Proceedings of the 6th International Ship Stability Workshop, Webb Institute, 2002

EXPERIMENTAL TESTS ON SHIPS WITH LARGE VALUES OF B/T, OG/T AND ROLL PERIOD

Alberto Francescutto, Department of Naval Architecture, Ocean and Environmental Engineering, University of Trieste, Italy, e-mail: francesc@univ.trieste.it
Andrea Serra, Fincantieri SpA, Cruise Ship Business Unit, Trieste, Italy, e-mail: andrea.serra@fincantieri.it

SUMMARY

The papers was developed in the frame of a cooperation between University of Trieste and Fincantieri Shipyard on the possible revision of IMO Weather Criterion for ships having the characteristics identified in the title, like the modern cruise passenger vessels. Previous studies on the development of Weather Criterion identified the weak-points which to large extent lie in the overestimate of rollback angle due to several factors. These factors concern both the metocean conditions and the roll motion modelling. This last factor was explicitly addressed and a thorough research plan was prepared concerning the nonlinear roll motion modelling and a campaign of tests on scale models aimed to identify appropriate ranges of roll damping and effective wave slope coefficients. Tests in beam wind to update the drag coefficients for large windage area ships will also be done. The general idea, the experimental difficulties and the data analysis procedures are presented in the paper.

NOMENCLATURE

SLF is the Stability, Load Lines and Fishing Vessels Sub-committee of MSC
MSC is the IMO Maritime Safety Committee
IMO is the International Maritime Organisation
SOLAS International Convention for Safety of Life at Sea
ϕ_1 rolling amplitude
T ship draught ("d" of IMO Weather Criterion)
B ship beam
C_B block coefficient
s, s_w wave steepness
X_1 factor expressing the roll damping dependence on B/T
X_2 factor expressing the roll damping on CB
k factor expressing the effect of bilge keels on roll damping
α_0 , r effective wave slope coefficient
T_ϕ rolling period
OG=KG-T height of centre of gravity on waterline
KG height of centre of gravity on keel
GM initial metacentric height
N,β coefficient of quadratic roll damping
μ coefficient of linear roll damping
Δ ship displacement
GZ righting arm
ω_0 natural roll frequency
ω wave frequency
ϕ_{syn} peak roll amplitude

1. INTRODUCTION

A research program was undertaken a few years ago at the University of Trieste in cooperation with Fincantieri Shipyard to study the possibility of updating the IMO Weather Criterion for modern large passenger cruise ships. This study was originated by the observation that the estimates of some quantity obtained from the formula of the IMO Weather Criterion [6] were different from those measured in full scale or from model basin test. Often for these ships the requirements of Intact Stability were much more stringent than those of SOLAS'90 in a wide range of loading conditions [1,2]. The analysis identified many possible weak points in the present formulation of the stability criterion, *while its general philosophy was not put in discussion*. Both the environmental actions, i.e. wind and waves were found to lead to an overestimate of the resulting required stability. In particular, the roll back angle results roughly overestimated for ships having large values of the following parameters:

- OG/T
- B/T
- Roll period (T_ϕ)

Like the modern large passenger vessels and, at the other extreme, also the small passenger vessels [3].
The critical document submitted to IMO/SLF in 2001 [4] was really effective and during the discussion in plenary it was decided to start the revision of the intact stability Code. The MSC ratified this decision and in the SLF 45 in July 2002 this exercise was started. A summary of the discussion and of the decisions taken, together with the Work programme for the short and long term activity of the ad hoc working group constituted during the SLF 45 are given in [5].
It was decided, in particular, that the Weather Criterion should be improved with priority in the short term, while a performance based criteria approach should be developed in the long term. On a provisional basis, some changes to the expressions and tables used to evaluate the roll-back angle in original IMO Weather Criterion [6] were changed as proposed in [2] and [7] (see Appendix in [5]). These

changes mainly concern the effective wave slope coefficient “r” and the wave steepness “s” characterizing the regular wave train exciting roll motion by resonance in beam sea. In addition, the possibility was introduce to use numerical, experimental or combined approaches to evaluate the relevant parameters of Weather or of other Stability Criterion and the concept of equivalent level of safety was enforced.

The “correction” of the factor s rests on two factors:

a) the correct evaluation of the roll period period, which cannot be any longer based on the IMO formula;
b) an improved knowledge of metocean conditions, especially at large periods.

On the other hand, the roll-back angle ϕ_1 is also based on extrapolation of original studies [8] for the mentioned ship types. Its correct evaluation rests on the improvement of:

c) the effective wave slope coefficient r;
d) the damping and its dependence on C_B (factor X_2) and, most important, on B/T (factor X_1).

Of course the factors c) and d) are strongly correlated due to the tuning which was made in the original formula for the evaluation of the maximum roll amplitude in beam waves [8] when passing from the Japanese Weather Criterion to the present IMO one [6]. The overall capability of these formula should thus be compared with experimental results for new ship typologies.
In the following of this paper, several series of experiments performed in order to improve knowledge on the roll-back and on the factors r, X_1 and X_2 will be discussed in some details, identifying open problems and needs, together with some assessed trend in the results.

2. EXPERIMENTAL SETUP AND DATA ANALYSIS TECHNIQUE

2.1 MOORING TECHNIQUE

Before starting the extensive campaigns of experiments, a check of the experimental procedure best suited to obtain reliable information on ship rolling in beam waves was undertaken.

Table. 1. Main dimensions and mechanical data of tested model (scale 1:30).

L_{bp} (m)	1.752
L_{oa} (m)	1.947
B (m)	0.333
T_{dwl} (m)	0.095
Trim (m)	0.000
Δ (kg_f)	25.63
C_B	0.55

To this end, the scale model, hull #C84-234, of a small Ro-Ro ship (Fig. 1 and Table. 1) was tested in different mooring conditions in the loading condition #3: tight elastic ropes, soft ones and finally unrestricted model. In this last case the model was just manually corrected in alignment when needed, but left completely free in drift (Loading conditions 1 to 3 in Table 2).
The results for the most severe wave steepness are reported in Fig. 2 [9] and show no significant difference (apart a negligible effect of ship drift on encounter frequency).

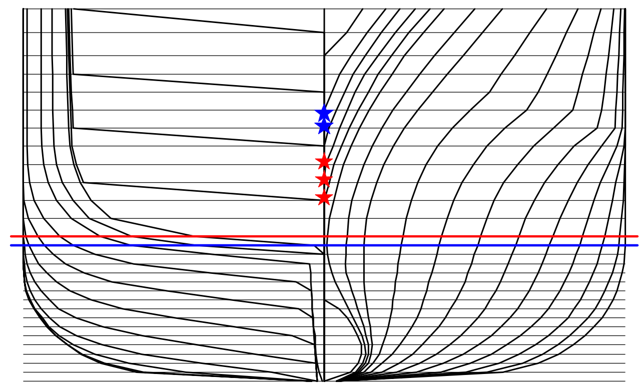

Fig. 1. Schematic body plan of the tested ship model. The waterline and the position of the centre of gravity in the three loading conditions 1÷3 are evidenced in red. The centre of gravity and the waterline of loading conditions 4÷5 is in blue.

Table. 2. Ship model stability data in the different loading conditions.

Loading condition	# 1	# 2	# 3	#4	#5
T (m)	0.080	0.080	0.080	0.075	0.076
B/T	4.163	4.163	4.163	4.44	4.382
$\overline{KG}$ (m)	0.1015	0.1115	0.1215	0.1411	0.1481
OG/T	0.269	0.394	0.519	0.88	0.95
$\overline{GM}$ (m)	0.078	0.068	0.058	0.042	0.055
To (s)	0.890	1.030	1.130	1.622	1.50
ω_0 (rad/s)	7.060	6.100	5.560	3.873	4.189
α_3 fixed trim α_3 free trim	-25.61 -33.19	-21.02 -27.47	-19.57 -25.95	-13.00 -17.36	-17.20 -23.39
α_5 fixed trim α_5 free trim	10.98 20.45	9.351 17.31	9.056 16.98		

2.2 MATHEMATICAL MODELLING

The results of the test series#3 indicated that there was no significant influence of heave and sway on roll, while a description of heave and sway could not be given without taking roll motion influence into account [9]. As a result, the analysis of these tests and of all the following was made with a one degree of freedom mathematical model:

$$\ddot{\phi}+2\mu\,\dot{\phi}+\beta\left|\dot{\phi}\right|\dot{\phi}+\delta\,\dot{\phi}^3+\omega_0^2\,\phi+\alpha_3\,\phi^3+\alpha_5\,\phi^5+\ldots \\ =\pi\left(\alpha_1\,\omega^2-\alpha_2\,\omega_0^2\right)\cos(\omega t) \tag{1}$$

A parameter estimation Technique was developed based on the nonlinear least-squares fitting of Eq. 1 to experimental data [10]. Since several wave steepness were used for each loading condition in a range of frequencies including the roll resonance peak, the obtained set of parameters can be really considered relevant to the description of the rolling motion of the ship in the assigned loading condition at any wave steepness.
In Eq. 1, several damping terms are present. They will be effectively selected depending on the results of the fit with the PIT. On the other hand, the excitation is described by two terms to account for diffraction. The link with the traditional description based on the use of an equivalent linear damping and an effective wave slope coefficient is given by:

$$\alpha_{0\,eq}=\alpha_1-\alpha_2$$

and (2)

$$\mu_{eq(\phi_a)}=\mu+\frac{4}{3\pi}\beta\omega_0\phi_a+\frac{3}{8}\delta\omega_0^2\phi_a^2$$

being ϕ_a a significant roll amplitude.

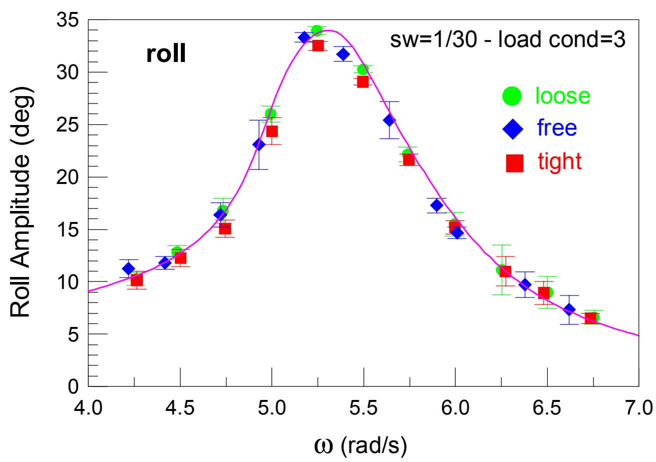

Fig. 2. Roll motion amplitude as a function of wave frequency for the three different mooring conditions used in the loading case #3. The continuous curves refers to the time domain simulation by PIT.

3. RESULTS RELATIVE TO HULL C84-234

Further to the first three series of measurements, conducted with three different wave steepnesses, s_w=1/90, 1/50, 1/30, in a series of loading conditions with different heights of centre of gravity, while maintaining the same light ship displacement (indicated in red in Fig. 1), a second series (4-5, indicated in blue in Fig. 1 [11]) was undertaken with higher KG and lower T to simulate as much as possible the case of ships with large values of OG/T and of B/T. All these experiments were conducted in the towing tank of the University of Trieste.
The ship length is not so important in beam sea experiments, so that, apart the relative smallness of C_B, the results of these tests should be indicative of the roll motion of the modern ship typologies as regards large passenger cruisers.

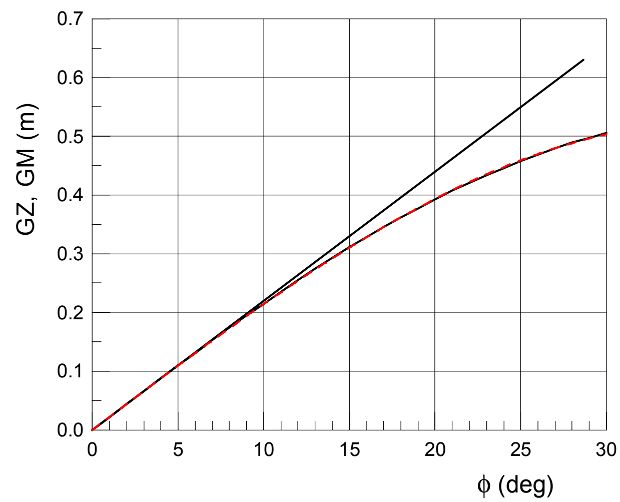

Fig. 3. Righting arm corresponding to case 4. Fix trim calculations. The red curve indicates the cubic polynomial approximation.

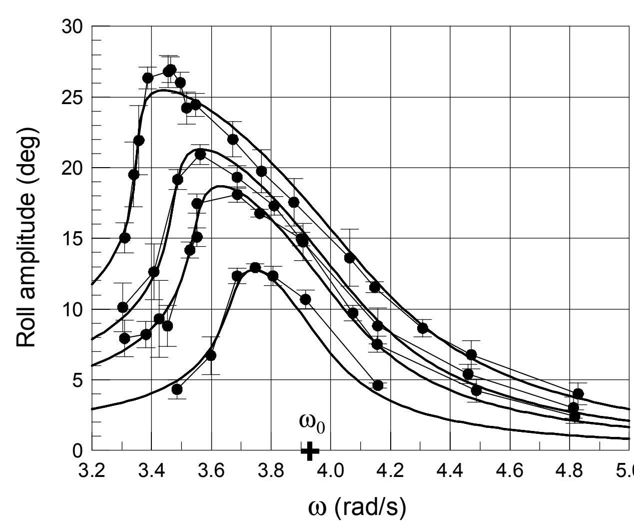

Fig. 4. Experimental results relative to the loading case#4. The different curves correspond to the set of wave steepnesses used: s_w=1/50, 1/70, 1/90, 1/180.

In Table. 2 the data related to the particular loading condition are given at model scale together with the coefficients of the best fit of righting arm curves calculated with fixed or free trim by standard ship stability codes. In the cases 4 and 5 the righting arm could be conveniently represented by a 3rd degree polynomial as in Fig. 3.
The results were analysed in terms of the PIT described above. The fit with Eq. 1 is excellent, as shown in Fig. 2.
In Fig. 4 and 5 the experimental results relative to the series #4 and respectively #5 are reported (all wave steepnesses). Superposed is also the result of the PIT.
The estimated parameters are collected in Table. 3.
The wave steepness in tests #4 and #5 was not pushed beyond 1/40 because of the tendency to exhibit strongly nonlinear phenomena as indicated in Fig. 6 at the highest peak. This of course is a consequence of the quite large nonlinear behaviour of the righting arm curve (Fig. 3).

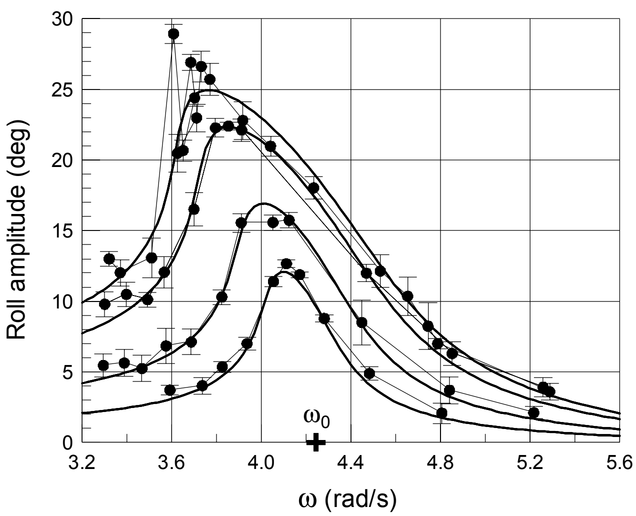

Fig. 5. Experimental results relative to the loading case#5. The different curves correspond to the set of wave steepnesses used: s_w=1/40, 1/50, 1/90, 1/180.

Table. 3. Estimated values for the coefficients of the mathematical model Eq.1 relative to ship hull c84-234.

	Loading condition				
	1	2	3	4	5
α_1	0.825	0.624	0.833	1.108	1.11
α_2	0.312	0.027	0.227	0.317	0.417
μ	0.279	0.109	0.012	0.072	0.057
β	0.086	0.168	0.230		
δ				0.193	0.240
α_3				-16.65	-18.66
α_{0eq} ("r")	0.514	0.597	0.606	0.791	0.693
μ_{eq} 20deg (model scale)	0.37	0.26	0.20	0.20	0.25

It appears that a cubic damping model fitted better the experimental data (the use of a quadratic led sometimes to negative linear coefficient) in the last two series. Of course the equivalent quadratic or linear damping coefficient can in any case be calculated by using Eq. 2. The introduction of the nonlinear restoring coefficient α_3 in the PIT for the cases #4 and #4 indicated that the transversal inclination was intermediate between fix and free trim but closer to this last.

4. THE EXPERIMENTAL RESULTS WITH SCALE MODELS OF LARGE PASSENGER CRUISE SHIPS

Further to the small RoRo a series of tests was done with large scale models (~1:40) of existing large passenger cruise ships.
A summary of the main data of these ships is given in Table. 4.
These models were tested in Vienna Model Basin in loading conditions with an height of centre of gravity sensibly lower than the actual ones, which lead to values of OG/T around 1.0, due to the difficulties connected with wave generation in the basin, having used already manufactured large models (scale 1/40). We will come back later with this problem. All the tests were conducted with s_w=1/40 and the models were unappended (like C-84-236). The experimental results are reported in Figs. 6 to 9.

Table. 4. Main data and characteristic ratios of the set of large passenger ships tested.

	Ship			
	25293	25294	25296	25335
C_B	0.6976	0.6975	0.6462	0.6884
B/T	4.5	4.5	4.5	4.737
OG/T	0.46	0.23	0.46	0.46
Lbp (m)	242.2	242.2	254	242.2
B (m)	36.000	36.000	32.25	36.000
T (m)	8.000	8.000	7.17	7.60
GM (m)	8.160	10.000	7.94	9.19
T_0 (s) design	12.7	11.4	11.5	11.9
T_0 (s) tested	12.3	11.5	11.2	12.0

The aim of the test program was to analyse the influence of the variation of B/T, C_B, OG/T on the roll amplitude with a limiting number of tests. The analysis of the data was performed with Eq. 1 modified as regards the excitation, represented by a single term $\alpha_{0_{eq}}$. The damping adopted was purely quadratic in the velocity, following Bertin's approach used in the original development of weather criterion. The third parameter obtained in the PIT is the natural roll frequency. Usually this is given as input data, but here there was a sensible difference between the required roll frequency and that obtained by roll decay tests, so that it was decided to leave it free data in the least-square searching. This also explains some inhomogeneity in the data distribution around the natural frequency. The use of a limited number of fitted parameters is connected with the limited number of point available for every series.

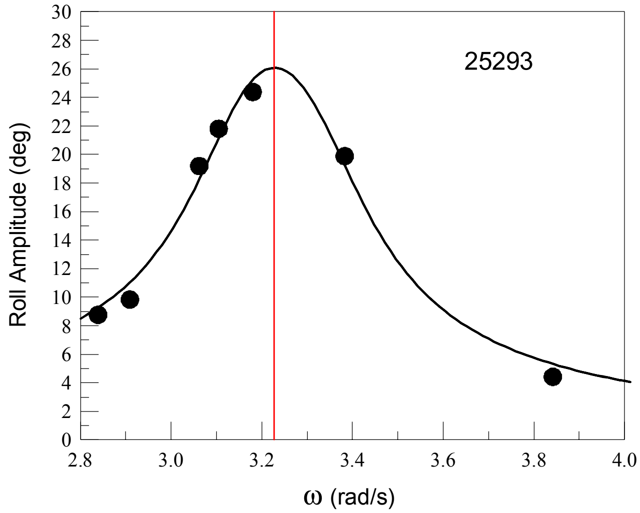

Fig. 6. Roll amplitude versus frequency for the test series #25293 in beam waves with s_w=1/40. The solid curve represents the results of the PIT. The natural frequency is indicated by the vertical line.

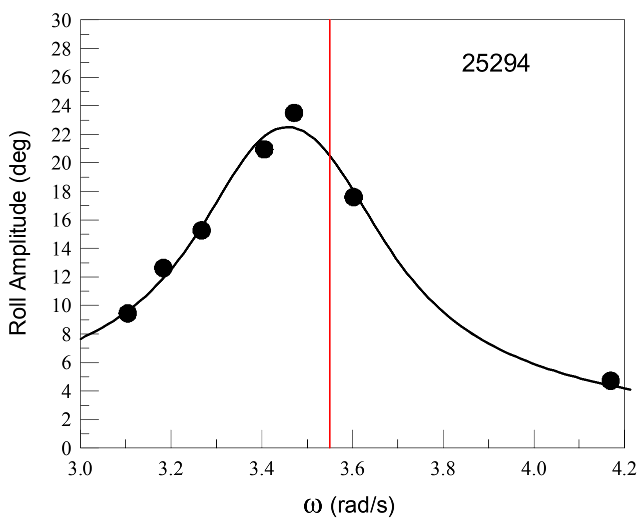

Fig. 7. Roll amplitude versus frequency for the test series #25294 in beam waves with s_w=1/40. The solid curve represents the results of the PIT. The natural frequency is indicated by the vertical line.

Table. 5. Estimated values for the coefficients of the mathematical model Eq.1.

	Ship			
	25293	25294	25296	25335
β	0.216	0.261	0.397	0.271
α_{0eq} ("r")	0.481	0.432	0.489	0.507

The goodness of fit is nevertheless surprisingly good, probably due to the particular righting arm of these ships which was substantially linear up to the maximum tested angles and beyond. To this end, the righting arm was represented by the linear term only.

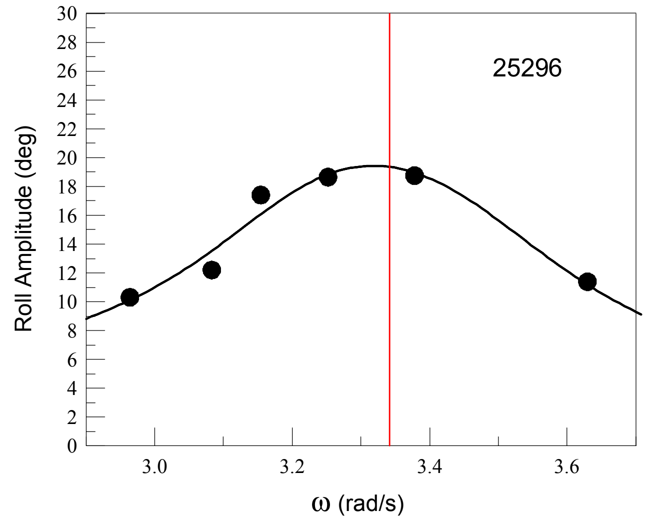

Fig. 8. Roll amplitude versus frequency for the test series #25296 in beam waves with s_w=1/40. The solid curve represents the results of the PIT. The natural frequency is indicated by the vertical line.

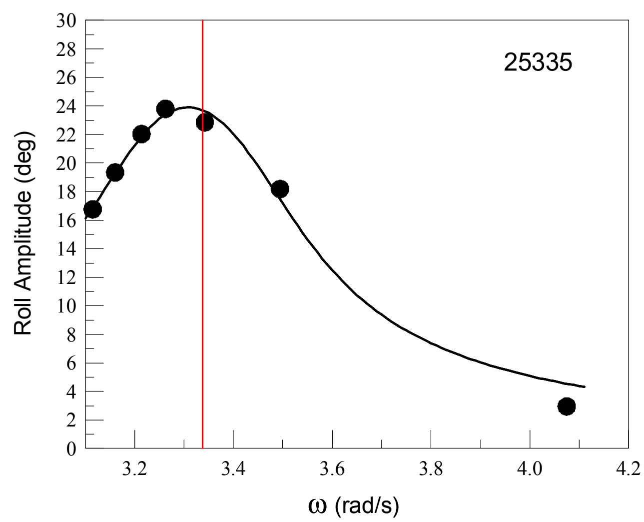

Fig. 9. Roll amplitude versus frequency for the test series #25335 in beam waves with s_w=1/40. The solid curve represents the results of the PIT. The natural frequency is indicated by the vertical line.

5. POSSIBLE CHANGES IN EFFECTIVE WAVE SLOPE FORMULA

We just remind that following Watanabe formula (see [6,8]) in IMO instrument the effective wave slope coefficient is indicated with "r" and given by:

$$r = 0.73 + 0.6\frac{\overline{OG}}{d} \quad (3)$$

where $\overline{OG} = \overline{KG} - d$ and d≡T. Expression 3 gives values much higher than experimentally derived (Fig.10). This is in agreement with results obtained on small passenger vessels and car ferries [3,13,14]. The possible change indicated in Fig. 10 is certainly an interim one waiting for more elaborate conclusions. It was accepted by IMO during last SLF in July 2002. On the other hand, the original formula for the roll-back angle was tuned on experiments. This means that, unless the global evaluation of roll angle is also wrong, decreasing the effective wave slope coefficient will necessarily be accompanied by a decrease in one or more factors representing damping (originally N=0.02 for ships with bilge-keels).

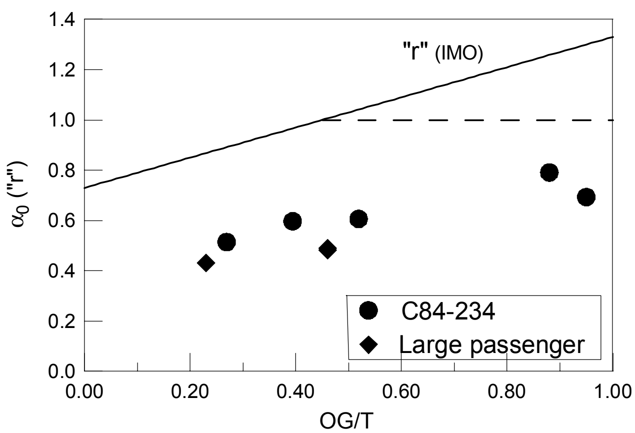

Fig. 10. Effective wave slope coefficients as a function of OG/T. For comparison the calculation procedure recommended in Weather Criterion is also given (solid line as per Eq. 3. The dashed line represents the provisional assumption made in IMO [2,5].

We are not in the position to discuss damping at this stage, since more data are needed from the programme that will be described below. At the same time we are not in the position to compare the maximum roll angle forecast, since this entails the realisation of experiments in the presence of more severe sea waves than we did up to now. What can be done, also on an interim basis, is comparing the maximum roll angles obtained by experiment with those obtained by applying the original IMO formula [6]:

$$\phi_1 = 109\, k\, X_1\, X_2 \sqrt{r\, s} \quad (4)$$

assuming that it preserves its validity at different wave steepnesses than originally considered. Of course, since the roll period evaluation is another drawback of IMO formulation, the actual one will be used. Although there are many uncertainties in this exercise, the comparison of values, Table. 6, indicates that IMO formula generally underestimates the maximum roll amplitude.

6. EXPERIMENTAL DIFFICULTIES AND FUTURE RESEARCH PROGRAMME

It was already mentioned that the experiments could not be performed on the large scale models with the wave steepness required by IMO rule. This is due to the fact that with the typical natural period of these ships (25-30 s and more), full scale waves are above 1000 m in length, which means above 25 m model scale, with a height of more than 0.6 m. Only few waves basins can generate regular trains of waves like these. If we reduce the scale, on the other hand, it is really questionable the evaluation of damping and in particular the effect of appendages like bilge keels, skegs, azipods, etc.

As an alternative we could in the meantime proceed in the evaluation of a reasonably high wave as a function of period for ships with very high rolling period [5,7].

Table. 6. Comparison between maximum roll amplitude calculated following IMO prescriptions and from experiments. The theoretical results are already increased by 30% to account for regular waves.

Ship	s experim.	ϕmax experim	ϕmax Eq. 4 s=0.025	ϕmax Eq. 4 s from [6]
25293	0.025	24.5	19.4	30.2
25294	0.025	24	18.0	30.0
25296	0.025	19.5	19.1	31.6
25335	0.025	24	19.3	31.3
C84-234#1	0.0333	31	19.11	31.4
#3	0.0333	34	20.7	35.7
#5	0.025	25-28	21.7	41.2

These preliminary results clearly indicate that the roll period and the effective wave slope coefficients are overestimated by present IMO Weather Criterion suggested procedure. As regards the maximum roll angle, the results are a bit confusing and hopefully some clarification will result from the full program. Of course on small models we are more confident on the estimate of the effective wave slope than on that of damping. The use of calculations in the Froude-Krylov hypothesis is in any case not viable because it also leads to an overestimate of the effective wave slope coefficient [3].

An extensive European research project, SAFENVSHIP, has been started on this subject. It will include a parametric search of the dependence of effective wave slope and of damping on the relevant parameters, including the presently used position of centre of gravity, block coefficient and B/T. Tests in beam wind to update the drag coefficients for large windage area ships will also be done. Of course, the series of tests will include the case of stochastic excitation to verify the 1/3 reduction implied in Eq. 4.

7. ACKNOWLEDGEMENTS

This paper has been developed as part of the research "Analisi critica del Criterio di Stabilità Meteorologico e formulazione di proposte di modifica per le grandi navi passeggeri" financed by CETENA SpA in the frame of CETENA Research Plan 2000/02.

8. REFERENCES

[1] Francescutto, A and Serra, A (2001). "Weather Criterion for Intact Stability of Large Passenger Vessels," Proc. 5th Int. Workshop on Ship Stability and Operational Safety, A Francescutto Ed., Trieste, pp. 4.6.1-4.6.4.

[2] Francescutto, A, Serra, A and Scarpa, S (2001). "A Critical Analysis of Weather Criterion for Intact Stability of Large Passenger Vessels," *Proc. 20th Int. Conf. OMAE'2001*, Rio de Janeiro.

[3] Fujino, M, Fuji, I, Hamamoto, M, Ikeda, Y, Ishida, S, Morita, T, Tanai, K, Umeda, N (1993). "Examination of Roll Damping Coefficients and Effective Wave Slope Coefficients for Small Passenger Crafts," *Proc. U.S. Coast Guard Vessel Stability Symposium*, U.S. Coast Guard Academy, Avery Point, USA, 1993.

[4] SLF44/INF.6 (2001). "Weather Criterion for Large Passenger Ships," Submitted by Italy, IMO, London.

[5] Francescutto, A., "Intact Ship Stability – The Way Ahead", Proc. This Workshop.

[6] IMO Res. A.749, Code on Intact Stability for All Types of Ships Covered by IMO Instruments, London, IMO, 1995 - Amendments to the Code on Intact Stability for All Types of Ships Covered by IMO Instruments, IMO Res. MSC.75(69) London, IMO, 1999.

[7] Francescutto, A., "Sea Waves and Ship Safety - State of the Art in Current International Regulations", Proc. (CD) 12th Int. Symp. ISOPE'2002, Kita-Kyushu, 2002, Vol. 3, pp. 150-156.

[8] Yamagata, M, "Standard of Stability Adopted in Japan," *Trans. INA*, Vol. 101,1959, pp. 417-443.

[9] Francescutto, A., "Roll-Sway-Heave Coupling in Beam Waves", Proc. (CD) of 12th Int. Symp. ISOPE'2002, Kita-Kyushu, Vol. 3, pp. 281-287.

[10] Francescutto, A and Contento, G, "The Modelling of the Excitation of Large Amplitude Rolling in Beam Waves," *Proc. 4th International Ship Stability Workshop*, St.Johns, 1998.

[11] Andretich, M., "A Critical Study of the Weather Criterion for the Intact Stability of Modern passenger Cruise Ships", Thesis, University of Trieste, 2002.

[12] IMO/SLF45 Italy

[13] Iskandar, BH and Umeda, N (2001a). "Some Examination of Capsizing Probability Calculation for an Indonesian RoRo Passenger Ship in Waves," *Journal Kansai Society Naval Architects Japan*, N. 236, pp. 81-86.

[14] Iskandar, BH and Umeda, N (2001b). "Capsizing Probability of an Indonesian RoRo Passenger Ship in Irregular Beam Seas," *Journal Society Naval Architects Japan*, Vol. 189, pp. 31-37 and 414-415.