Journal of
Marine Science and Engineering

MDPI

Article

Method for Prediction of Extreme Wave Loads Based on Ship Operability Analysis Using Hindcast Wave Database

Tamara Petranović [1], Antonio Mikulić [1], Marko Katalinić [2], Maro Ćorak [3] and Joško Parunov [1,*]

[1] Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, 10000 Zagreb, Croatia; tamara.petranovic@fsb.hr (T.P.); antonio.mikulic@fsb.hr (A.M.)
[2] Faculty of Maritime Studies, University of Split, 21000 Split, Croatia; marko.katalinic@pfst.hr
[3] Maritime Department, University of Dubrovnik, 20000 Dubrovnik, Croatia; mcorak@unidu.hr
* Correspondence: josko.parunov@fsb.hr

Abstract: The method for the prediction of extreme vertical wave bending moments on a passenger ship based on the hindcast database along the shipping route is presented. Operability analysis is performed to identify sea states when the ship is not able to normally operate and which are likely to be avoided. Closed-form expressions are used for the calculation of transfer functions of ship motions and loads. Multiple operability criteria are used and compared to the corresponding limiting values. The most probable extreme wave bending moments for the short-term sea states at discrete locations along the shipping route are calculated, and annual maximum extreme values are determined. Gumbel probability distribution is then fitted to the annual extreme values, and wave bending moments corresponding to a return period of 20 years are determined for discrete locations. The system reliability approach is used to calculate combined extreme vertical wave bending moment along the shipping route. The method is employed on the example of a passenger ship sailing across the Adriatic Sea (Split, Croatia, to Ancona, Italy). The contribution of the study is the method for the extreme values of wave loads using the hindcast wave database and accounting for ship operational restrictions.

Keywords: seakeeping operability criteria; operability analysis; wave bending moment; transfer functions; hindcast wave database

Citation: Petranović, T.; Mikulić, A.; Katalinić, M.; Ćorak, M.; Parunov, J. Method for Prediction of Extreme Wave Loads Based on Ship Operability Analysis Using Hindcast Wave Database. *J. Mar. Sci. Eng.* **2021**, *9*, 1002. https://doi.org/10.3390/jmse9091002

Academic Editor: Decheng Wan

Received: 29 August 2021
Accepted: 10 September 2021
Published: 14 September 2021

1. Introduction

The extreme wave loads on ships are usually determined by weighting short-term sea state responses by their probabilities of occurrences. When linear seakeeping computations are performed, the transfer functions of ship responses are combined with the wave spectra to define short-term responses. The sea state statistics contained in the wave scatter diagram are then used to compute the long-term distribution from which design value can be derived. Extreme value adopted as the design value of global wave load is usually calculated from the long-term distribution for exceeding probability of 10^{-8}. The procedure recommended by the International Association of Classification Societies (IACS) for the computation of long-term global wave loads on ships is given in [1].

The recommended procedure assumes that the wave heading angles are uniformly distributed in all sea states. The possibility that the shipmaster changes heading angle in extreme sea conditions is not considered [2]. Such maneuvers are normally taken to reduce excessive ship responses in heavy weather, most often the ship rolling motion [3]. Consequently, the probability of beam seas is reduced, which is ignored in common computational procedure, but could affect the extreme wave loads [1]. The effect of the heavy weather avoidance is also neglected, although shipmasters in practice tend to avoid the most severe sea states, e.g., by changing ship course or by waiting for favorable weather forecast [4]. The avoidance of heavy weather is partially considered by accepting the wave atlas Global Wave Statistics (GWS) as the source of the wave data [5]. Namely, data in the GWS are collected by the observations from merchant ships that sail along standard trading routes, excluding thus implicitly the most severe weather conditions [3]. Another difficulty represents the fact that weather routing is not the same for all ship types. For example, container ships experience frequent weather routing while oil tankers and bulk carriers rarely change their planned course [6]. Wave statistics in the GWS are subjected to the uncertainties of visual wave observations and wave directionality, as equal probability of waves from all directions is assumed [3].

Alternative methods for the computation of extreme wave loads on ships are considered nowadays to account rationally for mentioned environmental and operational uncertainties. Thus, IACS recently redefined the vertical hull girder loads for container ships using the direct calculation approach [7]. The routing factor has been introduced to reduce the design loads, which were found larger compared to the rule formulation. The improvement of the wave data accuracy is considered by using hindcast numerical wave databases [8,9]. An example of the application of the hindcast database for vessel response prediction and fatigue damage estimation is presented in [10]. To efficiently employ the wave hindcast database for the computation of wave loads on ships, it is essential to account appropriately for weather routing effects. One possible approach is to compare the hindcast database to the visual observations [11].

Although hindcast databases have already been used in ship seakeeping and structural analysis (e.g., [8–10]), incorporation of the operability analysis in the calculation of the extreme wave loads on ships is still missing. That aspect is crucial to obtain realistic estimates of extreme wave loads. In the present study, a method is proposed to calculate extreme wave loads that a ship encounters along a specific route using the hindcast database and accounting for operational restrictions. A case study of a passenger ship sailing from Croatian port Split to Italian port Ancona and vice versa in the Adriatic Sea is presented. All sea states along the shipping route contained in the hindcast wave database for the period from January 1997 to January 2020 are considered in four available locations along the route. The most probable short-term extreme vertical wave bending moments are determined for each sea state that the ship could encounter. The probability distribution of annual extreme values is then determined for each location. System probability is determined by combining extreme wave bending moments along the route, and bending moments for large return periods are calculated. The effect of heavy weather avoidance is accounted for by ship operability analysis, considering different operability criteria. Wave loads are calculated for three cases:

1. Without any operational restrictions, i.e., for all sea states that ship could potentially encounter along the route;
2. Full operational restrictions, i.e., the case when sea states not satisfying any of the operational criteria are avoided;
3. Partial operability restrictions, i.e., the case when speed is considerably reduced for sea states not satisfying any of the operational criteria.

The focus of the present study is on the probabilistic method for the computation of extreme wave loads. Therefore, a simplified but efficient approach for the calculation of wave-induced responses is used, employing closed-form expressions formulated by Jensen et al. [12]. Seakeeping limiting values for operational criteria are taken specifically for the passenger ship [13].

The paper is organized as follows: The ship and shipping route used in the analysis are described in Section 2. Operability analysis is described in Section 3. The method for the prediction of extreme wave bending moments is given in Section 4, while the results of the analysis are provided in Section 5. Discussion of the results is given in Section 6, and conclusions of the study are provided at the end of the paper. In Appendix A, histograms of annual maximum vertical wave bending moments without and with operational restrictions are given, and in Appendix B, histograms of annual maximum vertical wave bending moments for a case with reduced speed are presented.

2. Ship and Shipping Route

2.1. Ship Particulars

The passenger ship (Figure 1) used for the seakeeping operability analysis is similar to the ferry currently used for coastal and international lines in the Adriatic Sea. The main particulars of the ship that correspond to the features of the vessel within the "larger ferry category" are provided in Table 1.

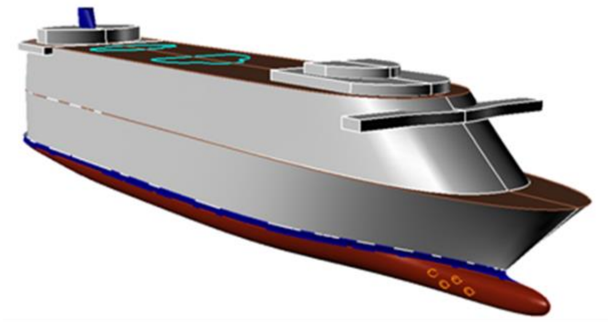


Figure 1. 3D model of the ship used in the study (Adopted from [14]).

Table 1. Main particulars of the ship (Adopted from [14]).

Particular	Value	Measuring Unit	Description
L_{OA}	114	m	Length overall
L_{PP}	103.2	m	Length between perpendiculars
B	18.7	m	Width
T	5	m	Draft
Δ	6565	t	Displacement
C_B	0.617	-	Block coefficient
GM	1.94	m	Metacentric height
v_{max}	17	kn	Maximum speed

2.2. Shiping Route

The passenger ship used in the study is intended to sail between the Croatian port Split and Italian port Ancona across the Adriatic Sea. The heading from Split to Ancona is 275° in nautical coordinates, and that from Ancona to Split is 95° (0° is toward the north). Operability criteria and loads of the ship are determined in four points near the shipping route, with geographical coordinates given in Table 2. The sailing route of the passenger ship, together with four considered points, is shown in Figure 2.

Table 2. Locations of points in the Adriatic Sea (Adopted from [15]).

Point in the Adriatic Sea	Latitude (°)	Longitude (°)
Point 1	43.5	15.5
Point 2	43.5	15
Point 3	43.5	14.5
Point 4	43.5	14

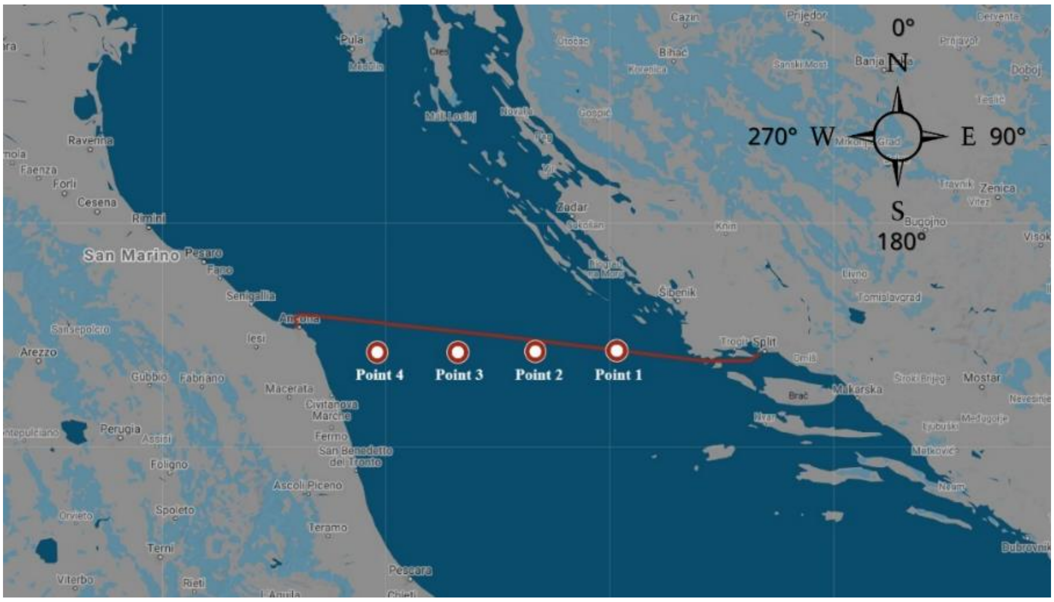


Figure 2. Points near the Split–Ancona route (Adopted from [15]).

3. Operability Analysis

3.1. Transfer Functions for Motions

Wave-induced ship motions are estimated by using closed-form, semi-analytical expressions [12]. The procedure requires only the main ship dimensions as input data: ship length, width, draft, block coefficient, and speed. Closed-form equations for the motion in the vertical plane are derived according to the linear strip theory by neglecting the coupling terms between heave and pitch and assuming a constant sectional added mass, equal to the displaced water. Semi-analytical expressions for transfer functions of heave and pitch are available in [12].

The transfer function of roll is defined in [12] as:

$$\Phi_{\varphi} = \frac{|M|}{\sqrt{\left[-\overline{\omega}^2 (T_N/2\pi)^2 + 1\right]^2 C_{44}^2 + \overline{\omega}^2 B_{44}^2}} \tag{1}$$

where $\overline{\omega}$ is the encounter frequency, $|M|$ is the amplitude of the roll excitation moment, B_{44} is the hydrodynamic roll damping, C_{44} is the restoring moment coefficient, and T_N is the natural roll period. The viscous roll damping needs to be included in the calculation, and in the present study, 20% of critical damping is used.

3.2. Wave Data

WorldWaves hindcast wave database, containing numerical wave simulation results, calibrated by satellite data over 39 evenly scattered points in the Adriatic Sea for a 23-year period (Figure 3) is employed. Historical information about sea states in four locations near the sailing route is used for this study (location numbers 10, 12, 15, and 18 in Figure 3). Each point contains 12 physical parameters measured every 6 h from January 1997 to January 2020, which makes a total of 33,600 recorded logs. For the purposes of this study, the significant wave height, the peak wave period, the mean wave directions, and time and date records are used [16].

Table 3 shows the maximum recorded significant wave heights in four considered points together with the dates of recordings. It is interesting to notice that maximum significant wave height at three locations is recorded on the same date, indicating a high spatial correlation among extreme sea states on this route.

Figure 3. Thirty-nine evenly distributed locations in the Adriatic Sea (Adopted from [14]).

Table 3. Maximum significant wave heights in 4 locations near the sailing route.

Point in the Adriatic Sea (Figure 2)	Max. H_S (m)	Date
1	5.89	29 October 2018
2	6.18	29 October 2018
3	5.98	29 October 2018
4	5.65	11 November 2013

3.3. JONSWAP Wave Spectrum

The Joint North Sea Wave Project (JONSWAP) wave spectrum, which is the adjustment of the Pierson–Moskowitz spectrum for the existence of a limited fetch and wind persistence, is employed in this study for the semi-enclosed basin of the Adriatic Sea. Adequacy of the JONSWAP wave spectrum formulation for the Adriatic Sea is shown in [16].

The JONSWAP wave spectrum used in the present study is defined by Det Norske Veritas [17]:

$$S_J(\omega) = A_\gamma S_{PM}(\omega)\gamma^{exp\left(-0.5\left(\frac{\omega-\omega_p}{\sigma\omega_p}\right)^2\right)}, \quad (2)$$

where γ is a non-dimensional peak shape parameter, $A_\gamma = 1 - 0.287\ln(\gamma)$ is a normalizing factor, $S_{PM}(\omega)$ is the Pierson–Moskowitz spectrum, $\omega_p = 2\pi/T_p$ is the angular spectral peak frequency, T_p is the peak wave period, and σ is the spectral width parameter.

The non-dimensional peak shape parameter reads:

$$\begin{gathered} -\gamma = 5\ for\ \frac{T_p}{\sqrt{H_s}} \leq 3.6; \\ \gamma = exp\left(5.75 - 1.15\frac{T_p}{\sqrt{H_s}}\right)\ for\ 3.6 < \frac{T_p}{\sqrt{H_s}} < 5; \\ \gamma = 1\ for\ 5 \leq \frac{T_p}{\sqrt{H_s}}. \end{gathered} \quad (3)$$

3.4. Operability Criteria and Limits

Seakeeping operability criteria considered in this paper are the root mean square (RMS) of roll, the RMS of pitch, the RMS of the vertical acceleration at the forward perpendicular (FP), the probability of slamming, the probability of green water, the probability of propeller emergence, and the weighted average motion sickness incidence (WAMSI). The operability analysis is performed to estimate the percentage of time during which the ship may not be able to sail on the given route and with a given speed. Limiting values of selected operability criteria are shown in Table 4. Limiting values employed are universal for all ship types, except limiting values of the roll and the vertical acceleration at FP, which are specific for passenger ships [13].

Table 4. Operability criteria limiting values.

Operability Criterion	Limiting Value
RMS of roll	2.5°
RMS of pitch	1.5°
RMS of vertical acceleration at FP	0.05 g
Probability of slamming	0.03
Probability of green water	0.05
Probability of propeller emergence	0.25
WAMSI	20% in 4 h

Expressions for calculating operability criteria using response spectra and corresponding spectral moments are provided, e.g., in [18].

The passenger comfort criterion used in the present study is the WAMSI, given by:

$$\text{WAMSI} = \frac{\int \text{MSI}\, W\, dx}{\int W\, dx} \tag{4}$$

where MSI is the motion sickness incidence and W is the weighting function. Integrals in Equation (4) are determined along the length of the passenger deck. The weighting function represents the distribution of the people on the passenger deck, taken equal to 1 in the present study, which means that equally weighted subjects are evenly distributed along the passenger deck. The MSI is defined as the percentage of subjects who experienced nausea within a certain amount of time calculated according to the expressions provided in [19]:

$$\text{MSI} = 100\left[0.5 + erf\left(\frac{log_{10}\left(\frac{0.798\sqrt{m_{0_v}}}{g}\right) - \mu_{MSI}}{0.4}\right)\right], \tag{5}$$

where:

$$\mu_{\text{MSI}} = -0.819 + 2.32\left(log_{10}\left(\sqrt{\frac{m_{0_v}}{m_{2_u}}}\right)\right)^2, \tag{6}$$

where m_{0_v} and m_{2_u} are the zeroth moment of the response spectrum of vertical acceleration and the second moment of the response spectrum of vertical motion.

Recently, Overall Motion Sickness Incidence (OMSI) has been introduced as a measure of passenger comfort, defined as the mean MSI over the length and breadth of the passenger deck [20], which is not considered in the present study.

4. Method for the Prediction of Extreme Wave Loads

The transfer function of vertical wave-induced bending moment (VWBM) at midship is calculated according to the closed-form expression [12]:

$$\Phi_M = \kappa\frac{1-kT}{(k_eL_{pp})^2}\left[1-\cos\left(\frac{k_eL_{pp}}{2}\right) - \frac{k_eL_{pp}}{4}\sin\left(\frac{k_eL_{pp}}{2}\right)\right]\cdot F_V(F_n)\cdot F_C(C_B)\cdot\sqrt[3]{|\cos\beta|}\cdot\rho g B_0 L_{pp}^2 \tag{7}$$

where k_e represents the effective wave number, β is the heading angle, κ is the Smith correction factor, $F_V(F_n)$ is the speed correction factor, $F_C(C_B)$ is the correction factor for the block coefficient, $\rho = 1025\ \text{kg/m}^3$ is the sea density, and B_0 is the measured maximum ship breadth at the waterline. Details on how to calculate terms appearing in Equation (7) are given in [12].

The most probable extreme value (MPEV) of VWBM in the short-term sea state depends on the sea state duration T_d = 21,600 s , which corresponds to wave data recording at 6-hour intervals:

$$\text{MPEV}(\text{VWBM}) = \sqrt{m_{0_M} \cdot 2ln\left(\frac{T_d}{T_z}\right)}. \tag{8}$$

T_z is the average zero-crossing period of the response, and it is defined as:

$$T_z = 2\pi\sqrt{\frac{m_{0_M}}{m_{2_M}}} \tag{9}$$

where m_{0_M} and m_{2_M} are the zeroth and second moments of the response spectrum of VWBM [21].

For a period of the availability of wave data (January 1997 to January 2020), annual maximum VWBMs are extracted for all sea states in four locations along the route. Histograms are fitted with Gumbel distribution, which is commonly used as the extreme value distribution function. Parameters of Gumbel distribution are estimated using the method of moments [22,23].

The probability of exceedance of the long-term extreme VWBM can be written as:

$$Q = \frac{1}{RP} \tag{10}$$

and the probability of non-exceedance is:

$$F = 1 - Q. \tag{11}$$

where RP is the return period in years [23].

To determine the resulting extreme value distribution along the shipping route, extreme value distributions at individual locations are to be statistically combined. A certain level of VWBM is exceeded along the whole route if exceeded in any of the locations along the route. This can be modeled by considering individual locations as members in a series probabilistic system. First-order upper and lower bounds on the extreme value distribution along the route can be set by considering members of the series system as statistically independent or fully correlated, respectively. The concept was initially proposed by Mansour and Preston considering wave zones in GWS along the route [24]. If one looks at the data given in Table 3, it appears that extreme values at different locations along the route occur at the same time, so the correlation of sea states between locations could be quite large.

If sea states along the location are assumed statistically independent, the system probability of non-exceedance of the extreme vertical bending moment along the sailing route $P_{ne,SI}$ reads:

$$P_{ne,SI} = \prod_{i=1}^{n} (P_{ne_i})^{k_i}, \tag{12}$$

while the system probability of non-exceedance of extreme vertical bending moment for fully correlated sea states along the route $P_{ne,FC}$ is [25]:

$$P_{ne,FC} = \min_i (P_{ne_i})^{k_i}. \tag{13}$$

k_i appearing in Equations (12) and (13) represents the fraction of time that the ship spends in each of n wave locations. If the time spent in port is neglected, then $\sum_{i=1}^{n} k_i = 1$. It is assumed in this study that the ship spends an equal amount of time at each of four locations; i.e., n = 4 and k_i = 0.25. If probability distributions are different for two opposite traveling directions at the same location, then n = 8 and k_i = 0.125.

Combined probability distributions along the route, given by Equations (12) and (13), can be calculated numerically. Combined probability distributions are plotted on the VWBM $-$ P_{ne} diagram, and VWBMs for a 20-year return period are obtained.

5. Results

5.1. Operability Plot

The polar plot in Figure 4 represents the limit values of calculated operability criteria for different wave heading angles and significant wave heights. Only a maximum ship speed of 17 knots is considered in the operability analysis. Values in the polar plot are estimated for the modal spectral frequency ω_m, which is in the Adriatic Sea given as [17]:

$$\omega_m = 0.52 + \frac{1.4}{0.7 + H_s}. \quad (14)$$

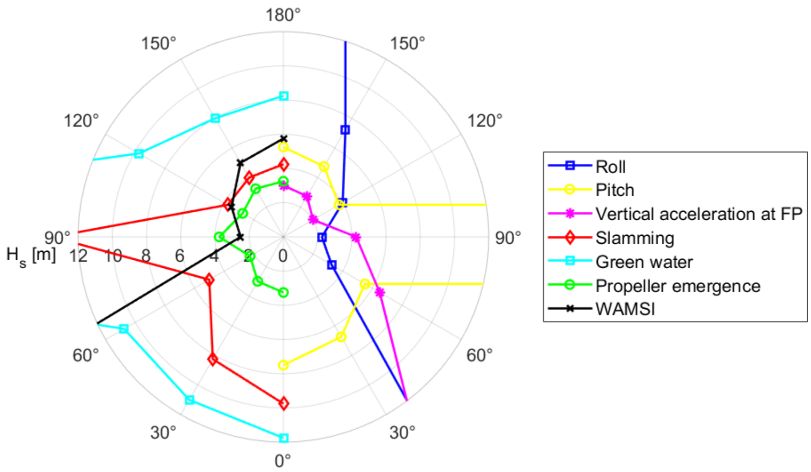


Figure 4. Polar plot (head sea is 180°) (Adopted from [15]).

When the ship sails from Ancona to Split, during the most frequent south-eastern wind, waves encounter the ship at 220°, which is equal to 140° due to symmetry. From Figure 4, one may notice that the limiting vertical acceleration at the FP is exceeded firstly at the significant wave height $H_s = 2.75\ m$. When the ship sails from Split to Ancona, waves encounter the ship at 40°, and it can be seen from Figure 4 that the limit value of the propeller emergence is exceeded firstly at significant wave height $H_s = 2.75\ m$.

The frequencies of exceedance of operability criteria limits for all sea states contained in the hindcasted wave database are presented in Table 5. Frequencies of exceedance for each criterion are obtained by dividing the number of exceedances by the total number of sea states. The total frequency of exceedance when at least one criterion is not satisfied is given in the last column of Table 5. Values outside parentheses in Table 5 refer to westward voyages from Split to Ancona, and values in parentheses are valid for the opposite direction. It can be seen the route from Ancona to Split has an appreciably larger frequency of exceeding operability criteria than the direction from Split to Ancona.

5.2. Probability Distributions of Extreme VWBM at Individual Locations

Short-term yearly extreme VWBMs are calculated in four points along the sailing route for all sea states and only for sea states satisfying operability criteria. The fitting of the Gumbel distribution to the histogram of VWBM is presented in Figures A1–A3 in Appendix A. It may be noticed that the Gumbel distribution in some of the cases does not follow VWBM histograms, so other distribution functions may also be considered for that purpose. However, as the Gumbel distribution is often used for modeling annual extreme values of waves and wave-induced responses (e.g., [18]) it is adopted in the present study as well.

Table 5. Frequencies (in %) of exceeding operability criteria limits for wave data at points 1, 2, 3, and 4 (Figure 2) for the route Split to Ancona (values for the opposite route in parentheses) (Adopted from [15]).

Point	Operability Criteria							
	Roll	Pitch	Vertical Acc. at FP	Slamming	Green Water	Propeller Emergence	WAMSI	Total
1	0.40 (0.17)	0 (0.04)	0.11 (2.12)	0 (0.11)	0 (0)	1.89 (1.14)	0.01 (0.14)	2.06 (2.62)
2	0.36 (0.16)	0 (0.07)	0.11 (2.76)	0 (0.17)	0 (0)	2.13 (1.34)	0.01 (0.15)	2.25 (3.24)
3	0.38 (0.22)	0 (0.07)	0.11 (2.89)	0 (0.18)	0 (0)	2.02 (1.38)	0.02 (0.18)	2.15 (3.40)
4	0.55 (0.36)	0 (0.08)	0.09 (3.44)	0.003 (0.23)	0 (0)	1.82 (1.56)	0.02 (0.23)	1.97 (4.03)

According to the Equation (7), VWBMs are the same in both sailing directions. Consequently, there are no differences in extreme values when operability criteria are not considered. However, the extreme VWBMs calculated only for those sea states satisfying operability criteria are different for two sailing directions due to differences in meeting the operability criteria.

For a 20-year return period, $F = 0.95$ is determined using Equations (10) and (11). The most probable long-term extreme value of VWBM is then obtained from the corresponding Gumbel probability distribution and presented in Table 6. It may be seen that in sea states meeting seakeeping operability criteria, extreme VWBMs are quite similar in different points along the route. Expectedly, extreme wave moments are considerably larger in sea states when operability criteria were not considered than moments when the operability criteria were considered.

Table 6. The most probable long-term extreme values of vertical wave bending moments for a 20-year return period at individual locations along the route (MNm).

Point (Figure 2)	Long-Term Extreme VWBM for 20-Year Return Period (MNm)		
	All Sea States	Sea States Satisfying Operability Criteria	
		Split–Ancona 275°	Ancona–Split 95°
1	124	76	68
2	139	76	73
3	152	78	73
4	150	77	68

5.3. System Probabilities

System probabilities of extreme VWBM for all sea states and for only those sea states satisfying operability criteria are shown in Figure 5. The curves obtained in Figure 5 are determined numerically by the procedure described in Section 4.

For the long return period of 20 years, bounds of extreme VWBM can be determined from diagrams in Figure 5. These values are presented in Table 7, where the left column represents values determined from fully correlated system probabilities and the right column represents statistically independent system probabilities.

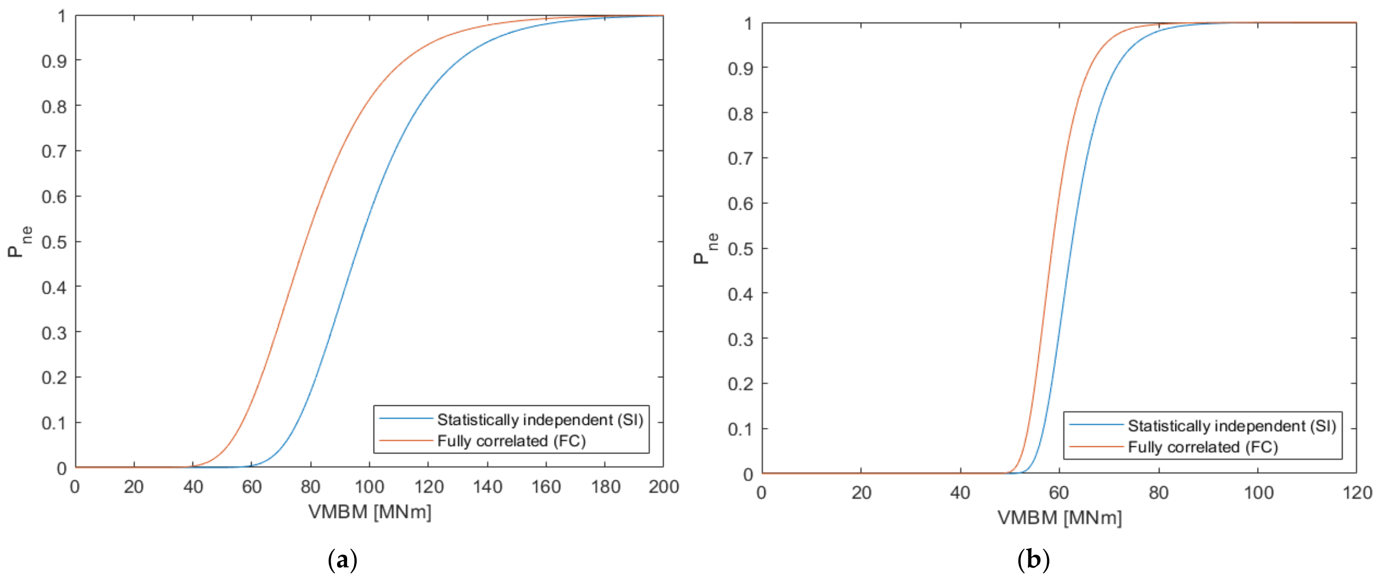


Figure 5. System probabilities of non-exceedance of extreme VWBM calculated for (**a**) all sea states and (**b**) sea states satisfying operability criteria.

Table 7. Bounds of extreme vertical bending moments.

	VWBM (MNm) Determined from $P_{ne,FC}$	VWBM (MNm) Determined from $P_{ne,SI}$
All sea states	125	143
Sea states satisfying operability criteria	69	75

It may be seen from Table 7 that the effect of possible operational restrictions is huge, as the extreme VWBMs are halved if operational restrictions are imposed. The effect of the assumption of the statistical independence is to increase VWBM by about 10% compared to the assumption of full correlation between different locations along the route. The assumption of full correlation seems to be more realistic, according to Table 3. Namely, extreme sea states and consequently extreme wave bending moments at different locations are likely to be achieved during the same voyage.

5.4. The Effect of the Speed Reduction in Severe Sea States

It is unlikely that navigation will be completely suspended during heavy seas. If waves increase during the voyage, and the possibility of exceeding the limits of operability criteria appears, the captain will either reduce the speed or change the direction of navigation.

Extreme VWBMs in Sections 5.2 and 5.3 are calculated for a case where the ship is sailing with a constant speed of 17 knots. To investigate the effect of speed reduction, only for those sea states where the operability criteria limits are exceeded, speed is reduced to 5 knots. Histograms of annual maximum VWBM calculated for courses 275° and 95° are shown in Figures A4 and A5 in Appendix B, together with the Gumbel distribution fitted. The most probable long-term extreme VWBMs for a return period of 20 years at each location are shown in Table 8. Figure 6 presents system probabilities of non-exceedance of the extreme VWBM, and Table 9 presents the bounds of the most probable long-term extreme VWBM for this case.

Table 8. The most probable long-term extreme values of vertical wave bending moments for a 20-year return period calculated for a speed of 17 knots on sea states satisfying operability criteria and a speed of 5 knots on sea states not satisfying operability criteria.

Point (Figure 2)	Long-Term Extreme VWBM for 20-Year Return Period (MNm)	
	Split–Ancona 275°	Ancona–Split 95°
1	104	103
2	116	117
3	126	126
4	124	125

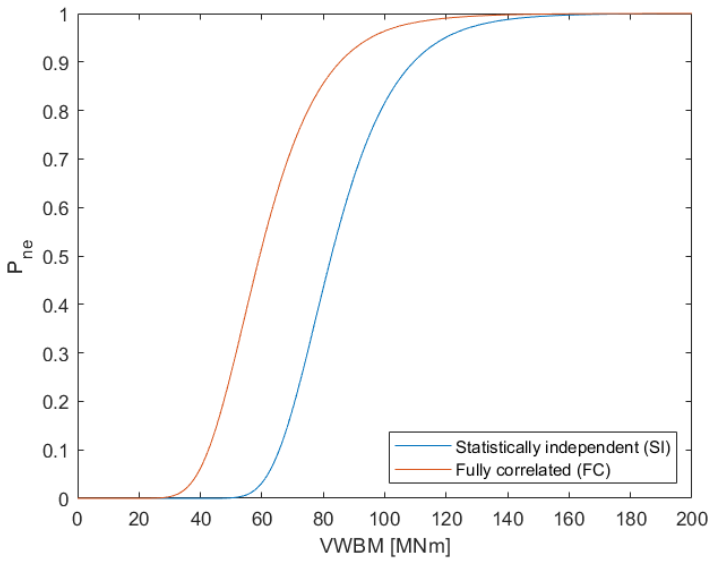


Figure 6. System probabilities of non-exceedance of extreme VWBM for reduced speed.

Table 9. Bounds of extreme vertical bending moments calculated for speed of 5 knots on sea states not satisfying operability criteria.

VWBM (MNm) Determined from $P_{ne,FC}$	VWBM (MNm) Determined from $P_{ne,SI}$
95	120

6. Discussion

The most probable extreme VWBM for the return period of 20 years along the shipping route is summarized in Figure 7. Results are shown for statistically independent and fully correlated extreme values along the shipping route and using different assumptions about the consequences of the operability analysis.

The first, albeit unrealistic option is to use full ship speed in all sea states recorded along the traveling route (in Figure 7a). If all sea states not satisfying operability criteria are avoided, the most probable extreme wave loads are reduced by a factor of 2 (in Figure 7b). If these sea states are not avoided, but ship speed is reduced to the minimum cruising speed, then extreme VWBM decreases by about 20% compared to the full speed (in Figure 7c). The effect of the correlation between short-term sea states along the route is to reduce extremes obtained by assuming statistical independence by 8–21%.

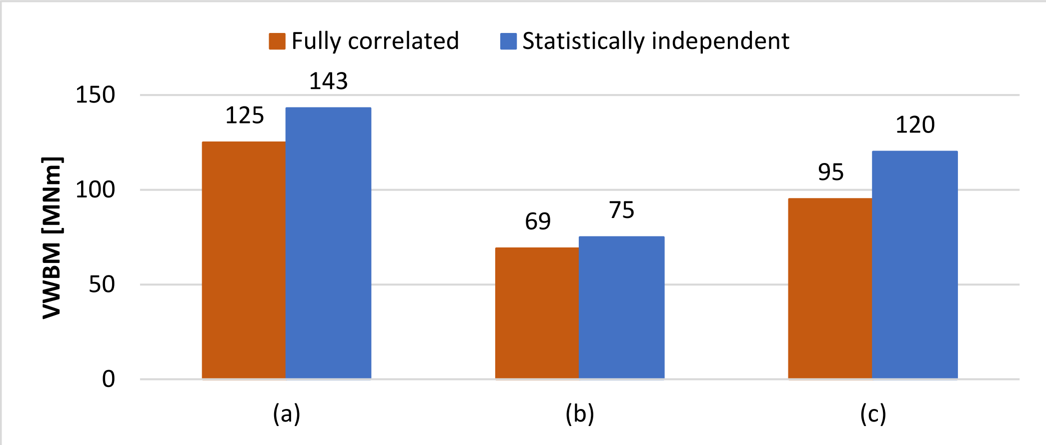


Figure 7. Comparison of extreme VWBMs determined from fully correlated and statistically independent system probabilities for (**a**) all sea states, (**b**) only sea states satisfying operability criteria with speed of 17 knots, and (**c**) a case when ship speed is reduced to 5 knots on sea states not satisfying operability criteria.

The results presented in Figure 7 are compared to the commonly used long-term procedure for the calculation of the extreme wave loads [1]. A combined wave scatter diagram is obtained for four considered locations. All heading angles in the interval 0–2π are assumed to be equally probable and the JONSWAP wave spectrum is used. Constant ship speed of 17 and 5 knots is used in two separate analyses. VWBM corresponding to 10^{-8} probability level is extracted from the long-term distribution and considered as the extreme value for the return period of 20 years. Software developed in [26] is used for a long-term analysis. The most probable extreme VWBM of 145 and 123 MNm is obtained for ship speed of 17 and 5 knots, respectively. These values are almost identical to the corresponding results presented in Figure 7 for the statistically independent case.

Validation of the method for the prediction of extreme wave loads could ideally be done by comparison with full-scale measurements. Such long-term measurement campaigns are, however, rare and difficult to organize [27]. An alternative approach would be to compare the results of the operability analysis with the practice of shipmasters of actual ships in service. This can be done by organizing an interview with shipmasters having experience with similar ships and in a similar wave environment to the one analyzed in the present study. An example of such an interview regarding analysis of a large container ship is presented in [28].

The rare examples of passenger ship accidents in the Adriatic Sea caused by large waves are a possible source of validation of the operability analysis. One such accident happened in November 2012, at 3 a.m., to the ferry sailing from Ancona to Split. Seventy vehicles collided with other vehicles and sides of the ferry, which caused great damage. The accident happened because the roll amplitudes were too large [28]. Significant wave height at the time of the accident was just above 5 m, while wave heading angle was about 140°. Comparing these values with the operability plot in Figure 4, one may conclude that ship was sailing at the operability limit for roll motion while limiting values for bow acceleration and pitch motion were largely exceeded. It is interesting to notice that the shipmaster had to change the course to following waves to avoid large rolling amplitudes [28].

The present analysis is performed for a ship sailing in the Adriatic Sea, as a specific sea environment. Similar analysis can be performed for other ship types and other shipping routes. When other ship types are analyzed, differences are expected in the first place regarding operability criteria limiting values, as the values adopted in the present study are valid for the passenger ships. Regarding different wave environments, the North Atlantic, which is considered as the design wave environment for ocean-going ships sailing without limitation, is of particular interest. Such analysis for the sailing route in the North Atlantic could be performed using, e.g., the ERA5 wave database [25].

It is to be mentioned that the Gumbel distribution is not always a perfect fit to the histogram of annual extreme VWBM, as may be seen in the appendices. Therefore, other distribution functions may also be considered for that purpose. The goodness-of-fit analysis is to be performed to find out the appropriate probability distribution.

To perform the extreme value analysis, it is necessary to have wave information for a period of at least 20 years [29], which is satisfied in the present study. For the analysis based on the long-term distribution, a minimum length of 20% of the desired return period is advised [30]. A convergence study to determine the sensitivity of predicted extreme values on the length of the wave data set is nevertheless recommended.

It should be noted that only linear wave loads are considered in this study. The most important effect of nonlinearity is the difference between sagging and hogging VWBM. The effect is particularly important for fine-form ships with low block coefficients, where sagging and hogging bending moments are larger and smaller than linear values, respectively. Simplified corrections for nonlinear VWBM that can be implemented in the present procedure to extend linear computation are presented in [31,32].

7. Conclusions

The method for calculating long-term extreme values of wave loads on a ship along a defined traveling route is described. The method is based on the hindcast wave database at discrete locations along the shipping route and ship operability analysis. Multiple operability criteria are considered, while transfer functions of wave-induced motions and loads are determined using closed-form expressions developed by Jensen et al. [12]. As the hindcast databases provide sea states in regular time intervals, the most probable extreme values of wave loads are determined for short-term sea states with a duration equal to the time resolution of the database (6 h). Annual maximum values of wave-induced loads are then determined for each location along the route, and Gumbel distribution is fitted. Gumbel distributions are then statistically combined along the route considering sea states at individual locations as independent or fully correlated members of a serial probabilistic system. The procedure enables a determination of the most probable values of wave loads for long return periods that may be used in ship structural design. The present method and the commonly used long-term distribution method result in almost the same long-term extreme values if the assumption of statistical independence among sea states at different locations is adopted. Furthermore, the presented method enables consideration of correlation among wave zones and quantification of the sensitivity of wave loads regarding operational criteria when direct calculation methods are used in ship structural design.

The following conclusions in terms of numerical results are obtained in the study:

- Operational criteria are not satisfied in 2–4% of sea states in four locations along the shipping route.
- If sea states where operability criteria are not satisfied are completely avoided, long-term extreme vertical wave bending moment is reduced by a factor of 2.
- If ship speed is reduced to the minimum cruising speed in sea states where operability criteria are not satisfied, instead of avoiding those sea states, long-term extreme vertical wave bending moment is reduced by about 20%.
- If the assumption of full statistical correlation among sea states along the shipping route is adopted, long-term extreme vertical wave bending moment is reduced by 8–21%. It should be mentioned that wave data in the database indicate that assumption of correlation is justified for this specific, relatively short shipping route.

Author Contributions: Conceptualization, J.P. and T.P.; methodology, J.P. and T.P.; software, A.M. and T.P.; validation, J.P., T.P. and M.Ć.; formal analysis, J.P. and T.P.; investigation, J.P. and T.P.; resources, J.P and M.K.; data curation, M.K.; writing—original draft preparation, T.P.; writing—review and editing, J.P.; visualization, J.P.; supervision, J.P.; project administration, J.P.; funding acquisition, J.P. All authors have read and agreed to the published version of the manuscript.

Funding: This work has been fully supported by Croatian Science Foundation under the project IP-2019-04-2085.

Institutional Review Board Statement: Not applicable.

Acknowledgments: This work has been fully supported by Croatian Science Foundation under the project MODUS (IP-2019-04-2085). The WorldWaves data used in the study are provided by Fugro OCEANOR AS.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Appendix A. Annual Maximum Vertical Wave Bending Moments

Appendix A.1. All Sea States

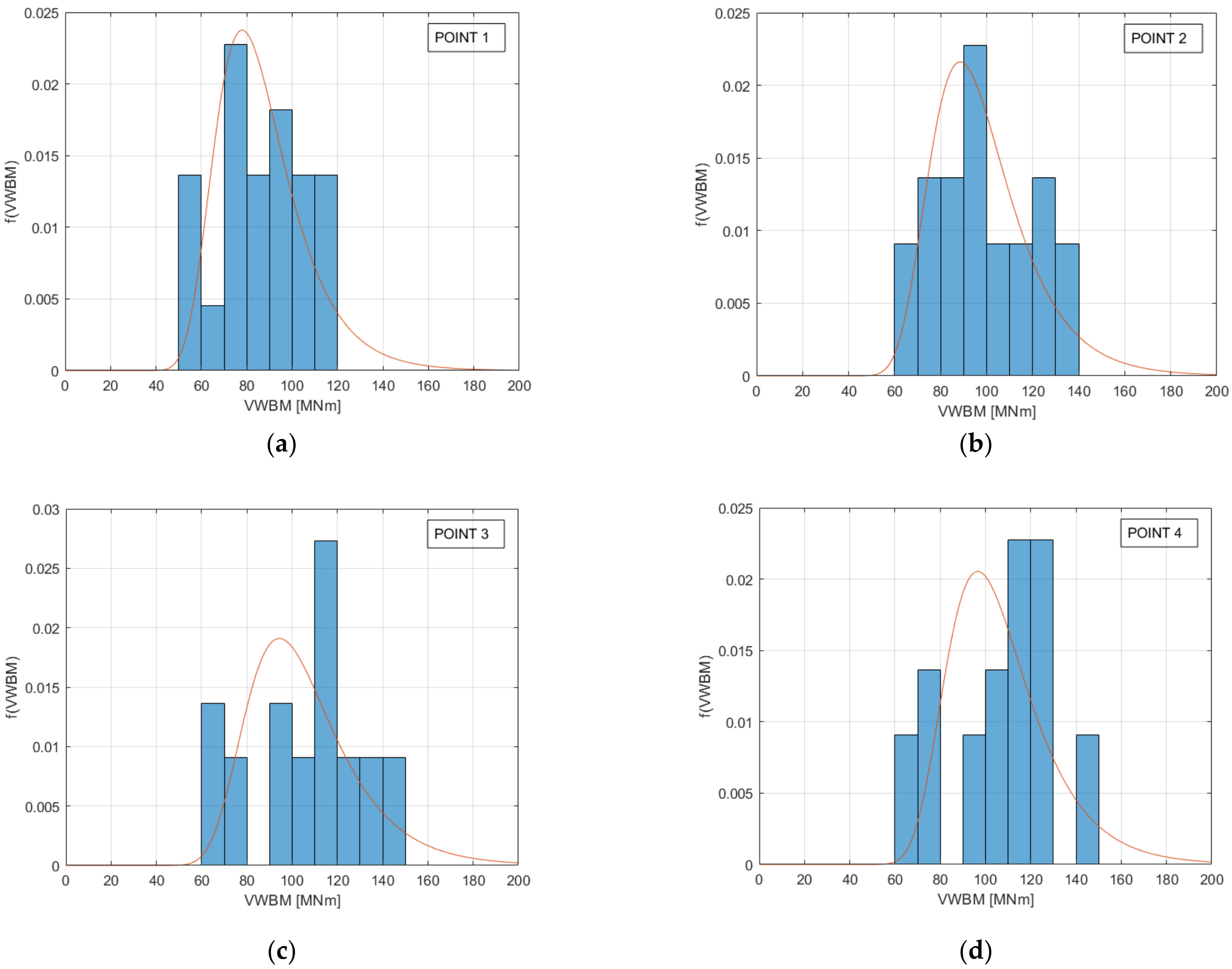


Figure A1. Annual maximum vertical wave bending moments calculated for all sea states: (**a**) at point 1; (**b**) at point 2; (**c**) at point 3; (**d**) at point 4.

Appendix A.2. Sea States Satisfying Operability Criteria on the Sailing Route from Split to Ancona

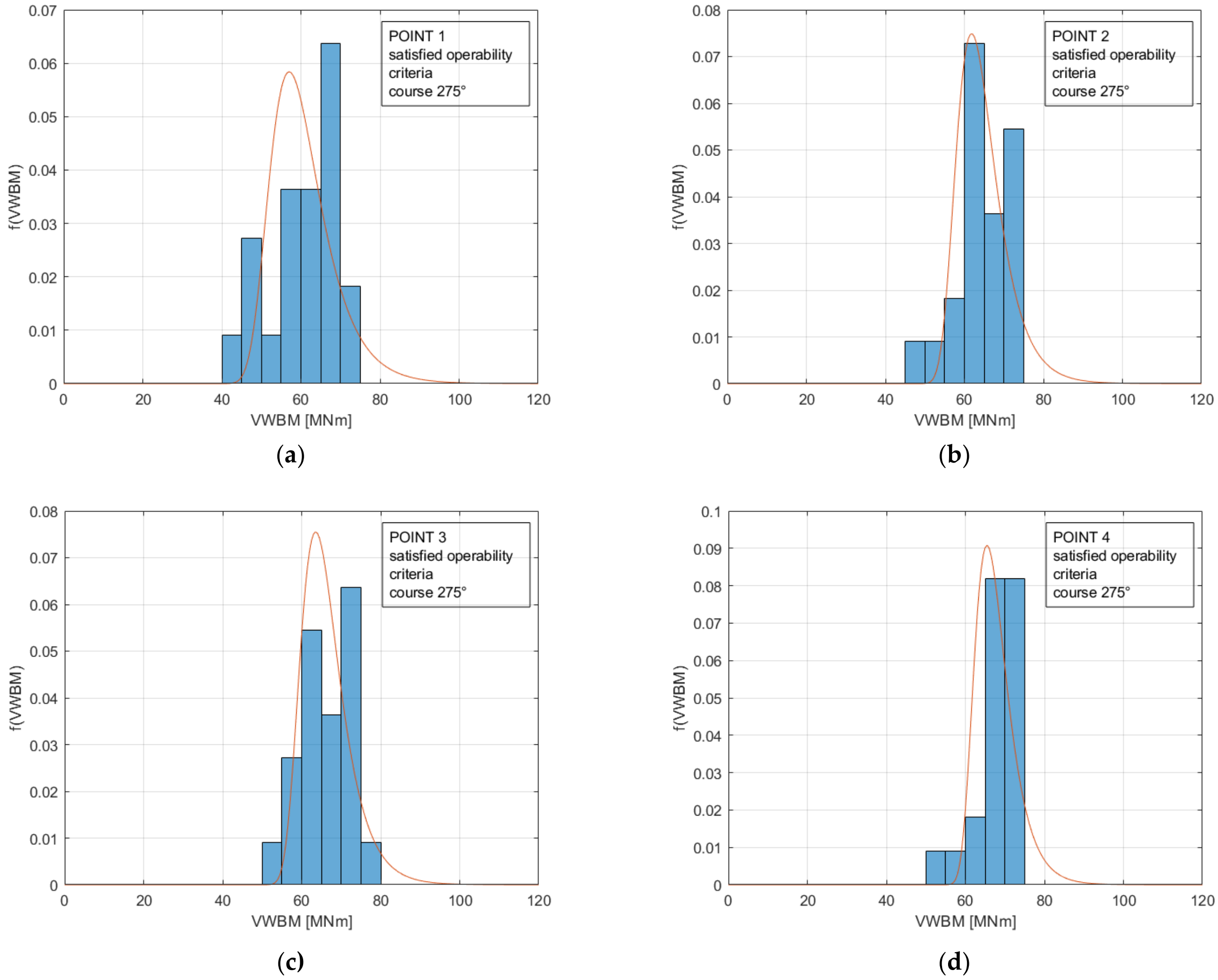


Figure A2. Annual maximum vertical wave bending moments calculated for the ship sailing from Split to Ancona for sea states satisfying operability criteria: (**a**) at point 1; (**b**) at point 2; (**c**) at point 3; (**d**) at point 4.

Appendix A.3. Sea States Satisfying Operability Criteria on the Sailing Route from Ancona to Split

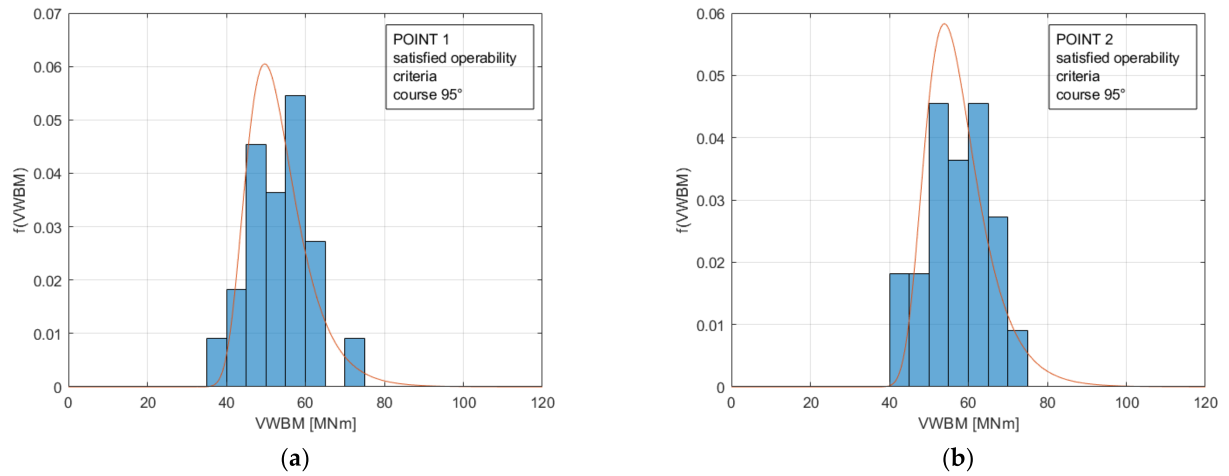
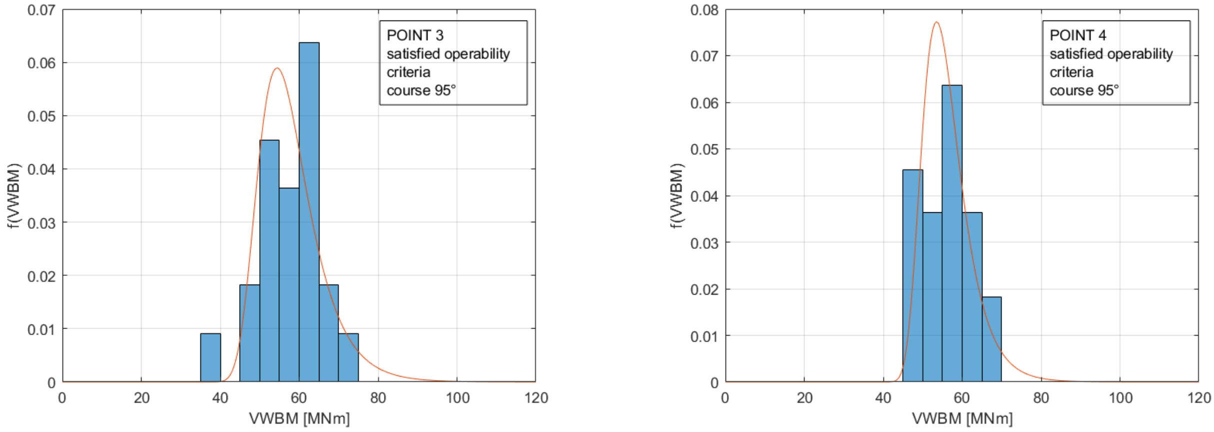


Figure A3. *Cont.*

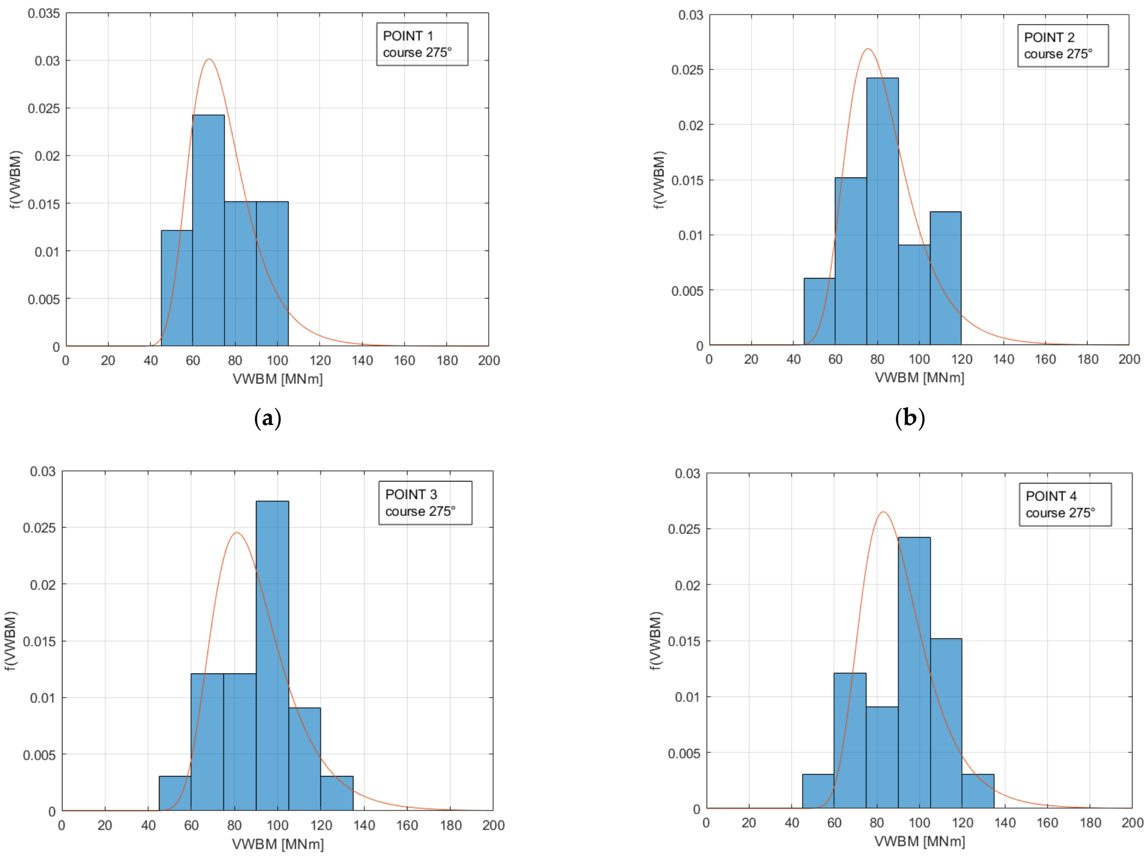


(**c**) (**d**)

Figure A3. Annual maximum vertical wave bending moments calculated for the ship sailing from Ancona to Split for sea states satisfying operability criteria: (**a**) at point 1; (**b**) at point 2; (**c**) at point 3; (**d**) at point 4.

Appendix B. Annual Maximum Vertical Wave Bending Moments for a Case of Reduced Speed on Sea States That Do Not Meet Operability Criteria

Appendix B.1. Voyage from Split to Ancona



(**a**) (**b**) (**c**) (**d**)

Figure A4. Annual maximum VWBM calculated for a speed of 17 knots on sea states satisfying operability criteria and a speed of 5 knots on sea states not satisfying operability criteria: (**a**) at point 1; (**b**) at point 2; (**c**) at point 3; (**d**) at point 4 on course 275°.

Appendix B.2. Voyage from Ancona to Split

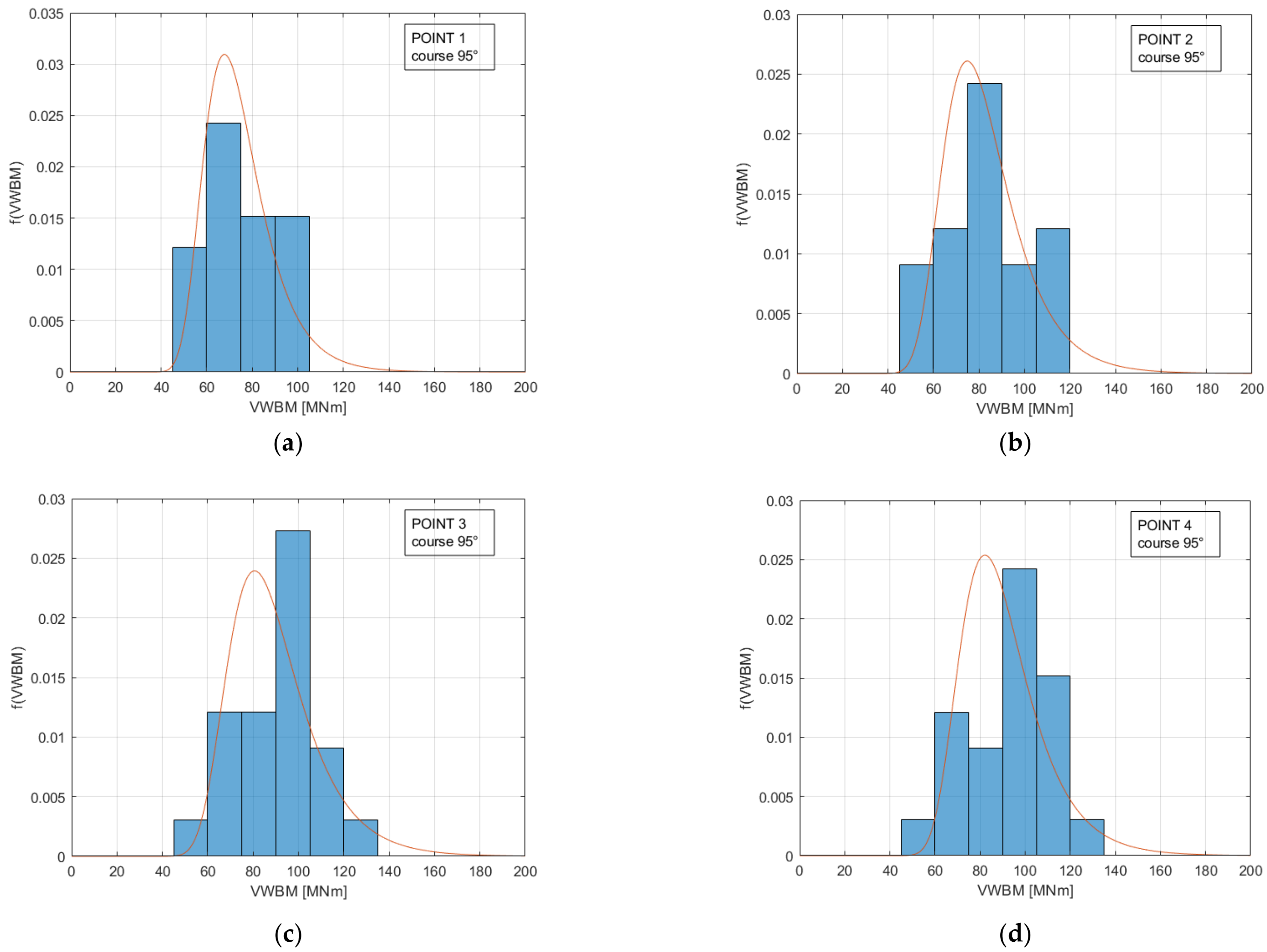


Figure A5. Annual maximum VWBM calculated for a speed of 17 knots on sea states satisfying operability criteria and a speed of 5 knots on sea states not satisfying operability criteria: (**a**) at point 1; (**b**) at point 2; (**c**) at point 3; (**d**) at point 4 on course 95°.

References

1. IACS Rec. *No. 34. Standard Wave Data*; IACS: London, UK, 2001.
2. Moan, T.; Shu, Z.; Drummen, I.; Amlashi, H. Comparative reliability analysis of ships—Considering different ship types and the effect of ship operations on loads. *Trans. Soc. Nav. Archit. Mar. Eng.* **2007**, *114*, 16–54.
3. Guedes Soares, C. On the Definition of Rule Requirements for Wave Induced Vertical Bending Moments. *Mar. Struct.* **1996**, *9*, 409–425. [CrossRef]
4. Prpić-Oršić, J.; Parunov, J.; Šikić, I. Operation of ULCS—Real Life. *Int. J. Nav. Archit. Ocean. Eng.* **2014**, *6*, 1014–1023. [CrossRef]
5. Hogben, N.; Dacunha, N.M.C.; Oliver, G.F. *Global Wave Statistics*; Feltham: British Maritime Technology Ltd.: London, UK, 1986.
6. Bitner-Gregersen, E.M.; Dong, S.; Fu, T.; Ma, N.; Maisondieu, C.; Miyake, R.; Rychlik, I. Sea state conditions for marine structures' analysis and model tests. *Ocean. Eng.* **2016**, *119*, 309–322. [CrossRef]
7. Derbanne, Q.; Shiguntov, V.; Storhaug, G.; Xie, G.; Zheng, G. Rule formulation of vertical hull girder wave loads based on direct computation. In Proceedings of the PRADS 2016, Copenhagen, Denmark, 4–8 September 2016.
8. de Hauteclocque, G.; Johnson, M.; Zhu, T.; Austefjord, H.; Bitner-Gregersen, E. Assesment of global wave datasets for long term response of ships. In Proceedings of the ASME 2020 39th International Conference on Ocean, Offshore and Arctic Engineering OMAE 2020, Fort Lauderdale, FL, USA, 28 June–3 July 2020.
9. Perrault, D.E. Probability of Sea Condition for Ship Strength, Stability, and Motion Studies. *J. Ship Res.* **2021**, *65*, 1–14. [CrossRef]
10. Schirmann, M.L.; Collette, M.D.; Gose, J.W. Significance of wave data source selection for vessel response prediction and fatigue damage estimation. *Ocean. Eng.* **2020**, *216*, 107610. [CrossRef]
11. Vettor, R.; Guedes Soares, C. Assessment of the Storm Avoidance Effect on the Wave Climate along the Main North Atlantic Routes. *J. Navig.* **2016**, *69*, 127–144. [CrossRef]

12. Jensen, J.J.; Mansour, A.E.; Olsen, A.S. Estimation of ship motions using closed-form expressions. *Ocean. Eng.* **2004**, *31*, 61–85. [CrossRef]
13. Ghaemi, M.H.; Olszewski, H. Total ship operability -review, concept and criteria. *Pol. Marit. Res.* **2017**, *24*, 74–81. [CrossRef]
14. Katalinić, M.; Parunov, J.; Mikulić, A. Toward operability analysis of a passenger ship in the Adriatic Sea based on the JONSWAP-Adriatic wave spectrum. In Proceedings of the XXIV Symposium Theory and Practice of Naval Architectures (SORTA 2020), Malinska, Croatia, 15–17 October 2020.
15. Petranović, T.; Katalinić, M.; Mikulić, A.; Parunov, J. Operability study of passenger ship in the Adriatic Sea using hindcast database. In Proceedings of the 8th International Conference on Marine Structures (MARSTRUCT 2021), Trondheim, Norway, 7–9 June 2021.
16. Katalinić, M.; Parunov, J. Comprehensive Wind and Wave Statistics and Extreme Values for Design and Analysis of Marine Structures in the Adriatic Sea. *J. Mar. Sci. Eng.* **2021**, *9*, 522. [CrossRef]
17. Katalinić, M.; Ćorak, M.; Parunov, J. Optimized Wave Spectrum Definition for the Adriatic Sea. *Naše More* **2020**, *67*, 19–23. [CrossRef]
18. DNV GL. *Recommended Practice DNVGL RP C-205: Environmental Conditions and Environmental Loads*; Edition August 2017; Det Norske Veritas Germanischer Lloyd: Oslo, Norway, 2017.
19. Lloyd, A.R.J.M. *Seakeeping: Ship Behaviour in Rough Water*; Gosport: Hampshire, UK, 1998.
20. Scamardella, A.; Piscopo, V. Passenger ship seakeeping optimization by the Overall Motion Sickness Incidence. *Ocean. Eng.* **2014**, *76*, 86–97. [CrossRef]
21. DNV GL. *Class Guideline DNVGL CG 0130: Wave Loads*; Det Norske Veritas Germanischer Lloyd: Oslo, Norway, 2018.
22. Mansour, A.; Liu, D. *The Principles of Naval Architecture Series: Strength of Ships And Ocean Structures*; The Society of Naval Architects and Marine Engineers: Jersey City, NJ, USA, 2008; pp. 4–56.
23. Katalinić, M.; Parunov, J. Uncertainties of Estimating Extreme Significant Wave Height for Engineering Applications Depending on the Approach and Fitting Technique—Adriatic Sea Case Study. *J. Mar. Sci. Eng.* **2020**, *8*, 259. [CrossRef]
24. Mansour, A.E.; Preston, D.B. Return periods and encounter probabilities. *Appl. Ocean. Res.* **1995**, *17*, 127–136. [CrossRef]
25. Mikulić, A.; Katalinić, M.; Ćorak, M.; Parunov, J. The effect of spatial correlation of sea states on extreme wave loads of ships. *Ships Offshore Struct.* **2021**, *16* (Suppl. S1), 22–32. [CrossRef]
26. Ćorak, M.; Parunov, J.; Guedes Soares, C. Long-term prediction of combined wave and whipping bending moments of container ships. *Ships Offshore Struct.* **2015**, *10*, 4–19. [CrossRef]
27. Jiao, J.; Ren, H.; Guedes Soares, C. A review of large-scale model at-sea measurements for ship hydrodynamics and structural loads. *Ocean. Eng.* **2021**, *227*, 108863. [CrossRef]
28. Mudronja, L.; Katalinić, M.; Vidan, P.; Parunov, J. Route planning based on ship roll in numerically modelled heavy seas. In Proceedings of the XXII Symposium Theory and Practice of Naval Architectures (SORTA 2016), Trogir, Croatia, 6–8 October 2016.
29. World Meteorological Organization. *Guide to Wave Analysis and Forecasting*; Secretariat of the World Meteorological Organization: Geneva, Switzerland, 1998.
30. Lavidas, G.; Venugopal, V. Wave energy resource evaluation and characterisation for the Libyan Sea. *Int. J. Mar. Energy* **2017**, *18*, 1–14. [CrossRef]
31. Mansour, A.E.; Wasson, J.-P. Charts for Estimating Nonlinear Hogging and Sagging Bending Moments. *J. Ship Res.* **1995**, *39*, 240–249. [CrossRef]
32. Mansour, A.E.; Jensen, J.J. Slightly Nonlinear Extreme Loads and Load Combinations. *J. Ship Res.* **1995**, *39*, 139–149. [CrossRef]