Comparison of Present Wave Induced Load Criteria with Loads Induced by an Abnormal Wave

C. Guedes Soares, N. Fonseca, R. Pascoal

Unit of Marine Engineering and Technology, Technical University of Lisbon,
Instituto Superior Técnico
Av. Rovisco Pais, 1049-001 Lisboa, Portugal
{guedess, nfonseca, rpascoal}@mar.ist.utl.pt

Abstract.

In this work, values determined from existing design load criteria are compared with loads determined by a first principles based method that has the novelty of using a wave trace including an abnormal wave from a real field measurement. A time domain seakeeping code is used in the linear and non-linear variants to solve the equations of motion and assess the structural loads for oceangoing vessels. Linear and nonlinear calculations are compared in time domain for the S-175 containership with speed of advance. Nonlinear time domain computations are compared with experimental results from physical model tests with a moored FPSO. For both, the S-175 and the FPSO, probability domain comparisons are made between long-term probability distributions, experimental results and minimum rule requirements. The uncertainty associated even with methodologies strongly based on first principles is also discussed.

1 Introduction

In order to build safer and more cost efficient ocean structures, there should be a continuous strive to increase the confidence level at all stages of design. One of the major sources of uncertainty are the loads themselves and therefore a complementary method is sought and compared with existing criteria.

The more traditional design criteria originate in some kind of statistical analysis of existing data or a probability based methodology that attempts to replicate this type of analysis. Statistical analysis is possible and useful when there are existing data that can characterize the wave loads within a desired confidence level. This means that, when compared to the vessels from which the data sets have originated, the new design should not have significant specificity of any type, be it for instance on the hydrodynamic behavior, climatology it must encounter or cargo distributions. In order to be useful, appropriate low order multivariate regression models are derived. The result of this methodology is easiest to use because it omits the analysis steps and can provide intuitive and pragmatic relations between wave loads and vessel main particulars for instance. Rules minimum values are a good example of this more pragmatic approach that can easily provide starting values in the design spiral.

More direct analysis depends on determining long-term distributions based on calculations with an underlying principle of linearity of responses. The main hydrodynamic calculations are then performed in the frequency domain and after the needed estimators are calculated, appropriate probability distributions are used to determine the design value at the desired probability level, sometimes referred to a return value. Probably the most common form of this calculation is the long-term distribution determined as the sum of linear short term distributions ([1], [2]). The short term distributions are determined for each seastate of interest and the weighted sum gives the result for any return period. All seastates may be used or just those over a certain threshold.

Some variants of the probability based calculation aim to further simplify the procedure by reducing the number of calculation steps. As examples of such there is the use of a design seastate and also the environmental contour line method ([3]). Attention should be given however, to the fact that these seastates must be carefully chosen or else it can give bad estimates. For instance in case of a system with a very narrow band response, the worst loads may not be at the more energetic seastate but at one with a different period. Other variants attempt to explicitly include the nonlinearity due to vessel hydrodynamic response, as for instance in [2] and [4] by the use of form functions to correct for the nonlinearity, or more recently by direct use of nonlinear pseudo transfer functions as in [5].

Here, following previous work on the subject ([6], [7], [8] and [5]), it is proposed that measured sea surface elevations containing abnormal wave events become data for advanced time domain codes and the result from these be used in parallel with current design procedures, making it possible to assess if design load values are reasonable and to alert for problems. This methodology arises because there is an understanding that current design procedures do not account for abnormal wave events and available data can be used directly to eliminate the need for heavy data fitting, with all the problems that can arise. Easily, data fits will include failure to acknowledge the existence of special events such as is the case of abnormal waves, which have come to be considered as an important design survival case (see [9]). Furthermore, this method makes way to assess a whole new design with more confidence and detail.

The variability of results deriving from the uncertainty in climate, from different approaches to perform first principles hydrodynamic calculations, etc, may be alleviated if deterministic weather traces, which may include waves and other meteorological data, also have to be used to assess a design, at least as better assurance that the vessel survives such a combination.

2 Time Domain Seakeeping Code

2.1 General Description

The seakeeping code used in this investigation is based on a time domain formulation and the hydrodynamic forces are represented by a strip theory approach. The method assumes that the nonlinear contribution to the vertical bending moment is dominated by hydrostatic and Froude-Krilov forces and therefore these components are calculated over the instantaneous hull wetted surface. Radiation and diffraction forces are linear. Green water loads on the deck, which contribute to the calculation of motions and global loads, are represented by the momentum method.

The exciting forces due to the incident waves are decomposed into a diffraction part and the Froude-Krilov part. The diffraction part, which is related to the scattering of the incident wave field due to the presence of the moving ship, is kept linear. Since this is a linear equation and the exciting waves are known a priori, it can be solved in the frequency domain and the resulting transfer functions be used to generate a time history of the diffraction heave force and pitch moment. The Froude-Krilov part is related to the incident wave potential and results from the integration at each time step of the associated pressure over the wetted surface of the hull under the undisturbed wave profile.

The hydrostatic force and moment are calculated at each time step by integration of the hydrostatic pressure over the wetted hull under the undisturbed wave profile. The radiation forces, which are calculated using a strip method, are represented in the time domain by infinite frequency added masses, radiation restoring coefficients (which are zero for the zero speed case), and convolution integrals of memory functions. The convolution integrals represent the effects of the whole past history of the motion accounting for the memory effects due to the radiated waves.

The vertical forces associated with the green water on deck, which occurs when the relative motion is larger than the free board, are calculated using the momentum method. The mass of water on the deck is proportional to the height of water on the deck, which is given by the difference between the relative motion and the free board of the ship.

A detailed presentation of this solution to the hydrodynamics problem is given in [10] and [11].

2.2 Code validation for ships with forward speed

In order to perform code validation for vessels with speed of advance, a segmented and instrumented model of the S-175 containership has been subject to extensive experimental tests at El Pardo seakeeping basin. The model was sectioned at ¼ and ½ L_{pp} from the forward perpendicular in order to measure the cross sectional loads at these positions and subject to regular and irregular wave trains. Table 1 presents the ship main particulars and figure 1 shows the model whilst undergoing tests at the basin. In [12] and [13] are presented details of this experimental program and the analysis of results, while some of the comparisons with numerical results are reproduced here.

S-175 Containership		
Length betw. perp.	$L_{pp}(m)$	175.0
Beam	$B(m)$	25.40
Draught	$T(m)$	9.50
Displacement	$\Delta(ton)$	24742
Long. posit. of CG	$LCG\ (m)$	-2.43
Pitch rad. of gyr.	K_{yy}/L_{pp}	0.24

Table 1 S175 main particulars

Figure 1 to Figure 3 present some results of the experimental program plotted together with the results of the numerical simulation using the aforementioned time domain code. These are results for the vessel advancing at a Froude number of 0.25 in an irregular seastate with significant wave height of 6.13m and a peak period of 11.5s.

Figure 1 presents the empirical cumulative distribution function for positive and negative maxima of the heave motion. Very good general agreement is found, with the numerical model, as compared with the experiments, having slightly overestimated the number of larger positive and negative peaks. Opposite behavior is found for the smaller peaks.

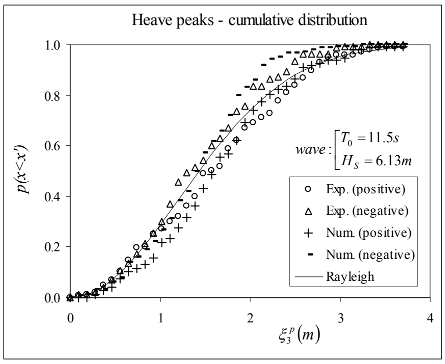

Figure 1 Empirical cumulative distribution function for heave motion maxima at Fn = 0.25.

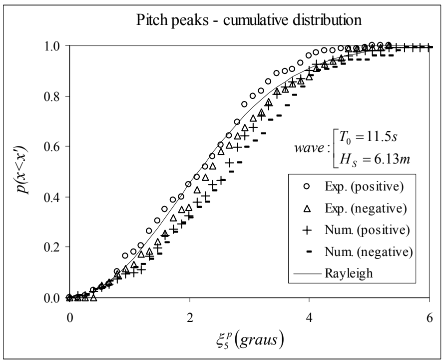

Figure 2 Empirical cumulative distribution for pitch motion maxima at Fn = 0.25.

The results for pitch, represented in Figure 2, show that the numerical model slightly underestimated the number of pitch peaks over most of the range. The underestimation in pitch may have a direct explanation by considering that 3D flow effects are not taken into account in the numerical code and thus any higher order moment of the pressure loads amplify the effects of this simplification. In this case the simplification probably resulted in a lower pitching moment due to 3D effects at the vessel fore and aft ends.

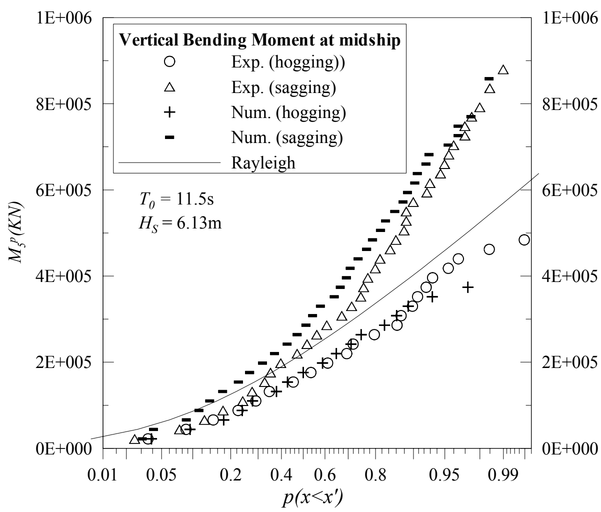

Figure 3 Vertical Bending Moment at Fn = 0.25.

Figure 3 shows the vertical bending moment cumulative distribution function for the midship section. Hogging peaks from the experiments and numerical results are in excellent agreement, the sagging peaks are in very good agreement with the code slightly underestimating the number of values below a given level.

3 Simulation of Abnormal Wave Records and Time Domain calculations

In order to conduct experiments with abnormal waves, they must be generated within the test area. The Technical University of Berlin (TUB) has developed the necessary software for numerical processing of real wave records and the adequate control laws to use the processed data to generate them within a test basin ([14], [15] and [1516]). TUB's test basin has been used to perform experiments with zero speed of advance.

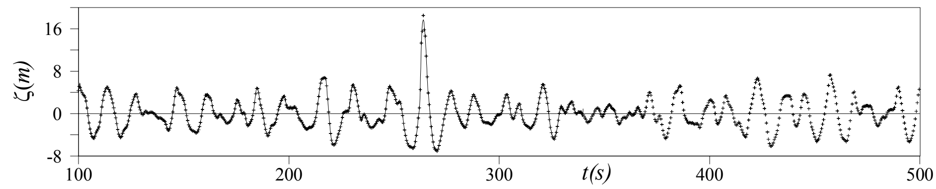

Figure 4 Time trace with 4 minutes duration using the 100 largest harmonics superimposed with the original trace (symbols).

Real data can also be numerically processed in such a way that it provides high level inputs for time domain codes such as the one described herein. Draupner "New Year Wave" time trace, which has been reported the first time in [17], has been processed using an FFT algorithm and the most important harmonic components have been used within the time domain code in such a way that, to a desired degree of approximation, the numerical model of the vessel is subject to the same wave time trace as in the tank. In order to have a spatial description of the wave field, a deep water wave dispersion relation has been used in the numerical simulation. It is important to stress that only the wave elevation at a fixed point in space has been verified at this time, because no other wave kinematics has been recorded. In Figure 4 is an example of how the numerical code uses a prescribed number of harmonics to adequately reproduce the wave trace. All calculations have assumed long crested head waves.

4 S175 Containership in the "New Year Wave"

A time domain calculation has been performed specifically for the S-175 advancing over the "New Year Wave" time trace at a reduced ship speed of 13 knots. There exist no experimental results for this specific trace, but the numerical code has shown good estimation with the previous tests so it is expected that results are at least qualitative. The numerical simulation was carried out using the non-linear and linear versions of the numerical code and it is possible to see in Figure5 that linear code fails to account for on-off events related to greenwater and for the memory effects resulting thereof. The bending moment determined from the non-linear code shows the effect of a strong greenwater event as the vessel passes the large crested wave and plunges into the trough and the next incoming crest.

Table 2 presents the results of rule minimum requirements, linear and non-linear long-term distributions calculated with the same procedure as in [5], calculated for European Area 8 (see [18]) and for the 1E-8 probability level, along with the absolute maximum hogging and sagging bending moments in the "New Year Wave" time trace. Very large disparity is found even though the same hydrodynamic code has been used, but it is evident that the first principles based methodologies estimate that the sagging bending moment will be larger than minimum requirements, anywhere from 1.5 to 2.7 times.

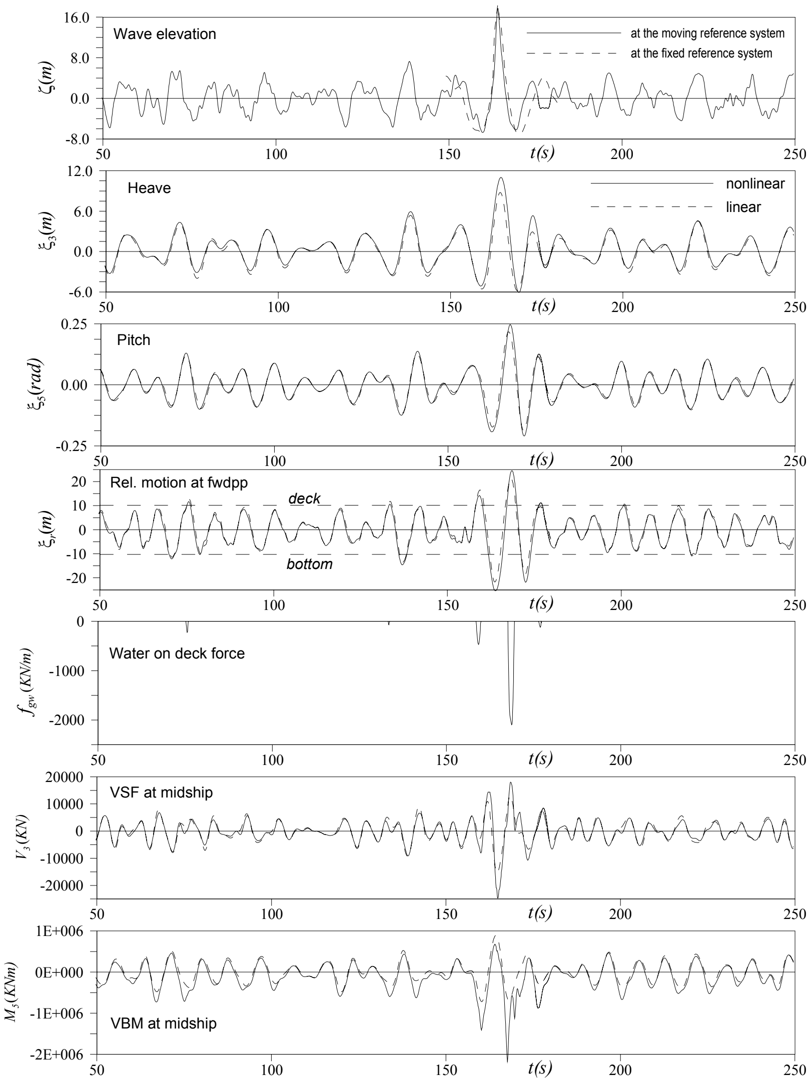

Figure 5 Time domain simulations for the "New Year Wave" at Fn = 0.16.

	Sagging [GNm]	Hogging [GNm]	Sagging normalized by Rule Value [-]	Hogging normalized by rule value [-]
Linear $\left(p = 10^{-8}, 20 \text{ years}\right)$	1.504	1.504	1.48	1.91
Nonlinear $\left(p = 10^{-8}, 20 \text{ years}\right)$	2.73	-	2.69	-
Rules minimum	1.0163	0.7879	1.0	1.0
New Year Wave	2.1796	0.6758	2.14	0.86

Table 2 Values of bending moment determined from several procedures.

The fact that long term distribution calculations give significantly larger vertical bending moments than rule values have been identified before (see [19] for instance). What is interesting to note here is that is that the maximum bending moments in this extreme wave are lower than those from the non-linear long term distribution. Since both results are based on calculations from the same nonlinear time domain code, the conclusion seems to be that during its operational life time the ship will encounter wave conditions (non abnormal) that result in larger bending moments than those induced by the "New Year Wave"

4 FPSO in the "New Year Wave"

This section presents some results for a FPSO ship, which include experimental data and time domain simulations in the "New Year Wave" trace, linear and nonlinear long term distributions and rule values.

A model of the FPSO has been subject to experimental tests at TUB's test tank. The model was sectioned at ¼ and ½ L_{pp} from the forward perpendicular in order to measure cross sectional loads at these positions. The vessel main particulars are given in Table 1. Details of the experimental program, the complete set of experimental data and comparisons with numerical results have been presented in [5]. This section presents a couple of graphs from those publications.

Some results of the experimental campaign and the corresponding numerical simulations for the moored vessel excited by a replica of the "New Year Wave" time trace are plotted in Figure6. It can be observed that the general agreement is very good, with the numerical code slightly underestimating the motions and presenting a phase advance. Because the model had the possibility of rolling and the measurement methodology is ideal for heave-pitch only, the experimental heave motion measurement may have been lightly corrupted and thus the large difference at some points with no special particularity, such as between 500 and 550s. As for the bending moment, very good agreement is achieved with the only relevant mismatch being found around the very large wave.

There was also simulation of the "New Year Wave" such that it occurred at different longitudinal positions relative to the vessel's midship section. These results are presented in Figure 7 and it is observed that with these different positions of occurrence, interestingly enough, there is no significant change of the maximum values of the bending moment.

280m FPSO		
Length between perp.	$L_{pp}(m)$	259.8
Beam	$B(m)$	46
Draught	$T(m)$	16.67
Displacement	$\Delta(ton)$	174000
Block coefficient	C_b	0.87

Table 1.- Main particulars of the FPSO vessel.

Table 4 presents results from the linear and non-linear long-term distributions for the 1E-8 probability level, together with the maximum values of bending moment from the "New Year Wave" simulation, and the rules minimum requirement. The long-term distributions have been calculated for European area 8 ([18]) which encompasses the measurement point of the "New Year Wave".

For the FPSO the maximum bending moments in the "New Year Wave" are smaller than those required by the rules. Comparing the results in the New Year Wave with the long term distributions values, one concludes, again, that this abnormal wave will not induce the largest bending moment during the ship operational life time.

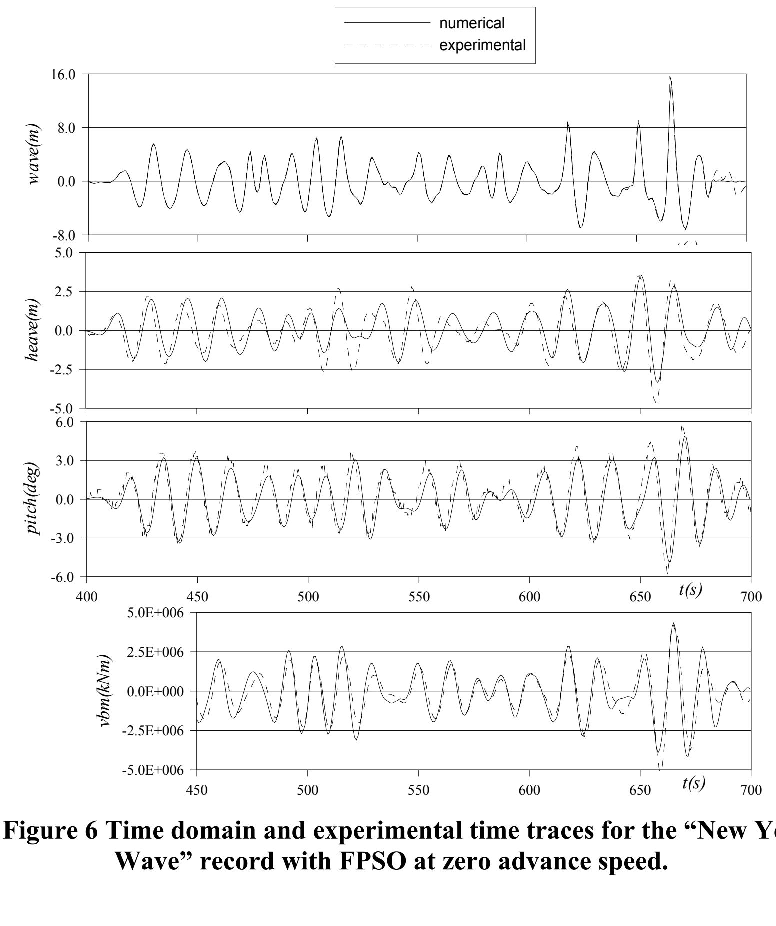

Figure 6 Time domain and experimental time traces for the "New Year Wave" record with FPSO at zero advance speed.

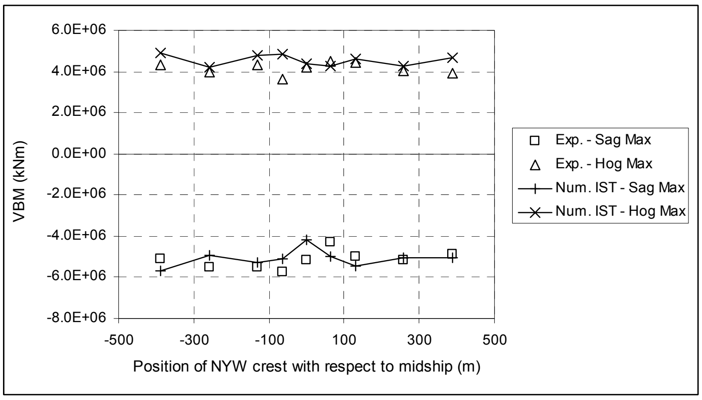

Figure 7 Maxima for different positions of occurrence of the "New Year Wave" relative to midship.

	Sagging [GNm]	Hogging [GNm]	Sagging normalized by rule value [-]	Hogging normalized by rule value [-]
Linear $\left(p = 10^{-8}, 20 \text{ years}\right)$	7.3	7.3	1.30	1.38
Nonlinear $\left(p = 10^{-8}, 20 \text{ years}\right)$	8.1	-	1.45	-
Rules minimum	5.6	5.3	1.00	1.00
New Year Wave	5.1	4.5	0.91	0.85

Table 2 Values of bending moment determined from several procedures.

5 Discussion and Conclusions

There is published material that has dealt with the various degrees of uncertainty arising from both the initial climate data and from the procedures themselves. In [20] it is reported that a 14% uncertainty in the final values of design bending moment due to use of different climates, while according to [19] a 15% variability in the final results arises simply from comparison of strip and panel methods and 9% if only strip theories are considered.

Here it has been shown that the uncertainty of first principles based design values is large, especially visible when comparing probability based calculations performed with linear and nonlinear pseudo transfer functions. It remains to establish the degree of detail to be included in the short term calculation such that the values can readily compare with the design values that the shipbuilding industry uses.

The direct time domain calculation for the S-175 containership estimates wave induced bending moments that are much larger than the rules minimum requirements, while the FPSO would survive this abnormal "New Year Wave" simply by having met the rules minimum requirements. It was noted earlier that long term distribution calculations give significantly larger vertical bending moments than rule for conventional ships. What has been concluded by this investigation is that such an extreme wave like the "New Year Wave" will not induce the largest bending moment for these two ship hulls during their operational lifetimes, although its relative effect is significantly different for the containership and FPSO.

Finally, it is considered that when data exists for a specific region and there are exceptional wave events, like the "New Year Wave", there should be an effort to evaluate the behavior and survival capability of structures that are being designed to cross or that will be fixed at the location, as if such an encounter were to happen. This method should then be taken to accompany the evolution of software in such a way that climate records become an integral part of the design stage.

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References

1. Fukuda, J., 1967, "Theoretical Determination of Design Wave Bending Moments", *Japan Shipbuilding and Marine Engineering*, Vol. 2, No. 3, pp. 12-22.
2. Guedes Soares, C., 1993, "Long-Term Distribution of Non-Linear Wave Induced Vertical Bending Moments", *Marine Structures*, Vol. 6, pp. 475-483.
3. Sagli, G. and Moan, T., 2001, "Application of Contour Line Method to Estimate Extreme Ship Hull Loads Considering Operational Restrictions", *Journal of Ship Research*, Vol. 45, No. 3, 228-240.
4. Guedes Soares, C. and Schellin, T. E., 1998, "Nonlinear Effects on Long-Term Distributions of Wave-Induced Loads for Tankers", *Journal of Offshore Mechanics and Arctic Engineering*, Vol. 120, nº 2, pp. 65-70.
5. Guedes Soares, C., Fonseca, N., Pascoal, R., Clauss, G.F., Schmittner, C.E. and Hennig, J., 2004, "Analysis of Wave Induced on a FPSO due to Abnormal Waves", *Proc. of OMAE Specialty Conference on Integrity of Floating Production, Storage& Offloading (FPSO) Systems*, Houston, TX.
6. Fonseca, N., Guedes Soares, C. and Pascoal, R., 2001, "Prediction of Ship Dynamic Loads in Ship in Heavy Weather", *Proceedings of the Conference on Design and Operation for Abnormal Conditions II (RINA)*, London, United Kingdom, pp. 169-182.
7. Guedes Soares, C., Fonseca, N and Pascoal, R., 2003, "An Approach for the Structural Design of Ships and Offshore Platforms in Abnormal Waves", *Proceedings of the Maxwave Workshop on Rogue Waves – Forecast and Impact on Marine Structures*, Geneva.
8. Clauss, G., Schmittner, C., Hennig, J., Guedes Soares, C., Fonseca, N. and Pascoal, R., 2004b, "Bending Moments of an FPSO in Rogue Waves", *Proceedings 23rd International Conference on Offshore Mechanics and Arctic Engineering (OMAE2004)*, paper OMAE2004-51504.

9. Faulkner, D. and Buckley, W. H., 1997, "Critical Survival Conditions for Ship Design", *Proceedings International Conference on Design and Operation for Abnormal Conditions*, RINA, paper no. 6, pp. 1-25.
10. Fonseca, N. and Guedes Soares, C., 1998a, "Time-Domain Analysis of Large-Amplitude Vertical Motions and Wave Loads", *Journal of Ship Research,* Vol. 42, nº 2, pp. 100-113.
11. Fonseca, N. and Guedes Soares, C., 1998b, "Nonlinear Wave Induced Responses of Ships in Irregular Seas", *Proceedings 17th International* Conference *on Offshore Mechanics and Arctic Engineering (OMAE'98)*, ASME, New York, paper OMAE 98-0446.
12. Fonseca, N. and Guedes Soares, C., 2004a, "Experimental Investigation of the Nonlinear Effects on the Vertical Ship Motions and Loads of a Containership in Irregular Waves", *Journal of Ship Research*, Vol. 48, No 2, June 2004, pp. 118-147.
13. Fonseca, N. and Guedes Soares, C., 2004b, "Experimental Investigation of the Nonlinear Effects on the Vertical Ship Motions and Loads of a Containership in Regular Waves", *Journal of Ship Research*, Vol. 48, No 2, June 2004, pp. 148-167.
14. Clauss, G., and Kühnlein, W., 1995. "Transient wave packets – an efficient technique for seakeeping tests of selfpropelled models in oblique waves". Proceedings Third International Conference on Fast Sea Transportation, pp. 1193–1204, Vol. 2.
15. Kühnlein, W., Clauss, G., and Hennig, J., 2002. "Tailor Made Freak Waves Within Irregular Seas", *Proceedings 21st International* Conference *on Offshore Mechanics and Arctic Engineering (OMAE2002)*, paper OMAE2002-28524.
16. Clauss, G., Hennig, J., Schmittner, C., and Kühnlein, W., 2004a. "Non-linear Calculation of Tailored Wave Trains for the Experimental Investigation of Extreme Structure Behaviour", *Proceedings 23th International* Conference *on Offshore Mechanics and Arctic Engineering (OMAE2004)*, paper OMAE2004-51195.
17. Haver, S. and Karunakaran, D.,1998, "Probabilistic description of crest heights of ocean waves", *Proceedings 5th International Workshop of Wave Hindcasting and Forecasting*, Melbourne, Florida.
18. Hogben, N., da Cunha, L.F. and Olliver, H.N., 1986, *Global Wave Statistics*, Brown Union London.
19. Guedes Soares, C., 1999, "On the uncertainty in long-term predictions of wave induced loads on ships", *Marine Structures*, Vol. 12, pp. 171-182.
20. Guedes Soares, C., 1996, "On the Definition of Rule Requirements for Wave Induced Vertical Bending Moments", *Marine Structures*, Vol. 9, pp. 409-425.
21. Guedes Soares, C., and Moan, T., 1991, "Uncertainty in the Long Term Distribution of Wave Induced Bending Moments for Fatigue Design of Ship Structures", *Marine Structures*, Vol. 4, pp. 294-315.