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Extrapolation of model tests measurements of whipping to identify the dimensioning sea states for container ships

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ABSTRACT

Whipping can contribute to increased fatigue and extreme loading of container ships, and guidelines have been made available by the leading class societies.

Reports concerning the hogging collapse of MSC Napoli and MOL Comfort suggest that whipping contributed. The accidents happened in moderate to small storms.

Model tests of three container ships have been carried out in different sea states under realistic assumptions. Preliminary extrapolation of the measured data suggested that moderate storms are dimensioning when whipping is included due to higher maximum speed in moderate storms.

This paper considers various extrapolation methods to investigate the uncertainty in the extrapolation methods and to see if all methods confirm that the moderate storms are dimensioning.

KEY WORDS: Whipping; Container ships; Model tests; Extrapolation; Extreme Value Prediction; Hydro-elasticity; Wave induced vibrations.

INTRODUCTION

Whipping is a sudden increase of the wave bending moment due to a wave impact. The rise time of the initial whipping peak amplitude is in the order of one second, i.e. half of the vibration period of the governing vertical 2-node vibration mode. High vertical and horizontal accelerations, associated with the whipping impact, may be easily felt by the crew, e.g. at the wheel house.

The initial whipping impact is followed by slowly decaying vibration cycles. The typical whipping events are caused by bow flare slamming, and the initial peak of the whipping occurs just a second or two before the peak of the wave induced sagging moment. It can therefore effectively increase the wave sagging moment. Due to the low damping, the vibrations will continue for many vibration cycles, in

some cases for more than a minute, and whipping may effectively also increase the peak of the wave hogging moment. Andersen (2014) has, however, shown that the whipping may apparently also start in the wave hogging phase in some storm events based on full scale measurements of container ships. This has earlier been demonstrated to occur in full scale and model tests for blunt ships (Storhaug, 2007). It is important that numerical tools cover all excitation sources and not only bow flare slamming.

A container ship is a slender ship with a large engine designed to achieve speeds above 20 knots at design draught at some sea margin and at less than 100% maximum continuous rating (MCR). It can therefore also achieve much higher forward speeds in moderate head sea storms than blunt ships. Container ships, especially the Post Panamax ships with high breadth, may be associated with high bow flare angles above 45°. This combination of high speed in head sea storms and high bow flare angles, may give high whipping response due to bow flare slamming. Andersen (2014) has shown that whipping may often double the dynamic wave bending moment in different full scale storm events. This does not directly imply that it may also double the design dynamic wave bending moment. The highest increase compared to the design wave bending moment, that has been measured so far, is 50% (Barhoumi and Storhaug, 2013) in way of the engine room bulkhead. The same increase amidships has been 25% (Storhaug, 2009, Barhoumi and Storhaug, 2013). None of these measurements refers to extreme storms and the latter two references refer to about 6 meter significant wave height (Hs) and bow quartering seas.

The container ships are hogging ships, i.e. the still water bending moment is typically a hogging moment. In design, it is therefore important to verify that the hogging collapse strength for container ships exceed the hogging moment, which is the sum of the permissible still water hogging moment and the design wave hogging moment. This check is referred to as the ultimate hull girder capacity check, which has been required by the leading class societies, but not all class societies.

In January 2007, the 4400TEU Post Panamax ship MSC Napoli broke in two in way of the engine bulkhead (about at the aft quarter length of the ship). In June 2013, the 8110TEU Post Panamax ship MOL

Comfort broke in two amidships. In both accidents, the progressive collapse started in the bottom plating, with direct relevance to the ultimate hull girder capacity check. The reports from the accidents suggest however that also whipping has been a contributing factor (MAIB 2008, NK 2014).

This has increased the industry concern regarding whipping, and some of the leading class societies has published voluntary guidelines for how to account for whipping in design of container ships. MAIB has also recommended IACS to look more into container ship rules, whipping and hull monitoring (MAIB 2008). IACS has responded by establishing a group, whose mandate is to propose new minimum requirements for container ships for all the class societies, to try to assist some of the class societies to upgrade their requirements to what is regarded as minimum by the leading class societies.

What is of particular interest in relation to MSC Napoli and MOL COMFORT is that both ships broke in moderate to small storms. MSC Napoli broke in head seas between 7 and 9 m Hs (Storhaug, 2009), while MOL COMFORT broke in bow quartering sea state of about 5.5 m Hs (NK, 2014). These are not extreme sea states. This justifies the question: What is the dimensioning sea state when whipping is included?

The question was raised even before MSC Napoli and MOL COMFORT broke. Model tests of three ships, 4400TEU, 8600TEU and 13000TEU, were carried out in the period of 2005 to 2011 in order to investigate the importance of whipping for both fatigue and extreme loading considering realistic moderate storms. The test duration in full scale in each sea state was typically 30-45 minutes, but also up to three hours. Considering a design wave environment, the duration of each sea state can be estimated. Storhaug (2014) used a Weibull extrapolation, based on a percentage of the highest responses. The results pointed towards 7 to 9 m Hs as dimensioning. It was however emphasized that there were uncertainties to the extrapolated results, and a more thorough study of this was recommended. This is the background for the current paper.

The measurement data for the three ships is reassessed using different extrapolation procedures to confirm if the conclusion derived by Storhaug (2014) is still holding. As concluded by Andersen (2014), no single extrapolation procedure is superior for all full scale data from different ships. The following methods are therefore considered: Gumbel fit from Weibull parameters, Peak-Over-Threshold (POT) and ACER including clustering effects. The codes differ from the code used by Storhaug (2014). The results from all estimates are compared.

THE THREE CONTAINER SHIP DESIGNS

The three container ships are all tested at Marintek in their 260 meter towing tank, implying head seas. All three models have flexible joints at the aft quarter length, midship and forward quarter length. The moments are also measured at these positions, but only the moment amidships will be considered in this paper.

Due to the model construction, the hull girder vibrates as a real ship. The 2-node vertical mode has the best fit, while the 3- and 4-node vertical mode is less accurate. The target natural frequencies are realistic for the vertical 2-node modes and are partly based on full scale measurements and partly based on numerical calculations with global finite element models. The 3-node and 4-node vertical modes are slightly too stiff. The ship speed in the different sea states are selected based on full scale measurements for the smallest ship, implying that voluntary seamanship is included, and numerical calculations for the

two largest ships, without voluntary seamanship.

The loading conditions are close to design draught. The smallest ship has a special design with a draught being less than typical, and is tested for a draught above design draught, which corresponds better to other ships of the same size. The hull lines for all three ships are designed by recognized and leading yards, and two of the ship designs are in operations, and possibly also the largest is delivered now.

Everything about the models and the test conditions are realistic, with one exception. The damping is slightly less than obtained by full scale measurements by Storhaug (2007) and Andersen (2014). The model test damping is about 0.6% for the smallest ship and about 0.9-1.0% for the larger ships. The real damping may be in the order of 1.5-2% of the critical damping. The damping affects the decay of the vibration, and may affect the level in a subsequent whipping event if this is in phase with the former whipping event (it may also cancel the former whipping if out of phase). The likelihood of this is small, but it may occur, and may be inherent in the data. For most whipping events in the sagging phase lower damping will give higher whipping response in the hogging phase because the decay is slower than it should be. A rough estimate based on the difference between 2% and 0.6% as an extreme case, based on a vibration period of 2 seconds and an encounter wave period of 10 seconds, would suggest a decay of 1% instead of 3% after 2.5 vibration cycles from the sagging phase to the hogging phase in case of 0.6% and 2% damping, respectively. A bit low damping suggests only a small overestimation, less than 2%, of the measured whipping peaks in hogging and thereby in the whipping response from the subsequent extrapolation. The error made due to a bit low damping in the model tests is then secondary to other uncertainties in e.g. the extrapolation method. In future model tests damping should however be added for container vessels (not for blunt vessels).

Further descriptions of the models are given by Drummen (2007), Storhaug et al (2010a) and Storhaug et al (2010b).

SHIPS CHARACTERISTICS

The main ship particulars of the three container ships are listed in Table 1.

Table 1 Ship characteristics and model properties

Property	4400 TEU	8600 TEU	13000 TEU
Length btw. perp., Lpp (m)	281	322.6	350
Breadth moulded, B (m)	32.26	45.6	48.2
Depth moulded, D (m)	21.50	24.6	29.85
Draught tested (m)	11.75	13.86	14.50
Mass tested (tons)	78571	128307	169692
2-node frequency (Hz)	0.56	0.48	0.48
3-node frequency (Hz)	1.31	0.99	0.91
4-node frequency (Hz)	2.04	1.77	1.48
Meas. pos. aft from AP (m)	80.4	90.98	106.24
Meas. pos. midship from AP (m)	150.6	155.68	178.44
Meas. pos. forw. from AP (m)	220.9	241.54	250.6
Scale of model	1:45	1:45	1:45
2-node critical damping for the model (%)	0.65	0.9	0.9
Design speed (knots)	23.1	28.6	28.6
Bow flare angle (°)	42.1	58.3	49.5

TESTED SEA STATES

The tested sea states are listed in Table 2 to Table 4 for the 4400, 8600, 13000TEU, respectively. The sea states are characterized by the significant wave height (Hs), zero up-crossing period (Tz) and peak period (Tp) and Jonswap peakness factor (γ). When γ is 1.0 the Jonswap wave spectrum is the same as Pierson-Moskowitz wave spectrum for fully developed sea. A higher γ refers to a more peaked sea state, which is regarded as steeper. The storms encountered and under development are often not fully developed and associated with a peakness factor above 1. As a rule of thumb, the average peakness factor is 2.0 for encountered sea states in real life, but good studies on this have not been found. A more peaked sea state has a tendency to produce higher whipping events, but this is also only a rule of thumb and depends also on the motions of the ship in the specific sea state. The tested sea states are not regarded as extreme when it comes to the peakness factor, and most may be less steep than normally encountered in real life.

The duration of the sea states is 30 to 45 minutes, while for sea state 14 and 17 in Table 4 covers at least 1.5 hours and sea state 18 in Table 4 covers at least 3 hours. From the three latter sea states, also uncertainties related to half hour sea states can be assessed.

For the largest ship in Table 4, the model test has been carried out based on a design speed which is about 4 knots higher than what has been actually delivered on such ships after the financial crisis (and higher oil prices).

Table 2 Sea states used for the 4400TEU ship

Sea state	Hs (m)	Tz (s)	Tp (s)	γ	Speed (knots)
1	3	7.5	10.6	1	22
2	3	9.5	13.4	1	22
3	3	11.5	16.3	1	22
4	3	13.5	19.1	1	22
5	5	7.5	10.4	1.5	20
6	5	9.5	13.4	1	20
7	5	11.5	16.3	1	20
8	5	13.5	19.1	1	20
9	7	7.5	9.5	5	16
10	7	9.5	13.4	1	16
11	7	11.5	16.3	1	16
12	7	13.5	19.1	1	16
13	9	7.5	9.5	5	12
14	9	9.5	12.8	2.3	12
15	9	11.5	16.3	1	12
16	9	13.5	19.1	1	12

Table 3 Sea states used for the 8600TEU ship

Sea state	Hs (m)	Tz (s)	Tp (s)	γ	Speed (knots)
1	3.5	7.5	10.5	1	27
2	3.5	9.5	13.3	1	27
3	3.5	11.5	16.1	1	27

4	3.5	13.5	18.9	1	27
5	5.5	7.5	10.5	1	24
6	5.5	9.5	13.3	1	24
7	5.5	11.5	16.1	1	24
8	5.5	13.5	18.9	1	24
9	7.5	7.5	10.5	1	20
10	7.5	9.5	13.3	1	20
11	7.5	11.5	16.1	1	20
12	7.5	13.5	18.9	1	20
13	9.5	7.5	10.5	1	15
14	9.5	9.5	13.3	1	15
15	9.5	11.5	16.1	1	15
16	9.5	13.5	18.9	1	15

Table 4 Sea states used for the 13000TEU ship

Sea state	Hs (m)	Tz (s)	Tp (s)	γ	Speed (knots)
1	3.5	7.5	10.5	1	27
2	3.5	9.5	13.3	1	27
3	3.5	11.5	16.1	1	27
4	3.5	13.5	18.9	1	27
5	5.5	7.5	10.5	1	24
6	5.5	9.5	13.3	1	24
7	5.5	11.5	16.1	1	24
8	5.5	13.5	18.9	1	24
9	7.5	7.5	10.5	1	20
10	7.5	9.5	13.3	1	20
11	7.5	11.5	16.1	1	20
12	7.5	13.5	18.9	1	20
13	9.5	7.5	10.5	1	15
14	9.5	9.5	13.3	1	15
15	9.5	11.5	16.1	1	15
16	9.5	13.5	18.9	1	15
17	11.5	9.5	13.3	1	10
18	11.5	11.5	16.1	1	10

EXTRAPOLATION PROCEDURE

The extrapolation is based on different extrapolation methods, but in all methods the basis for the extrapolation is the estimated duration of each sea states (tested) based on the probability of occurrence from the design scatter diagram. This is based on the relative amount of observations in particular sea state compared to all observations and based on a design life of 20 years at sea. The probability of head sea is also given the factor of 1/12. Both the design life of 20 years and the probability of 1/12 could be discussed but will not change the results significantly. The duration for a specific sea state in Eq.1 is thereby estimated as:

$$\text{Duration (in hours)} = \text{no. of obs.}/100000 \cdot 20 \cdot 365 \cdot 24/12 \quad (1)$$

The duration for the different sea states in Table 2 to Table 4 for the three container ships are given in Table 5 based on the North Atlantic scatter diagram (IACS, 2001).

Table 5 Duration (in hours) for the three ships and the tested sea states

Sea state	Duration for the 4400TEU ship	Duration for the 8600TEU ship	Duration for the 13000TEU ship
1	880.2	600.6	600.6
2	927.0	949.2	949.2
3	163.7	207.4	207.4
4	11.0	15.7	15.7
5	172.4	92.8	92.8
6	579.9	441.7	441.7
7	223.5	209.6	209.6
8	26.2	28.1	28.1
9	20.4	9.7	9.7
10	172.4	110.6	110.6
11	125.7	97.7	97.7
12	23.5	20.8	20.8
13	1.8	0.8	0.8
14	33.3	19.0	19.0
15	41.8	28.3	28.3
16	11.7	9.0	9.0
17	-	-	2.5
18	-	-	5.8

The extrapolation methods are briefly described in the following subsections.

Method 1: Weibull extrapolation of upper tail

This method is described and used by Storhaug (2014). Method 1 is regarded as the most simplified method and is based on one maximum (or minimum) between each up crossing with a Weibull fit to the 10 or 20% of the highest values in the tail for the total moment and 40% of the highest values for the wave moment. The mean caused by the forward speed or the nonlinearity in the response is not removed. This is however relatively small effects.

It has been discovered that the data provided for the 4400TEU ship has wrong sign convention from the definition of hogging being positive (as for the other two ships). The hogging data in Storhaug (2014) is thereby sagging data, and the data for the 4400TEU has been reassessed herein by changing the sign of the moments.

Method 2: Gumbel fit based on Weibull parameters

For method 2-4 only the wave induced response is considered i.e. the still water bending moment and static moment due to the forward speed of the model is removed. Low frequency contributions below 0.01 Hz and high frequency noise above 1.6 Hz are filtered away.

The peak value distribution for the wave-frequency and the total VBM including the high-frequency vibrations is fitted with the Weibull distribution using all the positive (hogging) peaks. The standard Weibull probability distribution function is given by:

$$F(x, a, c) = 1 - \exp(-(x/a)^c) \quad (2)$$

A special case of the Weibull distribution is the exponential distribution, where $c = 1$. As found from full scale measurements in Andersen (2014) the peaks are nearly exponentially distributed as the Weibull parameter c is close to 1 in most cases. The Weibull parameter a and c are derived from the Weibull fit to the data using the Matlab WAFO package (Brodtkorb et al., 2011) as illustrated in Figure 1.

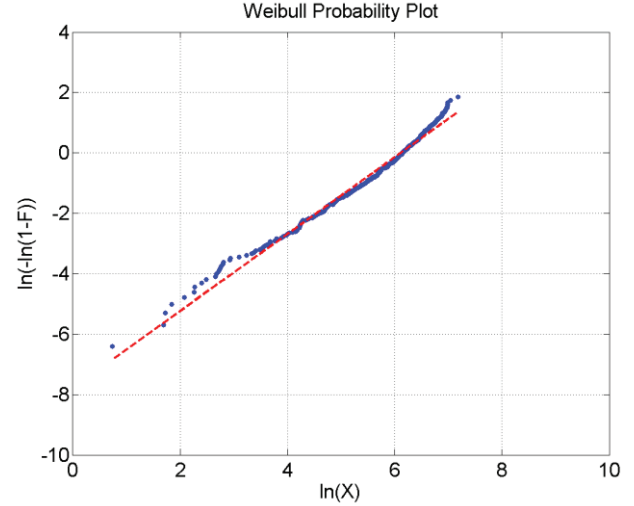


Figure 1 Weibull probability plot for the hogging bending moment including whipping. 4400TEU model in sea state 1.

When the individual peak distribution follows a Weibull distribution, the extreme peaks asymptotically follow a Gumbel distribution. The Gumbel distribution function is given by:

$$F(x, b, d) = \exp(-\exp(-(x-b)/d)) \quad (2)$$

Using the Weibull parameters a Gumbel fit can be derived for the prediction of the extreme values in the tail, i.e. the distribution of the largest peak among n peaks. The most probable largest value, the Gumbel parameter b , is found from the Weibull parameters for the individual peak distribution c.f. Soares and Teixeira (2000):

$$b = a^c \sqrt{\ln(n)} \quad (3)$$

Similarly, the Gumbel parameter d is found from:

$$d = \frac{a}{c} [\ln(n)]^{1/c-1} \quad (4)$$

Method 3: Peak over threshold (POT) and Gumbel fit

A widely used procedure for estimation of the distribution of extreme values is the peak-over-threshold (POT) method. The method assumes that the peaks in the tail of the distribution occur approximately randomly and independently of each other even though, for whipping events, this may not truly be the case. Different probability distributions can be fitted to the peaks over the threshold. Provided the excess over a given threshold is exponentially distributed, the extreme distribution becomes the Gumbel distribution with parameters defined by the exponential distribution. In this paper, the Gumbel distribution is assumed to be the appropriate extreme value distribution, but other

distributions such as the Generalized Extreme Value distribution could possibly also be applied.

The Gumbel parameter d is determined from an exponential fit to the excess of the threshold level, u . The threshold is set to 50% of the average of the three largest peaks in each time series. d is the mean of the peaks over the threshold, and if c is exactly 1 then $d = a$ from the Weibull distribution.

Method 4: ACER-metod

As described previously, the peak-over-threshold method assumes that the peaks occur randomly and independently of each other. In real life, this is not the case and the peaks will be somehow clustered for each whipping event. Naess and Gaidai (2009) have developed a method for extreme value estimation based on sampled time series. The method accounts for the statistical dependence between the peaks in a time series of measured data points. The procedure has been generalised to take into account up to five preceding peaks and is denoted the ACER (Average Conditional Exceedance Rate) method (Naess and Gaidai, 2009). The ACER program is provided by NTNU¹. Here $k = 2$ is used meaning that one preceding peak is removed. In addition to the removal of some statistically dependent peaks, Naess and Gaidai (2009) also fit the numerical distribution with an analytical distribution of the form:

$$F(x, q, r, s, t) = q \exp(-r(x-s)^t), \quad x > s \quad (5)$$

guided by the expected Gumbel type of asymptotic extreme value distribution of the response. Naess and Gaidai (2009) use a fitting procedure for determination of the parameters q , r , s and t . This fitting procedure removes the largest peaks where the uncertainty is highest.

The ACER procedure is aimed at providing an accurate estimation of the return period rather than a global extreme value distribution. However, in order to facilitate the comparison with the previous extreme value predictions using the Weibull and POT procedures the results from the optimised ACER functions are transformed into the Gumbel distribution (Eq. (2)). Linearization is carried out around the most probable largest value $x = b$ and the Gumbel parameters b and d are derived from the ACER parameters:

$$b = s + t \sqrt{\frac{1}{r} \ln(nq)} \quad (6)$$

Similarly, d can be found from (see Andersen (2014) for details):

$$d = t^{-1} r^{-1/t} (\ln(nq))^{1/t-1} \quad (7)$$

The Gumbel in method 2-4 are thus derived for the largest peak among n peaks. For the Gumbel distribution, the distribution of the largest peak among N peaks becomes:

$$F_N(x) = F_n(x)^{N/n} \quad (8)$$

With the most probable largest value b_N :

$$b_N = b_n + d_n \ln(N/n) \quad (9)$$

¹ <http://folk.ntnu.no/karpa/ACER/>

Eq. (9) is used for the extrapolation from the model tests to the durations given in Table 5. The limitation of using the Gumbel distribution is that the time duration should be sufficiently large so that the number of peaks, n , is large. Here, the runs carried out in sea states 1-14 are rather short which may give rise to uncertainties, particularly when extrapolating to the long time periods in Table 5.

EXTRAPOLATED RESULTS

The extrapolated results for each tested sea state are given for the hogging moment amidships with and without whipping, referred to as total and wave hogging moment, respectively. The extrapolated results are based on the duration in North Atlantic as given in Table 5 and as indicated in Eq.1. The results of the extrapolated results for the total hogging moment are shown in Table 6 to Table 8 for the three ships, respectively. Similar results are shown for the wave hogging moment in Table 9 to Table 11 for the three ships, respectively.

The extrapolated results in this paper may also be compared to the observed maximum values from the measured time series for the total hogging moments with whipping (and without the still water hogging) as given in Storhaug (2014). The observed maximum values were based on test duration of 30 minutes to 3 hours for the different sea states. Only the highest sea states, 13, 17 and 18, have extrapolated target duration which is close to the test duration (maximum 3 hours). For all other sea states it should be expected that the extrapolated results should be larger than the maximum observed values from the limited tested durations. It becomes inconveniently expensive to test all sea states for their relevant duration. Therefore extrapolation is necessary and the accuracy of the extrapolation method is important.

The uncertainty related to the short test duration (not to the statistical method) of half hour is illustrated by Storhaug et al (2010b). The longest tested sea state of 3 hours (sea state 18 of the 13000 TEU ship) where split into 6 half hours tests. The standard deviation was 10.6% of the mean value. The 95% confidence interval is then within the mean value \pm two times the standard deviation assuming a normal distribution, i.e. the extrapolated result could be also related to a 21% uncertainty, which is substantial. The maximum observed value during 3 hours is 13986MNm. The average extrapolated value from the 4 methods for duration of 5.8 hours is 13210, i.e. 5.5% below the maximum observed value.

Generally, it has been observed that the total moments are larger than the wave moments by a significant margin, however in some sea states with low contribution of whipping it may happen that the extrapolated wave hogging moment exceeds the extrapolated total moment, due to the specific single "extreme" whipping events and uncertainties in extrapolation. This is however rare.

It is also observed that the 8600TEU ship has higher whipping contribution than the two other ships with more moderate bow shapes. Also the 13000TEU has a tendency of more whipping contribution, but there are some single high whipping events also for the 4400TEU ship.

Sea state 10 has the highest total moments for the 4400TEU ship for three of the methods. This sea state refers to 7 m Hs. Sea state 10, with 7.5 m Hs, has the highest total moment for the 8600TEU ship from three of the methods. Sea state 11, with 7.5 m Hs, has the highest total moment for the 13000TEU ship for 2 of the methods, while for the third method 11 and 14 (with 9.5m Hs) are equivalent. The moderate sea states are therefore still regarded as dimensioning as suggested by the simplest method 1 by Storhaug (2014).

There are also uncertainties to the extrapolated values related to the short durations of the tested sea states and the effect of the voluntary speed reduction as well as the wave quality and variation of the speed in a single sea state. The natural variation of the speed is not reflected by the towed tests.

Table 6 Total moment based on the different extrapolation methods for the 4400TEU ship

Sea state	Total method 1 (MNm)	Total Method 2 (MNm)	Total method 3 (MNm)	Total method 4 (MNm)
1	1642	3738	2721	2047
2	3077	4740	3020	2584
3	1928	3574	2938	2610
4	1210	2434	2082	1748
5	2517	5650	4389	3980
6	3896	6155	5864	4312
7	2615	5208	4948	4983
8	3583	4077	3595	2857
9	5923	5106	6168	5159
10	5973	8360	7926	7761
11	4260	8757	6371	6227
12	2895	5675	4650	3832
13	3975	4973	4843	4767
14	4778	9781	7274	6209
15	4624	8579	6758	5223
16	3805	6705	5660	4685

Table 7 Total moment based on the different extrapolation methods for the 8600TEU ship

Sea state	Total method 1 (MNm)	Total Method 2 (MNm)	Total method 3 (MNm)	Total method 4 (MNm)
1	1611	4913	4104	3330
2	4284	8024	6722	5267
3	3267	8412	5372	4939
4	1897	4806	4295	3833
5	4706	7687	6487	6145
6	9083	12003	11849	1086
7	6724	10566	10654	9537
8	3813	8702	6400	5633
9	8032	7485	9614	8839
10	18925	15921	19310	16074
11	11244	19310	14241	13795
12	7553	14241	9857	9707
13	7823	8577	8523	8772
14	17600	16357	17689	14540
15	13290	17033	15098	15996
16	8915	11467	10161	9216

Table 8 Total moment based on the different extrapolation methods for the 13000TEU ship

Sea state	Total method 1 (MNm)	Total Method 2 (MNm)	Total method 3 (MNm)	Total method 4 (MNm)
1	3413	7322	4984	4600
2	6462	9203	6807	6032
3	4293	9849	6886	5710
4	4759	7031	5929	6039
5	4411	7099	6236	5816
6	7995	11180	10141	7882
7	6750	13951	9934	8030
8	5896	10998	7362	6917
9	5503	9699	7421	6651
10	9183	17825	14237	11676
11	14789	15474	14872	14921
12	8860	13990	10524	8856
13	8168	10099	9792	10168
14	12500	16459	14987	14078
15	10771	16885	14662	14538
16	10072	15442	12982	10558
17	12389	15517	14004	12968
18	13939	15305	12107	11490

Table 9 Wave moment based on the different extrapolation methods for the 4400TEU ship

Sea state	Wave method 1 (MNm)	Wave Method 2 (MNm)	Wave method 3 (MNm)	Wave method 4 (MNm)
1	1606	4759	2594	1895
2	2218	3326	2978	2532
3	2007	2808	2899	2574
4	1292	2524	2111	1667
5	2361	4296	4352	3293
6	3150	4480	5053	4132
7	2876	4738	4604	3797
8	3278	4054	3378	2764
9	3930	5082	4186	3701
10	4461	7926	6597	5666
11	4328	5764	6103	4397
12	3172	4052	4482	3740
13	2983	3759	3337	3170
14	4248	6947	6734	4658
15	4638	5975	6574	5207
16	3751	5119	5336	3964

Table 10 Wave moment based on the different extrapolation methods for the 8600TEU ship

Sea state	Wave method 1 (MNm)	Wave Method 2 (MNm)	Wave method 3 (MNm)	Wave method 4 (MNm)
1	1777	3643	2744	2350
2	1808	4096	5024	4066
3	2119	5905	4748	4161
4	1626	3939	3358	3131
5	2936	5038	3854	2935
6	3911	6214	6187	4740
7	3973	8092	5702	5390
8	2207	4786	5330	4025
9	3241	5024	5045	5459
10	6287	7297	7162	7745
11	5051	9022	8491	6162
12	4878	7937	7075	6521
13	3207	5360	4510	4086
14	7358	8723	8643	7596
15	6345	10168	8410	8337
16	6290	7422	7736	7705

Table 11 Wave moment based on the different extrapolation methods for the 13000TEU ship

Sea state	Wave method 1 (MNm)	Wave Method 2 (MNm)	Wave method 3 (MNm)	Wave method 4 (MNm)
1	1911	3876	3967	2620
2	4148	6933	6024	4164
3	3868	7344	6396	5571
4	3764	5356	5127	5284
5	2924	5283	5008	4067
6	5974	9050	9245	7938
7	5296	16628	9712	7614
8	4782	7380	6946	5709
9	4250	7082	5737	5376
10	7501	12107	11270	8293
11	9544	12402	12445	9702
12	6471	9769	9491	7702
13	5746	6017	6445	7131
14	7320	12005	10882	8105
15	7791	13517	11568	8789
16	6986	19977	10540	8062
17	7637	11972	9191	8014
18	9576	10744	9010	8361

The results for the four methods are graphically illustrated in Figure 2 for the total hogging moment of the 4400TEU ship. The average normalized standard deviation for the 16 sea states is 0.24. A number of

0.24 is considerable. This suggests that it is necessary to be careful when selecting an extrapolation method to be used as basis for design values. The y-axis in Figure 2 is normalized with the rule hogging moment (IACS URS11). Method 1 has been used previously to estimate design values, and this also displays the lowest ratio (1.79). Method 3 and 4 show slightly higher and equivalent estimates and method 2 shows a much higher estimate (2.92). The wave hogging moment is not displayed, since it shows similar variation between the methods with an average normalized standard deviation for of 0.21. Sea state 10 is most important for method 1, 3 and 4, while sea state 14 is most important for method 2.

Figure 3 and Figure 4 show results for the 8600 and 13000TEU ships, respectively. The 8600TEU has an average normalized standard deviation for the 16 sea states of 0.24 for both the total moment and the wave moment. Sea state 10 is most important for method 1, 3 and 4, and sea state 11 is most important for method 2. Method 4 gave the smallest value, while the other three gave equivalent estimates. The 13000TEU have an average normalized standard deviation for the 18 sea states of 0.20 for the total moment and 0.24 for the wave moment. Sea state 11 is most important for method 1 and 4. Sea state 11 and 14 is similar for method 3 and sea state 10 is most important for method 2. Method 1, 3 and 4 gave equivalent results and method 1 gave higher results.

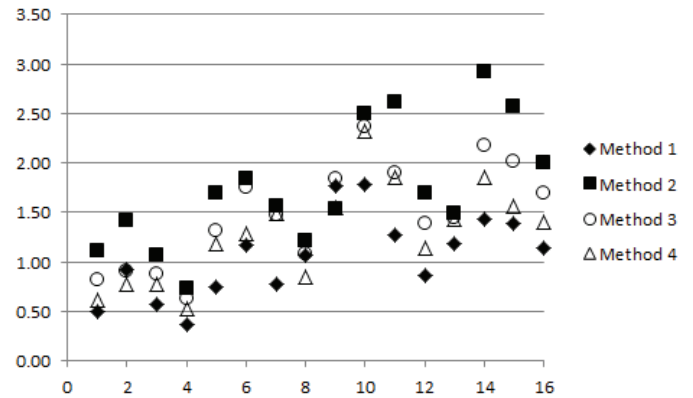


Figure 2 Comparison of extrapolation methods for the normalized total hogging moment of the 4400TEU ship for the 18 sea states

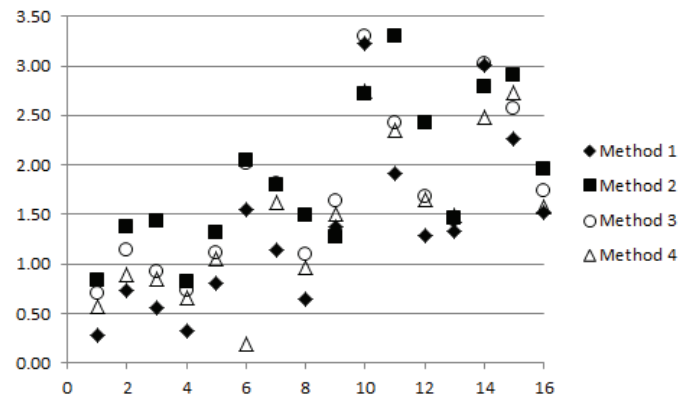


Figure 3 Comparison of extrapolation methods for the normalized total hogging moment of the 8600TEU ship for the 16 sea states

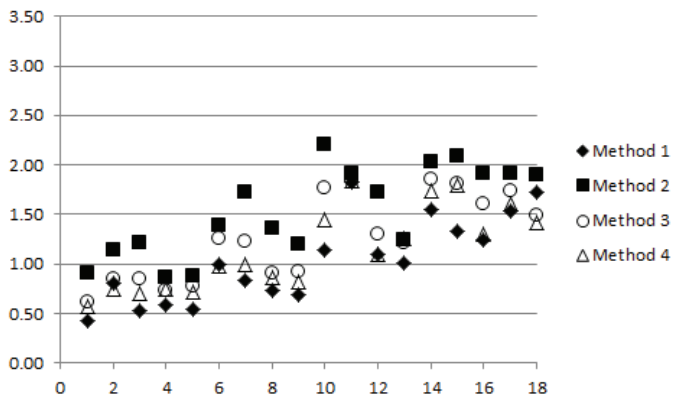


Figure 4 Comparison of extrapolation methods for the normalized total hogging moment of the 13000TEU ship for the 18 sea states

An estimate of the uncertainty related to the extrapolation of the total moment by the method 1 and for sea state 10 is made. The threshold is set at different probability levels of being below the threshold, i.e. Table 7 the 80% value is given. Using probabilities from 10 to 90% with a step of 10%, the minimum is 17383 and the maximum is 19123MNm, i.e. a difference of 10%. Assuming a normal distribution the 95% confidence interval is within 17892 and 19047MNm. In this case all the other methods give values outside this range. Hence, choosing the right method may be more important than how the method is used. In other words the uncertainty in the estimate may be less than the uncertainty of the method.

CONCLUSIONS

Model tests of three container ship designs (4400, 8600 and 13000TEU) have been carried out in sea states from 3 to 11.5 m in head seas. The models vibrate as real ships with realistic vibration shapes, frequencies but with slightly low damping. The ships are tested at realistic speeds in each of the sea states, implying higher speeds in the lower sea states. The smallest ship includes voluntary speed reduction, and the two largest ships are tested at full achievable speed.

From all of the tested sea states the measured moment amidships has been extrapolated to realistic duration for the North Atlantic design trade. The extrapolation has been carried out based on the following methods:

- Weibull fit of upper tail
- Gumbel fit from Weibull parameters
- Peak over threshold (POT) and Gumbel fit
- ACER

The results show that the different methods give significant variation in the extrapolated results and that it is important to choose the right extrapolation method and handle the upper tail with care. This is illustrated in Figure 5 where it can be seen that the tail of the total m (red) is quite irregular and more variable than the tail of the wave frequency response (blue) in this case. This makes the extrapolation very sensitive to the choice of threshold value, u and to any removal of statistically dependent peaks. In general it was similar uncertainties between the methods based on the wave moment and based on the total moment, so also for the wave moment selection of extrapolation method is important.

Method 2 does not seem to be a useful method, and will in most cases also give significantly higher estimates of the extreme values. Method 2

results should basically be disregarded. Method 1, 3 and 4 give more similar results, but only for the largest ship they gave equivalent results, while for the smallest ship method 1 gave the smallest value and for the 8600TEU ship method 4 gave the smallest value. For the two smallest ships the two other methods gave equivalent results.

Method 1 can still be regarded as useful provided that the upper tail is inspected, and that it is the easiest method. However method 4 may possibly be regarded as more reliable and robust. There is however no strong arguments for disregarding method 3. From a design perspective it is however important not to use a method that gives too conservative results as the consequence in terms of steel weight may be considerable.

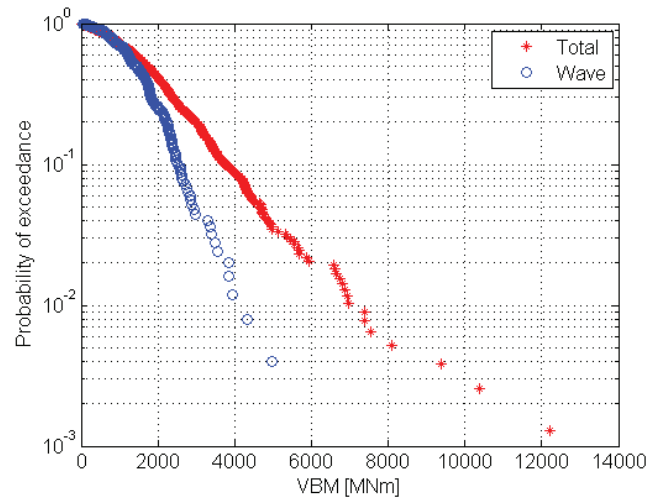


Figure 5 Probability of exceedance of the vertical hogging bending moment for the 8600TEU ship – sea state 10

The results for the three container ships confirm that the moderate sea states from 7 to 9.5 m can give the dimensioning total hogging moment including whipping. Three of the methods points to 7.5 m as most important. This confirms the conclusion made by Storhaug (2014). This conclusion is thereby independent on the extrapolation method (except method 2 which is disregarded).

Moderate storms and head or bow quartering seas at realistic speed with voluntary speed reduction is, based on this study, regarded as a good design basis for estimating the total moment including whipping for container ship design. Not considering voluntary speed reduction may lead to too high design moments.

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