Recommendation No. 34 "Standard Wave Data"

Summary

Rec 34 is revised with validated wave data combined with ship traffic information including evaluations of bad weather avoidance. Recommendations of vessel speed in adverse seas and effect of heading distribution for direct analyses are included.

Part A. Revision History

Version no.	Approval date	Implementation date when applicable
Rev.2 (Dec 2022)	19 December 2022	-
Corr.1 (Nov 2001)	November 2001	-
Rev.1 (June 2000)	June 2000	-
New (1992)	1992	-

- **Rev.2 (Dec 2022)**

1 Origin of Change:

☑ Based on IMO Regulation (GBS - SOLAS II-1/3-10)

2 Main Reason for Change:

It has been observed during the GBS verification that "Modern data show both an increase in mean significant wave height for the North Atlantic and that more extreme weather is being experienced in recent years, including the existence of rogue waves and the possible effect of climate change."

IACS Recommendation No. 34 revision 1 is based on old wave statistics from visual eyeball observations. Revision 2 is updated with modern hindcast data originating from a model with documented good accuracy in the North Atlantic area.

3 List of non-IACS Member classification societies contributing or participating in IACS Working Group:

None

4 History of Decisions Made:

During Hull Panel workshop held in September 2016 in London on Longitudinal Strength Harmonization, it was stated that UR S11, S11A and CSR are intended to be harmonized and to avoid double work, PT PH40 was formed to set up a plan and budget for updating the recommendation No 34 before going forward in the strength harmonization (loads, etc.). In January 2018 the plan and budget was approved and PT PH40 started the work on updating Recommendation No 34.

5 Other Resolutions Changes:

The following rules and unified requirements relate to IACS Recommendation No. 34

- CSR rules
- UR-S11
- UR-S11a

6 Any hinderance to MASS, including any other new technologies:

The recommendation has been derived for manned ships; it may be suitable for Maritime Autonomous Surface Ships (MASS) if similar design criteria and operational limits are applied.

7 Dates:

Original Proposal	: 01 December 2017	(Made by Hull Panel Chair 17176_PHa)
Panel Approval	: 30 November 2022	(Ref: PH17013_IHba)
GPG Approval	: 19 December 2022	(Ref: 17176_IGh)

- **Corr.1 (Nov 2001)**

No records are available

- **Rev.1 (June 2000)**

No records are available

- **New (1992)**

No records are available

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Part B. Technical Background

List of Technical Background (TB) documents for Rec 34:

Annex 1. **TB for Rev.2 (Dec 2022)**

See separate TB document in Annex 1.

Note: There are no separate Technical Background (TB) documents available for New (1992), Rev.1 (June 2000) and Corr.1 (Nov 2001).

Technical Background (TB) document for Rec 34 (Rev.2 Dec 2022)

1 Scope and objectives

IACS Recommendation No. 34, hereafter Rec.34, describes wave statistics intended for design of sea-going ships above 90 meters including the effect of bad weather avoidance. It is based on North Atlantic trade, which represents the most severe conditions ships tend to operate in. The recommendation includes advice on sea states as well as wave spectrum, spreading, heading distribution and vessel speed. The update from revision 1 to revision 2 is expected to lead to consequent changes in design loads such as pressures, motions, accelerations and hull girder loads.

2 Engineering background for technical basis and rationale

Rec.34 revision 1, hereafter Rec.34 v1, was based on human eyeball observations of significant wave heights and periods from sea-going ships. For a long time, these were considered the best data available for the purpose. An evaluation of available hindcast wave data bases was performed by IACS in 2020 [1] showing that modern wave models have sufficient quality to act as basis for a revision 2 of Rec.34. Detailed information of the work is given in section 5.

3 Source/derivation of the proposed IACS Resolution

None; work has been conducted entirely within IACS.

4 Summary of Changes intended for the revised Resolution:

No side-by-side comparison of text is included here as revision 2 represents a major change of Rec34; but Table 4-1 summarises the main changes.

Table 4-1 Changes between revision 1 and 2

	Revision 1	**Revision 2**
Source of wave data	Eyeball	Hindcast
Wave spectrum	Pierson Moskowitz	JONSWAP, gamma=1.5
Cosine wave spreading power	2	3
Design lifetime	Not defined	25 years
Return period for extreme loads	At least 20 years	25 years
Reference probability level for fatigue	Not defined	10^{-2}
Vessel speed for strength assessments	0 knots	5 knots
Vessel speed for fatigue assessments	Not defined	¾ design speed

Item 4, 5, 9, 10 and 11 from IACS Rec. No. 34 revision 1 are removed in IACS Rec. No. 34 revision 2.

5 Main technical discussion points

5.1 Data sources and geographical area

The update is based on a combination of data from two sources, (i) simulated historic wave data (ii) records of the time and location of relevant ships operating in the area under question. Furthermore, the geographical area representing the North Atlantic is redefined.

Particular points of discussion in the IACS working group with respect to and arising from the source data were:

Issue	Resolution
Which ships should be included?	The group decided to effectively restrict the work to the fleet of IACS members by means of a 90m length criterion – this means most commercial seagoing ships are included, such as merchant ships and passenger ships. Excluded are many fishing vessels, offshore vessels, naval ships and ships operating at fixed location e.g. FPSOs.
Choosing type of source for wave data	The group considered different sources such as eyeball derived atlases, buoy networks and satellite altimeters, but only global wave models (numerical hindcast) offered the spatial and temporal resolution required.
Choosing global wave model from several options	Several freely available public sources from major institutions were compared and found to be adequate; Commercially available weather services were also an option, but paid solution was not found necessary.
Accuracy of synthetic wave data	The group compared four different models against benchmark data from moored buoys and altimeters. Most were quite accurate at low to mid wave heights, the model IOWAGA was selected as it also performed very well at high wave heights.
Extent of historic synthetic wave data	Only 7 years was available to match the available AIS ship track data. It is argued that the huge volume of AIS data compensates a great deal for that limitation. Additionally, it was observed several of these 7 years were amongst the roughest ever recorded, meaning that possible bias due to the limited duration should at least lead to conservative design.
Procedure for fitting of idealised spectral models to the wave data	The group fitted idealised spectral shapes to non-dimensionalised spectra to find the best fitting spectral type and shape controlling parameters. The JONSWAP spectrum (developed for restricted North Sea waters) performed better than traditional open water spectra.
Choosing T0m1 as principal period	The group considered more common wave period measures such as Tz and Tp but found that T0m1 fitted best to the data. The group recognised that T0m1 is not so well known and provided conversion methods so users can work from the common period measures if necessary.
Accuracy of the AIS location records	The ship AIS records represent discrete lat/long positions. It was necessary to collate these into meaningful continuous voyages in the North Atlantic. Further it is necessary to 'clean' the records of occasional rogue and inconsistent data to ensure the reliability of those voyage records.
Is North Atlantic the most severe sea area?	The group reviewed global sea areas for their roughness using the modern wave model data. It was confirmed that, from a combined traffic and wave data set, both for extreme wave heights and for intermediate wave heights (relevant for fatigue design), the North Atlantic was most severe. The group confirmed that as well as for pure wave properties,

	similar conclusions would be reached considering ship responses.
Definition of the North Atlantic Ocean area	The working group chose to define the bounds for the North Atlantic for itself based on the geography, wave climate maps and shipping density maps. The historic definitions did not fit these criteria well. A point of discussion was how far south the area should extend, into areas with slightly less severe wave climate. The group eventually adopted the slightly larger of two candidates; this showed acceptable absolute values of safety level across all ship types, and also showed consistency of the safety level for both fatigue and strength design. A further point of discussion was whether the area should extend to the coasts of North America and Europe; a band was excluded so that purely coastal ship traffic was rejected from the analysis, also hindcast models are known to reduce in quality near to the shore.
How to include routing effect	The group could have defined a small number of fixed routes, or used long term mean traffic density data to produce a scatter diagram with some routing effect built in. But it was found technically possible to perform the best possible analysis by accumulating the scatter diagram data from thousands of individual in-voyage locations with individually co-located wave data. This naturally gives a full representation of the routing effect in a 'routed' scatter diagram. The group also found it useful to include 'unrouted' calculations for benchmarking purposes; for this analysis 30 years of hindcast data from the entire North Atlantic area was included so that weather avoidance effect was eliminated.
How to construct the scatter diagram	The cleaned AIS track records were interpolated every 3 hours to exactly match the time of the wave model hindcast. This lead directly to an empirical scatter diagram. An improvement on resolution (number of digits) was possible compared with Rec.34 v1. It was necessary to 'smooth' the empirical diagram so that the variation in sparsely sampled bins towards the edges do not create bias problems when extrapolating toward even lower probabilities.

The geographical area adopted in Rec.34 v2, shown in Figure 5-1, is defined as the polygon limited by the following latitude, longitude coordinates:

Start Point (Clockwise)
(60, -60), (60, -8), (56, -8), (56, -11), (50, -11), (50, -8), (44, -8), (44, -10), (32, -10), (32, -11), (30, -11), (30, -70), (40, -70), (40, -69), (43, -69), (43, -59), (46, -59), (46, -52), (50, -52), (50, -54), (54, -54), (55, -54), (55, -57), (56, -57), (56, -60) and (60, -60) **End Point.**

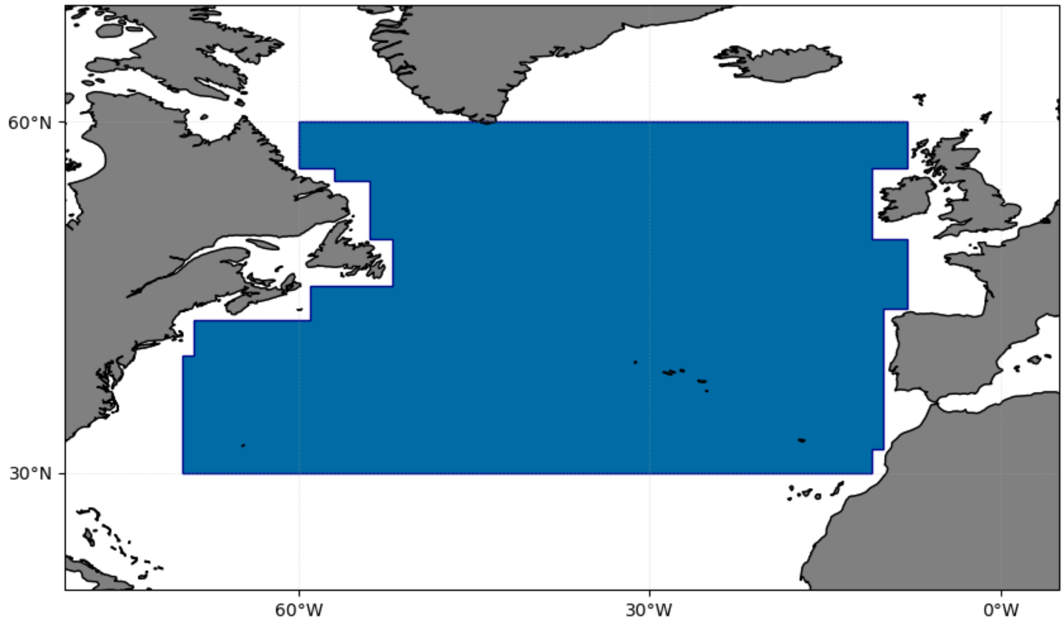

Figure 5-1 Definition of North Atlantic area

The evaluated data is made from a combined AIS-hindcast data set resampled at 3-hour interval for the period June 1st 2013 – May 31st 2020 covering the polygon defined in Figure 5-1. A total of 13.3 million observations are recorded from more than 23000 different vessels.

5.2 Scatter diagram including smooth fitting process

The previous section introduced the process followed by the IACS working group to derive Rec.34 v2 scatter diagram from a combination of vessel tracks and hindcast wave data.

Once the empirical scatter diagram was obtained from AIS and hindcast wave data, a statistical model was fitted. The statistical model smooths out some of the sampling uncertainties, allows extrapolation to unobserved wave periods and provides the scatter diagram in a compact form (the scatter diagram can be reconstructed at any desired resolution from a few coefficients).

The statistical model underlying Table 1 of Rec.34 v2 is written as:

$$p(H_s, T_{0m1}) = p_H(H_s) * p_{T_{0m1}}(T_{0m1}|H_s)$$

Where $p_H(H_s)$ is the marginal distribution of wave height, and $p_{T_{0m1}}$ is the conditional distribution of wave period.

A mixture of Weibull distributions with coefficients from Table 5-1 is used to model the marginal distribution:

$$P_H(H_s) = \chi\, F_{H,1}(H_s) - (1-\chi)F_{H,2}(H_s)$$
$$= 1 - \chi \exp\left[-\left(\frac{H_s - \varepsilon}{\lambda_1}\right)^{\alpha_1}\right] - (1-\chi)\exp\left[-\left(\frac{H_s - \varepsilon}{\lambda_2}\right)^{\alpha_2}\right]$$

Table 5-1 : Hs distribution coefficients.

	Unrouted	Routed
α_1	1.3460	1.4230
ε	0.9180	0.9360
λ_1	2.0610	1.8150

α_2	1.9130	1.3940
λ_2	5.0960	2.8050
χ	0.9507	0.9499

The conditional period distribution is a split generalised normal distribution:

$$p_{T_{om1}}(t|H_s) = \begin{cases} c \cdot e^{-\left[\frac{x_0 - t}{\sigma_l}\right]^{d_l}} & for\ t < x_0 \\ c \cdot e^{-\left[\frac{t - x_0}{\sigma_u}\right]^{d_u}} & for\ t \geq x_0 \end{cases}$$

With $c = \frac{1}{\sigma_l \Gamma\left(1+\frac{1}{d_l}\right) + \sigma_u \Gamma\left(1+\frac{1}{d_u}\right)}$

Parameters are then functions of H_s, with the following shapes and coefficients given in Table 5-2:

$$x_0(h_s) = l_0 + 1.0 * h_s + l_1 * h_s * \sqrt{h_s}$$

$$\sigma_u(h_s) = \begin{cases} su_2 + su_1 * (1 - \cos(\frac{\pi * h_s}{su_0})) * 0.5 \text{ for } h_s < su_0 \\ (su_2 + su_1) * \cos(\sigma_d * \pi) \text{ for } h_s \geq su_0 \text{ with } \sigma_d = \frac{1}{1+e^{-su_3 * (h_s - su_0))}} - 0.5 \end{cases}$$

$$\sigma_l(h_s) = sl_0 * h_s + sl_1$$

$$d_u = 2$$

$$d_l = 3$$

Table 5-2 : Conditional model coefficients.

	Unrouted	Routed
l_0	5.261561	5.427251
l_1	-0.086510	-0.085340
su_0	1.986849	2.549443
su_1	2.480241	2.435955
su_2	1.080E-06	0.705177
su_3	-0.162740	0.133225
sl_0	0.007157	0.018557
sl_1	0.969472	1.005918

Thus the final scatter diagram can be defined, with discretisation performed within 1m and 1s bins. Values in each bin are calculated using midpoints, except for the Hs = [0.0m, 1.0m] where exact integration is used.

Table 5-3 : Routed

Significant wave height, H_S (m)	Mean wave period, T_{0m1} (s) 4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	19.5	Sum
0.5	6.82	202.00	333.61	187.76	45.59	4.74	0.21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	780.73
1.5	0.33	2028.35	12750.82	11693.39	7215.76	3006.80	846.07	160.77	20.63	1.79	0.10	0.00	0.00	0.00	0.00	0.00	37724.81
2.5	0.00	3.38	2805.81	8517.74	7835.85	5885.37	3608.30	1805.81	737.71	246.00	66.96	14.88	2.70	0.40	0.05	0.00	31530.96
3.5	0.00	0.00	23.06	2742.51	4666.81	4100.83	2936.41	1713.38	814.68	315.65	99.66	25.64	5.38	0.92	0.13	0.01	17445.07
4.5	0.00	0.00	0.00	82.06	1759.81	2069.19	1715.42	1151.29	625.51	275.12	97.96	28.24	6.59	1.24	0.19	0.02	7812.64
5.5	0.00	0.00	0.00	0.08	149.74	811.81	791.81	609.66	375.67	185.26	73.12	23.09	5.84	1.18	0.19	0.02	3027.47
6.5	0.00	0.00	0.00	0.00	1.02	147.59	305.37	271.71	190.23	104.79	45.42	15.49	4.16	0.88	0.15	0.02	1086.83
7.5	0.00	0.00	0.00	0.00	0.00	4.77	88.62	107.20	86.26	53.35	25.36	9.27	2.60	0.56	0.09	0.01	378.09
8.5	0.00	0.00	0.00	0.00	0.00	0.02	9.40	38.70	36.80	25.95	13.63	5.33	1.55	0.34	0.05	0.01	131.78
9.5	0.00	0.00	0.00	0.00	0.00	0.00	0.20	9.34	15.15	12.51	7.39	3.12	0.94	0.20	0.03	0.00	48.88
10.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.81	5.73	5.96	4.08	1.90	0.60	0.13	0.02	0.00	19.23
11.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	1.29	2.68	2.23	1.18	0.40	0.08	0.01	0.00	7.89
12.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11	1.01	1.14	0.72	0.27	0.06	0.01	0.00	3.32
13.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22	0.51	0.42	0.18	0.04	0.00	0.00	1.37
14.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.19	0.21	0.12	0.03	0.00	0.00	0.57
15.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.09	0.07	0.02	0.00	0.00	0.22
16.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.04	0.01	0.00	0.00	0.08
17.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.01	0.00	0.00	0.04
18.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.02
Sum	7.15	2233.73	15913.30	23223.54	21674.58	16031.12	10301.81	5868.69	2909.77	1230.31	437.79	129.62	31.47	6.11	0.92	0.09	100000.00

Table 5-4 : Unrouted

Significant wave height, H_S (m)	Mean wave period, T_{0m1} (s) 4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	19.5	Sum
0.5	20.86	400.31	508.13	174.39	17.04	0.47	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1121.20
1.5	0.62	2897.82	12015.92	10074.26	5442.95	1892.83	423.69	61.04	5.66	0.34	0.01	0.00	0.00	0.00	0.00	0.00	32815.14
2.5	0.00	5.93	4108.88	9207.22	7617.69	4546.87	1957.92	608.24	136.32	22.04	2.57	0.22	0.01	0.00	0.00	0.00	28213.91
3.5	0.00	0.00	41.48	4168.26	5773.19	4399.97	2392.91	928.64	257.16	50.82	7.17	0.72	0.05	0.00	0.00	0.00	18020.37
4.5	0.00	0.00	0.00	173.75	3040.91	3117.84	2125.34	1010.71	335.31	77.61	12.53	1.41	0.11	0.01	0.00	0.00	9895.53
5.5	0.00	0.00	0.00	0.12	403.33	1739.52	1509.92	883.00	347.48	92.01	16.40	1.97	0.16	0.01	0.00	0.00	4993.92
6.5	0.00	0.00	0.00	0.00	2.66	522.98	892.46	660.17	311.83	94.05	18.11	2.23	0.17	0.01	0.00	0.00	2504.67
7.5	0.00	0.00	0.00	0.00	0.00	21.82	416.47	432.17	254.45	88.92	18.44	2.27	0.17	0.01	0.00	0.00	1234.72
8.5	0.00	0.00	0.00	0.00	0.00	0.04	67.68	242.23	190.45	80.64	18.34	2.24	0.15	0.01	0.00	0.00	601.78
9.5	0.00	0.00	0.00	0.00	0.00	0.00	1.27	91.23	125.41	69.92	18.29	2.24	0.13	0.00	0.00	0.00	308.49
10.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	9.21	66.73	55.17	18.16	2.34	0.12	0.00	0.00	0.00	151.73
11.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11	19.68	35.65	17.24	2.54	0.11	0.00	0.00	0.00	75.33
12.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.48	16.92	14.29	2.84	0.12	0.00	0.00	0.00	35.65
13.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	4.12	8.75	3.08	0.15	0.00	0.00	0.00	16.12
14.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.28	3.65	2.84	0.21	0.00	0.00	0.00	6.98
15.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.81	1.72	0.29	0.00	0.00	0.00	2.82
16.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.64	0.36	0.00	0.00	0.00	1.06
17.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.14	0.26	0.01	0.00	0.00	0.41
18.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.09	0.02	0.00	0.00	0.12
19.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.03	0.00	0.00	0.05
Sum	21.48	3304.06	16674.41	23798.00	22297.77	16242.34	9787.66	4926.75	2051.98	688.49	174.82	29.45	2.68	0.11	0.00	0.00	100000.00

5.3 Spectrum shape

Rec.34 v1 requires a two parameter Pierson-Moskowitz spectrum (equivalent to JONSWAP with gamma = 1.0), with associated $\cos^2$ spreading. Analysis of full spectra from hindcast wave data has shown that a JONSWAP spectrum with peakedness parameter gamma = 1.5 and $\cos^3$ spreading was more appropriate to represent extreme sea states for Rec.34 v2. Furthermore, this spectral shape also provides accurate results for fatigue loads. This section provides some background justification.

The full spectra data here analysed are from the model ERA5 [5], at a single point located in the North Atlantic, over the period 1990-2014.

Figure 5-2 shows the shape of 306 sea-state spectra contributing the most to the 25-years extreme (~Hs > 10m), normalised according to alternative wave period measures T0m1, Tp or Tz. The extreme sea states have remarkably constant shape and seem to be well represented by a JONSWAP spectrum with gamma = 1.5 (rounding from the raw least-square minimisation value 1.43). It was also observed that matching T0m1 or Tp provides much better results than Tz.

A slight trend of gamma increasing with Hs was observed; however, it was found that with other parameters fixed, varying gamma did not significantly change the overall accuracy of ship responses. For simplicity and practicality, a gamma varying as a function of Hs was therefore not adopted and gamma fixed at 1.5 was recommended.

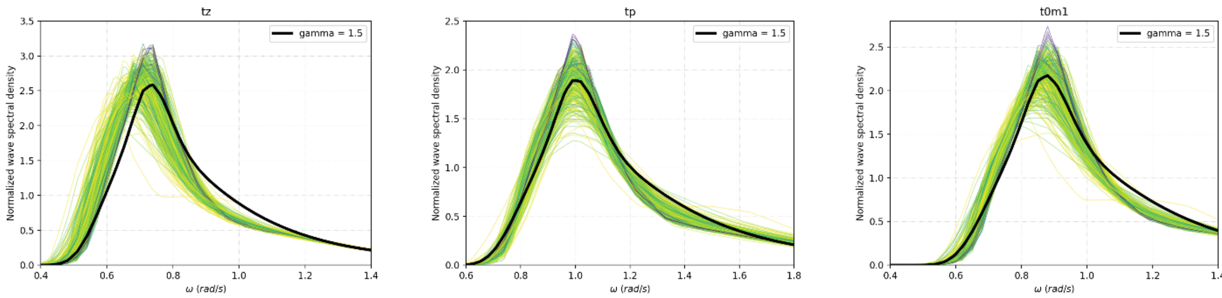

Figure 5-2 Shape of contributing spectrum (Hs > 10m) and parameterised spectra (JONSWAP, gamma = 1.5), based on 25 years of data

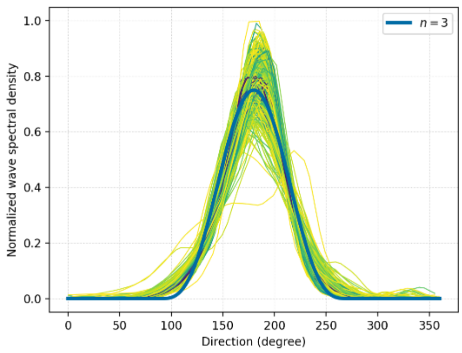

Figure 5-3 : Shape of contributing spectrum (Hs>10m) - directionality

Similarly, Figure 5-3 shows the directional shape of sea states contributing to the extreme. As with the frequency shape, the directional spreading is very similar among the different sea-states and well approximated by a $\cos^n$ formulation with n=3.

Finally, to evaluate the accuracy loss induced by this simple parametrisation, a validation was performed in on a database of 50 bulk carrier, tanker and container vessels. The following responses were analysed:
- Vertical wave bending moment
- Horizontal bending moment
- Pitch
- Roll

Those four RAOs (multiplied by 50 ships) are believed to represent a sufficiently broad and representative variety of possible response characteristic shapes.

The 25 years extreme value were calculated for all ship responses:
- using full spectra (reference)
- using gamma = 1.0 and n = 2 (Rec.34 v1)
- using gamma = 1.5 and n = 3 (Rec.34 v2)

The Rec.34 v1 shape resulted in a 7% quadratic error compared with the reference, which reduced to 5% using Rec.34 v2 parameter.

Fatigue loads (at 10^{-2} probability) are less sensitive to spectrum shape. With the same test cases, Rec.34 v1 and Rec.34 v2 results had quadratic error of 2.7% and 3.2% respectively compared with the reference. Those errors are considered comparable and acceptable.

Those findings are confirmed by a similar analysis conducted at several global locations [2].

5.4 Vessel speed and relative wave heading

5.4.1 Introduction

Rec.34 v1 included recommendations for how ships are assumed to operate in different sea conditions. Equal probability for all ship headings was applied in long-term prediction of various wave-induced responses. Zero speed was assumed when evaluating extreme wave loads in extreme sea conditions for strength assessment.

In this section, summarising results from the combined AIS-hindcast dataset specified in 5.1, basic estimates are made of the probability distributions of ship speeds and relative wave headings in sea states actually encountered according to the wave model.

5.4.2 Results and discussions on ship speeds and relative wave heading

5.4.2.1 Sensitivity of responses to relative wave heading

The probability distributions of the relative wave headings in different ranges of the hindcast encountered significant wave heights (hereafter, Hs) are investigated. It is noted:

- There is no significant difference for all relative wave headings when Hs is less than 6m.
- The probability of the relative wave headings in bow seas from starboard (120 deg. and 150 deg.) and quartering sea from portside (330 deg.) increases when Hs becomes higher than 6m.
- The probability of the relative wave heading in bow sea from starboard (150 deg.) increases a little bit more (several percentages) when Hs is larger than 10m.

Figure 5-4 shows the probability distribution of the relative wave headings when Hs is larger than 10m. It is observed that the bow sea from starboard (150 deg.) is the most probable. This is also consistent with the distribution from worldwide trade.

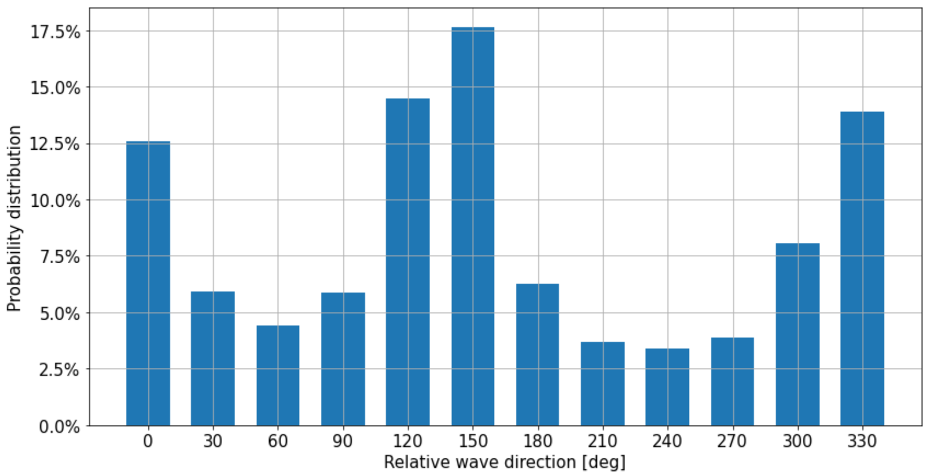

Figure 5-4 Probability distribution of relative wave headings when Hs≥10.0m

Rec.34 v1 recommends a uniform distribution of ship headings relative to the waves for long term predictions of wave-induced responses. In this sub-section, results using this uniform probability distribution shall be called "Upd". In reality, the probability distribution of the relative wave headings is not uniform in rough seas, as shown in Figure 5-4. Results are also calculated by this non uniform distribution shall be called "N-Upd".

In order to investigate the sensitivity to relative wave headings with regard to Hs, the long-term prediction values of eight wave-induced responses listed below are calculated for both "Upd" and "N-Upd".

- Vertical as well as horizontal wave bending moment amidships (Mwv, Mwh);
- Heave, Roll and Pitch motions (Heave, Roll, Pitch);
- Vertical acceleration at the centreline of FP (Azclfp);
- External pressure at the waterline and bottom centreline amidships (Pwlmi, Pclmi).

Table 5-5 shows the overview of ships used for this work. The sensitivity is investigated based on a series of direct analyses by a linear strip method program. For each ship, full loading condition is chosen. Similar to Rec.34 v1, the Pierson-Moskowitz wave spectrum, spreading function of $\cos^2$ and the Rec. 34 v1 wave scatter diagram are used. The ratios (N-Upd results / Upd results) of the eight wave-induced responses were checked to quantify the sensitivity to heading distribution, for long-term prediction values at probability level 10^{-8}; these are shown in Figure 5-5. Moreover, the ratio statistics (mean values, maximum and minimum values, standard deviation and coefficient of variation) are summarised in Table 5-6.

Table 5-5 Overview of the bulk carriers, oil tankers and container ships used in the investigation

Type	Numbers	Lpp (m)	B (m)
Bulk Carrier	22	107 – 285	20 – 50
Oil Tanker	27	110 – 322	20 – 60
Container ship	26	110 – 350	18 – 59

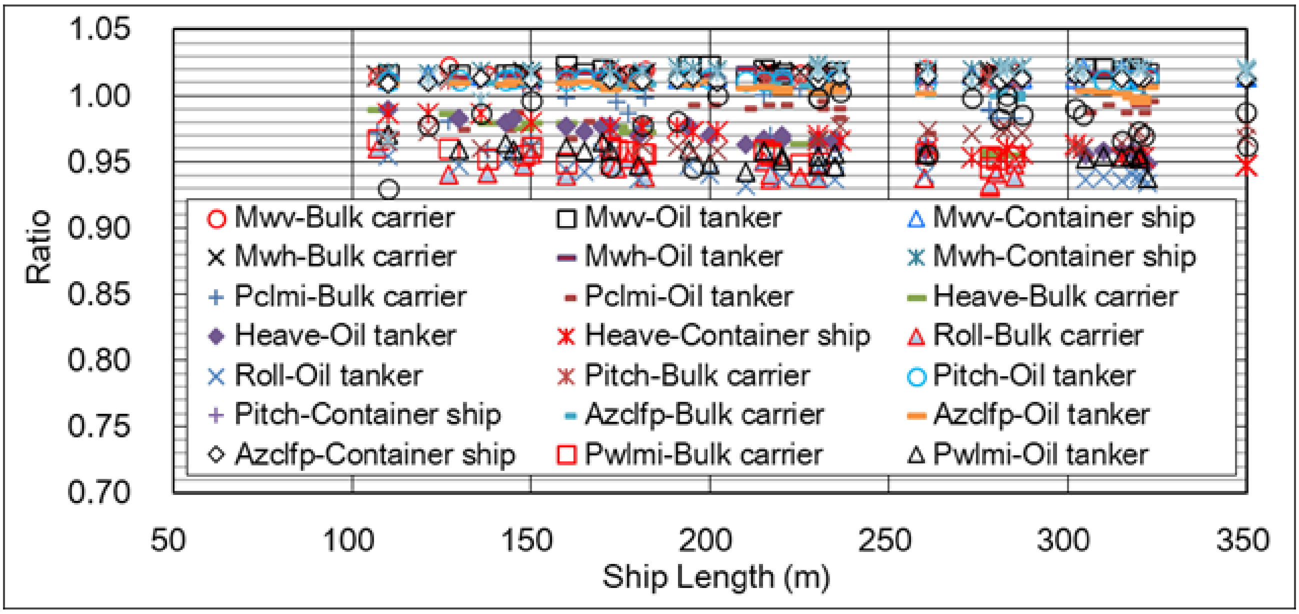

Figure 5-5 Sensitivity to heading distribution: Ratios (non-uniform / uniform) of the eight wave-induced responses at the 10^{-8} probability level for sample of 75 ships

Table 5-6 Ratio (non-uniform / uniform) statistics of the eight wave-induced responses at 10^{-8} for 75 ships

Response Items	Bulk Carrier					Oil Tanker					Container Ship				
	Ratio					Ratio					Ratio				
	Mean	Sdv	CV	Max.	Min.	Mean	Sdv	CV	Max.	Min.	Mean	Sdv	CV	Max.	Min.
Mwv	1.017	0.002	0.002	1.023	1.013	1.017	0.003	0.003	1.023	1.013	1.015	0.002	0.002	1.021	1.011
Mwh	1.016	0.002	0.002	1.019	1.013	1.016	0.002	0.002	1.021	1.013	1.019	0.004	0.004	1.024	1.003
Heave	0.969	0.011	0.011	0.990	0.955	0.968	0.010	0.011	0.990	0.949	0.965	0.012	0.013	0.986	0.948
Roll	0.943	0.008	0.008	0.961	0.931	0.943	0.008	0.009	0.963	0.931	0.980	0.019	0.020	1.004	0.930
Pitch	1.011	0.001	0.001	1.014	1.009	1.012	0.001	0.001	1.014	1.009	1.012	0.001	0.001	1.014	1.010
Azclfp	1.007	0.004	0.004	1.012	0.999	1.006	0.004	0.004	1.011	0.995	1.013	0.002	0.002	1.017	1.010
Pwlmi	0.956	0.005	0.005	0.967	0.946	0.955	0.007	0.007	0.971	0.938	0.967	0.007	0.007	0.978	0.955
Pclmi	0.986	0.016	0.016	1.018	0.959	0.986	0.009	0.009	0.997	0.969	1.016	0.011	0.011	1.023	0.968

From the obtained results, the sensitivity (ratio) to relative wave headings regarding the various wave-induced responses at the probability level 10^{-8} could be summarised as follows:

- There is some variation in the sensitivity (ratio) across the various wave-induced responses, but the variation is relatively limited and small.
- The mean values of the ratios of various wave-induced responses are around 0.956 to 1.017.
- The mean value of the ratios of eight wave-induced responses for all 75 ships is almost 1.000.
- The mean values of the ratios increase 1% to less 2% for Mwv, Pitch and Aclfp which are known to be dominated by head sea (180 deg.), bow sea (150 deg.) or following sea (0 deg.).
- The mean values of the ratios decrease 3% to 5% for Heave, Roll, Pwlmi which are known to be dominated by beam sea (90 deg.).
- The mean value of the ratio increases about 1.7% for Mwh which is known to be dominated by bow sea (120 deg.).
- The standard deviations of the ratios regarding various wave-induced responses are about 0.001 to 0.019.

Based on the results and discussions mentioned above, it could be concluded that equal probability of occurrence as indicated in Rec.34 v1 for the extreme wave loads for strength assessment remains practical and reasonable to be continued in Rec.34 v2.

5.4.2.2 Sensitivity of responses to ship speeds

This sub-section investigates the relationship when Hs, ship speed, and relative wave heading are considered simultaneously. The response sensitivity to ship speeds alone is also studied.

Generally, ships tend to reduce their speed in rough seas, to ensure the safety and integrity of hull structure, fittings and loaded cargoes. The technical background of IACS Common Structural Rule for Bulk Carriers and Oil Tankers [3] (hereafter, the TB-CSR) indicates 5 knots as the ship speed corresponding to the extreme wave loads for strength assessment and 3/4 of the design speed corresponding to the wave loads for fatigue assessment. In order to evaluate ship speed reduction, the relationships between ship speed, Hs and relative wave heading are investigated.

Figure 5-6 shows the relationships between the average relative ship speed (Average speed/Design speed) with Hs and relative wave headings. The relative speed in head sea (180 deg.), bow seas (120 deg. to 240 deg.), beam seas (90 deg. and 270 deg.) and quartering seas (60 deg. and 300 deg.) decrease inversely with Hs, but the degree of ship speed reduction is a bit different for different relative wave headings. On the other hand, the relative speed in following sea (0 deg.) and quartering seas (30 deg. and 330 deg.) show almost no decrease when Hs become higher. This tendency seems appropriate since the ships generally reduce speed when encountering rough waves, especially in head, bow and beam seas. The possible reasons causing ship speed reduction are considered to be voluntary in ship operation or involuntary natural speed loss due to wave resistance increased by high waves.

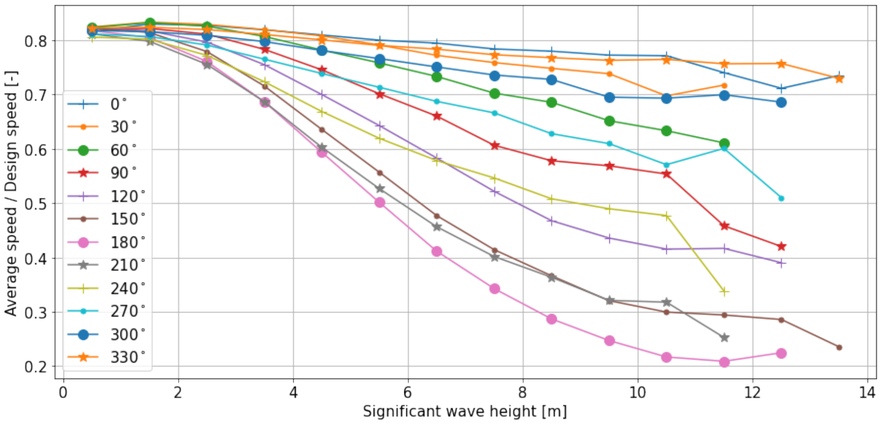

Figure 5-6 Average ship speed as function of Hs and relative wave heading

Figure 5-7 shows the head sea behaviour in more detail. The red line indicates median value, the box covers the 25th to 75th percentile range and the whiskers represent the 1st to 99th percentile range. It is observed that the ships reduce speed below 5 knots in extreme sea states.

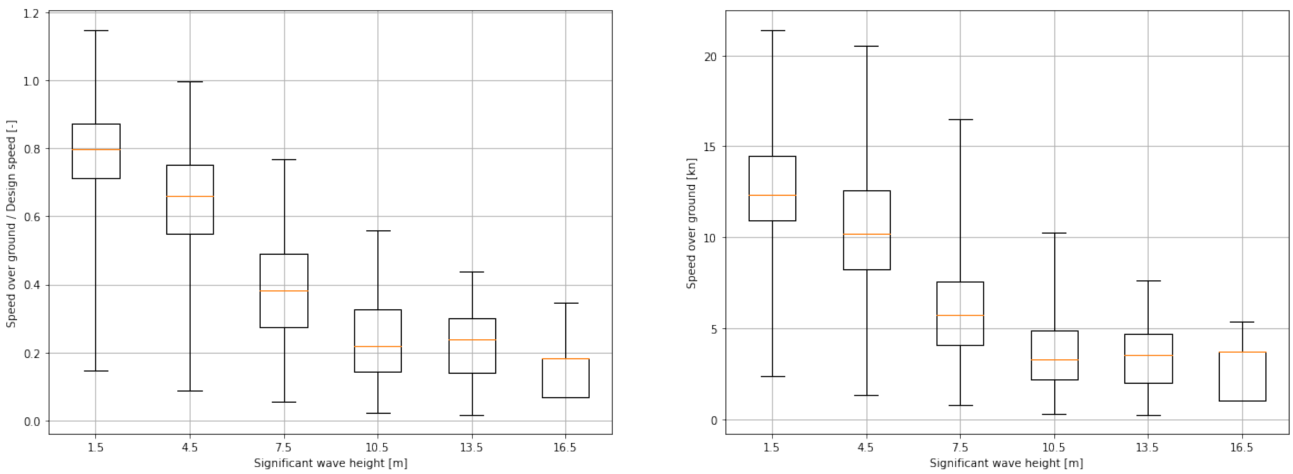

Figure 5-7 Relative and absolute ship speed in head sea as function of Hs. Box: 25th-75th percentiles, Whiskers:1st-99th percentiles

As mentioned above, 5 knots speed is the standard ship speed used for the extreme wave loads for strength assessment in the TB-CSR. The RAOs of various wave-induced responses (hull girder forces/bending moments, ship motions, acceleration and hydrodynamic pressures) in 5 knots for all relative wave headings are used when predicting extreme wave loads. However, in reality the ship speed varies at different relative wave headings in different extreme wave heights, as shown in Figure 5-6. In this sub-section, the possible consequences of allowing varying speed instead of the fixed 5 knots on the wave-induced responses in extreme waves are checked. The extreme waves are used as it is expected that the extreme wave loads arise from the extreme wave conditions. The results shown in Figure 5-6 have been simplified in the following way to select RAOs at appropriate speeds for this study:

- 0.75Vs: for following sea (0 deg.), quartering seas (30 deg. and 330 deg.)
- 0.50Vs: for quartering seas (60 deg. and 300 deg.) and beam seas (90 deg. and 270 deg.)
- 5 knots: for head sea (180 deg.) and bow seas (120 deg., 150 deg., 210 deg. and 240 deg.).

Hereafter, the RAOs varied with the ship speed for different relative wave headings mentioned above are called "RAOs (SP)", while the RAOs at the 5 knots fixed speed for different relative wave headings are called "RAOs (5)" in the following long-term predictions. To investigate the sensitivity to ship speed regarding Hs and relative wave headings, the long-term prediction values of eight responses specified in 5.4.2.1 are calculated for both "RAOs (SP)" and "RAOs (5)" at the probability level 10^{-8} based on the scatter diagram in Rec.34 v1. Other items (loading condition, wave spectrum, spreading function) in the calculation are all same as those used in 5.4.2.1. Furthermore, uniform ship heading probability distribution is applied in the all wave headings long-term prediction. The long term prediction results are presented in the form of the ratio Load [RAOs(SP)] / Load [RAOs(5)].

The ratios obtained for the eight wave-induced responses are shown in Figure 5-8. Moreover, the statistics of the ratios (mean, maximum and minimum values, standard deviation and coefficient of variation) are summarised in Table 5-7.

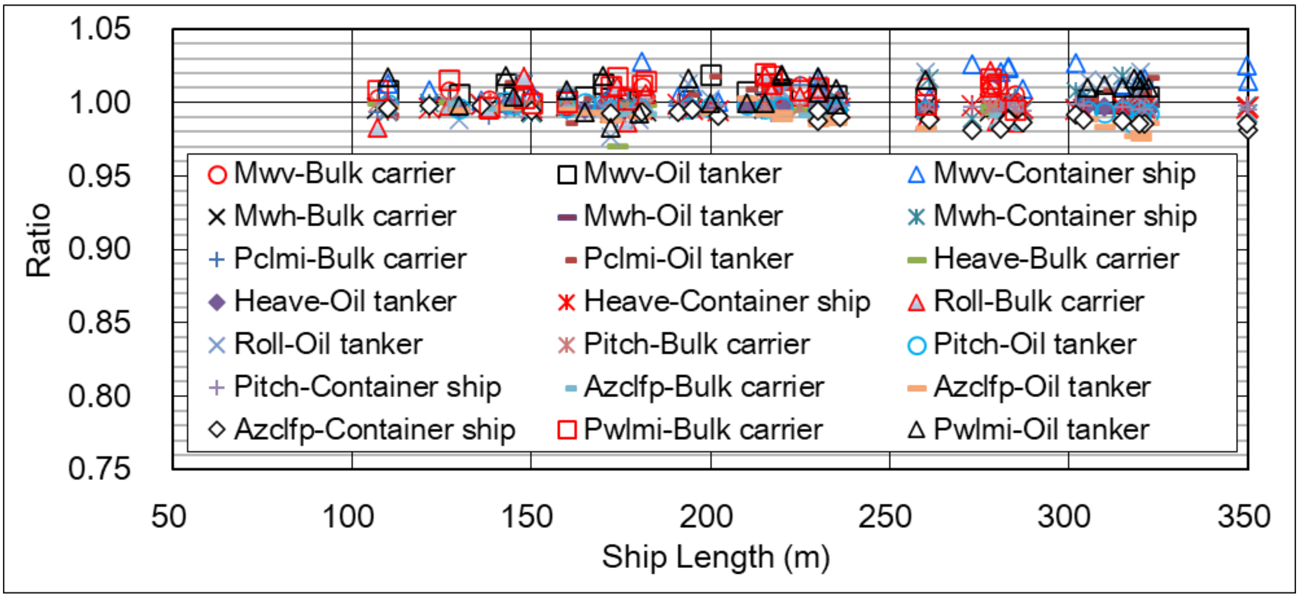

Figure 5-8 Ratio of loads (varying speed / 5 knots fixed speed) of the eight wave-induced responses at 10^{-8} probability level for sample of 75 ships

Table 5-7 Ratio statistics of the eight wave-induced responses at 10^{-8} for 75 ships

Bulk Carrier					Oil Tanker					Container Ship				
Ratio					Ratio					Ratio				
Mean	**Sdv**	**CV**	**Max.**	**Min.**	**Mean**	**Sdv**	**CV**	**Max.**	**Min.**	**Mean**	**Sdv**	**CV**	**Max.**	**Min.**
1.000	0.006	0.006	1.022	0.971	1.000	0.006	0.006	1.021	0.976	0.999	0.005	0.005	1.028	0.981

From the results shown in Figure 5-8 and Table 5-7, the observed sensitivity (ratio) regarding the various wave-induced responses at the probability levels 10^{-8} could be summarised as follows:

- The mean values of the ratios of the eight wave-induced responses are very close to 1.00.
- The standard deviations of the ratios regarding the eight wave-induced responses are about 0.005 to 0.006.

As the sensitivity (ratio) to ship speeds regarding various wave-induced responses is very limited and small, it could be concluded that to use 5 knots as the ship speed for the extreme wave loads for strength assessment as indicated in the TB-CSR [3] is appropriate and reasonable for Rec.34 v2.

The roll related responses of container ships are excluded from Figure 5-8 because the accuracy of the roll motion for container ships based on the linear strip theory used in this study is not satisfactory. It should be noted that appropriate speed and viscous damping need to be applied when evaluating roll related responses by numerical simulations for vessels with very low metacentric height and operating without reduced speed in stern quartering seas. It is assumed that these effects are considered in the development of rule formulae of roll motions by individual classification society.

5.5 Design lifetime and ship speed for fatigue assessment

The design lifetime for strength and fatigue assessments, the ship speed used for evaluating wave loads for fatigue assessment and the probability level selected for wave loads for fatigue assessment have been investigated in PT PH40.

Regarding the design lifetime for strength and fatigue assessments, twenty-five years, which has been already used in the TB-CSR [3] is recommended in order to satisfy the IMO GBS requirement Tier II [4]. Consequently, a return period of twenty-five years is recommended for evaluating the extreme design wave loads for the strength assessment. The return period of a value X_{RP} can be formally defined by $P(x < X_{RP}, RP) = 1/e$, i.e. the non-exceedance probability of the extreme (at RP=25 years) in 25 years is 36.8%.

Moreover, 3/4 of the design speed is recommended for evaluation of the design wave loads for the fatigue assessment in the Rec.34 v2, which is corresponding to that used in the TB-CSR [3]. The probability distributions of different relative ship speeds regarding Hs based on the combined AIS and hindcast dataset mentioned above in 5.1 is shown in Figure 5-9. It can be seen that the most probable relative speed for moderate sea states is indeed 3/4 of the design speed.

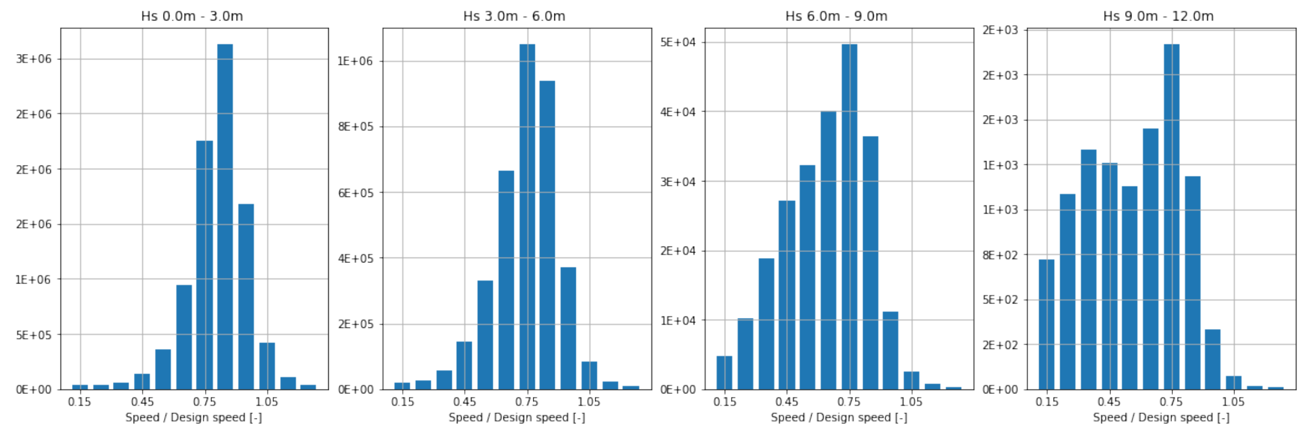

Figure 5-9 Probability distributions of different relative speeds to Hs

Furthermore, the design wave loads at the probability level of 10^{-2} are selected for the fatigue assessment as the reference value to derive their long-term prediction distributions for fatigue assessment in Rec.34 v2, which follows the same consideration used in the TB-CSR [3].

5.6 Limitations

Whilst the studies, techniques and data used by IACS to contribute to the up-issue of Rec.34 are considered state-of-the-art, there are limitations and these are highlighted here.

5.6.1 Wave models

IACS Rec.34 v2 relies heavily on synthetic hindcast data. Although those have been validated through comparison with satellite altimeters, some uncertainties with this technology can be expected for all relevant derived parameters including wave height, period and direction. It can also be noted that moored buoys used for validation of the altimeters are themselves only present at the Atlantic basin margins, so there could be a bias present. In coming years, drifting buoys may fill this gap in the central ocean.

Wave modelling is an active academic field and the accuracy of the global wave models is expected to continue to improve year on year.

5.6.2 Climate change

The updated wave environment recommendations proposed by IACS are a present day snapshot and do not include any climate forecast change effects. This might be considered a limitation, but has been disregarded for reasons given here:

Reviewing the relevant literature on climate change mainly coming from the sessions of the Intergovernmental Panel on Climate Change (IPCC), it was observed that there was a great deal of uncertainty about the effects relevant to shipping. Long term *hindcasting* using the atmospheric models is hampered by the lack of reliable measured data over long time scales. Long term *forecasting* is hampered by lack of confidence in the scenarios themselves, particularly the wind models used to drive the forecasts. However, even changes at the highest end of IPCC projections of +/- 0.5m (positive or negative) in extreme and average wave heights for the North Atlantic would be expected to have negligible effect on the Rec.34 v2 scatter diagram due to the robustness of the derivation procedure. Furthermore, since even under extreme wave environment changes due to climate change, ships in service will continue to avoid rough weather at the levels encapsulated in the new scatter diagram. In effect the Rec.34 v2 scatter diagram does include some future-proofing.

5.6.3 Bad weather avoidance

The bad-weather avoidance embedded within this work represents the current performance level of global shipping. The technical quality, availability and take-up of routing services is increasing under current industry drive towards digitalisation. Therefore, the new recommendation might be regarded as including a slightly conservative bias as time goes on and those improvements become more definite.

5.6.4 Statistics

Synchronised weather data with ship position was limited to only 7 years. This was compensated by the fact that a huge number of ship positions was used, roughly 4500 ship-years, and that these later years were among the roughest recorded. It is theoretically possible to improve the scatter diagram derivation by 'de-clustering' the data to remove sampling effect, but that would not be a trivial exercise. IACS considers the amount of data used is sufficient to correctly assess the 25 years ship responses, though this limitation is to be kept in mind when using the proposed scatter-diagram to estimate response at very lower probabilities (i.e. very higher return period). Even so, the new scatter diagrams are considered a huge improvement on Rec.34 v1 derived from eyeball observations.

Finally, it might be considered the industry standard design approach using scatter-diagram is itself a limitation to design success. Recent research shows that by grouping time-series data into Hs-T0m1 bins, the serial correlation of sea-states is lost and an overestimation bias about 5% on VBM is possible for large vessels. It is to be seen whether these practices become adopted.

5.7 References

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[3] IACS, "Common Structural Rules for Bulk Carriers and Oil Tankers, Technical Background Rule Reference," PT01, 2019.

[4] IMO, "Adoption of the International Goal-Based Ship Construction Standards for Bulk Carriers and Oil Tankers", 2010.

[5] Hersbach H. et al, "The ERA5 global reanalysis", Quarterly Journal of the Royal Meteorological Society, 146(730):1999–2049, 2020.

6. Attachments if any

None