

Influence of Wave Environment on Vessel Response and Fatigue Life Assessment

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INTRODUCTION & AIM

Marine navigation is strongly influenced by oceanographic conditions such as waves, currents, and rapidly varying sea states, which affect both vessel motions and structural loads. Wave-induced actions represent the main source of cyclic loading on ships and are therefore the primary driver of fatigue damage. Among these loads, the vertical bending moment plays a critical role in the structural integrity of large vessels, with several studies reporting the onset of severe cracks within the first years of service. This emphasizes the need for accurate prediction methods capable of capturing the complexity of ship–wave interactions, beyond simplified empirical formulations traditionally used in design. The characterization of realistic sea states through spectral descriptions, such as the JONSWAP model, enables the evaluation of wave energy distribution and the computation of ship responses in irregular seas. Modern hydrodynamic tools based on linear potential flow theory and boundary element methods provide detailed estimates of ship motions, pressures, and internal loads. In this study, the vertical bending moments were evaluated through panel-based hydrodynamic simulations in both the frequency and time domains, considering waves coming from 180°. Response Amplitude Operators (RAOs) were derived for regular waves, while structural loads in irregular seas were obtained using a JONSWAP spectrum. These loads were compared with classification society limits and used to estimate nominal stresses and fatigue life in midship section, including damage accumulation during severe North Atlantic conditions. The overarching aim is to enhance understanding of ship behaviour in complex wave environments and to establish a foundation for advanced structural analyses and real-time health monitoring, ultimately supporting safer and more efficient vessel operation.

METHOD

Fatigue in ship structures arises mainly from cyclic wave-induced loads acting on the hull. Accurately estimating these global loads is essential to preserve the vessel's structural integrity and to assess fatigue life. Three main approaches can be used for fatigue assessment: Simplified, Spectral-based, and Deterministic methods [1]. In this study, a spectral approach was adopted for its computational efficiency and its ability to treat fatigue as a linear process between wave loads, ship response, and damage accumulation. The vessel is modeled as a linear system where the wave spectrum represents the input and the stress response spectrum the output, linked by the Response Amplitude Operator (RAO) according to:

$$S_{\sigma}(\omega) = RAO^2 \cdot S(\omega) \tag{1}$$

where $S(\omega)$ is JONSWAP spectrum and the relative formula is:

$$S(\omega) = \alpha g^2 \omega^{-5} \exp \left[-\frac{5}{4} \left(\frac{\omega_p}{\omega} \right)^4 \right] \gamma \exp \left[-\frac{(\omega - \omega_p)^2}{2\alpha^2 \omega_p^2} \right] \tag{2}$$

Nominal stresses were derived from the vertical bending moment using Navier's formula while fatigue damage was computed using the Palmgren–Miner cumulative damage rule combined with S–N curves for the selected structural details. The design life was assumed to be 25 years. The comparison of the vertical bending moments obtained from the software simulation with those prescribed by classification societies was carried out using the formulas provided by the DNV rules [2]:

$$M_{WH} = 0.19 C_W L^2 B C_B \tag{3}$$

The study was carried out on a container ship whose principal dimensions are reported in Table 1. The hydrodynamic analysis was performed starting from the CAD model (Figure 1a), which was simplified to obtain a uniform surface and subsequently meshed with quadrilateral elements, as shown in Figure 1b. In the simulation, only the wetted surface of the hull was considered, since this is the primary region affected by hydrodynamic interactions.

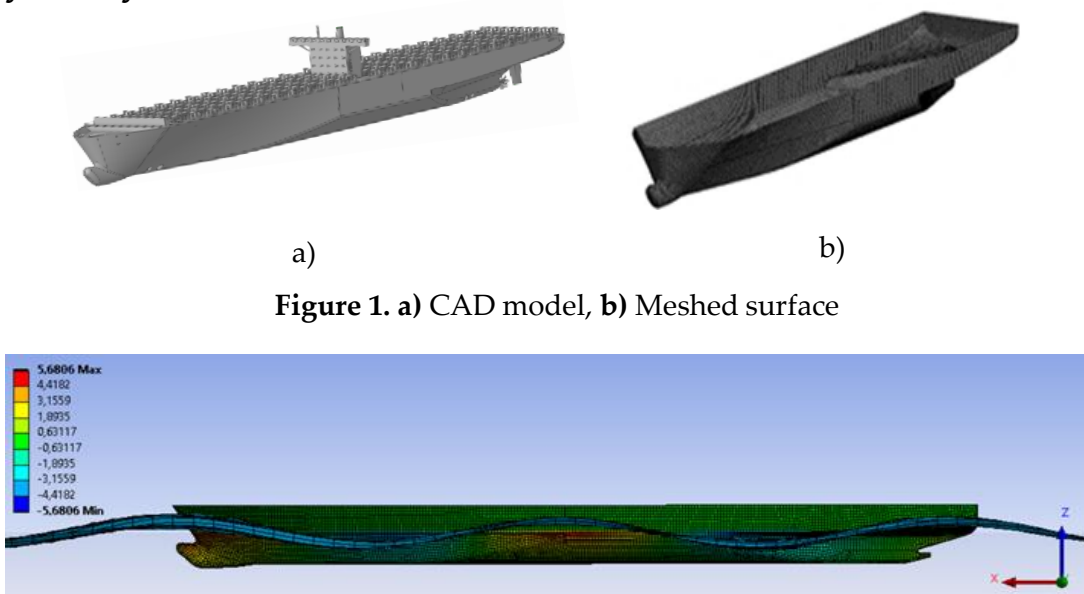


Table 1. Main dimensions container ship.

Dimension	Values	Units
Length overall	254	m
Length between Perpendicular	240	m
Beam	32.2	m
Draught	12.4	m
Depth	19	m
l_{W1}	231	m ⁴
l_{W2}	661	m ⁴
Z_{NA} Neutral axis	8.93	m

The fatigue damage was calculated using the Palmgren–Miner cumulative damage rule in combination with the S–N curves for the material and structural details of interest:

$$D = \sum_{i=1}^n \frac{n_i}{N_i} \tag{4}$$

RESULTS & DISCUSSION

The study began by analyzing regular waves. From the frequency range analyzed in the ANSYS AQWA simulations and considering the most critical wave direction (180°), the results show that the wave frequencies of 0.06432 Hz, 0.11272 Hz, and 0.16112 Hz correspond to significant wave periods of approximately $T_z = 15.5$ s, 8.9 s, and 6.2 s, respectively. Figure 2 shows the pressure distribution along the ship at the critical frequency of 0.06432 Hz. These frequencies represent, as shown in Figure 3a, the critical conditions at which the highest vertical bending moment values are obtained. Notably, they fall within the range of the most commonly observed sea states in the North Atlantic and provided by Campana [3]. To gain a comprehensive overview of the ship's response, a comparison with the classification society's criteria for vertical bending moments in head seas is also carried out. The analysis results are shown in the Figure 3b, and it can be observed that the standardized bending moment limit is not exceeded for wave amplitudes up to 6 meters.

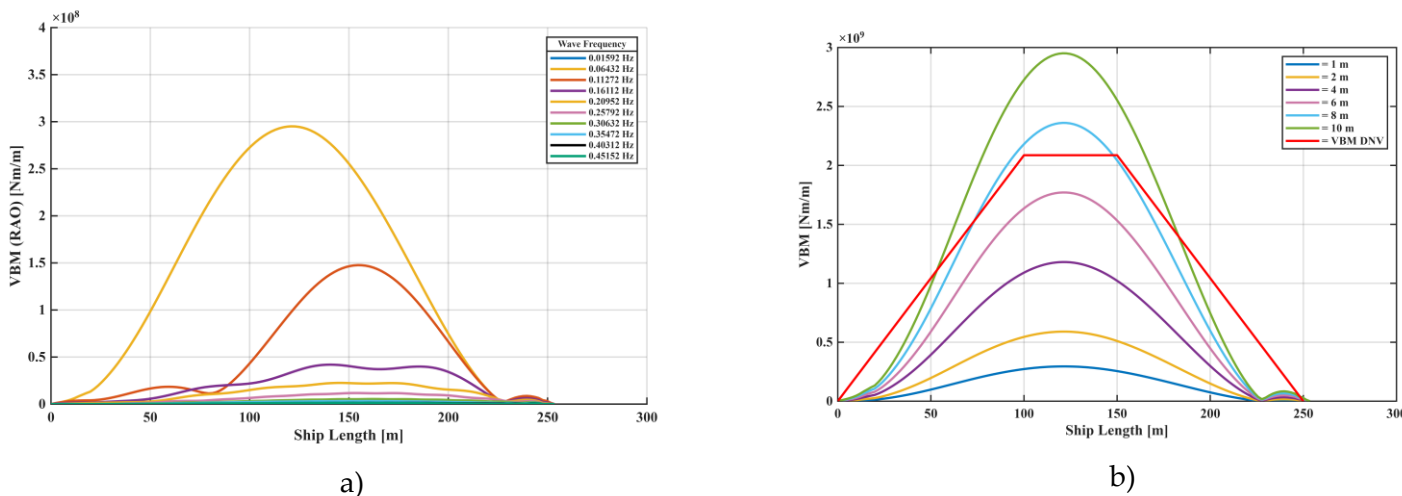


Figure 3. a) Critical frequencies, b) Comparison wave-induced vertical bending moment with DNV rules

Results for different sea states and critical frequencies are reported in Table 2. Vertical bending moment are obtained with software simulation while the stress agent is calculated from Navier formula. Probabilities values represent the percent time of occurrence within the 20 years of data available. For example, a 10% probability of occurrence of a sea state means that this sea state occurs for 10% of the total number of modeled time step.

Table 2. Structural response for different sea states.

	Hs [m]	T [sec]	Θ [°]	%	years	Mw [KNm]	σ [MPa]
Sea state 1	1	8.9	180	4.57	1.14	71344.6	2.8
Sea state 2	2	8.9	180	32.49	8.12	142689.3	5.5
Sea state 3	3	8.9	180	27.77	6.94	214033.9	8.3
Sea state 4	4	8.9	180	15.64	3.91	285378.6	11
Sea state 5	5	8.9	180	8.97	2.24	356723.2	13.8
Sea state 6	6	8.9	180	5.03	1.26	428067.9	16.5
Sea state 7	7	15.5	180	2.59	0.65	2367475	91.5
Sea state 8	8	15.5	180	1.19	0.30	2705685.8	104.6
Sea state 9	9	15.5	180	0.49	0.12	3043896.5	117.7
Sea state 10	10	15.5	180	0.18	0.05	3382107.2	130.7
Sea state 11	11	15.5	180	0.06	0.02	3720317.9	143.8
Sea state 12	12	15.5	180	0.01	0.003	4058528.6	156.9

Table 3. Fatigue damage accumulation for sea states analyzed.

	Ni	ni	Di (0,85)
Sea state 1	Safe	4048301	Safe
Sea state 2	Safe	28781029	Safe
Sea state 3	Safe	24599852	Safe
Sea state 4	Safe	13854580	Safe
Sea state 5	Safe	7946009	Safe
Sea state 6	Safe	4455789	Safe
Sea state 7	1690000	1317391	0.66
Sea state 8	1550000	605288	0.33
Sea state 9	1420000	249236	0.15
Sea state 10	1290000	91556	0.06
Sea state 11	1130000	30519	0.02
Sea state 12	1000000	5086	0.004

The fatigue analysis was conducted using ASTM A36 steel ($\sigma_0 = 63$ MPa, $\sigma_y = 250$ MPa, $\sigma_u = 400$ MPa), a material commonly employed in shipbuilding. The results clearly show (Table 3) that sea states with wave heights up to 6 meters do not pose a significant risk of fatigue damage, whereas sea states 7 to 12 represent the most severe conditions and contribute substantially to fatigue failure. The total accumulated fatigue damage is equal to 1.23, corresponding to a fatigue life of 20.3 years. These findings are in reasonable agreement with the work of Fricke et al. [4], who investigated the fatigue life of a container ship in the North Atlantic and reported a fatigue life considerably shorter than the conventional 25-year design threshold. The study was further extended to include irregular waves (Figure 4) in order to analyze the ship's response under more realistic conditions. Time-domain simulations were performed using the most critical frequency, 0.06432 Hz. The simulated time window was 1 hour, excluding the first 200 seconds, which correspond to the transient phase of wave generation [5]. The analysis of the vertical bending moment in irregular waves was carried out by incorporating the JONSWAP spectrum into the simulations, which take to account the nonlinear effects in real sea conditions, using a gamma parameter of 1.5, which is typical for North Atlantic conditions [6]. This quantifies the energy of developing and fully developed sea states, has practical applications in ocean engineering studies and is particularly suitable for representing irregular waves.

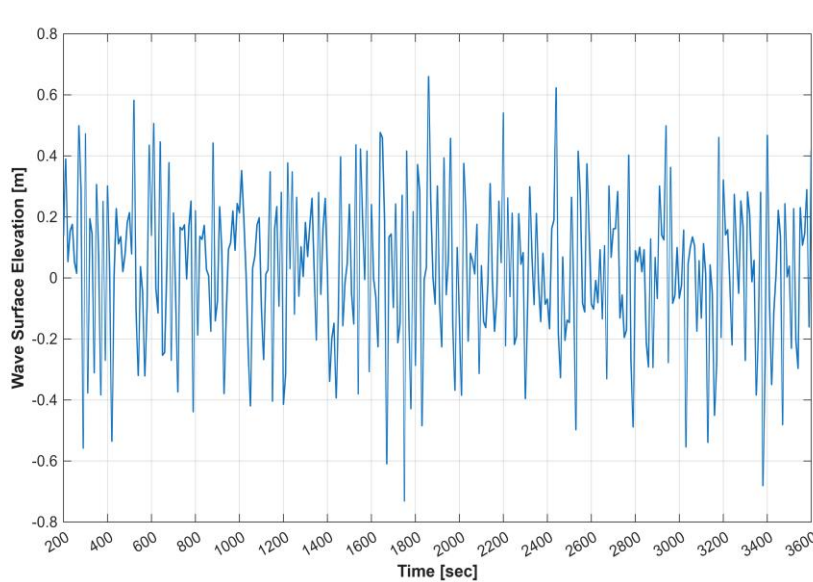


Figure 4. Wave surface elevation.

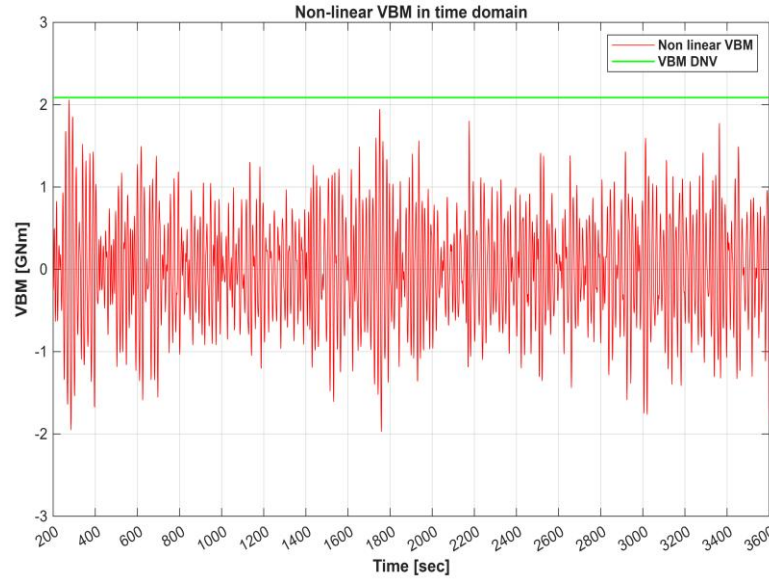


Figure 5. Comparison VBM in time domain with DNV rule.

In this case as well, the results were compared with the standardized DNV values in order to assess the ship's response under irregular wave excitation, as shown in Figure 5. The results show that this condition leads to a higher vertical bending moment; indeed, the classification society's reference value is reached for waves with a height of 5 m, compared with 7 m in the case of regular waves. Applying Navier's formula now, it is possible to know the stress trend over time and therefore analyze which irregular sea conditions lead to an overshoot of the fatigue limit ($\sigma_0 = 63$ MPa) of ASTM A36 steel [7].

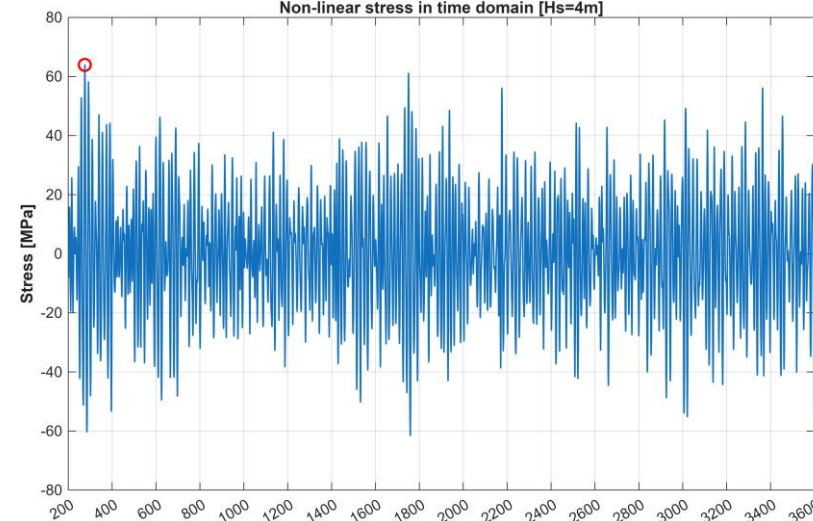


Figure 6. Stress-time in irregular sea with Hs=4m.

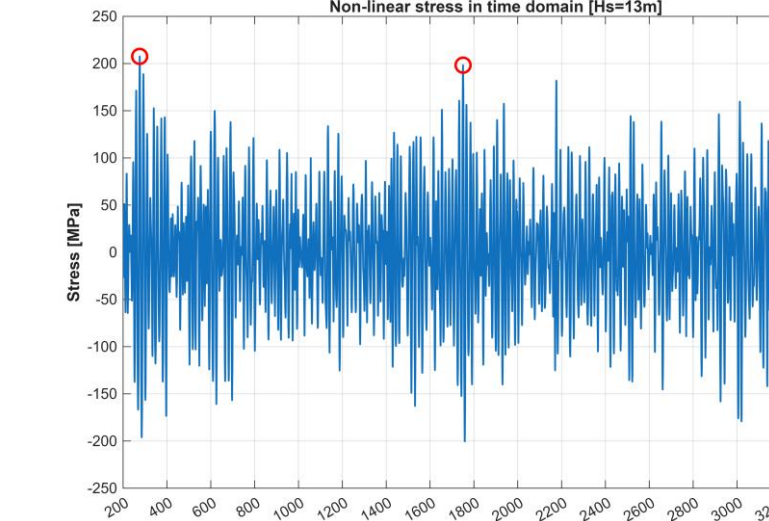


Figure 7. Stress-time in irregular sea with Hs=13m

The simulation results indicate that the fatigue limit begins to be exceeded under sea states characterized by waves with a height of 4 meters. Specifically, this occurs at 275.8 s, where a peak stress of 63.9 MPa is recorded, as shown in Figure 6. Irregular waves lead to cumulative damage already at a significant wave height of 4 meters. In contrast, in the case of regular waves, this condition is observed only for wave heights of 7 meters or bigger. For irregular sea states characterized by wave heights exceeding 4 meters, the fatigue limit will be surpassed multiple times, resulting in increased and repeated partial cumulative damage. A similar analysis, as shown in Figure 7, was conducted using the permissible stress $\sigma_{perm} = 196$ MPa based on IACS standards (safety factor equal to 1,27) [8]. The irregular sea state with $H_s = 13$ m leads to an exceedance of its elastic safe limit, and plastic deformation or failure risk increases. However, considering the presence of welds and accumulated damage, exceedances may occur even under smaller waves.

CONCLUSION/ FUTURE WORK

A comparison between DNV design rules and numerical simulations of a container vessel in North Atlantic conditions shows that irregular seas lead to earlier exceedance of structural limits than regular waves. The standardized VBM limit is exceeded at 5 m in irregular waves, compared to 7 m in regular waves, and Miner's rule fatigue damage initiates at 4 m and 7 m, respectively. These results demonstrate that irregular sea states produce higher bending moments and stresses than regular-wave assumptions, highlighting the need to include realistic wave spectra in design and operational assessments. The study supports the development of real-time structural health monitoring systems for improved prediction of ship response.

REFERENCES

[1] Makris P, Sillionis N, Anyfantis KN. Spectral fatigue analysis of ship structures based on a stochastic crack growth state model. Int J Fatigue 2023;176.
[2] DNV. Rules for Classification of Det Norske Veritas. 2016.
[3] Campana JD. Multi-Scale summary of Global wave Statistics. 2023.
[4] Fricke W, Cui W, Kierkegaard H, Kihl D, Koval M, Mikkola T, et al. Comparative fatigue strength assessment of a structural detail in a containership using various approaches of classification societies. vol. 15. 2002.
[5] Kim S, De Hauteclocque G, Bouscasse B, Lasbleis M, Ducrozet G. Experimental analysis of extreme wave loads on a containership. Ocean Engineering
[6] IACS. Standard Wave Data, No. 34 Rec. 1992/ Rev. 2 2022
[7] Preedawiphath P, Mahayotsanun N, Sa-ngoen K, Noipitak M, Tuengsook P, Sucharitpatskul S, et al. Mechanical investigations of astm a36 welded steels with stainless steel cladding. Coatings 2020;10.
[8] IACS UR S4 Rev. 4 Apr. 2017
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