The Specialist Committee on Stability in Waves

Final Report and Recommendations to the 24th ITTC

1. INTRODUCTION

1.1 Membership and Meetings

Membership. The Committee appointed by the 24th ITTC consisted of the following Members:

- Dr. Jan-Otto de Kat (Chairman). Maritime Research Institute Netherlands, The Netherlands.
- Dr. Naoya Umeda (Secretary). Osaka University, Japan.
- Prof. She-Ming Fan. Marine Design and Research Institute of China, China.
- Prof. Alberto Francescutto. University of Trieste, Italy.
- Prof. Jerzy Matusiak. Helsinki University of Technology, Finland.
- Mr. Timothy C. Smith. Naval Surface Warfare Center, USA.
- Prof. Apostolos Papanikolaou. National Technical University of Athens, Greece.
- Prof. Dracos Vassalos. Universities of Glasgow and Strathclyde, UK.

In addition, the following individuals contributed greatly to the work of the Committee:

- Mr. K. Brink and Dr. W. L. Kuehnlein. HSVA, Germany.
- Dr. S. Ishida. NMRI, Japan.
- Mr. A. J. Peters. QinetiQ, UK.
- Prof. K. J. Spyrou. NTUA, Greece.
- Mr. W. L. Thomas. USCG Engineering Logistics Center, USA.

Meetings. Four Committee meetings were held as follows:

- New York, USA, October 2002.
- Madrid, Spain, September 2003.
- Trieste, Italy, February 2004.
- Shanghai, China, November 2004.

1.2 Tasks from the 23rd ITTC

- Report on the collective experience and knowledge of Member Organisations in the prediction of ship capsizing.
- Monitor and assess the implementation of the proposed experimental procedures for testing intact and damage stability, and recommend refinements as necessary.
- Identify weaknesses and recommend improvements to numerical models for predicting capsize of intact and damage ships in regular and irregular waves, and test their validity.

- Review the application of existing numerical and physical model testing techniques to ships other than RoRo's, including high-speed craft. In particular review and suggest improvements to the IMO Draft MSC Circular -Interim Guidelines for the Conduct of High-Speed Craft Model Tests.
- Develop numerical and experimental procedures for assessing both intact and damage stability for conventional and novel vessels.
- Review experimental and numerical techniques to predict extreme motions and course keeping characteristics in stern quartering seas, which may lead to broaching.
- Review experimental and numerical techniques for evaluating evacuation systems of ships and offshore structures in waves.

Following conferral with the Seakeeping Committee after the start of the work programme, it was agreed that the Stability in Waves Committee would develop and propose an ITTC procedure for the prediction of parametric rolling as an additional task.

2. PREDICTION OF EXTREME MOTIONS AND CAPSIZING OF INTACT SHIPS

2.1 Literature Review

The Specialist Committee on Stability of the 22nd ITTC (1999) reviewed published works from the early days on this subject. Then the Specialist Committee on Prediction of Extreme Motions and Capsizing of the 23rd ITTC (2002) focused on CFD in its literature review. Here the Committee reviewed the latest literature for collecting new techniques from published works and for facilitating a revision of the procedure on model tests.

Beam-Sea Capsize. Kuroda et al. (2003) studied some nonlinear features of extreme roll motion in beam seas. Jumps between high and low drift velocities, leading to different roll motions, were observed and explained as coexistence of multiple stable solutions of a system consisting of wave drifting force and viscous drag. McCue and Troesch (2003 and 2004) developed a sway- heave-roll model, with the hydrodynamic coefficients obtained from the existing linear seakeeping theory. They investigated how to extend the so-called integrity diagrams of stability taking into account sway and heave, in addition to the roll that was taken into account up to now, and attempted to utilise Lyapunov exponents.

A major weakness of current approaches to predict extreme roll motions, especially if they are owed to a resonance mechanism, is the lack of first-principles methods for calculating roll damping at the design stage. Molin (2004) analytically investigated the viscous roll damping for laminar, non- separated flow. His prediction method, applied to rectangular barge sections, has confirmed the very small values of frictional roll damping. A CFD application to this problem was reported by Sarker and Vassalos (2000). In the absence of established theoretical approaches, roll damping coefficients are customarily obtained from tests with scaled models. An analytical method showing the nonlinear decay mechanism at very large angles and offering a way to extract nonlinear damping coefficients was presented by Spyrou (2000 and 2004a). A similar approach but with an analytical solution based on averaging was proposed by Bulian (2004).

Francescutto and Naito (2004) have shown the possibility, at a theoretical level, of complex roll dynamics for a stochastic beam sea, even without the hypothesis of a narrow-band sea spectrum that should produce regular-like excitation. Alternative theoretical and parametric models were examined to determine the probability of ship encounter with successive wave periods in the critical range. Spyrou et al. (2002) an approach for determining the critical combinations of environmental excitation, damping, inertia and restoring, based on rigorous Melnikov's method of nonlinear dynamics which can be applied in a deterministic and in a stochastic context. Huang (2004) attempted to estimate capsizing probability by combining Melnikov's method and probability density of roll angle obtained from the Fokker-Planck-Kolmogorov equation.

Multi-Degree of freedom Numerical Models. The 6 degrees-of-freedom (DOF) time domain code FREDYN has been extended with an option to compute the hydrodynamic radiation and Froude-Krylov forces using a 3-D panel method instead of using nonlinear strip theory; in addition for course keeping purposes an adaptive autopilot has been added (De Kat et al., 2002). The large amplitude ship motion code LAMP (3-D time-domain potential flow panel method based on a body-nonlinear formulation) has been used in several stability investigations: Belenky et al. (2002 and 2003a) reported an attempt to predict nonlinear roll motion with water-on-deck. The flow on the deck is computed using a concurrent time-domain solution driven by the relative motion of the ship and the incident wave at the deck edge and the motion of the deck. Green water is modelled with a finite volume technique assuming shallow water. Kim (2002) combined the LAMP code with a finite difference method for the internal flow in a tank, developing a tool that could be used for studying the interaction of rolling motion and sloshing. The method was tested with application to the anti-rolling tank of a containership.

Ayaz et al. (2001) extended an earlier 4-DOF "manoeuvring-type" model to 6 DOF. The new model can be used in order to assess the importance of the memory effect and also the effect of heaving and pitching on the tendency to capsize.

Parametric Rolling. France et al. (2003) performed experiments and observed parametric rolling of a post-Panamax container ship in regular waves and in long-crested and short-crested irregular head waves, which were correlated to numerical simulations with the FREDYN and LAMP codes. Levadou and Palazzi (2003) extended this investigation to study the short-term and long-term probability distributions to assess the operational risk of parametric roll on a typical route across the North Atlantic. Bulian et al. (2004a) carried out model tests for a Ro-Ro in long-crested irregular head waves. No capsizing associated with parametric roll in head seas was observed.

To investigate the occurrence of combination resonances in head seas Neves (2002) employed an analytical approach expressing restoring in the heave, roll and pitch modes up to second order. Wave action was taken into consideration through Froude-Krylov plus first order diffraction forcing functions, plus second order terms resulting from changes of submerged hull due to wave passage. Belenky et al. (2003b and 2004) reported simulations of parametric rolling in irregular long-crested waves. The simulations resulted in questions concerning the assumption of ergodicity of parametric roll during physical or numerical model tests. Bulian et al. (2004c) concluded that the standard procedures for seakeeping analysis are not appropriate for analyzing parametric roll.

Matusiak (2003) examined the effect of initial conditions, damping and wave amplitude on tendency for parametric roll with a 6 DOF numerical model. Bulian et al. (2004a) have reviewed current methods for deriving stability boundaries of parametrically excited, single-degree-of-freedom systems, both for the deterministic and stochastic case. For the stochastic case in particular, the question of suitable criteria seems to be still open in scientific terms. Deterministic criteria for containerships aimed at parametric roll susceptibility and severity were proposed by Shin et al. (2004). Spyrou (2004b) proposed an alternative approach based on transient motions and stressing the need to interface the deterministic and stochastic treatments by exploiting wave groupiness. Ribeiro e Silva et al. (2005) directly calculated probability of exceedance of roll angle with a 5 DOF numerical code.

Surf-Riding. Occurrence of surf-riding, which could lead to broaching, can be estimated by a heteroclinc bifurcation of a system of surge motion. An analytical formula for a simplified surge equation was proposed by Spyrou (2001). A numerical algorithm for estimating this bifurcation has been reported with a successful example by Umeda et al. (2004c).

Capsize Model Tests in Regular Waves. Umeda et al. (1999) proposed systematic experimental procedures to identify the critical conditions associated with capsizing in a seakeeping and manoeuvring basin. Examples of application can be found for fishing vessels (two purse-seiners). Their capsize modes cover broaching, loss of stability in the wave crest and bow-diving in following and quartering seas. Matsuda et al. (2002, 2004) added examples, which cover two other purse-seiners, a high-speed fishing craft and trawler. Their capsize modes include broaching, loss of stability in the wave crest, bow-diving and flip bifurcation in following and quartering seas.

Capsize Model Tests in Deterministic Wave Trains. Clauss and Hennig (2004) reported an experimental capsize testing procedure with deterministic wave trains in a towing tank by using Z-Manoeuvres. Hennig et al. (2003) further developed the technique for generating deterministic wave trains reported by Clauss (2000) and compared results from the computer-controlled experimental techniques with measured results.

Hirayama and Takezawa (for example, 1982) developed experimental techniques with transient wave trains for many years. Their application to capsizing in breaking beam waves can be found in Motora (1982) for a totally enclosed life boat, Ishida and Takaishi (1990) for a high-speed craft, Hirayama et al. (1994 and 1995) for a sailing yacht even in short-crested cases, Nimura et al. (1994) and Deakin (2000b) for sailing yachts including multihulls.

Capsize Model Tests in Irregular Waves. Umeda et al. (1995) started capsizing experiments in short-crested irregular waves with a container ship and a purse-seiner in a seakeeping and manoeuvring basin utilising side-wall reflections invented by Takezawa et al. (1988). Their capsizing mode covers parametric rolling. Hirayama and Nishimura (2000) reported their experiment in short-crested irregular waves with a purse-seiner in a towing tank.

2.2 Benchmark Study of Numerical Codes for Predicting Intact Stability in Waves

The objective of this study was to establish capability and weaknesses of existing numerical codes that have been developed for predicting extreme ship motions and capsizing of intact ships in waves.

As a part of the 23rd ITTC activities an intact stability benchmark study had been carried out using two ships: a container ship (A-1) and a purse-seiner (A-2) for which model test data were available from the National Research Institute of Fisheries Engineering of Japan (NRIFE). From this benchmark a number of issues and inconsistencies of numerical codes had been identified (ITTC, 2002).

From the tests with the fishing vessel A-2 at NRIFE it was known that the model had capsized mainly due to broaching in the higher speed region. As additional test data were available, it was decided to use this vessel again in this study as a continuation of the previous, 23rd ITTC benchmark study.

A benchmark study of a multi-degree of freedom, nonlinear system, such as a steered ship in extreme waves, is confronted with several uncertainties, concerning both the experimental and numerical procedures that produce the data. It is exceedingly difficult to ensure that the wave profile in the vicinity of the moving ship as well as the initial position, velocities and orientation relatively to the waves are in perfect coincidence during the physical and numerical test runs. A simple direct comparison of a limited number of time histories would leave many questions unanswered. In a move towards establishing a systematic benchmark method, a stepped approach has been adopted. More specifically, organisations were invited to submit their predictions addressing the following categories:

- Dynamic behaviour in still water (roll decays from extreme and moderate angles and basic manoeuvrability).
- Roll and sway responses in beam seas.
- Roll, sway, yaw and surge responses in quartering seas.
- Magnitudes of hydrodynamic loads associated with the above.

Organisations were encouraged to investigate possibly different outcomes due to different initial conditions. Indeed, some predictions have shown a different outcome depending on initial conditions (leading in one case to capsize and in another not). For deeper insight it was decided to carry out the benchmark study in two stages: in “Phase I”, organisations had no access to the experimental time series of ship responses (Spyrou et al., 2004). This was allowed in “Phase II” where a direct, one to one, comparison of numerical and experimental predictions was pursued (Spyrou et al., 2005). Both phases of the study were coordinated by the National Technical University of Athens.

The following organisations participated in the benchmark study:

- Federal University of Rio de Janeiro (UFRJ) LabOceano/COPPE, Brazil
- Helsinki University of Technology, Finland
- Korea Research Institute of Ships and Ocean Engineering, Korea
- Maritime Research Institute Netherlands, The Netherlands
- National Maritime Research Institute, Japan
- The Ship Stability Research Centre of the Universities of Glasgow and Strathclyde, UK
- Osaka University, Japan (Phase II only)

The main hull parameters and characteristics of ship A-2 have been described in the previous ITTC report (2002), but in the present study the metacentric height was GM = 0.75 m (natural roll period 9.7 s), unless stated otherwise.

The plan of the benchmark tests for Phase I is given below:

Establishment of Level of Agreement for Still-Water Behaviour.

- Roll decays a) from 80% of the vanishing angle without forward speed; and b) from 30% of the vanishing angle with Fn=0.2.
- Turning circle with 35^0 rudder from $Fn = 0.3$. Comparison of track reach for 10^0 and 20^0 change of heading, maximum heel, transfer, advance and tactical diameter. Alternatively, a $20^0/20^0$ zig-zag test at Fn=0.3, measuring yaw overshoot, time to first and second execute and maximum heel.

Comparison of Behaviour in High Waves.

- Rolling in beam waves (“free to drift”) with $\lambda/L = 1.0, 1.5$ and $H/\lambda = 1/15$ at zero speed. Comparison of amplitude and phase of response if there is no capsize; occurrence of capsize and number of wave cycles required, behaviour during initial transients (max heel angle and number of wave cycles to reach it).
- Dynamic behaviour in quartering seas for combinations of the following conditions $\lambda/L = 1.5$, $H/\lambda = 1/30, 1/20$, Fn = 0.2, 0.3, 0.4 and desired heading 5^0, 15^0, 30^0. Comparisons of amplitudes and phases of responses for yaw, rudder, roll and surge; occurrence or not of capsize. In addition, comparison of ampli-

tude and phase of excitations arising from rudder, wave and hydrodynamic reaction.

It is noted that no organisation submitted the requested excitation time series during Phase I. One organisation did this in Phase II.

During Phase II it was deemed necessary to modify slightly the specification in order to achieve a closer correspondence between numerical and experimental testing conditions.

More specifically, roll decays were requested principally for:

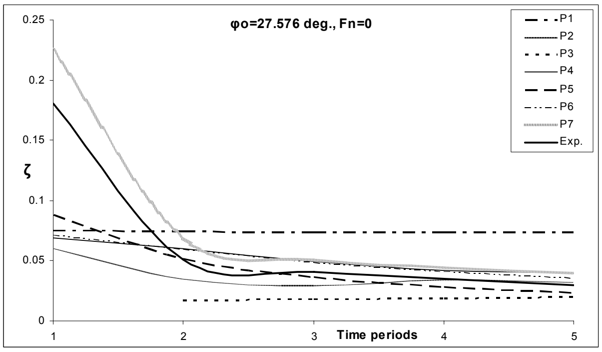
- $\varphi_0 = 27.576^0$ at Fn=0;
- $\varphi_0 = -20.041^0$ at Fn=0.2 (GM=1.0 m).

For quartering seas, the behaviour was examined for the combinations of the following conditions: $\lambda/L = 1.5$; $H/\lambda = 1/15$; Fn=0.2, 0.3, 0.4; desired heading $5^0, 15^0, 30^0$.

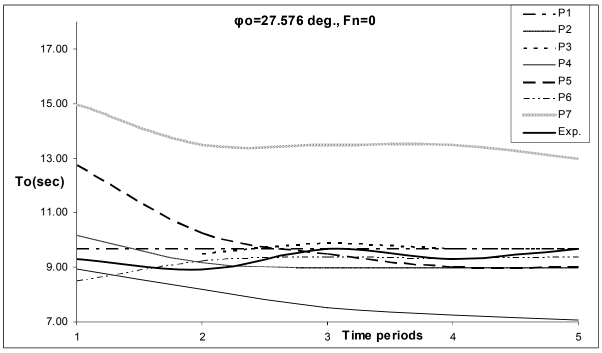
The key findings of Phase II of the benchmark study are summarised below.

Test 1: Roll Decay. In Fig. 2.1 are shown comparisons between numerical and experimental predictions for the two decay scenarios mentioned above. The log of the ratio of consecutive maxima leads to a "local" linear damping ratio ζ at the corresponding amplitude.

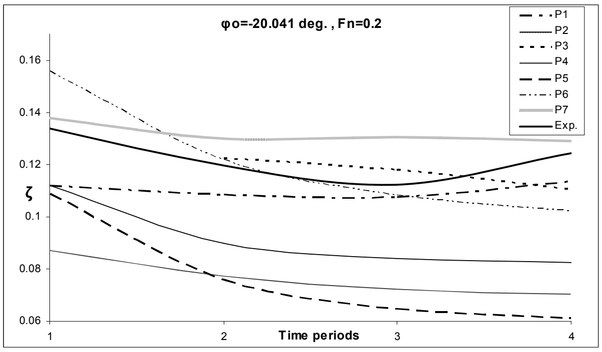
Most codes predict well the decay at zero speed as soon as the amplitude has become small (Fig. 2.1a). However, only one method succeeds at larger amplitudes. A comparison on the basis of local ζ reveals a considerable increase of the damping ratio with speed, predicted quantitatively reasonably well in one case and qualitatively in three cases (Fig. 2.1c). The variation of the natural roll period per roll cycle, for each participant, is shown against the appropriate experimental record in Figs. 2.1b (no speed) and 2.1d (with speed). Known differences in the assumed roll radius of gyration only partly could justify the lack of agreement.



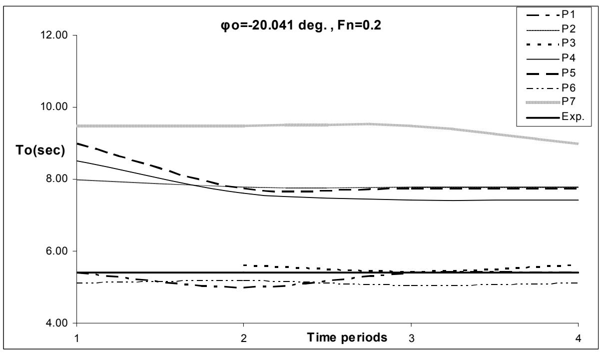
(2.1a)



(2.1b)



(2.1c)



(2.1d)

Figure 2.1- Variation of local damping ratio and period during decay for two cases (with and without forward speed).

There is a need for modelling improvement in roll decay prediction for a ship with forward speed. It should be noted however that, for the decay starting at 27.5^0, the experimental curve shows a variation in the roll period during the decay (see Fig. 2.1b). This is likely due to the presence of water on the deck.

Test 2: Performance in Standard Manoeuvre. The turning circle with 35 deg rudder angle revealed that one organisation produced successful predictions for steady yaw rate, steady heel angle and max heel angle. The mean value of all submissions concerning these three quantities was within 11% of the corresponding experimental values. Heel angles were reasonably well predicted by most organisations. Two methods predicted very well (within 5% error) the steady yaw rate. Results are shown in Table 2.1.

Table 2.1- Turning circle with 35 deg rudder.

Participant	Advance (m)	Tactical Diameter (m)	Transfer (m)	Track Reach 10deg (m)	Track Reach 20deg (m)	Max Heel (deg)	Steady Heel (deg)	Steady Yaw (deg/sec)
1	2.94	2.5	1.11	1.19	1.60	8.13	5.12	4.38
2	3.75	5.95	2.6	0.93	1.48	9.96	5.5	3.05
3*	2.21	2.13	0.67	0.86	1.24	9.67	3.69	4.52
5	3.28	3.26	1.64	1.22	1.67	3.96	2.27	3.46
6	2.91	3.07	1.30	1.2	1.59	N/A	N/A	4.43
7	N/A	N/A	N/A	N/A	N/A	7.62	6.07	3.17
Mean	3.02	3.38	1.46	1.08	1.52	7.87	4.53	3.84
Standard deviation	0.56	1.50	0.73	0.17	0.17	2.40	1.54	0.68
Experiment	N/A	N/A	N/A	N/A	N/A	8.77	4.66	4.35

Test 3: Rolling in Beam Seas. In general, the submitted roll responses revealed differences in terms of the qualitative pattern of transient and steady state and also in terms of magnitude (Fig. 2.2). Key parameters of these responses, the steady roll angle and the mean roll angle at steady state, have been compared against the corresponding experimental parameters, for wave steepness $H/\lambda = 1/15$. The results are summarised in Table 2.2 for two wave length-to-ship-length ratios: λ/L=1 in Table 2.2a and λ/L=1.5 in Table 2.2b. For the shorter wave, the mean prediction of the six participating organisations for the steady roll amplitude exceeded the experimental value by just over 6%. On an individual basis, two methods predicted well the steady roll amplitude. For the longer wave, one organisation produced satisfactory predictions of steady roll. However, the mean values of the six submissions, concerning the steady roll amplitude departed by nearly 50% from the corresponding experimental value. It should be noted that despite the high wave steepness, roll responses were low due to off-resonance conditions.

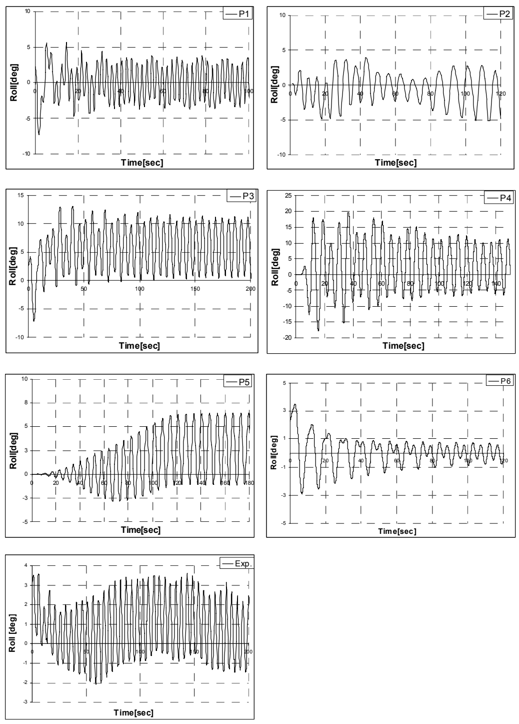


Figure 2.2- Time series of beam sea roll simulation and experiment.

Test 4: Motions in Quartering Seas. A characteristic collection of submitted time series, referring to two different scenarios of simulation and obtained during Phase II of the study, is shown in Fig. 2.3.

Differences in the patterns of roll, yaw and rudder motions are notable. We preferred, rather than simply contrasting the numerical with the experimental time series, to compare some key measures of these responses: namely, the mean and the amplitude of the response at steady state and the obtained maximum response during transient, as shown in Fig. 2.4. A comparison of steady states is advantageous because it is free of the effect of initial conditions (unless multiple steady states coexist which calls for further work).

Table 2.2- Result of beam-sea roll tests.

(2.2a)

Participant	Roll amplitude (deg)	Mean roll (deg)
1	3.50	-0.03
2	3.90	0.42
3	5.50	5.79
4	3.03	1.08
5	1.99	1.65
6	0.74	0.13
7	N/A	N/A
Mean Value	3.11	1.51
Standard Deviation	1.64	2.19
Experiment	2.93	0.69

(2.2b)

Participant	Roll amplitude (deg)	Mean roll (deg)
1	6.52	0.05
2	4.70	0.17
3	8.91	8.28
4	9.53	2.59
5	4.01	2.46
6	1.84	0.03
7	N/A	N/A
Mean Value	5.92	2.26
Standard Deviation	2.97	3.18
Experiment	4.20	0.79

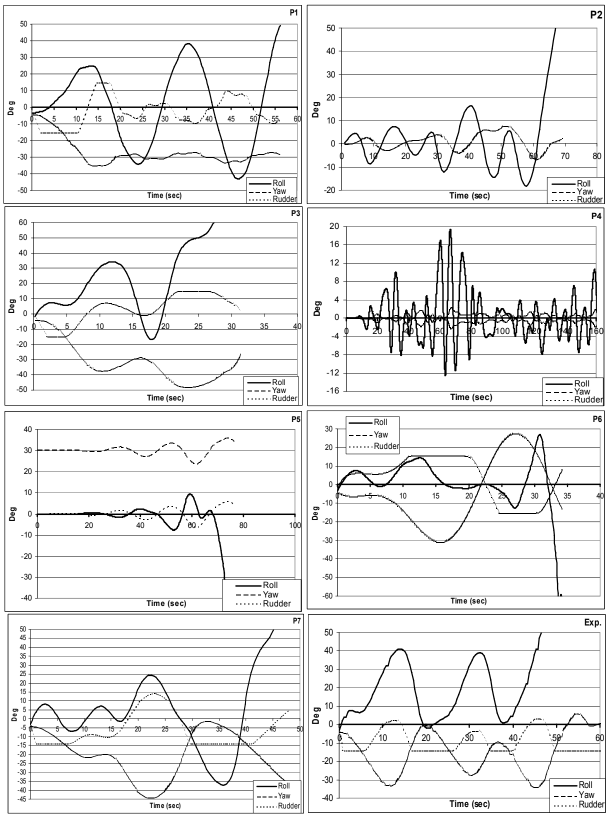


Figure 2.3- Predictions of response for heading 30^0, *Fn*=0.4, λ/L=1.5 and H/λ=1/15.

It was endeavoured to establish trends for the numerically predicted roll, yaw and rudder responses as we move towards higher: a) wave steepness b) Froude number and c) desired heading (away from a perfectly following sea). It is noted that the surge, sway, heave and pitch, motions were also monitored in order to understand whether the ship is in large amplitude surging or in surf-riding. Some codes were capable to predict the steady roll amplitude at lower Froude numbers. However, all codes seem to deviate from the experimental result as the speed is raised.

Furthermore, satisfactory prediction of the maximum roll angle was obtained only in few cases. The majority of the codes did predict capsizing where observed experimentally (Fig. 2.3), but there were significant discrepancies in the associated time series of the motions.

These discrepancies could be associated with the following:

- force coefficients, including roll damping;
- coupling of manoeuvring model to sea-keeping model;
- rudder-roll coupling;
- unknown initial conditions and position relative to the waves.

An additional discussion on the influence of certain force contributions is given Section 2.3. Acceptable values of mean yaw, for each examined heading and Froude number, were obtained in two cases. Some codes predicted mean yaw values near to 0 degrees, even though the desired heading was much larger, e.g. 30°. The steady yaw amplitude was predicted reasonably well by three codes. Predictions appear to be relatively good for the lower speed and heading. Capsize was predicted well for Fn=0.4 and heading 30°. Tables 2.3 to 2.5 summarise the mean and standard deviation of the predictions of all methods for: a) mean steady yaw; steady yaw amplitude; and steady roll amplitude, for each examined scenario. This is basically a consistency check of the predictions for all methods. Overall, yaw predictions may be characterised as reasonable, although standard deviation is often large. The overall prediction of roll parameters in following/ quartering seas is not satisfactory.

Further Investigation. One organisation looked deeper into the origins of some of the noted discrepancies. They represented hull geometry by means of a 18x40 grid of quadrilateral surface panels. These panels, used for computing the Froude-Krylov forces in the undisturbed wave field only, were interpolated from a spline fitted through the stations. Added mass and damping were deduced from strip theory, with conformal mapping, using the spline.

It was noticed that, computing the submerged volume and centre of buoyancy with the spline produced a different result than computing these directly from the panel description. The difference in volume was less that 0.5%; however the difference in LCB position caused a trim by the stern of 0.55° for the spline method relatively to that of the panel method. Long panels near the stern caused this difference. The gently upwards sloping stern contour and large increase of water-plane area, when trimmed by the stern, increases dynamic stability from marginal to sufficient. The initial series of runs (free running with a 1/15 wave steepness) used the panel geometry and in all cases the ship capsized. When the spline description was used, capsize occurred only for the highest speed, which is consistent with the experimental result (Fig. 2.5). Therefore, for ships like the present one, results are sensitive to the accuracy of hull geometry's description.

Conclusions. On the basis of the extensive investigations performed during the current benchmarking, the following conclusions are drawn:

No code has reproduced consistently all required simulation scenarios with satisfactory conformance to the experimental data. Furthermore, the standard deviation of the predictions of the various organisations is large. However, satisfactory predictions were noted for some codes, for subsets of the recommended scenarios.

Given the extremity of the testing conditions and the fact that the experimental data had not been obtained specifically for benchmarking, the degree of accuracy of the experimental data cannot be taken for granted.

No correlation can be deduced between the accuracy of predictions on the one hand and certain features of the modelling approach on the other (e.g. calculation of radiation and diffraction forces, inclusion of memory effect etc). Further investigation is necessary.

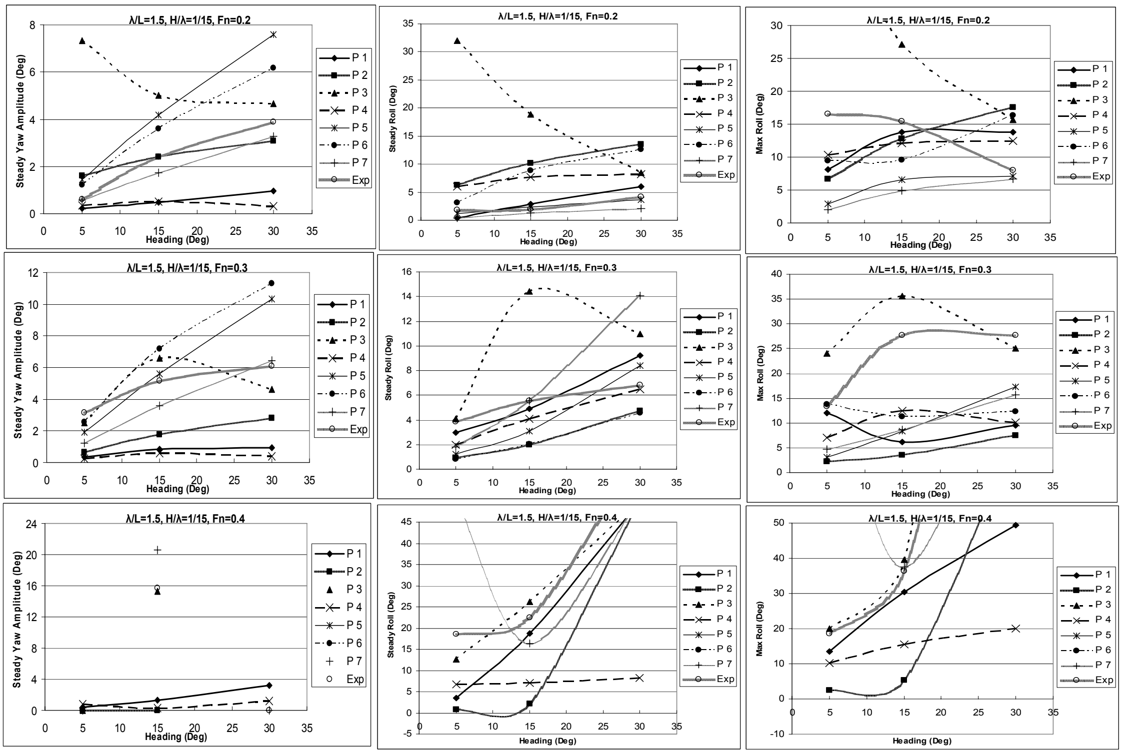


Figure 2.4- Sensitivity of maximum roll, steady roll and steady yaw to variations of the heading and the Froude number for λ/L=1.5 and H/λ=1/15.

Table 2.3- Mean and standard deviation of mean steady-state yaw for all participants.

Desired heading (deg)	**Fn = 0.2**			**Fn = 0.3**			**Fn = 0.4**		
	Mean	**Std dev.**	**Exp.**	**Mean**	**Std dev.**	**Exp.**	**Mean**	**Std dev.**	**Exp.**
5	4.57	4.09	1.85	2.57	2.39	4.59	cap. /broach	cap. /broach	broach
15	10.85	11.73	8.69	9.91	11.31	12.12	8.66	8	19.86
30	16.38	16.78	20.6	18.72	20.15	25.59	capsize	capsize	capsize

Table 2.4- As above for steady yaw amplitude.

Desired heading (deg)	**Fn = 0.2**			**Fn = 0.3**			**Fn = 0.4**		
	Mean	**Std dev.**	**Exp.**	**Mean**	**Std dev.**	**Exp.**	**Mean**	**Std dev.**	**Exp.**
5	1.83	2.48	0.62	1.35	1.01	3.13	cap. /broach	cap. /broach	broach
15	2.56	1.77	2.4	3.73	2.75	5.15	7.5	9.75	15.74
30	3.72	2.63	3.9	5.26	4.35	6.12	capsize	capsize	capsize

Table 2.5- As above for steady-state roll amplitude.

Desired heading (deg)	***Fn* = 0.2**			***Fn* = 0.3**			***Fn* = 0.4**		
	Mean	**Std dev.**	**Exp.**	**Mean**	**Std dev.**	**Exp.**	**Mean**	**Std dev.**	**Exp.**
5	7.06	11.27	1.85	1.98	1.20	3.85	5.89	5.08	18.52
15	7.47	6.12	1.95	5.16	4.31	5.55	14.10	9.56	22.40
30	7.79	4.27	4.10	8.36	3.45	6.83	capsize	capsize	capsize

When the testing conditions could be specified more accurately (Phase II), some improvement was noticed regarding extreme responses in beam and quartering waves with respect to Phase I.

An accurate definition of the hull form geometry is required for broaching and capsize predictions.

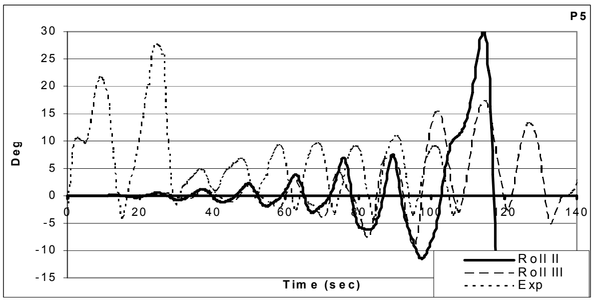


Figure 2.5- Effect of hull panelisation (heading 15°, *Fn*=0.2). "Roll III" is based on more accurate hull form definition; "Roll II" represents the original simulation of one participant.

<u>Recommendations.</u> For future benchmark studies, it is imperative to obtain a structured experimental data set for more than one ship type and with undisputed repeatability, suitable for validation of large amplitude codes.

Organisations should evaluate the results and identify possible sources of inaccuracies in their models. In particular, all empirical data used as input in the codes should be listed in a future benchmark study.

2.3 Identification of Critical Elements in Numerical Modelling

To further investigate the importance of different force contributions in capsize prediction, an analysis was made of captive experiments of the ship A-2 with a fixed heel angle in stern quartering waves.

Figure 2.6 suggests that the total measured roll moment variation (expressed in terms of an effective lever GZ) in stern quartering waves is smaller than a computation using only the Froude-Krylov forces for a statically balanced ship. The difference could be induced by hydrodynamic disturbances such as wave radiation, diffraction and lift effects.

As the next step, a numerical approach with different force contributions included was applied to two A-2 test cases, in which periodic motion and capsizing due to broaching were observed in the model tests. For this purpose one of the numerical methods from the ITTC benchmark test in 2.2 was used and termed "original".

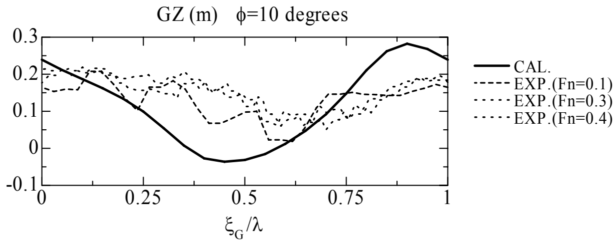


Figure 2.6- Comparison of righting arm based on the Froude-Krylov roll moment for a statically balanced ship and the measured roll moment divided by displacement. Experiment for the Ship A-2 with H/λ=1/15, λ/L=1.5 and heading angle of 30 degrees from wave direction.

As shown in Fig. 2.7, if the forces in the numerical model would be based only on the Froude-Krylov approach, the prediction results in immediate capsizing for both test cases; the prediction for periodic roll motion and broaching with capsizing is improved by taking into account additional wave effects. See also Umeda et al., (2004b and 2004c).

From the combination of captive tests and comparative simulations it was concluded that the following elements are essential for accurate numerical prediction (Umeda and Hashimoto, 2002, Umeda et al., 2003 and Hashimoto et al., 2004):

- wave effect on manoeuvring coefficients;
- nonlinear hull manoeuvring coefficients in calm water;
- nonlinear wave-induced surge force;
- nonlinear coupling between sway and roll;
- nonlinear hydrodynamic forces and moments acting on a hull running with a large heel angle in calm water.

More theoretical and experimental investigations are indispensable to address these issues and to improve numerical methods.

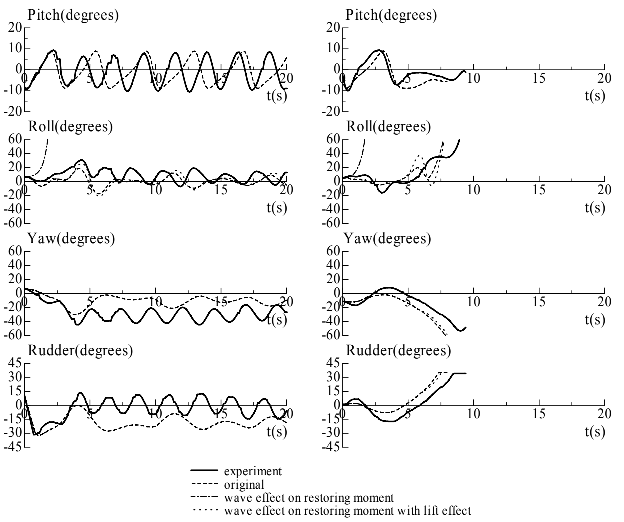


Figure 2.7- Comparison among the free-running model experiments and three numerical prediction methods for the A-2 ship with H/λ=1/10, λ/L=1. 1.637, nominal Froude number of 0.43 and the autopilot course from wave direction of -10 degrees.

2.4 Experimental Procedures

For ITTC Member organisations, intending to undertake capsizing model tests of intact ship models in waves, the 23rd ITTC recommended the Procedure on Model Tests of Intact Stability, 7.5-02-07-02.5. This procedure deals with mainly free-running model experiments in waves at a seakeeping and manoeuvring basin or a wider towing tank.

To refine the current procedure, the Committee executed a detailed questionnaire on the current procedure for organisations active in this area. The following six organisations replied to this questionnaire:

- Naval Surface Warfare Center, USA with help of USCG Engineering Logistics Center
- NMRI, Japan
- NRIFE, Japan with help of Osaka University
- HSVA, Germany
- Australian Maritime College
- UFRJ, Brazil

Considering the above replies, comments from the Quality Systems Group and other ITTC instruments, the Committee recommends refinements of the current procedure for the Conference as Procedure 7.5-02-07-02.5 (Revision 1). The major points of this refinement is summarised as follows:

- *Model size*: Smaller model length is allowed for smaller vessels if viscous roll damping effect is properly modeled.
- *Steering*: Manual steering is not recommended.
- *Measurements*: Calibration procedures including wave qualities are described in detail. Sampling rates are specified with the natural roll period.
- *Wave* Generation: The ITTC and JONSWAP spectra are recommended for ocean waves and fetch-limited waves, respectively.
- *Roll damping*: Detailed procedures of roll decay tests are described.
- *Validation*: Difficulties of uncertainty analysis of capsizing relating to chaotic behaviour due to strong nonlinearity are remarked. For guaranteeing accuracy of capsizing probability in irregular waves the calculation of confidence level using binomial distribution is recommended.

2.5 Procedure for Predicting Occurrence and Magnitude of Parametric Rolling

The problem of parametric rolling derives from the periodic variation of the roll restoring lever between successive wave crests and troughs, exhibited by many ships in steep longitudinal waves. These may set up a mechanism of internal (parametric) excitation in roll.

In the newly developed Guideline for Predicting Occurrence and Magnitude of Parametric Rolling the relevant mechanisms and conditions leading to parametric roll are explained. Formulas are provided to estimate the onset of parametric rolling in regular waves and the required minimum threshold wave height.

A number of critical remaining issues have been identified in the Guideline. One of these concerns the prediction of parametric roll in irregular waves, for which further work is needed. In head seas pitch and heave motions are likely to influence roll. Whilst for a following sea study a single-degree-of-freedom mathematical model (and the associated simple analytical formulae) may offer a reasonable prediction of the critical wave and roll amplitudes, the same may not be said with confidence for a head sea situation where simulation on the basis of a multi-degree-of-freedom mathematical model is recommended.

Apart from further developing the procedure for the numerical prediction of parametric roll, it is necessary to further develop a model testing procedure aimed at parametric roll identification, possibly in combination with computations.

3. PREDICTION OF DYNAMICS OF DAMAGED SHIPS

3.1 Recent Literature

In the last years significant experience has been gained through systematic research in the area of the numerical prediction of motion of damaged ships in waves and marginal stability conditions leading to capsize. The international scientific community kept developing and further improving the numerical methods to closely match the findings of physical model experiments, especially where deficiencies in the predictions have been identified.

The ITTC Specialist Committee on Stability in Waves has conducted two benchmark studies on numerical methods for the prediction of capsize of damaged ships in sea waves. The first study was completed under the coordination of the 23rd ITTC Committee, (2002) and the second was completed by 24th ITTC Committee (Papanikolaou and Spanos, 2004). Both studies have contributed to the assessment of the state of the art and have ascertained that numerical prediction methods can contribute to the assessment of the survivability of damaged ships in waves.

The two main sources of information on developments and achievements in the theoretical and experimental prediction of damaged ship stability in waves are the series of *International Conferences on the Stability of Ships and Ocean Vehicles* (STAB) and the *International Stability Workshops* (ISSW). Some additional references as to the application of numerical methods to ship design can be found in the proceedings of the *8th International Marine Design Conference* (IMDC03) held in Athens 2003.

Finally, relevant significant research was undertaken in recent years within the E.U. funded projects HARDER (2000), and NEREUS (2000).

The numerical methods for the simulation of motions of damaged ships in waves presented so far might be categorized according to the employed modelling and integration of the basic three constituents of the relevant problem, which are:

- Ship with zero forward speed moving on the free surface under the excitation of waves;

- The behaviour of the accumulated floodwater inside the ship's compartments and its interaction with the ship;
- The flooding phenomenon itself, namely the process of water inflow and outflow through damage openings and the progressive flooding through internal spaces.

As a basis of most numerical methods, potential theory is commonly employed to address the sub-problem of ship-wave interaction, and is adapted to account for large amplitude motions and supplemented with empirical models for viscous effects. The influence of the damage opening on the wave forces is neglected by all models.

The hydrodynamic properties of the damaged ship are commonly calculated in the frequency domain and properly transferred to the time domain by means of retardation functions used in the memory effect integrals. The slow change of hydrodynamic properties, as the floodwater is accumulating inside the ship, hence changing the mean hull wetted surface, is commonly addressed by appropriate update of ship's hydrodynamic coefficients. A theoretical support of this approach has been addressed by Umeda et al. (2004a).

An alternative approach regarding the effects of floodwater and hull shell damage on the ship hydrodynamics was presented by Vassalos and Jasionowski (2002) where generalized hydrodynamic coefficients have been formulated, which integrate both effects of ship-sea interaction and ship-floodwater interaction.

The modelling of the floodwater inside the damaged compartments is a challenge for all numerical methods. There are different approaches addressing floodwater dynamics and the effects on ship motions. Their accuracy and efficiency depend on the underlying model. Higher accuracy CFD methods seem not yet practical for full integration with ship motion simulation methods (Gorski 2002 and Woodburn et al., 2002) whereas simple quasi-static approaches can result in non-satisfactory results. An efficient and satisfactorily accurate approach, omitting the internal waves of the floodwater free surface has been presented by Papanikolaou and Spanos (2002).

The possible use of shallow water equations for the problem in hand is limited by the difficulties occurring when partial emergence of the bottom of flooded compartment occurs, a phenomenon almost always present, at least over limited time. The use of the random choice method (or Glimm's method) overcomes these kind of difficulties and an approximate solution for the flow of floodwater in time domain can be obtain, which can be further coupled with the time domain solution of ship motions, Falzarano (2002), Santos and Soares (2003).

A combination of shallow water flow equations and a novel fine volume strategy is applied by Belenky et al. (2003a) to the 3D flow problem, converting it to a 2D problem, thus managing to substantially save computational requirements.

More sophisticated approaches of CFD solvers have been also employed to describe the internal flow. The use of Particle Methods, Naito and Sueyoshi (2002), Gonzalez et al. (2003), have demonstrated even complicated sloshing phenomena like the wave breaking and other violent sloshing behaviour. However the basic disadvantage of these promising methods is their heavy computational cost, thus also at present stage of computing power the lack of integration with the ship motions simulation solution.

Another effect of the floodwater process that needs to be modelled is that of the trapped air in cases of insufficiently ventilated compartments, which affects the water spread in the compartment space and mainly determines the initial stages of flooding. This has been considered in a numerical simulation presented by Palazzi and de Kat (2002).

For the initial stages of flooding, Spanos and Papanikolaou (2001b), has demonstrated the complicated character of transient flooding, a result of strong non-linear effects related to the floodwater dynamics and damage opening geometric properties, which could be well captured by the use of a developed numerical simulation method.

Responding to the needs of recent IMO regulatory work, numerical methods were finally employed for the estimation of the time to flood and the time to sink of damaged large passenger ships, Van't Veer et al. (2002, 2004) and Vassalos et al. (2004b). The modelling of the flooding process, the flow through openings of various geometries as well as the treatment of the complicated geometry internal spaces, progressive flooding, determines the accuracy and efficiency of the employed numerical methods.

3.2 Benchmark Testing of Numerical Modelling

Introduction. In December 2001 a first international benchmark study on numerical methods for the prediction of capsize of damaged ships in sea waves, coordinated by the 23rd ITTC Specialist Committee on the Prediction of Extreme Motions and Capsizing (2002), was concluded. There were five independent participants of five different countries, in this study each employing different and independently developed computer simulation code.

The study ascertained that at that time the state of knowledge theoretical-numerical prediction methods proved able to greatly contribute to the pre-assessment of the survivability of damaged ships in waves. However, considering the relatively low number of the benchmark participants and the complicated nature of the addressed benchmark study problem it was recommended to extend and refine the study in the future aiming at resolving to the extent feasible several open questions identified in the study.

Based on the above, the 24th ITTC Specialists Committee on Stability in Waves initiated in early 2004 the extension of the former benchmark study. The basic objective of this study was to provide an insight into the fundamental properties of the benchmark methods with respect to particular sub-problems comprising the complicated entire problem of the motions of a damaged ship in waves.

A summary of the obtained benchmark study results, the identified gaps and conclusive recommendations are given in the following. More detailed results can be found in Papanikolaou and Spanos. (2004a and 2004b)

Participants. The participants of this benchmark study are listed in Table 3.1. It is noted that the total number of participants was the same, as in the first study, though two out of five participants were new (IST and KRISO).

Table 3.1- Participants of the 24th ITTC damage stability benchmark study.

Institute	Acronym	Country
Instituto Superior Tecnico	IST	Portugal
Korea Research Institute of Ships and Ocean Engineering	KRISO	Korea
Marine Research Institute	MARIN	The Netherlands
National Technical University of Athens – Ship Design Laboratory	NTUA - SDL	Greece
Ship Stability Research Centre, Universities of Glasgow and Strathclyde	SSRC	United Kingdom

Benchmark Approach. Considering the complicated character of the numerical methods addressing the prediction of motion of damaged ships in waves and of ship's stability in extreme conditions the present study was set up to provide comprehensive comparative information about the basic properties of the methods and to enable their assessment individually as well as a whole.

The selected tests are derived by consideration of the fundamental physical phenomena taking place in the motion of damaged ships in waves and of the corresponding modelling implemented in numerical methods. The basic factors recognized for such a physical system, expressed as forces, are the inertia, the restoring, the damping and the wave induced forces. The flooding process through a damage opening and the floodwater effects on the ship motions are two additional phenomena characterizing the problem.

According to the specified benchmark procedure the different numerical methods are compared to each other for a selected number of test cases, while the overall efficiency of the investigated methods is assessed by comparison of the numerical results with relevant experimental data. The benchmark tests have been specified in such a way that the sensitivity of each method with respect to the change of various problem parameters could be studied.

Benchmark Test Series. The benchmark study has been divided into two discrete phases, namely phase A and B. In the first one, phase A, which was conducted in the present term of the ITTC Specialist Committee, the effect of wave induced forces was excluded and the ship models were tested in calm water conditions. In the second phase B, which should follow, the models are planned to be investigated also in the presence of waves.

Phase A consisted of four (4) test series, namely Test A, B, C and D. These tests are all referring to the free roll motion of ship models in calm water and they are defined as follows:

Test A – Free roll motion of an *intact* passenger/Ro-Ro model with two different KG values.

Test B – Free roll motion of the same passenger/Ro-Ro model in *damaged* condition and the same two KG values as Test A. The specified damage opening corresponds to SOLAS regulations and is continuously open during the test. At the start of the test the damaged compartment is already fully flooded. The flooding process and floodwater dynamics are both present in this test.

Test C – Free roll motion of a tanker model in *partially flooded* conditions. The model has one rectangular compartment amidships, partially flooded with constant amount of water inside, which corresponds to a compartment breadth to water fill depth ratios equal to 31.8, 7.9 and 2.0. In this test there is no damage opening and subsequent flooding process. The test focuses on the floodwater dynamics and its effects on ship motion.

Test D – Free roll motion of a second Passenger/Ro-Ro ferry in *transient* flooding. The intact model starts from equilibrium position. Then a standard SOLAS damage opening is released and the water ingress is initiated. After that the model freely oscillates under the effects of transient flooding. In this test the flooding process is of prime interest.

Tested Ship Models. Three ship models were used in the numerical tests. They were:

- one Passenger/Ro-Ro ferry of 170.0 m length in 1:40 model scale, coded as (PRR01)
- one Tanker of 310.2 m length in 1:82.5 model scale, coded as (TNK01), and
- one Passenger/Ro-Ro ferry of 174.8 m length in 1:38.25 model scale, coded as (PRR02)

Each model was studied in certain series of tests as follows:

- The (PRR01) model studied in tests series A and B. The damage case of Test B is depicted in Fig. 3.1.
- The (TNK01) model studied in tests series C. The arrangement of rectangular tank on the (TNK01) is shown in Fig. 3.2.
- The (PRR02) model studied in tests series D. The internal arrangement of the damaged compartments is presented in Fig. 3.3.

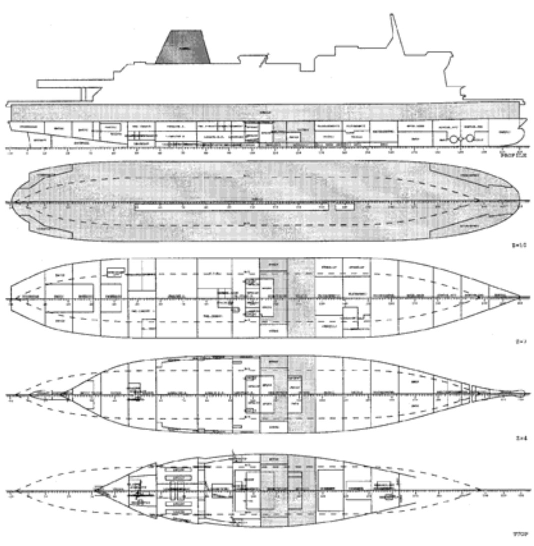


Figure 3.1- Damage case for model (PRR01).

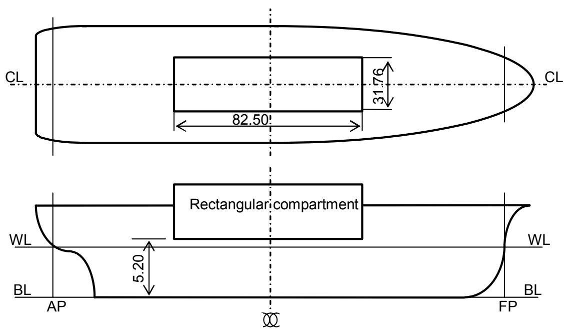


Figure 3.2- General arrangement of (TNK01) model.

Experimental Data. The comparative experimental data used in the study were obtained as follows:

- The ship model (PRR01) has been tested in systematic model experiments within the E.U. funded research project NEREUS (2000). The experimental data were provided to the study coordinator by the *Danish Maritime Institute* (DMI).
- The (TNK) model has been tested in free roll motion having its compartment partially filled with constant water. The corresponding experimental data were published by De Kat (2000).
- The ship model (PRR02) has been tested in systematic model experiments within the E.U. funded research project HARDER, and the experimental data for the needs of the study where taken from report (2000).

It is noted that the experimental data corresponding to each benchmark test were available beforehand to all study participants to enable equal benchmarking conditions for all study participants.

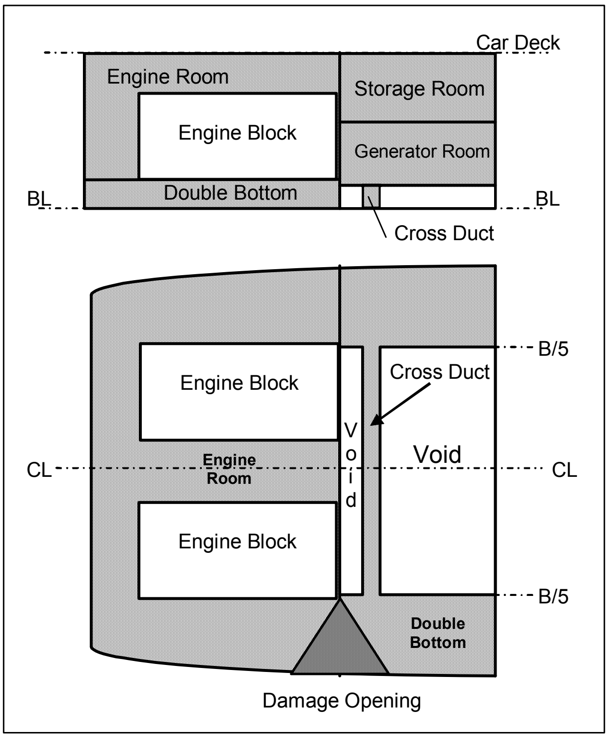


Figure 3.3- Damage case for (PRR02) model.

Numerical Methods. The mathematical models for the motion of the damaged ship in waves, employed within the present benchmark study, are presented in a unified way. In particular, the methods are categorized by their fundamental properties and the specific modelling applied to each part of the study.

In the following the identity of the participants and corresponding method is coded by P1 to P5 (there is no direct correspondence to the list of participants in).

The various simulation methods are characterized by the particular modelling and treatment they apply to the equations of motion, namely the inertia, the restoring and the damping terms, as well as the ship to wave interaction, the modelling of the floodwater effects on the ship motion and the flooding process itself.

All participating methods are non-linear time domain simulation methods considering the ship as a rigid body inertia system and accounting for nonlinearities of large amplitude motion and floodwater effects. The six degrees of freedom are considered for the ship motion, except for method P3 where surge and yaw are omitted. The restoring forces are calculated by direct integration of hydrostatic pressure over the instantaneous wetted surface.

The ship hydrodynamics, namely the ship to wave interaction forces, are commonly approached by potential theory, applying either strip theory or, in one case, 3D panel methods.

The radiation forces are first calculated in the frequency domain and are transferred to the time domain by use of retardation functions used in the memory effect integrals. The wave elementary diffraction forces are taken by superposition of wave harmonic components calculated in frequency domain and they are transferred to the time domain by use of a spectral incident wave formulation.

The part of wave excitation corresponding to the undisturbed incident wave, the Froude-Krylov forces, is calculated by direct integration of the dynamic wave pressure over the instantaneous wetted surface.

Viscous effects, which are particularly significant for the roll motion simulation, are treated in a semi-empirical way. All methods use quasi-linear or higher order models for the total viscous damping on the basis of empirically evaluated coefficients from relevant experimental data. A finer approach is partly also applied by decomposing the total damping into various components, like friction, eddy, bilge keels and other appendages damping, according to Ikeda et al.(1978).

The flooding process is uniformly approached by the use of hydraulic models. Pending the possible implementation of advanced CFD methods, the basic Bernoulli equation modified by semi-empirical coefficients proved to be satisfactory for the modelling of the water ingress/egress through a damage opening. The same approach is also applied to the progressive flooding, namely the flow between ship compartments through open doors and ducts and other internal openings.

The floodwater motion and its interaction with the ship are approached by omitting internal wave effects and assuming the internal free surface always plane. The instantaneous orientation of the free surface is part of the numerical solution. This approach is applied by participants P1 and P2. The floodwater modelling can be further simplified by assuming the internal free surface of water always horizontal, an approach that is adopted by the other participants. Participant P3 also applies a shallow water modelling to the internal water motion in case of the rectangular tank in Test C.

Further background information on the numerical methods can be found in Spanos (2002), Santos and Soares (2003), Jasionowski (2001) and Letizia (1997).

The Table 3.2 summarizes the basic attributes of the numerical methods as they have been applied in the present benchmark study.

Table 3.2: Basic attributes of the applied numerical methods in benchmark study.

Attribute	**Numerical Method**				
	P1	**P2**	**P3**	**P4**	**P5**
Ship motion degrees of freedom	6	6	6	4	6
Hydrostatic forces by direct integration	x	x	x	x	x
Strip theory	x	x		x	x
3D panel method			x		
Incident wave forces by direct integration	x	x	x	x	x
Memory effects	x	x	x	x	x
Semi-empirical roll viscous	x		x	x	x
Roll viscous analysis in components		x			
Floodwater with horizontal free surface		x		x	x
Floodwater with moving free surface	x		x		
Internal motion by shallow water equations				x	
Flooding by simple hydraulic model	x	x	x	x	x

<u>Benchmark Test Results.</u> The numerical results submitted in the present benchmark procedure were time series of ship motion responses for each test case considered. The results are directly comparable to each other as well as to corresponding experimental data enabling a first qualitative assessment of the performance of the methods. The analysis focuses mainly on the roll response as this motion is of prime interest in view of ship's stability, but other degrees of freedom have been also considered.

The ship's natural period and the damping rate can be deduced from the submitted results. These two quantities are considered to be representative for the modelling of ship's restoring to mass and hydrodynamic inertia relationship and the damping phenomenon correspondingly.

<u>Test A & B.</u> The first two test series, A and B, carried out in the benchmark study regard the free roll motion of the passenger/Ro-Ro ferry PRR01 in intact and damaged conditions. Two different KG values were investigated for each test.

As observed in Fig. 3.4 all participating methods were calibrated with respect to intact model's inertia properties, not known exactly beforehand, for the lower KG value. Thereafter, the methods predict the changes in natural period for changes of the hull condition (damage case) and as the KG value increases. The sensitivity of each method with respect to both changes can be observed in Fig. 3.4. In general, the sensitivity of the various methods with respect to the associated changes, when the model is damaged, is less satisfactory, whereas changes in the KG value are satisfactorily captured.

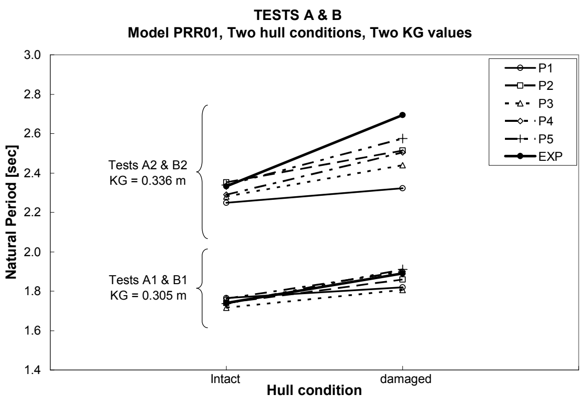


Figure 3.4- Natural periods for Tests A & B.

In particular, changes of the natural period occurring in the damage condition are related to the effects of floodwater and the particular modelling implied by each method. The remarkable changes due to the shift of the KG value are related to the alteration of the model's mass distribution, thus it should be expected that all methods could manage to provide more accurate predictions.

Regarding the prediction of the damping rate, the general performance level of the methods seems less satisfactory. As observed in Figs. 3.5 and 3.6, where the logarithmic decrement for the first oscillation of the free roll motion for the Tests A1 and B1 is presented, only two out the five methods manage to predict a damping rate of the same trend like the experimental measurements, while even these methods show differences with respect to experimental results in terms of absolute values. The logarithmic decrement is defined as the log(A_0/A_i) where A_i is the i-th roll amplitude and A_o the initial heel angle.

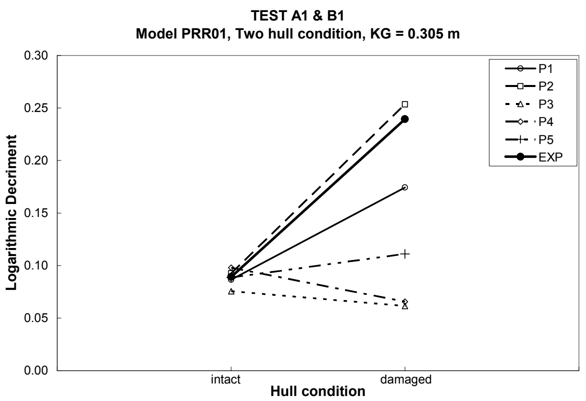


Figure 3.5- Damping rate for Tests A1 & B1.

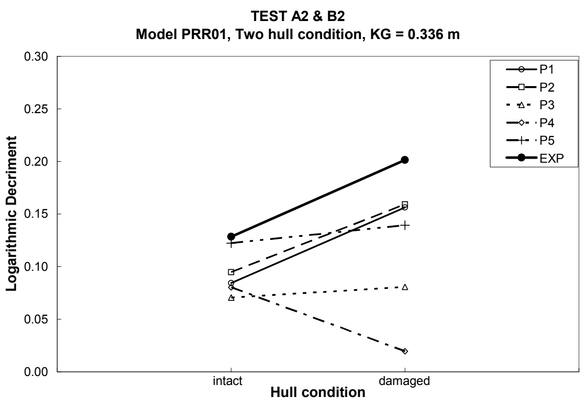


Figure 3.6- Damping rate for Tests A2 & B2.

The increase of the damping rate in the presence of floodwater is a result of the ship model to floodwater interaction. The weakness of the methods in the damping rate prediction seems to be related to the non-satisfactory modelling of the floodwater effects.

Test C. The results of the third Test C, namely the free roll motion of the tanker TNK having one compartment partially filled, are presented in Figs. 3.7 and 3.8 for the natural periods and the damping rate respectively.

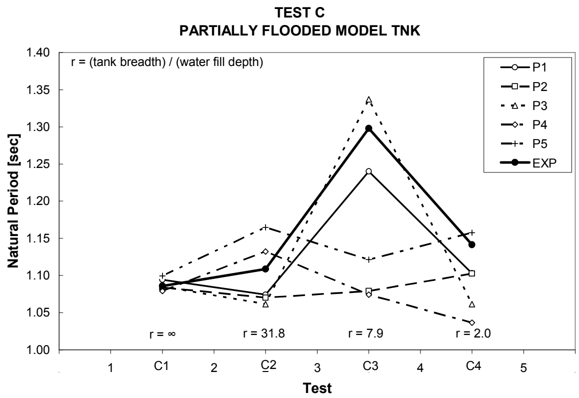


Figure 3.7- Natural periods for Tests C.

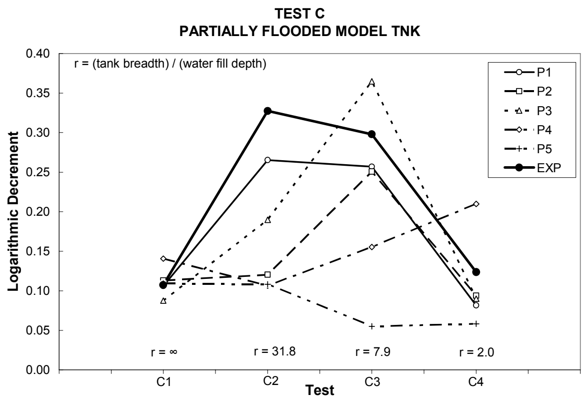


Figure 3.8- Damping rate for Test C.

As presented in Fig. 3.7 there were four conditions tested, each one with different amount of water inside the rectangular tank. In this test series the effects of the flooding process through any damage opening has been suppressed and the pure effect of floodwater can be observed.

All methods were calibrated with respect to the intact condition, shown in the left end of the diagram, similar to the previous Test A. Thereafter, the two methods P1 and P3 demonstrate similar sensitivity as the experimental measurements while the other methods appear to not capture properly the effects of the floodwater. It is underlined that the two methods P1 and P3 apply different modelling to the internal floodwater to ship interaction though they demonstrate quite similar results.

Regarding the damping rate, presented in Fig. 3.8, there is only method P1 demonstrating sensitivity similar to the experimental results for all tested cases, whereas two methods P2 and P3 give quite satisfactory results for the higher fill depths of floodwater.

Test D. The final test of phase A of the benchmark study, Test D, deals with the transient flooding of the Ro-Ro passenger ship model PRR02. In this test the flooding process is of dominant significance and determines the behaviour of the ship model. The ship model was tested in three different conditions were the cross duct, that connects the port and the starboard tanks in the double hull, differs in the cross area. In this respect a controllable progressive flooding process was present during the tests.

Figure 3.9 presents the heave motion predicted by the five numerical methods. As there were no experimental data to compare with, only the relative comparison between the methods was possible. The heave motion is a representative quantity for the flooding process through the damage opening. The method P1 demonstrates the slowest flooding of the damaged compartments whereas method P2 the fastest flooding. Although all the methods employ essentially the same simple hydraulic model to capture the flooding process through the damage opening, the differences in the implementation are obvious. The *semi-empirical* coefficient involved in this hydraulic modelling, seems to be the source of differentiation of results.

In these results the differences observed in the final draught that the ship model will accept in the fully flooded condition reveal some extra sources of differentiation. The participants appear to have modelled either a different volume of damaged compartment or a slightly different hull form.

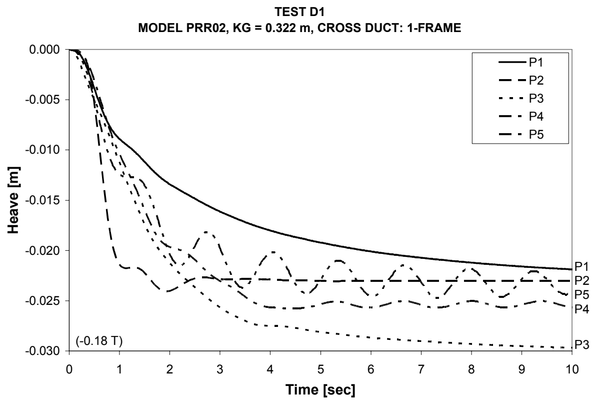


Figure 3.9- Heave motion for Test D1.

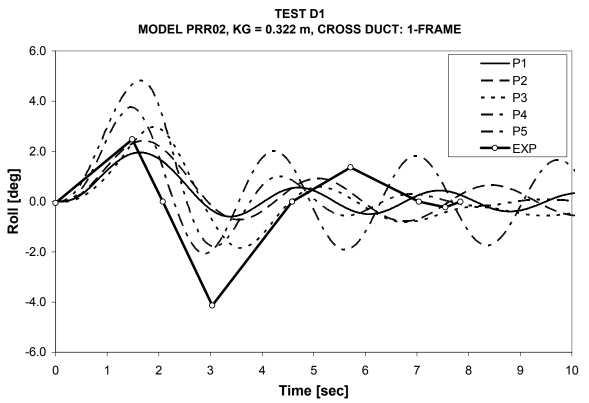


Figure 3.10- Roll motion for test D1.

The roll motion of Test D1 that corresponds to the lower cross duct area is presented in the next Fig. 3.10. The highly non-linear character of the roll motion in transient flooding is obvious, resulting to higher differentiation of each method.

Concluding Remarks and Recommendations. The reviewed results of the first phase of the 24th ITTC damage stability benchmark study provide a thorough insight to the present status of the numerical methods for the simulation of the motions of damaged ships.

The sensitivity of the reviewed methods with respect to the changes of the basic parameters of the problem has been demonstrated. By testing the methods in calm water conditions, the assessment of each method as well as the overall performance without the noise introduced by the waves and particularly the irregular waves was enabled.

The efficiency of the methods regarding the specific modelling of the inertia and restoring forces has been found to be satisfactory.

Recommendation (1): The scatter of numerical results for the natural roll period when the KG value is changed indicates the necessity for further investigation on the modelling of this change and subsequent impacts on the natural period. Special attention should be given in the evaluation and sensitivity of the roll radius of gyration both as to the inertia and associated hydrodynamic terms.

The estimation of the viscous roll damping, when satisfactory experimental data for the determination of employed semi-empirical coefficients are available, seems to be well addressed. However, all methods seem to be highly dependent on these data and lack of them might lead to serious differences. The above holds for the intact model condition and is highly more problematic in the damage condition.

Recommendation (2): A benchmark test that will not provide any information on the roll damping of the ship should demonstrate the actual status of the methods in the prediction of the roll damping effects, that appears at this moment unsatisfactory.

Observed deviations between the numerical methods in the damage condition are found to be mainly due to different approaches to the effects of floodwater on ship motions. It was found that numerical methods that consider the floodwater having its free surface continuously horizontal could not capture the floodwater dynamics properly. Those methods considering the free surface moving demonstrated satisfactory sensitivity with respect to the floodwater effects.

Recommendation (3): The significance of the floodwater dynamics on ship motion in terms of stability should be assessed. Since stability is a matter of many factors involved in the motion of the damaged ship, it is proposed that each method is studied on how the critical stability conditions for a ship are affected by the use of different floodwater modelling.

The results of the transient flooding tests showed that employed semi-empirical coefficients greatly affect simulated results.

Recommendation (4): Special focus should be given on the semi-empirical weir coefficient as well as the implementation of the flooding model. In the next phase of benchmark study it should be investigated how the critical stability conditions are affected by the weir coefficient.

This benchmark study should be completed with the conduct of its planned second phase that will enable the critical review of the methods in the presence of waves, which were excluded herein. In particular, the performance of the methods in calm water conditions gathered in this phase will enable a better interpretation of the behaviour of the methods in the complicated environment of sea waves.

3.3 Experimental Procedures

<u>Review of Existing Damage Stability Procedures.</u> The Committee examined the SLF45/14 Annex 5 revision (Revised Model Test Method) to SOLAS 1995 Resolution 14

model testing procedures for Ro-Ro damaged stability; the interim IMO HSC model testing procedures (SLF44/7); and Model Tests for Damaged Stability (7.5-02-07-02.6) procedures. The procedures were reviewed for areas of covered and consistency.

All the procedures provide for a focused experimental investigation of the effect of flooded water. There were inconsistencies in GM tolerance, roll period, and wave spectral shapes. The procedures assume the model is at rest and flooded when the waves start.

Questionnaire on ITTC Procedure. Additionally, a questionnaire was sent to Committee Member Organizations to determine existing practices and use of ITTC Damaged Stability Procedures. There were four responses, which covered government, commercial, and university facilities. To date, Resolution 14 testing has been done by only one of these facilities. None of them use extra guidelines or procedures for such testing.

The answers to the questionnaire indicate general agreement with the ITTC procedure as written. There were five areas where the facilities were different than the existing procedure. The five areas are: use of regular waves; compartment ventilation; sampling rate; number of seaway realizations; and wind generation. None of these warrant a rewriting of the procedure, except perhaps the number of seaway realizations section. All the facilities correctly applied that guidance, though the wording was confusing.

4. STABILITY SAFETY ASSESSMENT

4.1 Introduction

The development of procedures and methodologies for the assessment of intact and damage stability for conventional and novel vessels is practically related to the quite complex phenomenon constituted by the "Rules Making Process" which takes place in the relevant International Regulatory Bodies (principally IMO, the International Maritime Organization).

In the past, there was little need of developing assessment procedures, since the rules were of the prescriptive type and no possibility of alternate assessment was possible.

Recently several breaches were opened in the traditional procedure, to allow alternate assessments, based on numerical and/or experimental approaches, as an alternative to complying with prescriptive criteria. Finally, the long term plans of IMO Sub-Committee on Stability and Load Lines and on Fishing Vessel Safety (SLF) now include the development of performance based approaches to intact stability assessment. Previously, the Stockholm Agreement included the possibility of complying through experimental approaches. The related procedure for experimental testing has already been developed.

IMO High Speed Craft Code (IMO, HSC'2000) has also undergone a deep review as a consequence of some major accidents at sea. In particular, the new Code, states that:

"Other means of demonstrating compliance with the requirements of any part of this Chapter [Buoyancy, Stability and Subdivision] may be accepted, provided that the method chosen can be shown to provide an equivalent level of safety. Such methods may include:

1. mathematical simulation of dynamic behaviour;
2. scale model testing; and
3. full-scale trials."

Model or full-scale tests and/or calculations (as appropriate) shall also include consideration of a number of stability hazards to which high-speed craft are known to be liable, according to craft type.

The Annexes to the Code include several references to the need of measuring quantities relevant to Stability by means of model or full-scale tests.

4.2 Basic Frameworks for Stability Assessment

A review of the basic frameworks so far developed or under development to tackle ship stability has thus been undertaken following Papanikolaou and Konovessis (1999).

Prescriptive (Rules-Based) Assessment and Design. This approach is based on prescriptive, semi-empirical rules and regulations deriving from statistical data and practical experience like:

- the so called statistical criterion for intact stability (IMO Res. A.167);
- the subdivision and damage stability regulations based on the criterion of service, including the provision concerning the effect of water on deck for Ro-Ro vessels (Stockholm agreement);

or deriving from the consideration of only one capsize mechanism and a simplified modelling of the meteo-marine action like the current weather criterion (IMO Res. A.562).

Recently, the IMO/SLF Sub-Committee (Francescutto, 2004): "agreed that other means of demonstrating compliance with the requirements of any part of the future revised Code might be accepted, provided that the method chosen be shown to provide an equivalent level of safety. Such methods might again include:

1. mathematical simulation of dynamic behaviour;
2. scale model testing; and
3. full-scale trials".

In particular, for the weather criterion, in view of solving the difficulties encountered in the design of ships with relevant parameters outside the range on which original formulation was based, it was decided "to further consider the revision of the weather criterion with a view towards establishing interim provisions for model experiments and full-scale trials"

As a consequence, a set of Guidelines for the Alternative Assessment of Weather Criterion is currently under development. They consist of Guidelines for experimental determination of the wind heeling lever, lw_1, and Guidelines for experimental determination of the roll-back angle, ϕ_1, (Bulian et al., 2004b)

Probabilistic/Risk-Based Assessment and Design. This consists in the adoption of probabilistic description frameworks and eventually of risk assessment methods for the purpose of scientific quantification and unification of the measures regarding the safety level achieved by a vessel. The evaluation of risk (frequency times consequences) is generally a more difficult task so that most approaches of this type are limited to the evaluation of probabilities which have to comply with some minimum standard.

In addition, the evaluation of probabilities is often based on statistics of casualties, evaluation of experts and tradition more than being based on first principles. This is for example the case of the probabilistic subdivision and damage stability regulations, all along their development starting with IMO Res. A.265 through to the newly harmonized regulations (SOLAS Chapter II-1 Part B).

Performance-based (Simulation-Based) Assessment and Design. Use of numerical and/or physical model testing to assess safety performance based on the inherent characteristics of the vessel under consideration to respond safely to given scenarios and environmental conditions.

The safety level of a ship under consideration should account for specific operational aspects and can be evaluated by the execution of a series of specified physical and numerical tests for given scenarios and environmental conditions.

As previously mentioned, this will be the future as far as Intact Stability assessment is concerned. This will possibly also be the case of damage stability (Vassalos, 2004).

Several aspects concerning the development of performance-based approaches to ship stability assessment, mostly devoted to intact stability, but which can to some extent be generalised, have been presented and discussed in recent times.

De Kat et al. (1994) and McTaggart and de Kat. (2000) developed a rational approach based on a probabilistic framework to the survivability in waves addressing specifically the case of frigates. A capsize index is introduced and evaluated on the basis of an advanced time domain simulation tool able to reproduce the motions in waves.(FREDYN) The action of the environment is represented by means of the up to date statistical representations and taking into account a distribution of headings. The implications on design are discussed on the basis of an operational scenario and of relevant parameters of ship forms and loading conditions. The Gumbel distribution is shown to be sufficiently reliable to describe roll peak distribution.

The use of a capsize index for the development of new dynamic stability criteria based on performance is also proposed by Cramer et al. (2004), which utilises deterministic threshold and wave statistics.

Following the reopening of the Intact Stability Code by the IMO, a number of questions are being raised concerning the practical applicability of the Weather Criterion to modern passenger ships and answers sought on a way forward by way of either re-examining and suitably tuning the criterion to reflect current (and emerging) ship particulars or adopting merging approaches/philosophies to assessing ship safety, using first-principles performance assessment tools. Vassalos et al. (2004a) attempt to provide pertinent answers to these questions and recommend that the criterion as a whole be revisited and reanalysed using modern tools and current understanding of the perceived or actual intact ship stability risks in a seaway.

Umeda et al. (1992), Bulian and Francescutto (2004) and Francescutto et al. (2004) continued along this line presenting a framework for the development of a criterion for the assessment of ship safety in beam wind and waves properly taking into account their probability distributions. By using such procedures, Belenky (1995) and Umeda and Yoshinari (2003) evaluated the level of safety under a dead ship condition guaranteed by the current IMO Intact Stability Code for 16 and 75 ships, respectively. This type of approach was applied also to longitudinal and quartering seas (Umeda and Yamakoshi, 1991).

An integrated project based on the "Design for Safety" philosophy shaping into a formalised design methodology (Risk-Based Design) and a framework that facilitates the systematic integration of risk analysis in the design process with prevention/reduction of risk treated as a design objective, alongside standard design objectives is presented by Vassalos (2004).

Identified Gaps. It appears from previous analysis that the existing panorama of international ship stability regulations is presently dominated by prescriptive rules of deterministic or probabilistic type.

Only risk-based or performance based approaches can produce safety-oriented design and a uniformity in terms of demand-capability as regards stability (safety) issues. The real risk-based approaches, however, are missing (exception to a limited extent is HSC), while the performance-based approaches are just the new born of the family. Previous ITTC Specialist Committee on Extreme Motions and Capsizing identified big gaps in the numerical simulation tools which should constitute the main route to the development of performance-based stability assessment methodologies.

The assessment of ship stability versus "classical" prescriptive rules either deterministic or probabilistic in nature did not need the development of any new assessment procedure.

Recent work at IMO opened the possibility of assessing some of existing rules through alternate "equivalence" routes, mostly based on experimental approaches. This concerns the rule as a whole, as approved in the case of High Speed Craft Code (Van Walree et al., 2004) and the Stockholm Agreement (Vassalos et al. 1998), or as under discussion for the Intact Stability of conventional ships, or parts of the rule, as recently proposed as interim solution for the Weather Criterion.

This requires the development of methodologies:

- To allow the evaluation of the level of safety implied in an assessment mode (for example prescriptive versus experimental equivalent). The statement "average equivalent level of safety" is indeed often put as basic requirement of new developments;
- To allow numerical or experimental reliable alternative stability assessment, where possible.

The possibility of developing fully performance-based new regulations requires the availability of numerical/experimental procedures for stability assessment and their verification and validation (apart from robustness, reliability, etc.) versus the presently existing ones. For such purpose, the role of ITTC can be important under collaboration with international regulatory bodies.

5. IMO HSC MODEL TEST METHOD

The IMO Draft MSC Circular - Interim Guidelines for the Conduct of High-Speed Craft Model Tests – has been reviewed and the Committee has proposed improvements to these guidelines. Based on the experience from Member Organizations the main elements of the suggested changes comprise the following. The total number of required test cases was reduced, by focusing on the most onerous conditions only and by requiring fewer wave realizations per test case. Issues such as water accumulation were addressed and the formula for estimating the volume of accumulated water was slightly modified. In addition, the Committee proposed to omit the alternative method of performing ship motion and water on deck computations in combination with head and following sea model tests, due to the lack of appropriate validation procedures and accepted extrapolation methods for other heading angles.

6. EVACUATION IN WAVES

After the disasters of the car passenger ferries Herald of Free Enterprise, European Gateway and Estonia more concern is paid to the important problem of ship evacuation. A broad spectrum of activities has been started worldwide. These include a development and testing of the lifesaving equipment, revision and development of the considered maritime regulations, crew training and simulations of passenger evacuation.

6.1 Lifesaving Appliances Used Onboard Ships and in the Offshore Operations

The analysis of passenger Ro-Ro ship capsizing conducted by Spouge (1996) illustrates the important role of lifesaving equipment for the safe evacuation of a passenger ship. Lifesaving appliances can be divided into two groups:

(1) Transfer of persons from ship to life rafts and boats. Excluding airborne rescue, the first group comprises the equipment for transferring people from a ship to the lifeboats and to the life rafts. This group includes:

- Conventional davit-launched lifeboats and life rafts;
- Stern Ramp Deployment Systems.

(2) Marine Evacuation System (MES) comprising of:

- Slides;
- Chutes.

Slides and chutes are used to transfer passengers directly to life rafts or through floating platforms.

Life Rafts, Lifeboats and Man Overboard Boats. These craft are either the free fall or conventional davits launch type. Lifeboats are either open type, totally or partially enclosed.

Ship-deployed boats, such as free-fall lifeboats or Rigid Hull Inflatable Boats (RHIB) are more and more deployed onboard cargo and passenger vessels. RHIBs, which are often used in security, inspection, pilot and military missions, are typically launched via stern ramps that are integrated into the transom of the mother ship.

Both model scale and full scale testing are part of the development of Lifesaving Appliances. In particular there are a number of model tests reported in the open literature dedicated to the evaluation of launching ability in a sea state.

Tests of Lifesaving Appliances: Model Experiments. A number of model tests dealing with davit-launched lifeboats either from a ship (Werenskiold 2003) or from an offshore structure (Simoes et al. 2002) have been reported. The following performance features of large passenger ship evacuation using a large lifeboat were investigated and evaluated by Werenskiold (2003):

- Lifeboat launch;
- Lifeboat escape;
- Lifeboat seakeeping;
- Free fall.

From these tests it appeared that both launch and escape performance were satisfactory up to Sea State 6 (Hs = 5.5 m). The late release of hooks deteriorates the safe launching.

Model tests conducted at IMD (Simoes et al., 2002) considered the influence of several factors on lifeboat evacuation performance. These were amongst the others the position of the lifeboat in relation to a fixed offshore structure, sea conditions and wave phase at the instant of splash-down. As expected, tests suggest that davit-launched lifeboats' evacuation performance deteriorates with the worsening of the sea conditions. Human factors cannot be treated in evacuation model tests.

Deakin (2000a) reported model tests dedicated to the evaluation of life raft deployment. Models of two fishing vessels were used in the experiments. The release and subsequent behaviour of life raft canisters following capsize and sinking of the vessels were investigated. Recommendations concerning the stowage and deployment of the life rafts are given.

Tests of Lifesaving Appliances: Full-Scale Experiments and Exercises. Drill exercises conducted in well-controlled conditions and using fit and healthy volunteers disclose certain problems of MES. A large-scale mustering and evacuation exercise conducted in the United Kingdom was reported at the International Conference on Escape, Evacuation and Rescue (Wood 1996). The exercise was conducted using the Ro-Ro passenger ferry Stena Invicta. This well-prepared and analyzed exercise took 65 minutes instead of a target value of 30 minutes. The main reason for a prolonged evacuation was attributed to extreme caution exercised by the passengers and the crew. Minor failures of the life-saving equipment were noted. The main recommendations concern the development of additional guidance on emergency procedures and examination of the malfunctioning and launching arrangements of life rafts. It was also recommended to investigate the evacuation times using formal safety assessment techniques.

There have been several accidents related to MES chute systems, but only the most recent one has been properly documented (MAIB 2003), after a person got trapped inside the chute during an exercise in Dover and died. The other MES solution is slide based and although it has a better safety record, mainly due to it being launched from a lower height (6 to 15 m above the waterline), model tests showed that this system is also prone to failure in a particular sea state and when experiencing ship motions.

6.2 Simulation of Ship Evacuation

As a result of incidents such as the Estonia disaster, the International Maritime Organization developed a new regulation (SOLAS regulation II-2/28-1.3, i.e. revised SOLAS regulation II-2/13.7.4), which entered into force on 1 July 1997 and has been applied to Ro-Ro passenger ships. It states that during the early stages of design, an evacuation analysis must be completed to identify and eliminate congestion during the evacuation of a ship due to normal movement of passengers and crew along escape routes at sea in realistic circumstances.

The application of similar requirements to passenger ships other than Ro-Ro passenger ships has been discussed at IMO. For the purpose of unified enforcement of the regulations, the Interim Guidelines for a Simplified Evacuation Analysis on Ro-Ro Passenger Ships (IMO, 1999) were developed. Based on the above Guidelines, the Interim Guidelines For Evacuation Analyses For New and Existing Passenger Ships (IMO, 2002) were developed. These guidelines make allowance for conducting an evacuation analysis both with simplified and advanced methods. Four scenarios have to be considered as a minimum in the analyses to estimate the total time to evacuate:

- awareness time
- (mustering) travel time
- embarkation
- launching time.

For Ro-Ro passenger ships the total evacuation time should be less than 60 minutes.

The current state of the art in ship design evacuation analysis usually involves simplistic land-based approximations based on fire evacuation studies of multi-story buildings, which neglect factors such as list and motions in waves.

There are basically three kinds of methods to simulate passenger and crew motion during an evacuation. (1) The so-called simplified evacuation analysis (macroscopic or hydraulic model) assumes the flow of passengers to be affected by passenger density and escape route width only. This approach is concerned mainly with identifying the bottlenecks in the escape routes and thus gives an important but only a qualitative result. This approach may be also used as a Master aid when planning the evacuation routes or training the crew (Lopez and Perez, 2003).

(2) The micro model approach models the movement of every person (Vassalos et al., 2003, Schreckenberg, 2003, Katuhara et al., 2001 and Miyazaki et al., 2004). Each person (an agent), passenger or crew, may be assigned different speed, objectives, etc.

(3) The so-called meso-model is a mixture of the previous models. In this model the simulated humans are grouped to form an entity called a packet, which is given a task to follow a certain path (Gangi et al., 2003). Simulating human behaviour in emergency evacuations (Reisser-Weston, 1996) may be in principle included in evacuation analyses.

The effect of ship motions and that of heel in particular are usually disregarded in the modelling of human movement. If they are included in a model this is done in a simplified manner (Kostas et al., 2003). The so-called IMEX model (Intelligent Model for Extrication Simulation) reported by Park et al. (2001) attempts to combine ship and pedestrian dynamics. Also a human behaviour model is included in this ship evacuation simulation.

The influence of ship motion on walking speed has been studied by applying a simplified dynamic model for a person in a moving environment; by using the so-called motion-induced interruption index (MII) concept Crossland (2003) has derived a reduction factor of the walking speed as a function of lateral acceleration.

6.3 Other Full-Scale Tests Related to Ship Evacuation

A test facility aiming at evaluating human mobility in conditions simulating the dry areas of a damaged ship are described by Koss and Brumley (2003). A similar facility can be found in Canada (SHEBA).

The Technical Research Centre of Finland commissioned by the Finnish Maritime Administration has conducted tests with a listed passenger cabin (VTT, 1998). Five persons of both sexes and different age were used. For heel angles below 20 degrees no major difficulties in leaving the cabin without means of help were encountered.

An interesting study including the numerical simulation of a Ro-Ro passenger vessel evacuation and a full-scale validation trial was presented by Yoshida et al. (2001). The numerical simulation model used in the research is called the crowd movement model. There are two important conclusions of the study. First, the crowd movement model for simulation of egress behaviour would be suitable when passengers are guided by crew during evacuation. Second, based on additional full-scale measurements of flow coefficients for walking persons in inclined or rolling walkways, trim and list of the ship and rolling/pitching motions should be taken into consideration when simulating egress behaviour.

A series of full-scale experiments dedicated to the evaluation of ship motion on human walking speed has been reported by Bles et al. (2001). Tests were conducted in the TNO Ship Motion Simulator, where the propagation speed from subjects in corridors, while ascending and descending stairs, and the delays while opening doors were investigated. This was done as a function of increasing list angle and of increasing ship motion profiles involving a variety of persons. The authors recommended that their data be incorporated in the IMO Guidelines, especially for Ro-Ro passenger vessels, as the present guidelines may give far too optimistic estimates of the total evacuation time. They also recommended to investigate in more detail the effect of passenger density on the walking speed under list.

In addition to these studies, Miyazaki et al. (2003) conducted some full-scale experiments on evacuation including wheel-chair users and performed an evacuation simulation using a model derived from these tests.

7. ITTC MEMBER SURVEY

7.1 General Questionnaire on Model Test Procedures

The general questionnaire was designed with the intention to confirm whether the 23rd ITTC Recommended Procedures for Model Tests on Intact or Damage Stability have been known and implemented by relevant organisations. Forty-six organisations replied to the questionnaire. Among the repliers, 24 organisations have conducted capsizing experiments on intact models and 1/3 of them partly followed the ITTC Recommended Procedure. Sixteen organisations have had experiences on damaged model tests and half of them mainly implemented the Procedure. About 2/3 of the repliers were familiar with the Procedures.

For intact stability experiments, four more detailed questions, on experimental type, environmental condition, waves, and object ship, were attached to the general survey. It was found that most organisations used a free running model with autopilot to keep the model on course. In addition, seven organisations have conducted semi-captive model tests for measuring forces. Regular and long-crested irregular waves with arbitrary incidence angle were widely modelled during intact capsizing experiments. It should be noted that some model basins have expanded their stability investigations to multi-hull vessels.

In conclusion, the survey results indicate that an increasing number of organisations have carried out model tests in the study of intact and damage stability. The organizations were familiar with the 23rd ITTC Recommended Procedures for Intact and Damage Model Tests, but these have not been fully implemented. As mentioned in Sections 2.4 and 3.3 the Procedures have been revised by this Committee.

7.2 Questionnaire on Numerical Model for Prediction of Capsizing

The Committee also distributed a questionnaire to review the existing numerical models used in prediction of extreme motions and capsizing for intact or damaged ships.

Sixteen organisations replied to this questionnaire as shown in Table 7.1, where the numerical models were distinguished between intact stability and damage stability based on their capabilities.

Intact Stability. Participants of the Intact Stability benchmark study (see 2.2) filled in a questionnaire on numerical models for the prediction of capsizing. All codes can be characterised as “linear/nonlinear hybrid type” and “time-domain”. They predict ship motions in six degrees of freedom and they cater for large amplitude motions and angles. The codes were designed for mono-hulls although some have been applied also to multi-hulls. Hydrodynamic forces that are influenced by viscosity (in roll, sway and yaw) are modelled semi-empirically. Some incorporate modular manoeuvring models (hull – propeller - rudder). Froude-Krylov forces are determined by integrating the dynamic wave pressure over the instantaneous wetted hull. Most calculate radiation and diffraction forces on the basis of strip theory and a few use a 3-D panel method (some have both capabilities). PD or PID autopilots appear in all.

Most of the numerical codes listed in Table 7.1 can be applied to the prediction of parametric rolling, pure loss of stability and resonance in beam seas. Half of them can simulate loss of dynamic stability and broaching. Most numerical models are designed for a steered mono-hull. The codes ODYSSEUS and DINMA have been applied to multi-hulls. Regarding environmental effects, regular or irregular random waves and wind are modelled in most codes. The numerical codes DYNSTABROLL and DINMA are based on a 3 DOF model with roll, heave and pitch.

While much attention has been paid to the nonlinearity associated with the Froude-Krylov forces and dynamics at large angles, other nonlinear effects are under consideration at present (see also chapters 2 and 3).

The radiation and diffraction wave forces can be calculated by different methods: strip theory or slender body theory is applied more often than 3-D panel methods. Hydrodynamic memory effects are only considered in a few codes. Manoeuvring coefficients are mainly expressed using experimental data or empirical formulas. So far, linear or nonlinear empirical methods are used in the prediction of roll damping. All organisations take the wave effect (of the undisturbed wave) on roll restoring moment into account.

Table 7.1- Organisations and numerical models for prediction of capsizing.

Organisations	Intact Stability Codes	Damage Stability Codes
Australian Maritime College, Australia	FREDYN	FREDYN
Federal University of Rio de Janeiro, Brazil	MD2004 (Neves and Rodriguez, 2004)	
Helsinki University of Technology, Finland	LAIDYN (Matusiak, 2002 and Matusiak, 2003)	
Hamburgische Schiffbau Versuchsanstalt GmbH (HSVA), Germany	SIMBEL	ROLLS
National Technical University of Athens, Greece		CAPSIM (Spanos, 2002 and Spanos and Papanikolaou, 2001a)
Universita di Trieste, Italy	DINMA	
National Maritime Research Institute, Japan	NMRIW (Ogawa et al., 2005)	
Osaka University, Japan	OU-BROACH (Umeda, 1999)	OU-DAMAGE (Umeda and Mizogami, 2001)
Korea Research Institute of Ships and Ocean Engineering (KRISO), Korea		SODAS
Maritime Research Institute Netherlands (MARIN), The Netherlands	FREDYN (De Kat et al., 2002 and McTaggar and De Kat, 2000)	FREDYN (Palazzi and De Kat, 2002 and De Kat and Peters, 2002)
Delft University of Technology, The Netherlands		DYNING (Vredeveldt et al., 2000)
Krylov Shipbuilding Research Institute, Russia	DYNSTABROLL	
SSPA Sweden AB, Sweden	SEAMAN (Hua and Lundbäck, 2003)	SEAMAN
QinetiQ, United Kingdom	FREDYN	FREDYN
University of Glasgow and Strathclyde, United Kingdom	ODYSSEUS	PROTEUS3
Naval Surface Warfare Center, USA	FREDYN	FREDYN

Experimental or empirical data are used for determination of hull resistance, propeller thrust and rudder hydrodynamic force.

Damage Stability. Half of the numerical codes can be used for multi-hulls. The effects of random waves and wind are modelled in many codes. The effects of shallow water and current can be taken into account in the codes CAPSIM and SEAMAN.

A variety of approaches are applied to model the floodwater effects. Most codes adopt a simple method, which assumes the floodwater to be distributed inside the flooded compartment in a hydrostatic way with horizontal free surface. A more advanced approach, which considers the rotational motion of the floodwater, has been developed in the codes CAPSIM and PROTEUS3. For more details on numerical modelling see Section 3.1.

8. CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

Intact Stability. A review has been carried out concerning numerical and experimental techniques to predict extreme motions, broaching and capsizing of intact ships in waves, including high-speed craft.

A survey among ITTC Members has been conducted to obtain detailed technical information on numerical simulation methods related to ship stability in waves.

An intact stability benchmark study has been carried out by ITTC Members. Satisfactory predictions have been noted for some numerical models and for certain scenarios. No model has reproduced consistently all of the selected benchmark data; some elements that may contribute to discrepancies between physical and numerical results have been identified. In addition, some limitations of the current benchmark scheme have been identified.

The implementation of the Procedure for testing intact stability has been monitored through a survey among ITTC Members and the Procedure has been updated. A number of organizations have already applied these procedures.

A new Procedure for the prediction of parametric rolling has been developed.

Damage Stability. A review has been carried out concerning numerical and experimental techniques to predict extreme motions and capsizing of damaged ships in waves.

A damage stability benchmark study has been carried out by ITTC Members. Differences between prediction models have been observed with regards to roll damping, flow coefficients for openings, and interaction between floodwater and ship dynamics, though some benchmarked methods showed satisfactory prediction capability.

The implementation of the Procedure for testing damage stability has been monitored through a survey among ITTC Members and the Procedure has been updated. Some organizations have applied these Procedures.

Stability Safety. A review has been carried out concerning stability safety assessment methods for intact and damaged ships, including naval ships. Developments at IMO have been monitored related to stability assessment.

The Committee has reviewed and suggested improvements to the IMO Draft MSC Circular "Interim Guidelines for the Conduct of High-Speed Craft Model Tests".

A state-of-the-art review has been carried out concerning lifesaving appliances and evacuation systems from ships and offshore platforms in waves.

8.2 Recommendations to the Conference

Adopt the revised Procedure 7.5-02-07-02.5 "Model Tests on Intact Stability".

Adopt the revised Procedure 7.5-02-07-02.6. "Model Tests on Damage Stability in Waves".

Adopt the new Guideline "Predicting the Occurrence and Magnitude of Parametric Rolling".

9. REFERENCES AND NOMENCLATURE

9.1 References

Ayaz, Z., Spyrou, K.J. and Vassalos, D., 2001, "An Improved Numerical Model for the Study of Controlled Ship Motions in Extreme Following and Quartering Seas", Proc. of IFAC Conference on Control Applications in Marine Systems, Glasgow, CD.

Belenky, V.L., 1995, "Analysis of Probabilistic Balance of IMO Stability Regulation by Piece-Wise Linear Method", Marine Technology Transaction, 6, pp. 5-55.

Belenky, V.L. and Liut, D., Weems, K. and Shin, Y.S., 2002, "Nonlinear Ship Roll Simulation with Water-on-Deck", Proc. 6th ISSW, New York, CD.

Belenky, V.L., Weems, K., Liut, D. and Shin, Y.S., 2003a, "Nonlinear Roll with Water on Deck: Numerical Approach", Proc. of STAB 2003, Madrid, pp. 59-80.

Belenky, V., Weems, K.M. and Paulling, J.R., 2003b, "Probabilistic Analysis of Roll Parametric Resonance in Head Seas", Proc. of STAB 2003, Madrid, pp. 325-340.

Belenky, V., 2004, "On Risk Evaluation at Extreme Seas", Proc. of the 7th ISSW, Shanghai, pp. 188-202.

Bles, W., Nooy, S., and Boer, L.C., 2001, "Influence of Ship Listing and Ship Motion on Walking Speed", TNO-report TM-01-C015.

Bulian, G., 2004, "Estimation of Nonlinear Roll Decay Parameters Using an Aanalytical Approximate Solution of the Decay Time History", International Shipbuilding Progress, 51 (1), pp. 5-32.

Bulian, G. and Francescutto, A., 2004, "A Simplified Modular Approach for the Prediction of the Roll Motion due to the Combined Action of Wind and Waves", Journal of Engineering for the Maritime Environment, 218, Part M, pp. 189-212.

Bulian, G., Francescutto, A. and Lugni, C., 2004a, "On the Nonlinear Modelling of Parametric Rolling in Regular and Irregular Waves", International Shipbuilding Progress, 51 (2/3), pp. 173-203

Bulian, G., Francescutto, G., Serra, A. and Umeda, N., 2004b, "The Development of a Standardized Experimental Approach to the Assessment of Ship Stability in the Frame of Weather Criterion", Proc. of the 7th ISSW, Shanghai, pp. 118-126.

Bulian, G., Lugni, C. and Francescutto, A. 2004c, "A Contribution on the Problem of Practical Ergodicity of Parametric Roll in Longitudinal Long Crested Irregular Sseas", Proc. of the 7th ISSW, Shanghai, pp. 101-117.

Clauss, G., 2000, "Tailor-made Transient Wave Groups for Capsizing Tests", Proc. of STAB 2000, Launceston, B, pp. 847-860.

Clauss, G. and Hennig, J., 2004, "Deterministic Analysis of Extreme Roll Motions and Subsequent Evaluation of Capsizing Risk", International Shipbuilding Progress, 51 (2/3), pp. 135-155.

Cramer, H., Kruger, S. and. Mains, C., 2004, "Assessment of Intact Stability – Revision and Development of Stability Standards, Criteria and Approaches", Proc. of the 7th ISSW, Shanghai, pp. 55-62.

Crossland, P., 2003, "The Influence of Ship Motion Induced Lateral Acceleration on Walking Speed", Proc. of Pedestrian and Evacuation Dynamics 2003, Greenwich.

Deakin, B., 2000a, "Deployment of Life Rafts from Capsized or Sinking Vessels", Proc. of Sea Australia 2000, Sydney.

Deakin, B., 2000b, "Model Tests to Study Capsize and Stability of Sailing Multi-hulls", Proc. of STAB 2000, Launceston, B, pp. 619-639.

De Kat, J.O., 2000, "Dynamics of a Ship with Partially Flooded Compartment", Contemporary Ideas on Ship Stability, Elsevier Science, pp. 249-263.

De Kat, J.O. and Peters, A., 2002, "Model Experiments and Simulations of a Damaged Frigate", Proc. 10th International Congress of the International Maritime Association of the Mediterranean, Rethymnon.

De Kat, J.O., Brouwer, R., McTaggart, K.A. and Thomas, W.L., 1994, "Intact Ship Survivability in Extreme Waves: New Criteria from a Research and Navy Perspective", Proc. of STAB 94, Melbourne, 1.

De Kat, J.O., Pinkster, D. J. and McTaggart, K., 2002, "Random Waves and Capsize Probability Based on Large Amplitude Emotion Analysis", Proc. of OMAE 2002, J.V. Wehausen Symposium on Water Waves, Oslo.

Falzarano, J. M., 2002, "Analysis of the Dynamical Behaviour of an Offshore Supply Vessel with Water on Deck", Proc. of the 6th ISSW, New York, CD.

France, W.N., Levadou, M., Treakle, T.W., Paulling, J.R., Michel, R.K. and Moore, C., 2003, "An Investigation of Head-Sea Parametric Rolling and its Influence on Container Lashing Systems", Marine Technology, 40 (1), pp. 1-19.

Francescutto, A., 2004, "Intact Ship Stability - The Way Ahead", Marine Technology, 41, pp. 31-37.

Francescutto, A. and Naito, S., 2004, Large Amplitude Rolling in a Realistic Sea. International Shipbuilding Progress, 51 (2/3), pp. 221-235.

Francescutto, A., Umeda, N., Serra, A., Bulian, G. and Paroka, D., 2004, "Experiment-Supported Weather Criterion and its Design Impact on Large Passenger Ships", Proc. of the 2nd DfS, Osaka, pp. 103-113.

Gangi, M.D.,Russo, F. and Vitetta, A., 2003, "A Mesoscopic Method For Evacuation Simulation On Passenger Ships: Models And Algorithms", Proc. of Pedestrian and Evacuation Dynamics 2003, Greenwich.

Gonzalez, V., Talens, M., Riola, J.M., Valle, J., Quesada, T. and Espin, M., 2003, "Numerical Prediction of the Dynamic Behavior of a Ro-Ro Ship after Hull Side Damage", Proc. of STAB 2003, Madrid, pp. 215-227.

Gorski, J., 2002, "A Perspective on The Role of RANS Codes for Predicting Large Amplitude Ship Motions", Proc. of the 6th ISSW, New York, CD.

HARDER E.C. project, 2000, "Harmonization of Rules and Design Rational". DG XII-BRITE, 2000-2003.

Hashimoto, H., Umeda, N. and Matsuda, A. 2004, "Importance of Several Nonlinear Factors on Broaching Prediction", Journal of Marine Science and Technology, 9, pp. 80-93.

Hennig, J., Brink, K. and Kuehnlein, W., 2003, "Innovative Deterministic Seakeeping Test Procedures", Proc. of STAB 2003, Madrid, pp. 457-465

Hirayama, T. and Takezawa, S., 1982, "Transient and Irregular Experiments for Predicting the Large Rolling in Beam Irregular Waves", Proc. of STAB 82, Tokyo, pp. 379-397.

Hirayama, T. and Nishimura, K., 2000, "Physical and Numerical Simulation on Capsizing of a Fishing Vessel in Head Sea Condition", Contemporary Ideas on Ship Stability, Elsevier Science, pp. 368-376.

Hirayama, T., Kato, T., Miyagawa, K. and Takayama, T., 1994, "Generation and Simulation of Multi-Directional Transient Water Waves in a Longitudinal Towing Tank (in Japanese)", Journal of the Kansai Society of Naval Architects, 222, pp. 203-20.

Hirayama, T., Miyagawa, K., Takayama, T. and Satake, H., 1995, "Capsizing and Restoration of a Sailing Yacht in Breaking Isolated Triangular Transient Waves and Breaking Long Crested Transient Waves (in Japanese)", Journal of the Kansai Society of Naval Architects, 223, pp. 59-66.

Hua, J. and Lundbäck, O., 2003, "Issues in the Numerical Modelling of Wave-Induced Forces on a Ship in Following Waves", Proc. of STAB 2003, Madrid, pp. 597-605.

Huang, X., 2004, "Probability of Capsize of a Vessel on Random Beam Waves", Proc. of the 2nd DfS, Sakai, pp. 146-151.

Ikeda, Y., Himeno, Y. and Tanaka, N., 1978, "A Prediction Method for Ship Roll Damping", Department of Naval Architecture, Osaka Prefecture University, 405.

IMO, 1999, "The Interim Guidelines for a Simplified Evacuation Analysis on Ro-Ro Passenger Ships", MSC/Circ.909.

IMO, 2002, "The Interim Guidelines for Evacuation Analyses for New and Existing Passenger Ships", MSC/Circ. 1033.

Ishida, S. and Takaishi, Y., 1990, "A Capsizing Experiment of a Small Fishing Boat in Breaking Waves", Proceedings of STAB 90, Naples, 1, pp. 10-18.

ITTC, 1999, "Specialist Committee on Ship Stability. Final Report and Recommendations to the 22nd ITTC", Proc. of the 22nd ITTC, Seoul and Shanghai, 2, pp 399-431.

ITTC, 2002, "Specialist Committee on Prediction of Extreme Ship Motions and Capsizing. Final Report and Recommendations to the 23rd ITTC Proc. of the 23rd ITTC, Venice, 2, pp. 611-649.

Jasionowski, A., 2001, "An Integrated Approach to Ship Survivability Assessment", PhD thesis, University of Strathclyde, Department of Ship and Marine Technology.

Katuhara, M., Matsukura, H. and Ota, S., 2001, "Evacuation Analysis of Ship by Multi-Agent Simulation Using Model of Group Psychology", Proc. of Traffic and Granular Flow '01.

Kim, Y., 2002, "A Numerical Study on Sloshing Flows Coupled with Ship Motion – the Anti-Rolling Tank Problem". Journal of Ship Research, 46 (1), pp. 52-62.

Koss, L.L. and Brumley, A.T., 2003, "Ship Evacuation Mobility Data", Proc. of Pedestrian and Evacuation Dynamics 2003, Greenwich.

Kostas, K.V., Ginnis, A.I., Kaklis, P.D. and Papanikolaou, A.D., 2003, "A VR-Environment for Investigating Passengers' Locomotion under Dynamic Ship Motion Conditions", Proc. IMDC 2003, Athens.

Kuroda, T., Katayama, T., Shigehiro, R., Ikebuchi, T. and Ikeda, Y., 2003, "Drift

Induced Large Roll Motion of a Ship in Heavy Beam Seas", Proc. of 13th ISOPE, Honolulu, pp. 522-529.

Letizia, L., 1997, "Damage Survivability of Passenger Ro-Ro Vessels Subjected to Progressive Flooding in a Random Sea", PhD Thesis, University of Strathclyde.

Levadou, M. and Palazzi, L., 2003, "Assessment of Operational Risks of Parametric Roll", Transaction of SNAME, pp. 517-531.

Lopez, A. and Perez, F., 2003, "Ship Evacuation Optimisation - Tools for Master and Designer Aid", Proc. of Pedestrian and Evacuation Dynamics 2003, Greenwich.

MAIB, 2003, "Fatal Accident During a Marine Evacuation System Deployment Drill in Dover Harbour on 9 October 2002", http://www.dft.gov.uk/stellent/groups/dft_maritimesafety/documents/page/dft_masafety_507477.hcsp.

Matsuda, A., Umeda, N., Hashimoto, H. and Urano, S., 2002, "Comparison of North European and Japanese Purse Seiners by Capsizing Model Experiments (in Japanese)", Journal of Kansai Society of Naval Architects, 238, pp. 121-129.

Matsuda, A., Hashimoto, H. and Umeda, N., 2004, "Capsizing due to Bow-Diving in Following Waves", International Shipbuilding Progress, 51 (2/3), pp. 121-133.

Matusiak, J., 2002, "Two-Stage Approach to Determination of Large Amplitude Motions of a Rigid Ship in Waves", Proc. 15th Nordic Seminar on Computational Mechanics, Aalborg.

Matusiak, J., 2003, "On the Effects of Wave Amplitude, Damping and Initial Conditions on the Parametric Roll Resonance". Proc. of STAB 2003, Madrid, pp. 341-348.

McCue, M. and Troesch, A., 2003, "The Effect of Coupled Heave/Heave Velocity or Sway/Sway Velocity Initial Conditions on Capsize Modeling". Proc. of STAB 2003, Madrid, pp. 521-529.

McCue, M. and Troesch, A., 2004, "Use of Lyapunov Exponents to Predict Chaotic Vessel Motions", Proc. of the 7th ISSW, Shanghai, pp. 156-171.

McTaggart, K., and de Kat, J.O., 2000, "Capsize Risk of Intact Frigates in Irregular Seas", Transaction of. SNAME, 108, pp. 147-177.

Miyazaki, K., Matsukura, H., Katuhara, M., Yoshida, K., Ota, S., Kiriya, N.and Miyata, O., 2003, "Behaviours of Pedestrian Group Overtaking Wheelchair User", Proc. of Pedestrian and Evacuation Dynamics 2003, Greenwich.

Miyazaki, K., Katuhara, M., Ota, S. and Yoshida, K., 2004, "Application of and Consideration to the IMO Guidelines for Evacuation Analysis for Passenger Ships", Proc. of 2nd DfS, Sakai, pp. 183-187.

Molin, B., 2004, "On the Frictional Damping in Roll of Ship Sections", International Shipbuilding Progress, 51 (1) pp 59-85.

Motora, S., Shimamoto, S. and Fujino, M., 1982, "Capsizing Experiment on a Totally Enclosed Lifeboat", Proc. of STAB 82, Tokyo, pp. 481-490.

Naito, S. and Sueyoshi, M., 2002, "A Numerical Study on Complicated Motions of Floating Bodies", Proc. of the 6th ISSW, New York, CD.

NEREUS E.C. project, 2000, "First Principles Design for Damage Resistance against Capsize". DG XII-BRITE, 2000-2003.

Neves, M., 2002, "On the Excitation of Combination Modes Associated with Parametric Resonance in Waves", Proc. of 6th ISSW, New York. CD.

Neves, A. S. and Rodriguez, C. A., 2004, "Limits of Stability of Ships Subjected to Strong Parametric Excitation in Longitudinal Waves", Proc. of 2nd DfS, Sakai, pp. 139-145.

Nimura, T., Ishida, S. and Watanabe, I., 1994, "On the Effect of Hull Forms and Other Factors on the Capsizing of Sailing Yachts (in Japanese)", Journal of the Society of Naval Architects of Japan, 175, pp. 57-67.

Ogawa, Y., Matsunami, R. and Arai, M., 2005, "The Effect of a Bow Flare Shape on the Water Impact Pressure", Proc. of the 16th ISOPE, Seoul, CD.

Palazzi, L. and de Kat, J.O., 2002, "Model Experiments and Simulations of a Damaged Ship with Air-Flow Taken into Account", Proc. of the 6th ISSW, New York, CD.

Papanikolaou, A. and Konovessis, D., 1999, "Safety in Ship Design: Review of Fundamental Concepts and Methodologies", Proc. of 1st DfS, Glasgow.

Papanikolaou, A. and Spanos, D., 2002, "On the Modeling of Floodwater Dynamics and its Effects on Ship Motion" Proc. of the 6th ISSW, New York, CD.

Papanikolaou, A. and Spanos, D., 2004a, "24th ITTC Benchmark Study on Numerical Prediction of Damage Ship Stability in Waves: Preliminary Analysis of Results". Proc. of 7th ISSW, Shanghai, pp. 1-9.

Papanikolaou, A. and Spanos, D., 2004b "Benchmark Study on the Numerical Prediction of Damaged Ships in Waves. Final Report" ITTC Sub-Committee on Ship Stability in Waves.

Park, J.H., Kong, S.C., Lee, D., Kim, H. and Yang, Y.-S., 2003, "Development of Intelligent Evacuation Model for Ships and Marine Structures", Proc. IMDC 2003, Athens, pp. 426-434.

Reisser-Weston, E., 1996, "Simulating Human Behaviour in Emergency Evacuations", International Conference on Escape, Evacuation and Rescue, Design For Future, RINA, London.

Ribeiro e Silva, S., Santos, T. and Soares, C.G., 2005, "Parametrically Excited Roll in Regular and Irregular Head Seas", International Shipbuilding Progress, 52 (1), pp. 29-56.

Santos, T.A. and Soares, C.G., 2003, "Investigation into the Effects of Shallow Water on Deck on Ship Motions", Proc. of STAB 2003, Madrid, pp. 81-96.

Sarker, T. and Vassalos, D., 2000, "A RANS-Based Technique for Simulation of the Flow near a Rolling Cylinder at the Free Surface,", Journal of Marine Science and Technology, 5, pp. 66-77.

Schreckenberg, M., 2003, "Ship Evacuation Modelling", Proc. of Pedestrian and Evacuation Dynamics 2003, Greenwich.

Shin, Y.S., Belenky, V., Paulling, J.R., Weems, K.M. and Lin, W.M., 2004, "Criteria for Parametric Roll of Large Containerships in Longitudinal Seas", SNAME Annual Meeting, Washington D.C. (early copy).

Simoes, R. et al., 2002, "Systematic Investigation of Lifeboat Evacuation Performance", Transaction of SNAME, 110, pp 341-360.

Spanos, D. and Papanikolaou, A., 2001a, "On the Stability of Fishing Vessels with Trapped Water on Deck", Schiffstechnik, 48, pp. 124-133.

Spanos, D. and Papanikolaou, A., 2001b, "Numerical Study of the Damage Stability of Ships in Intermediate Stages of Flooding", Proc. of 5th ISSW, Trieste, pp. 2.1.1-2.1.8.

Spanos, D., 2002, "Numerical Simulation of Flooded Ship Motions in Seaways and Investigation of the Behaviour of Passenger/Ro-Ro ferries", Dr. Eng. Thesis, National Technical University of Athens, School of Naval Architecture and Marine Engineering.

Spouge, J., 1996, "Escape From Partly Capsized Ferries", International Conference on Escape, Evacuation and Rescue, Design For Future, RINA, London.

Spyrou, K.J., 2000, "Damping Coefficients for Extreme Rolling and Capsize: an Analytical Approach", Journal of Ship Research, 44 (1), pp. 1-13.

Spyrou, K.J., 2001, "Exact Analytical Solutions for Asymmetric Surging and Surf-Riding", Proc. of the 5th ISSW, Trieste, pp. 4.5.4-4.5.3.

Spyrou, K.J., 2004a, "Nonlinear Damping Coefficients from an Asymmetric Roll Decay Time Series: an Analytical Method", Journal of Engineering for the Maritime Environment., Part M, 218 (1), pp. 11-22.

Spyrou, K.J., 2004b, "Criteria for parametric rolling?", Proc. of the 7th ISSW, Shanghai, pp. 92-100.

Spyrou, K.J., Cotton, B. and Gurd, B., 2002, "Analytical Prediction of Capsize Boundary for a Ship with Roll Bias in Beam Waves", Journal of Ship Research, 46, pp. 167-174.

Spyrou, K.J. Themelis, N. and Tigkas, I., 2004, "Benchmark Study of Numerical Codes for the Prediction of Intact Stability of Ships in Extreme Seas: Phase I", ITTC Sub-Committee on Ship Stability in Waves.

Spyrou, K.J. Themelis, N. and Tigkas, I., 2005, "Benchmark Study of Numerical Codes for the Prediction of Intact Stability of Ships in Extreme Seas: Results of Phase II", ITTC Sub-Committee on Ship Stability in Waves.

Takezawa, S., Kobayashi, K. and Kasahara, A., 1988, "Directional Irrregular Waves Generated in a Long Tank (in Japanese)", Journal of the Society of Naval Architects of Japan, 163, pp. 222-232.

Umeda, N., 1999, "Nonlinear Dynamics on Ship Capsizing due to Broaching in Following and Quartering Seas", Journal of Marine Science of Technology, 4, pp. 16-26.

Umeda, N. and Yamakoshi, Y., 1991, "Probability of Ship Capsizing due to Pure Loss of Stability in Quartering Seas", Naval Architecture and Ocean Engineering, 30, pp. 73-85.

Umeda, N. and Hashimoto, H., 2002, "Qualitative Aspects of Nonlinear Ship Motions in Following and Quartering Seas with High Forward Velocity", Journal of Marine Science and Technology, 6, pp. 111-121.

Umeda, N. and Yoshinari, K., 2003, "Examination of IMO Weather Criterion in the Light of Capsizing Probability Calculation", Conference Proc. of The Society of Naval Architects of Japan, 1, pp. 65-66.

Umeda, N., Ikeda, Y. and Suzuki, S., 1992, "Risk Analysis Applied to the Capsizing of High-Speed Craft in Beam Seas", Proc. of 5th International Symposium on the Practical Design of Ships and Mobile Units, Newcastle upon Tyne, pp. 1131-1145.

Umeda, N., Hamamoto, M., Takaishi, Y., Chiba, Y., Matsuda, A., Sera, W., Suzuki, S., Spyrou, K.J. and Watanabe, K., 1995, "Model Experiments of Ship Capsize in Astern Seas", Journal of the Society of Naval Architects of Japan, 177, pp. 207-217.

Umeda, N., Matsuda, A., Hamamoto, M. and Suzuki S., 1999, "Stability Assessment for Intact Ships in the Light of Model Experiments", Journal of Marine Science of Technology, 4, pp. 45-57.

Umeda, N., Mizogami, Y., Ohkura, Y. and Hasegawa, K., 2002, "Numerical Prediction on Capsizing of a Damaged RoRo Ship in Irregular Beam Waves", Proc. of Asia Pacific Workshop on Marine Hydrodynamics, Kobe, pp. 32-36.

Umeda, N. Hashimoto, H. and Matsuda, A., 2003, "Broaching Prediction in the Light of an Enhanced Mathematical Model with Higher-Order Terms Taken into Account", Journal of Marine Science and Technology, 7, pp. 145-155.

Umeda N., Kamo T. and Ikeda Y., 2004a, "Some Remarks on Theoretical Modelling of Damage Stability", Marine Technology, 41 (1), pp. 45-49.

Umeda, N., Hashimoto, H., Vasalos, D., Urano, S. and Okou, K., 2004b, "Nonlinear Dynamics on Parametric Roll Resonance with Realistic Numerical Modelling", International Ship Building Progress, 51 (2/3), pp. 205-220.

Umeda N., Ohkura, Y., Urano, S., Hori, M., and Hashimoto, H., 2004c, "Some Remarks on Theoretical Modelling of Intact Stability", Proc. of the 7th ISSW, Shanghai, pp. 85-91.

van 't Veer, R., de Kat, J.O. and Cojeen, P., 2002, "Large Passenger Ship Safety: Time to Sink", Marine Technology, 41 (2), pp. 82-88.

van 't Veer, R., Peters, W., Rimpela, A. and de Kat, J.O., 2004, "Exploration of Different Arrangements of Semi-Watertight Spaces on Survivability of a Damaged Large Passenger Ship", Proc. of 7th ISSW, Shanghai, pp. 30-41.

van Walree, F., Peters, A.J. and de Kat, J.O., 2004, "Development of Model Testing and Numerical Simulation Techniques for Safety Assessment of High Speed Craft", Proc. of 2nd DfS, Sakai, pp. 114-123.

Vassalos, D., 2004, "Risk-Based Design: From Philosophy to Implementation", Proc. of the 2nd DfS, Sakai, Supplementary Vol., pp. 1-10.

Vassalos, D. and Jasionowski, A., 2002, "Damaged Ship Hydrodynamics", Proc. of the 6th ISSW, New York, CD.

Vassalos, D., Turan, O., Konovessis, D. and Tuzcu, C., 1998, "Comparison Between Prescriptive and Performance-Based Criteria for Assessing Ro-Ro Damage Survivability", International Shipbuilding Progress, 45, pp. 351-382.

Vassalos, D., Guarin, L., Vassalos, G.C., Bole, M., Kim, H.S. and Majumder, J., 2003, "Advanced Evacuation Analysis - Testing The Ground On Ships", Proc. of Pedestrian and Evacuation Dynamics 2003, Greenwich.

Vassalos, D., Jasionowski, A. and Cichowitz, J., 2004a, "Issues Related to the Weather Criterion", International Shipbuilding Progress, 51 (2/3), pp. 251-271.

Vassalos, D., Ikeda, Y., Jasionowski, A. and Kuroda, T., 2004b, "Transient Flooding on Large Passenger Ships", Proc. of the 7th ISSW, Shanghai, p. 10.

Vredeveldt, A. W., Journée, J. M. J. and Vermeer, H., 2000, "The Effect of Crashworthiness and Solid Buoyancy on Survivability of Damaged and Flooded Ro-Ro Ships", Proc. of STAB 2000, Launceston, pp. 396-407.

VTT, 1998, "Evacuation Tests For a Heeled Passenger Cabin", VAL36-980382.

Werenskiold, P., 2003, "UMOE Shat-Harding MPC60 Lifeboat Evacuation Operation REPORT - Model Tests", Marintek REPORT NO 820001.00.01.

Wood, A.G., 1996, "Validating Ferry Evacuation Standards", Proc. of International Conference on Escape, Evacuation and Rescue, Design For Future, RINA, London.

Woodburn, P., Gallagher, P. and Letizia, L., 2002, "Fundamentals of Damaged Ship Survivability", Transactions of RINA, pp. 143-163.

Yoshida, K., Murayama, M. and Itakaki, T., 2001, "Study on Evaluation of Escape Route in Passenger Ships by Evacuation Simulation and Full-scale Trials", Proc. of "INTERFLAM 2001", Edinburgh.

9.2 Nomenclature

DfS	International Conference on Design for Safety
IMDC	International Marine Design Conference
ISOPE	International Offshore and Polar Engineering Conference
ISSW	International Ship Stability Workshop
OMAE	International Conference on Offshore Mechanics and Arctic Engineering
RINA	Royal Institution of Naval Architects
SNAME	Society of Naval Architects and Marine Engineers
STAB	International Conference on Stability of Ships and Ocean Vehicles