessment of ship structures is typically carried out using the following approaches:

- S–N approach, using appropriate Woehler S–N curves directly in the case of constant amplitude loading or in conjunction with Palmer-Miner damage accumulation hypothesis in the case of variable amplitude loading;
- Crack propagation approach, normally using the Paris–Erdogan law for the crack propagation phase up to a specified failure criterion [2].

The SN curve method with the Palmgren-Miner linear summation rule is the most popular approach for computing fatigue damage [17]. The S-N curves are derived from fatigue tests conducted on specimen of the studied material by generally applying a cyclic stress with constant amplitude. Basic elements of the S–N approach are illustrated in figure 6.

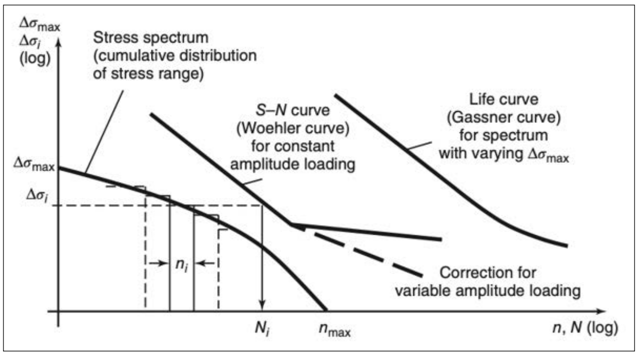

Figure 6: S-N Approach Curves [2].

Many S-N curve approaches exist. The main difference among the various approaches is the S parameter being used: nominal stress, hot spot stress or notch stress. The nominal stresses are generally calculated using the beam theory or Finite Element Analysis and include macro-geometric effects, concentrated load effects and misalignment effects. There are many cases where the nominal stress cannot be clearly defined due to the complex geometric effect. This disadvantage can be solved by using hot-spot stress, the local stress at the critical point in structural detail where a fatigue crack may be initiated. But also in this case the effects from the presence of welds are excluded. Stress concentrations due to the presence of welds are assessed just using notch stress approach, defined as the locally increased stress (peak stress) in a notch, at a weld toe or at the edge of a cut-out [12]. Figure 7 represents the trend on a weld toe of the three different stress approaches.

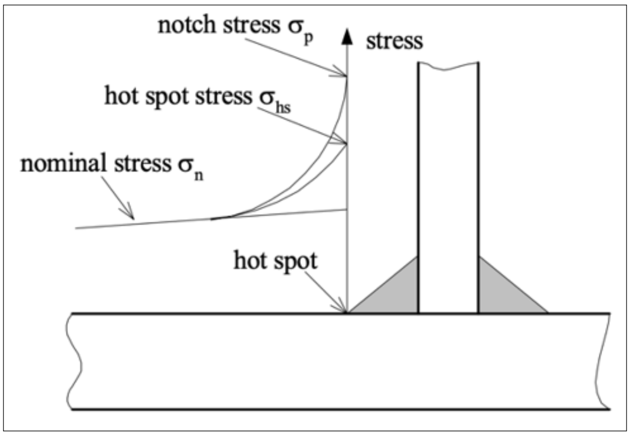

Figure 7: Different Types of Stresses on A Welded Toe [12].

A very interesting case-study was carried out by concerning the application of the direct calculation method using a frequency and time domain fatigue analysis procedure of a 4400 TEU container vessel in a harsh sea state [18]. The scope of the study is to determine the fatigue-critical locations in the ship adopting linear and nonlinear finite element analysis. The hydrodynamic simulation was carried out in frequency and time domain. In the frequency domain analysis, wave loads are described by a Pierson–Moskowitz spectrum. The results are used in a linear FE analysis, followed by a full-ship fatigue analysis. The results from the time domain analyses are used in a linear elastic FE analysis and in the non-linear FE analysis, to study the local sub-model details. The full-ship fatigue analysis in frequency domain shows that the fatigue critical locations are the midship hatch corners, the engine room bulkhead and in the bilge region (Figure 8). The non-linear analysis proves that there are only a few elements around the cut-out where plastic strains are accumulated, so structural detail should not be considered as a critical region requiring strain-based fatigue evaluation.

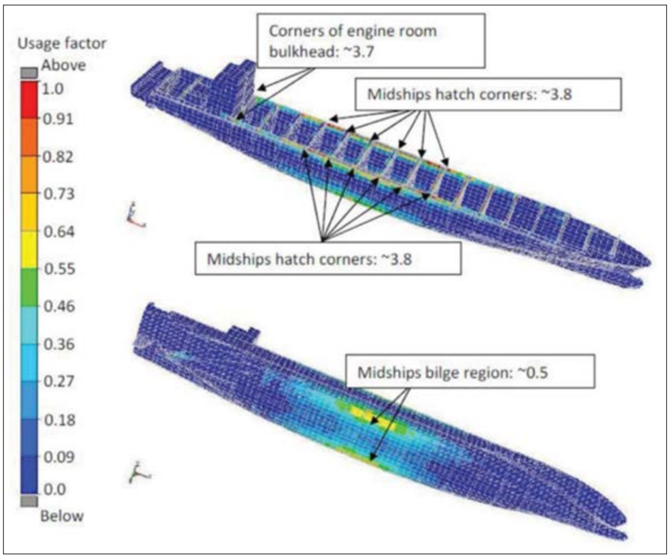

Figure 8: Fatigue Critical Location for Full-Ship Fatigue Analysis [18].

Fatigue assessment of ship side-shell structures was also studied in detail by by nonlinear time-domain hydrodynamic simulations followed by linear FE analyses, considering as case-study a Panamax container vessel sailing on the North Atlantic [13].

The results from the spectral method and time-domain procedure were also compared. Spectral method shows a fatigue life of 7.1 years, however time-domain method presents a fatigue life of 6.7 years. Thus, time-domain procedure is considered more realistic than the commonly used spectral method in frequency-domain.

Another recent study conducted by has examined in detail the fatigue life of ship structure, presenting a numerical procedure based on the finite element (FE) method using ANSYS software [19]. The purpose of this study is to determine the effects of geometric shapes and material types on the fatigue behaviour of ship structural components, using nominal stress and hot spot stress approach.

Carried out comparative study on the different fatigue strength assessment procedures according to the rules of 8 classification societies (ABS, RINA, DNV, GL, KR, LR, NK, RS). The study was contucted on a welded detail of the longitudinal hatch coaming of a Panamax container vessel [20]. The results have shown that the different procedures provide large discrepancy in terms of fatigue life of the structural component, ranging from 1,8 to 20,7 years.

Welded Joints

As indicated in the previous chapter, cyclic wave motion induces variable and complex loadings in the structures, which could generate fatigue damage. Welded joints are the main joining technique in marine industry and generally the weakest point of the structure, due to the presence of possible crack-like defects. Material properties of the areas where fatigue cracks are initiated and propagated are one of the most important influencing factors. Nowadays, ship structures are generally built in high tensile strength steel. This type of material improves the static strength of the structures, but cannot improve the fatigue strength, especially in welded joints of plates and girder. Welded connections are generally preferred to rivetted, bolted or adhesive connections in steel structures, due to their characteristics of low cost, aesthetics and geometrical flexibility [21]. However, the complex nature of the welding process - usually associated with induced defects, residual stresses and microstructural distortion - implies that the fatigue resistance at the welded connection areas is always inferior in comparison to the other types of joints [22]. For this reason, they represent a key point of major interest in the study of fatigue failure mode of ship structures.

Time-domain or frequency-domain fatigue analysis approaches may be employed to asses the fatigue damage of welded structures exposed to random loadings. As indicated in the previous paragraphs, the frequency-domain approach requires knowing the total stress distribution around the weld toe, evaluated by traditional methods as nominal stress, hot-spot stress and notch stress. As presented in Kalu and Liang review, an alternative weld stress evaluation method exists, called the Equilibrium Equivalent Struc- tural Stress (EESS), proposed by [23, 24]. This method decomposes weld toe stress distribution into 3 stress components: balanced primary membrane stress σm, bending stress σb, and self-equilibrating nonlinear stress σnl.

The welding processes modifies the material and mechanical properties in that specific area and introduce a residual stress field, due to microstructural factors, with the local mechanical properties depending on the base material (BM), the heat-affected zone (HAZ), and the welded zone (WZ) [25,26]. Consequently, welded joints become critical areas regarding fatigue damage, due to the presence of possible crack-like defects [27].

Fatigue crack creation and propagation in welded joints are strongly influenced by different factors: welding geometry, material, residual stress, environment, welding method, filler material and post-weld heat treatment [28].

It has been shown that fatigue crack creation and propagation are strongly influenced by geometrical weld parameters and weld imperfections, such as misalignment, weld radius, flank angle, weld thick. The quality of the weld is crucial. Poorly executed welds can introduce stress concentrations and reduce fatigue life.

The material of the areas from which the crack begin to spread is also an important influencing factor. The fatigue crack initiation life is strongly relative to that material properties. Residual stresses, induced by the fabrication process, also have a significant impact on the fatigue life of welded joints. The welding-induced residual stresses can increase the stress of the local stress-strain cycles, reducing the fatigue strength. However, some post-weld treatment processes can introduce favourable weld geometry that decrease residual stresses and improve fatigue strength [29].

Conclusion

As discussed, the main cause of fatigue failures can be attributed to wave-induced loads. The fatigue life of ship structures is closely related to waves characteristics, such as wave height, period, and steepness. To describe waves characteristics and define wave loads to which ships are subjected, the application of statistical methods is necessary. By means of Fourier analysis, the irregular waves are decomposed into a series of harmonic regular waves components. The energy density of each harmonic regular component of the system is represented by an energy density spectrum, in time and frequency domain. In ship design it is always preferable to use idealized wave spectra defined by theoretical formulas. As evidenced, the most widely used spectrum for engineering purposes is the Bretschneider spectrum, because it has the advantage to be valid for both fully developed sea and developing or endangered sea, in frequency domain. Despite their application restrictions, Pierson-Moskowitz and JONSWAP spectra still play a great oceanographic importance because its application validity can also be extended to include cases other than those initially envisaged. Thanks to these theoretical spectra, every sea region in the world can be described with a very good approximation.

Once defined the energy spectrum of a wave systems, it's possible to describe the relationship between waves energy and wave-induced ship responses, in terms of ship motion and loads distribution. Structural loads determination can be categorized in different methods, but the frequency-domain method is the most extensively used methods in fatigue analysis procedure. It's a statistical fatigue analysis technique based on the dynamic loading approach, known as spectral fatigue analysis, using the strip theory approximations.

Finally, once determined the stress distribution, in most cases fatigue damage is calculated using the Palmgren–Miner cumulative damage rule in combination with the S–N curves for the material, structural details and welded joints.

The fatigue analysis procedure just described will be the background knowledge for the development of a future theoretical/numerical models for predicting the fatigue life of ship structures subjected to different sea states.

Acknowledgements

This study has been supported by the project PRIN_2022TXST8X_002 "EMPATHY2, CUP J53D23002430001, and by the Research Project PRIN_2022PNRR_P2022Y3PBY_001 "MADELEINE", CUP J53D23001980006. Projects funded under the National Recovery and Resilience Plan (NRRP), Mission 4 Component C2 Investment 1.1 by the European Union – NextGenerationEU.

References

1. M Böhm, M Kowalski (2020) Fatigue Life Estimation of Explosive Cladded Transition Joints with the Use of the Spectral Method for the Case of a Random Sea State. Marine Structures 71: 1-14.
2. W Fricke (2017) Fatigue and Fracture of Ship Structures. In Encyclopedia of Maritime and Offshore Engineering DOI: 10.1002/9781118476406.emoe007.
3. A E Ræstad, T Gjestland (2017) Propeller- and Thruster-Induced Noise and Vibration. In Encyclopedia of Maritime and Offshore Engineering DOI: https://doi.org/10.1002/9781118476406.emoe057.
4. Y Dong, Y Garbatov, C Guedes Soares (2022) Review on Uncertainties in Fatigue Loads and Fatigue Life of Ships and Offshore Structures. Ocean Engineering. Elsevier 264: 112514.
5. I Drummen, G Storhaug, T Moan (2008) Experimental and Numerical Investigation of Fatigue Damage Due to Wave-Induced Vibrations in A Containership in Head Seas. J Mar Sci Technol 13: 428-445.
6. W L Johnson A (2020) Influence of Wave Characteristics on the Fatigue Life of Ship Structures. Ocean Engineering.
7. J Ringwood, G Bacelli, F Fusco, J V Ringwood (2014) Control, Forecasting and Optimisation for Wave Energy Conversion. IFAC Proceedings Volumes 47: 7678-7689.

8. R Nabergoj (2007) Fundamentals of Seaworthiness of Ships https://www.researchgate.net/profile/Radoslav-Nabergoj/publication/265004239_Fondamenti_di_Tenuta_della_Nave_al_Mare/links/55938e9c08ae5af2b0eb88ef/Fondamenti-di-Tenuta-della-Nave-al-Mare.pdf.
9. W Yang, Y Liang, J Leng, M Li (2020) The Autocorrelation Function Obtained from the Pierson-Moskowitz Spectrum. Global Oceans 2020: Singapore - U.S. Gulf Coast, Institute of Electrical and Electronics Engineers Inc https://ieeexplore.ieee.org/document/9389043?signout=success.
10. J Prendergast, M Li, W Sheng (2020) A Study on the Effects of Wave Spectra on Wave Energy Conversions. IEEE Journal of Oceanic Engineering 45: 271-283.
11. N Hogben (1988) Experience from Compilation of Global Wave Statistics. Ocean Engineering 15: 1-31.
12. B Blagojević, Ž Domazet (2002) Simplified Procedures for Fatigue Assesement of Ship Structures Simplified Procedures for Fatigue Assesement of Ship Structures http://bib.irb.hr/datoteka/90277.55.pdf.
13. Z Li, J W Ringsberg, G Storhaug (2013) Time-Domain Fatigue Assessment of Ship Side-Shell Structures. Int J Fatigue 55: 276-290.
14. J Yue, K Yang, L Peng, Y Guo (2021) A Frequency-Time Domain Method for Ship Fatigue Damage Assessment. Ocean Engineering 220.
15. W Mao (2014) Development of A Spectral Method and A Statistical Wave Model for Crack Propagation Prediction in Ship Structures. Journal of Ship Research 58: 106-116.
16. U D Nielsen, R E G Mounet, A H Brodtkorb (2021) Tuning of Transfer Functions for Analysis of Wave–Ship Interactions. Marine Structures 79.
17. K Doshi, S Vhanmane (2013) Probabilistic Fracture Mechanics-Based Fatigue Evaluation of Ship Structural Details. Ocean Engineering 61: 26-38.
18. J W Ringsberg, Z Li, A Tesanovic, C Knifsund (2015) Linear and Nonlinear Fe Analyses of a Container Vessel in Harsh Sea State. Ships and Offshore Structures 10: 20-30.
19. A Fajri, A R Prabowo, N Muhayat (2022) Assessment of Ship Structure Under Fatigue Loading: Fe Benchmarking and Extended Performance Analysis. Curved and Layered Structures 9: 163-186.
20. W Fricke, W Cui, H Kierkegaard, D Kihl, M Koval, et al. (2002) Comparative Fatigue Strength Assessment of a Structural Detail in A Containership Using Various Approaches of Classification Societies. Marine Structures 15: 1-13.
21. P Corigliano, M Ragni, D Castagnetti, V Crupi, E Dragoni, et al. (2021) Measuring the Static Shear Strength of Anaerobic Adhesives in Finite Thickness under High Pressure. Journal of Adhesion 97: 783-800.
22. Z Barsoum (2020) Guidelines for Fatigue and Static Analysis of Welded and Un-Welded Steel Structures https://kth.diva-portal.org/smash/get/diva2:1512235/FULLTEXT01.pdf.
23. U Kalu, X Liang (2023) An Equivalent Structural Stress-Based Frequency-Domain Fatigue Assessment Approach for Welded Structures under Random Loading. Materials 16.
24. H Kyuba, P Dong (2005) Equilibrium-Equivalent Structural Stress Approach to Fatigue Analysis of a Rectangular Hollow Section Joint. Int J Fatigue 27: 85-94.
25. Erny, David Thevenet, Jean-Yves Cognard, Manuel Körner (2012) Fatigue Life Prediction of Welded Ship Details. Marine Structures 25: 13-32.
26. P Corigliano (2022) On the Compression Instability during Static and Low-Cycle Fatigue Loadings of AA 5083 Welded Joints: Full-Field and Numerical Analyses. J Mar Sci Eng 10.
27. P Corigliano, V Crupi (2022) Review of Fatigue Assessment Approaches for Welded Marine Joints and Structures. Metals, MDPI 12.
28. P Corigliano, F Cucinotta, E Guglielmino, G Risitano, D Santonocito (2019) Thermographic Analysis during Tensile Tests and Fatigue Assessment of S355 Steel. In Procedia Structural Integrity, Elsevier BV 18: 280-286.
29. Y Dong, Y Garbatov, C G Soares (2022) Recent Developments in Fatigue Assessment of Ships and Offshore Structures. Journal of Marine Science and Application Editorial Board of Journal of Harbin Engineering 21: 3-25.