The Specialist Committee on Stability in Waves

Final Report and Recommendations to the 25th ITTC

1. INTRODUCTION

1.1 Membership and Meetings

Membership. The Committee appointed by the 25th ITTC consisted of the following members:

- Dr. N. Umeda (Chairman)
  Osaka University, Japan
- Mr. A. J. Peters (Secretary)
  QinetiQ, Haslar, UK
- Professor S. Fan
  Marine Design and Research Institute of China
- Professor A. Francescutto
  University of Trieste, Italy
- Dr. S. Ishida,
  National Maritime Research Institute, Japan
- Dr. J. O. de Kat (until 2006)
  Maritime Research Institute Netherlands
- Professor A. Papanikolaou
  National Technical University of Athens, Greece
- Dr. A. M Reed
  Naval Surface Warfare Center, USA
- Dr. F. van Walree (from 2007)
  Maritime Research Institute Netherlands

In addition, the following corresponding members contributed greatly to the work of the committee:

- Professor K. J. Spyrou,
  National Technical University of Athens, Greece
- Professor D. Vassalos (until 2006),
  Ship Stability Research Centre, UK

The committee would like to acknowledge the valuable contributions of experimental and simulation data to the benchmark studies from the following universities and research establishments: Helsinki University of Technology (TKK); Marine Design and Research Institute of China (MARIC); Maritime Research Institute Netherlands (MARIN); Maritime and Ocean Engineering Research Institute (MOERI); National Technical University of Athens (NTUA); Ship Stability Research Centre (SSRC), Osaka University; Instituto Superior Tecnico (IST); the EU project SAFEDOR; and the Office of Naval Research.

Meetings. Four Committee meetings were held as follows:

- Osaka, Japan - March 2008
- Gosport, UK - May 2007
- Rio de Janeiro, Brazil - September 2006
- Wageningen, NL - February 2006

1.2 Tasks from the 24th ITTC

- Develop a procedure for tank testing to predict the onset and extent of parametric rolling.
- Further develop the procedure 7.5-02-07-02.5 for intact stability testing, to include extreme motions such as broaching and deck diving in irregular waves, wind and breaking waves. Liaise with the Ocean Engineering Committee.

- Identify experimental techniques and data for validation of time-domain capsize codes, emphasising the selection of the important parameters that influence the capsizing behaviour of intact and damaged ships. Liaise with the Ocean Engineering and Seakeeping committees.
- Assess the state of the art for:
  - o Practical application of numerical methods for the prediction of capsizing and experiments for assessment of safety/risk against capsize.
  - o Make recommendations as to what scientific progress is required to move stability regulations from those based on hydrostatic calculations to those based on dynamic predictions, either using capsize codes or physical model experiments.
- Establish the importance of the following issues in predicting the dynamic behaviour of damaged vessels, including sinking and capsizing, coupling between floodwater dynamics and ship dynamics, influence of flow coefficients for openings and flooding of complex spaces (multiple compartments, stair wells, failing watertight doors, etc).
- Review numerical methods for assessing the length of time to sink or capsize for damaged passenger ships and associated validation techniques.
- Continue to review developments (relevant to ITTC) in stability safety assessment, with special attention on performance and risk-based approach and relevant developments at IMO.

2. PREDICTION OF EXTREME MOTIONS AND CAPSIZING OF INTACT SHIPS

2.1 Experimental Technique for Capsizing in Wind and Waves

Free Running Experiments. Free running model experiments can be used to investigate capsize scenarios, and have been used to identify different modes of extreme motions and capsizing of intact ships. To perform these experiments successfully, the ship model should be self-propelled and fitted with an auto-pilot to eliminate any external influences to the model's response to the waves. Generally, the ship motions should be measured by a fibre-optic gyroscope, a gyro accelerometer or an optical tracking sensor. The measured signals should be stored by an onboard computer, or transmitted to shore by radio link or umbilical cable.

Roll decay tests and inclining experiments should be performed to assess the roll damping and the transverse stability characteristics of the model.

Many free-running experiments on parametric rolling in head and bow seas have been conducted during the last three years and are reviewed in the following section.

Matsuda, et al. (2006) conducted free running model experiments for a purse-seiner vessel at several Froude numbers. The model capsized due to bow-diving in the severe following seas at intermediate speeds. The model also experienced stable surf-riding at higher speeds and broaching at lower speeds. Marón, et al. (2006) and Perez-Rojas, et al. (2007) investigated the accidents of small fishing vessels through free running model experiments in beam, following and quartering seas. This allowed the identification of the modes of loss and the appropriateness of the stability regulations for this type of vessel.

Guided Model Experiments. Captive and semi-captive model experiments can give repeatable and certifiable experimental results to verify the capability of numerical models, or to obtain information on forces, moments and motions. If the model is towed, the towing point should be carefully selected to avoid undesirable effects on the significant motions.

Ikeda, et al. (2005) carried out guided model experiments for a large passenger ship to investigate the effects of wave height and bilge keel arrangements on the occurrence of parametric roll in beam seas. The model was equipped with gimbals to keep the model on course, but was free to heave, pitch, sway and roll. Using this model, Munif, et al. (2006) measured ship motions in dead ship conditions in waves with various heading angles to confirm the region where parametric roll occurred. Fujiwara and Ikeda (2007) also studied the effects of roll damping and heave motion on parametric rolling.

Olivieri, et al. (2006) conducted model experiments in regular beam seas for the validation of a CFD code. The test conditions selected were free to heave and roll, whereas the other degrees of freedom were constrained. Lee, et al. (2006) observed experimentally the effects of the initial conditions on the capsizing of a box barge in beam seas. The model was fixed at an initial roll angle by electromagnets, which allowed the model to be released at an expected initial roll velocity.

Matsuda, et al. (2007) developed a new measuring system to realize the measurement of heel-induced hydrodynamic forces with deck submergence and forward velocity in following and quartering seas. This system restricts surge, sway, yaw and roll, but allows heave and pitch motions to be free.

Ayaz, et al. (2006) measured 6-degrees–of–freedom (DOF) forces and moments by using a dynamometer in captive model experiments, to enhance a numerical manoeuvring model. Lundbäck (2005) and Armaoğlu, et al. (2006) measured the surge force, sway force, roll moment and yaw moment with a 6-DOF loadcell. The models were free to move in heave and pitch in their experiments.

Wave Generation. Waves used in capsizing experiments include regular, long-crested irregular, short-crested irregular and transient waves. ITTC and JONSWAP spectra are usually chosen for the long-crested irregular waves. Hashimoto, et al. (2006) used cosine to the 2nd or 4th power as the directional distributions function for generating the short-crested irregular waves.

It is very important for capsizing experiments in transient waves in the basin to tailor a wave sequence leading to an extreme response over a short period of time; four approaches have been identified. The first approach adopted is based on linear, broad-banded wave theory and uses probability theory to find the expected value of the wave shape. The second approach uses the Sequential Quadratic Programming method to optimize the phases associated with an initial random wave train, such that the result produces the desired extreme waves. The third approach applies the first approach described above to find the shape of the most likely extreme response, and the amplitudes and phases of the incident wave components can then be back-computed via linear theory, giving the tailored wave shape near the desired crest. Alford, et al. (2005, 2006) reviewed the approaches described above and developed a fourth approach using a non-uniform distribution for the random phases associated with the component waves. This method constructs a response time series using linear superposition of sinusoidal waves with a non-uniform phase distribution to keep the stochastic nature of the problem.

Wind Generation. For capsize experiments at zero speed (drifting), wind forces can play an important part as they have a great effect on ship heading, drifting direction and heel angle. Experiments with wind effects at forward speed were not found in current published literature. This is due to fact that the profile of the wind velocity is difficult to model accurately.

Ogawa, et al. (2006) investigated the effect of wind and waves on the drift motion through free drifting tests in steady beam wind and irregular beam waves. In the experiment the wind fans, which are attached to the carriage, track the model as it drifts in the waves. The effect of the drift motion on the capsizing probability under dead ship condition was also examined. Umeda, et al. (2006b) carried out a model experiment in a towing tank with wind fans to create a beam wind profile to investigate the capsizing and sinking of a cruising yacht. This experiment determined the time-to-sink with and without water inside the yacht.

2.2 Experimental Technique for Head-Sea Parametric Rolling

A considerable number of model experiments investigating head-sea parametric rolling have been conducted in recent years. They have been carried out not only in regular waves but also in irregular waves. In the experiments, wave period, wave height, load condition and speed of the model were varied and their effects on the threshold for the occurrence of parametric rolling and the resultant rolling amplitude were investigated.

Model experiments on head-sea parametric rolling are divided into two categories. The first uses a model towed by a carriage or other device in a towing tank (Burcher, 1990; Silva and Guedes Soares, 2000; Francescutto, 2001; Neves, et al., 2002; Bulian, et al., 2004; Hashimoto, et al., 2007). The second uses a free-running model with autopilot in a wide rectangular basin (Dallinga, et al., 1998; France, et al., 2003; Matusiak, 2003; Levadou and van't Veer, 2006; Hashimoto, et al. 2006; Taguchi, et al. 2006).

Towing Arrangement. For head-sea parametric rolling the coupling between roll and vertical motions plays an important role in addition to the variation of the roll restoring moment in waves (Skomedal, 1982). Therefore, if a towed model is used, special attention should be paid to the towing arrangements to ensure that there is no interference with the vertical motions. Burcher (1990), Francescutto (2001), and Neves, et al. (2002) described this kind of towing arrangement. For example, Francescutto (2001) used a tethering system based on pairs of elastic mooring lines symmetric about the centre line of the model, to attach the model to the towing carriage. This system ensures the model remains on a straight course, while it is sufficiently loose to avoid any interference with the roll and vertical motions.

A towed model was used in tests in irregular waves (Bulian, et al., 2004; Hashimoto, et al., 2007). However, even with the elastic mooring line towing arrangement it is difficult to reproduce speed variation in irregular waves, which was noted to have some influence on the probability of parametric roll (France, et al., 2003). It is noted that comparative studies between free running and towed model experiments have shown acceptable agreement (SLF 49/5/7/Corr.1, 2006). However, in order to take into account the full effect of the vessels speed variation in waves, tests with a free-running model should be considered.

Non-Ergodicity of Head-sea Parametric Roll in Irregular Waves. It should be noted that there is a possibility of non-ergodicity in head-sea parametric rolling in irregular waves. Belenky, et al. (2003, 2006) and Bulian, et al. (2006) carried out numerical simulations of parametric rolling in irregular waves. Although proof of ergodicity or non-ergodicity for parametric rolling in irregular waves cannot be provided, based on careful analysis of simulated ship motion data, they concluded that roll motion is practically non-ergodic, while pitch and heave motions can be considered as ergodic processes. More recently, the possibility of non-ergodicity in head-sea parametric rolling has been confirmed by model experiment (Bulian, et al., 2004, 2006, Hashimoto et al, 2007). Bulian, et al. (2008) studied the dispersion in the estimated statistical characteristics of the measured processes in parametric rolling. This study showed that the uncertainty in the estimation from time histories of roll is significantly larger than those for pitch and wave elevation.

In order to consider the possibility of non-ergodicity in parametric rolling, the draft revision of the ITTC Recommended Procedures and Guidelines 7.5-02-0704.1 "Model Tests on Intact Stability," recommends that several realisations of irregular waves of shorter duration be used rather than one realisation of longer duration. However, it appears necessary to set up guidelines for the appropriate run length and number of realisations required. Therefore, further investigations on this issue from a theoretical, numerical and experimental perspective are required.

Nonlinear Feature of Head-sea Parametric Rolling Since parametric rolling is a non-linear phenomenon, different steady states could coexist at the same experimental conditions.

Oh, et al. (1992, 2000) carried out model experiments in longitudinal regular waves without forward speed. They continuously measured ship motions while varying the wave height by small amounts. The jump-up/down phenomena were observed and the range of wave amplitude where two steady states exist (non-rolling and parametric rolling) was clarified.

Bulian, et al. (2004) reported that two coexisting steady state roll motions were observed in regular waves. This was confirmed by Hashimoto, et al. (2007) in regular wave tests at no forward speed with different initial disturbances. To identify the threshold of parametric rolling by model experiments, it is therefore necessary to repeat experimental runs with the model starting with different initial conditions (as far as reasonably practicable).

Hashimoto, et al. (2006) reported that head sea parametric rolling may disappear when the wave height increases in the model experiment. This was noted earlier by several numerical simulation studies by Umeda et al. (2003), Spanos and Papanikolaou (2005), Umeda et al. (2005), and Neves and Rodriguez (2005). This implies that a threshold maximum wave height may also exist for parametric rolling. Therefore, it should be noted that the non-existence of parametric rolling in a certain wave height range does not necessarily mean that parametric roll will not occur in other wave height ranges.

Taking these nonlinear features of head-sea parametric rolling into account, the revised ITTC Recommended Procedures and Guidelines 7.5-02-07-04.1 "Model Tests on Intact Stability" has been drafted, stating that it is also desirable to carry out numerical simulations for systematically varied conditions and compare both experiments and simulations when determining the threshold for the occurrence of parametric rolling and the resultant rolling amplitude.

2.3 Revision of the Model Test Procedure

The Procedure 7.5-02-07-04.1 "Model Tests on Intact Stability" has been further developed based on a survey within ITTC member organizations, on the experiences of experts and published literature, to include extreme motions such as broaching and bow diving in irregular waves, transient waves, and in wind. An experimental procedure to examine parametric roll was incorporated into the model test procedures. The additions and revisions of the procedure are summarized as follows:

- Regarding the model design and construction, the following important considerations were added to the original procedure: the effects of model hull and bilge keel sizes on viscous roll damping, turbulence stimulation for rudders and fins, the projected areas of superstructure for testing in wind, the significant autopilot contributions to model roll, the towing point for towed model, etc.
- The methods for calibration of the deterministic transient waves at a target area were introduced based on members' experiences and a literature review. Two options for modelling wind forces were described: Firstly where wind loads act directly on the model and secondly with a wind velocity field around the model.
- The ranges of the ratio of wavelength to ship length for the model experiments in astern seas and head seas were specified. As an interim indication, the generation of transient waves was introduced based on relevant literature.
- For a floating structure, wind can be generated following the ITTC recommended procedures and Guidelines,

7.5-02-07-03.1 “Floating Offshore Platform Experiments”. For a free drifting model, a wind velocity field may be generated by an array of wind fans mounted on a carriage following the model.
- Details on roll decay tests were included with regards to the IMO weather criteria test guidelines published as MSC.1/Circ.1200 (2006).
- Procedures for conducting parametric rolling experiments were described in detail, including theoretical explanations of this phenomenon.

2.4 Benchmark Testing Plan of Numerical Codes for Predicting Parametric Rolling

Benchmark Testing in 23rd and 24th ITTC. To establish the capability and weaknesses of time-domain numerical capsize codes on intact stability, benchmark studies were conducted in the 23rd ITTC (The Specialist Committee on Prediction of Extreme Ship Motions and Capsizing) and the 24th ITTC (The Specialist Committee on Stability in Waves).

In the 23rd ITTC, free-running test data of a container ship (Ship A-1) and a purse-seiner (Ship A-2) in following and quartering seas were used for validation. The capsize modes were mainly parametric rolling at low speeds for the container ship and broaching in high speed conditions for the purse-seiner.

The same purse-seiner used in the 23rd ITTC (Ship A-2) was used in the 24th ITTC validation study. These validation tests included data from roll decay tests, free running tests in beam and quartering seas and captive tests for measuring GZ variation in waves. As in the 23rd ITTC, the main capsize mode was broaching in following and quartering seas.

Considering the activities of the current and previous specialist committees, emphasis should be placed on examining parametric rolling in head and bow seas in the next benchmark testing study.

Identification of Data. A considerable number of experiments examining parametric rolling in head and bow seas have been conducted by universities and research institutes/laboratories. In order to identify the suitability of the experimental data for validation of numerical benchmark testing, a questionnaire survey was carried out among the members of this specialist committee and some universities. Additionally, a review of publications from stability related conferences was made.

It was found that some experiments have restrictions on the public use of the results, especially on the hull form details. Some of the data do not include the necessary details for comparison with simulation results. Three sets of experimental data were selected as candidates for benchmark testing. A summary of the data is indicated in Table 2.1.

Table 2.1 Summary of Identified Data

Data Name			A	B	C
Ship type			Post Panamax container (C11-class)	Panamax container (4000TEU)	ITTC A-1 container
Length(Lpp)		[m]	262.0	260.0	150.0
Breadth		[m]	40.0	32.2	27.2
Depth		[m]	24.5	20.0	13.5
Mean draught		[m]	12.9	12.0	8.5
Block coefficient			0.593	0.640	0.667
GM		[m]	1.97	1.12	1.00
Natural roll period		[sec]	25.7	26.4	20.1
Model scale ratio			1/55	1/100	1/60
Type of test			Free running		
Froude number			0.11-0.22	0.0-0.25	0.0-0.25
Encounter angle		[deg]	120-180	180	180
regular wave	Wave / ship length		1.2	0.6-2.4	0.8-1.25
	Wave steepness		0.015	0.008-0.046	0.03-0.05
irregular wave	T_{02}	[sec]	13.6-16.2		
	$H_{1/3}$	[m]	11-13		
Key Reference			France et al. (2003)	Yang et al. (2008)	Umeda (2007)

From this data set, Data-C is the first candidate for head-sea parametric rolling. The hull form of Data-C, used in the 23rd ITTC, is not of a modern container ship. However, the measured roll restoring variation in waves, wave-induced surge force data and others are available from captive model experiment results.

The Data-A can be used as validation data for bow-sea parametric rolling, especially in irregular waves, though captive model experiments were not conducted.

Plan for Benchmarking. In the 24th ITTC, a benchmark study for broaching was carried out step by step as follows:

1) Dynamic behaviour in still water (roll decay and basic manoeuvrability);
2) Roll and sway responses in beam seas;
3) Roll, sway, yaw and surge responses in quartering seas;
4) Magnitudes of hydrodynamic loads associated with the above.

In the new benchmark study, similar steps would be effective for establishing the capability and weaknesses of the codes:

1) Roll decay test as a function of forward speed;
2) Roll, and pitch responses in head seas;
3) Hydrodynamic forces and moments in waves

When using Data-C for validation, the three steps described immediately above are possible, and the important factor, the roll restoring variation in head waves, can be compared with experimental data.

The benchmark study can be divided into two phases. In the first phase, all of the hydrostatic and hydrodynamic quantities will be estimated by the benchmark code from the hull form, shape of bilge-keels details, etc. In the second phase, the numerical simulation will be conducted using all of the measured data. Comparing the results of the two phases will allow the capabilities and weaknesses of the codes to be identified.

When Data-A is used, step 3 above will not be possible. However, comparing the results from steps 1 and 2 would allow the characteristics of the codes to be understood.

3. PREDICTION OF DYNAMICS OF DAMAGED SHIPS

Research has progressed in recent years in the area of numerical prediction of the motions of a damaged ship in waves with marginal stability conditions often leading to capsize and sinking. The international scientific community has further developed and improved numerical methods to match the findings from physical model experiments.

3.1 Numerical Simulation Modelling and Techniques

The numerical methods for the simulation of the motions of a damaged ship in waves can be categorized according to the modelling and integration of the basic three constituents of the problem which are employed, which are:

- The ship with zero forward speed drifting 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 the damage openings and the progressive flooding through internal spaces.

As a basis of most numerical methods, potential flow theory is commonly employed to address 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 generally neglected.

The hydrodynamic properties of the damaged ship are commonly calculated in the frequency domain and 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 accumulates inside the ship and changes the mean draft and trim, can be addressed by an appropriate update of the ship’s hydrodynamic coefficients. The effect of the mean heel angles on hydrodynamic coefficients is generally ignored.

The modelling of the floodwater inside the damaged compartments is a challenge for all numerical methods. There are different approaches used to address the floodwater dynamics and the effects on the ship motions. The accuracy and efficiency of the model is dependent on the underlying methods used. Higher accuracy CFD methods are currently not yet practical for full integration with ship motion simulation methods for multi-compartment configurations. The commonly used simpler quasi-steady approaches can result in unsatisfactory results, for instance in cases with large deck areas, when sloshing effects are significant. There is also uncertainty on the correct values for the discharge coefficients, which relate the pressure difference over an opening to the resulting flow velocity through the opening.

The possible use of shallow water equations for the flooding problem is limited by the difficulties which occur with the partial emergence of the bottom of the flooded compartment, a phenomenon which is almost always present, at least over a portion of the simulation time. The use of the random choice method or Glimm's method (Santos and Guedes Soares, 2006) overcomes the bottom emergence difficulty, where an approximate solution for the time-domain flow of floodwater can be obtained.

The use of particle methods has demonstrated the ability to model complicated phenomena like wave breaking and sloshing behaviour. The main disadvantage of these emerging methods is their heavy computational requirement, which currently makes it difficult to integrate with ship motion simulations.

An effect of the flooding process that also needs to be accurately modelled is that of trapped air in cases with unventilated or partially ventilated compartments. Trapped air will have a significant influence on the water accumulation in compartments.

3.2 Recent Literature

The two main sources of information on the developments and achievements in the theoretical and experimental prediction of damaged ship stability in waves are the series of STAB Conferences (eg. STAB, 2006) and ISSW Workshops (eg. ISSW 2005, 2007).

Flooding Process. Katayama and Ikeda (2005) carried out physical model tests and documented the dependence of the discharge coefficients on the basic geometric parameters of the damage opening, as well as the ventilation conditions of the damage compartment. The assumption of a constant value of the discharge coefficients appears to be a special case within the wide variety of discharge conditions that can be encountered.

Cho, et al. (2006) applied a 2-D analytical CFD method to the floodwater sloshing problem, which interacts with the motions of the damaged ship. The preliminary results presented could not demonstrate any improvement of the simulated motions of the damaged ship; however, there is evidence of an improvement of the computational performance of the overall method that supports the feasibility of such refined numerical methods for the analysis of at least more intricate flooding cases.

Ruponen (2006a) presents a new simulation method for progressive flooding of damaged ships. The method is based on the so-called pressure correction technique to deal with the coupled water and air flows. Water and air flows have very different densities and pressures which leads to numerical difficulties in ordinary time integration schemes. The iterative structure of Ruponen's method ensures time accurate results for complex compartment configurations. Ruponen also compares simulation results with experimental results and finds a very good agreement in calm water flooding.

Nabavi, et al. (2006) studied the effect of geometrical parameters of openings on the discharge rate for water flowing off a deck. The study was based on CFD simulations and the results were compared to experimental data. The results show that the propagation of longitudinal waves causes the discharge coefficient to fluctuate. Furthermore, results from two-dimensional simulations were in close agreement with these from three-dimensional simulations.

Skaar, et al. (2006) demonstrates the applicability of SPH techniques to model progressive flooding of a damaged ship section. The section was forced to oscillate in roll and heave. Despite a number of known difficulties pertinent to SPH methods (wave generation, wave reflection, numerical dissipation, wall boundaries), the ability to capture the flooding process with subsequent internal sloshing was demonstrated.

Ruponen (2007) discusses improvements and advances to his simulation method for progressive flooding. In particular, the way to deal with openings which have a large vertical extent and a sensitivity analysis of the developed method with respect to opening parameters are discussed.

It is found that the failure of (semi) water tight doors is rather sensitive to initial leakage which reduced the pressure differences over the doors. It is concluded that the failure processes should be more closely studied. On the other hand, the sensitivity analysis did not show significant differences in the overall flooding process due to small variations to critical pressure heads.

Ruponen and Routi (2007) describe a method for the dimensioning of air pipes on the basis of his flooding simulation method. The method is applied for the calculation of the time to cross-flood in a U-shaped void (double hull) of a large passenger ship. Air compressibility is accounted for in the method.

<u>Numerical Simulations for Damaged Ships.</u> Worldwide, the number of researchers dealing with the development of numerical simulation tools appropriate for the assessment of the damaged ship stability in waves appears to be increasing. Recently introduced simulation methods/codes previously unknown were those of Schreuder (2005), Jankowski and Laskowski (2006).

Santos and Guedes Soares (2006) describe a numerical method for the motions of a damaged ship in a seaway. The method considers the equations of motion in the time domain and describes the behaviour of the floodwater inside the ship's compartments using shallow water equations. Differential equations describing the properties of the water on the main deck are also given. A number of damage conditions are studied for the flooding of a double bottom and main compartments without water on the main deck. Comparisons with experimental results for a Ro-Pax ferry are discussed.

For intact conditions, the calculated and experimental roll characteristics were found to be in good agreement. For flooded conditions the agreement was less satisfactory. Nevertheless, a double peaked roll response spectrum found in the experiments could be reproduced with the numerical method.

Cho, et al. (2006) present a numerical method to solve ship motions with internal fluid. The ship motions problem is solved using a three-dimensional frequency domain panel method. The internal water motion is based on a VOF method modified to take account of sloshing effects. The ship and the internal water motions are coupled by adding sloshing forces to the ships equations of motion. In turn, the ship motions affect the sloshing of the internal water. Comparisons with experimental results for a Ro-Pax vessel show that for resonant roll conditions, a good agreement is found for the roll decay properties. For non-resonant conditions the agreement is not so good.

Spanos and Papanikolaou (2007) have analysed the time to capsize of a damaged Ro-Pax ship in waves by means of a numerical simulation procedure. The procedure consists of a non-linear hydrodynamic method for the simulation of the ship motions and flooding, with a statistical simulation method to account for the variability and uncertainty of the various parameters involved.

The hydrodynamic method consists of a non-linear time domain simulation method in six degrees of freedom. The motion problem is based on linear potential flow theory in combination with non-linear Froude-Krylov forces. The flooding problem is based on a quasi-steady approach using the Bernoulli equation.

The statistical method is based on the Monte Carlo approach in which the numerical method is applied for a series of randomly chosen conditions.

It is shown that there is no practical time margin for the evacuation of passengers and crew in non-survival conditions. The results also suggest that the ship, which complies with current damage stability requirements, will always capsize in waves exceeding a limiting (survival) wave height.

Walree and de Kat (2006) have applied their time domain simulation method to forensic research on the loss of a trawler and analyzed the survivability of the vessel in view of deck flooding and down-flooding through open hatch covers.

Vassalos and Jasionowski (2007) have examined a series of related numerical simulations and relevant experimental results for a Ro-Pax and cruise ship. They highlighted issues with the new harmonized probabilistic rules SOLAS2009 for these vessels types.

Valanto (2007) has applied a numerical simulation code for the re-investigation of the Estonia ferry accident; possible scenarios of sinking were deduced by analysis of simulations for the possible flooding of the car deck. Parallel forensic investigations by other simulation codes on the same subject were discussed during the international workshop on the Estonia ferry accident (Estonia Debate, 2007).

3.3 Benchmark Testing of Numerical Modelling

Since 2001, numerical simulation codes appropriate for the assessment of the survivability of a damaged ship in waves were monitored and have been benchmarked by the 23rd and 24th ITTC. For the assessment of the current performance of related codes, an international benchmark study was organized within the European research project SAFEDOR (2005-2008); this study was supported by the 25th ITTC Specialist Committee SiW and coordinated by the National Technical University of Athens NTUA.

Benchmark codes have been reviewed in a comparative way with respect to the prediction of the survival boundary of a damaged Ro-Pax ferry in waves, as well as with respect to the sensitivity of the numerical predictions on the basic simulation parameters of inherent uncertainty.

This benchmark is considered as a continuation of the two earlier benchmarks studies conducted for the 23rd and 24th ITTC. Although six (6) institutes initially expressed a formal interest in participating in the study, eventually only the results from four (4) of them were available in a timely manner and used in related comparisons, Table 3.1. The low participation provides evidence that there are only a limited number of independently developed and mature codes available world-wide for analysing this very complicated and important issue.

Table 3.1 List of Final Participants

Institute/ organization	Acronym	Country
National Technical University of Athens – Ship Design Laboratory	NTUA-SDL	Greece
The Ship Stability Research Centre, Universities of Glasgow and Strathclyde	SSRC	United Kingdom
Maritime Research Institute Netherlands	MARIN	The Netherlands
Instituto Superior Tecnico, Technical University of Lisbon	IST	Portugal

The Study Ship. The vessel used in the investigation is a modern Ro-Pax ferry with a bulbous bow and flat stern sections. The main dimensions of the ferry are given in Table 3.2

and the body plan is shown in Figure 3.1. The ship is of SOLAS 90 stability standard and has been investigated previously within the European research project *HARDER* (2000 -2003). Two bilge keels of 0.34m width are fitted on the hull; the astern one has a length of 23.6m and the forward one a length of 28.0m.

Table 3.2 Main Dimensions of the Study Ship

Length Lpp	174.80	m
Beam, B	25.00	m
Draft, T	6.40	m
Depth, D	9.10	m

The Damage Case. The damage case investigated includes damage to two adjacent compartments located amidships and corresponds to the worst SOLAS 90 damage case. The length of the damage opening is 8.25m (3%L+3.00 m), with a triangular penetration and unlimited vertical extent including damage to the vehicle space on the main deck. The general arrangement of the damaged compartments is shown in Figure 3.2.

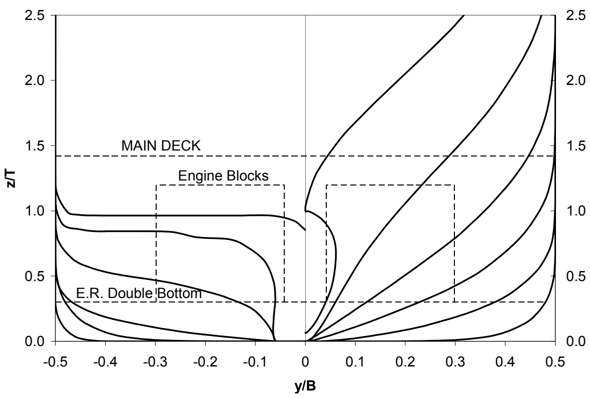

Figure 3.1 The Body Plan of the Study Ship

In the engine room (the aft damaged compartment) two intact blocks are used to model the main engines and result in an engine room permeability of 0.70. In the double bottom of the fore compartment the two side tanks are interconnected with a cross duct, while the rest of the space between them remains intact after the damage.

Benchmark Tests. The ferry is assumed to be free floating, without forward speed, in beam waves coming from the starboard side, the side that is damaged, and is free to drift.

As listed in Table 3.3, the benchmark tests consisted of the estimation of the survival boundary $H_{s,surv}$ for a set of five different conditions and an additional seakeeping test. All the tests were for the SOLAS damage case described above. Tests 2 to 5 were for the same conditions, as in Test 1, but had certain parameters varied as a sensitivity investigation. Hence, in Test 2 the KG was reduced by 1.0 m, in Test 3 longer period waves were considered, in Test 4 any assumption on the semi-empirical value of the roll viscous damping that was made for the initial test was doubled, and in Test 5 the assumed discharge coefficients for the initial test was reduced by half. The last test conducted, Test 6, was a seakeeping test in which the vessel started in the intact condition and after 30 minutes the damage (the same as for the other tests) was assumed to occur.

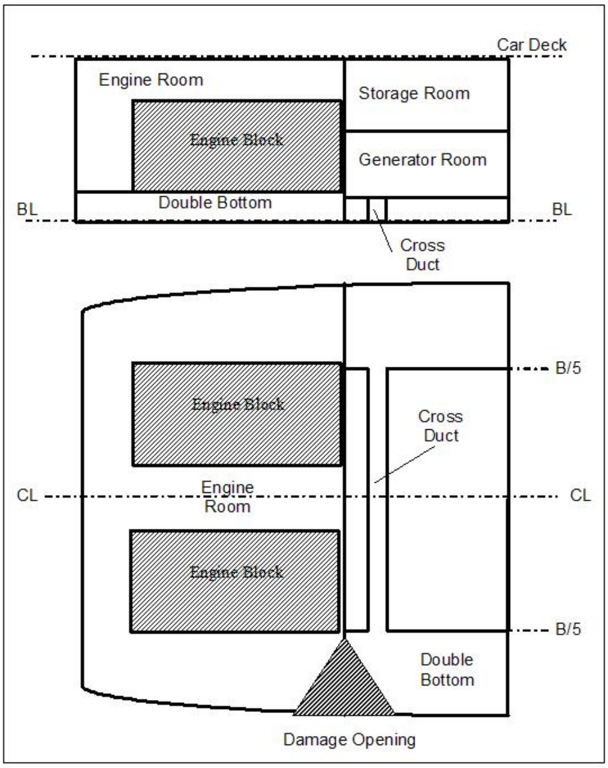

Figure 3.2 General Arrangement of the

Damage Case Investigated

Table 3.3 Benchmark Tests (with respect to the Particulars of Tests 2–5 only the differences relative to Test 1 are given)

Test	Description	Particulars
1	Basic	KG = 12.3 m, JONSWAP, $T_p = 4\sqrt{Hs}$, γ = 3.3, $B44_{v\text{-basic}}$, $C_{discharge\text{-basic}}$
2	Low KG	KG=11.3 m
3	Long waves	$T_p = 6\sqrt{Hs}$, γ = 1.0
4	High roll viscous damping	$B44v' = 2 \times B44_{v\text{-basic}}$
5	Reduced discharge coefficients	$C'_{discharge} = 0.5 \times C_{discharge\text{-basic}}$
6	Seakeeping	KG = 11.3 m, Hs = 3.0 m, Tp = 10.4 sec, γ =1.0, $B44_{v\text{-basic}}$, $C_{discharge\text{-basic}}$, Damage onset after 30 min

<u>Survival Boundary Estimations.</u> The study participants were required to deliver their best prediction for the specified conditions, considering any assumptions made and semi-empirical data used, and the application of the code as inherent to the benchmarked method. Comparable conditions were assumed to be established when the intact ship hydrostatics and the basic benchmark specifications were met by the benchmarked codes. Special care was taken to ensure the reliability of the delivered numerical results in view of the probabilistic nature of the problem.

The delivered numerical simulation results for the survival wave heights are shown in Table 3.4, where the names of participants are coded as P1 to P4 and kept anonymous.

Table 3.4 Survival Boundary in (m) for the Basic Test 1

Participant	$H_{s,surv}$	Mean	Differ. from mean	Exp.
P1	3.23	3.00	+0.23	≤ 3.00
P2	1.75		-1.25	
P3	4.00		+1.00	
P4	3.00		+0.00	

It should be noted that insufficient model tests were actually conducted to establish an experimentally measured survival boundary for the benchmark; the tests conducted showed, however, that the actual survival boundary was close to, but less than, 3.00 m.

Two of the simulation codes successfully predicted a survival boundary with a wave height of about 3.00 m, while significant deviations of 1.0 m were detected for the other two codes. Detailed background investigation on the two successful codes P1 and P4 revealed, however, that they substantially differed in intermediate results during the study, though this is not reflected in the final estimated survival wave height of the benchmarked ship.

The sensitivity of the numerical predictions with respect to the basic simulation parameters, namely those of the ship loading condition KG, the spectral sea wave periods, the roll viscous damping and the discharge coefficients were examined with an additional series of tests. The numerical results, summarized in the Table 3.5, show that the codes exhibited different sensitivities and predicted opposite trends in certain cases, with respect to the basic variations.

Table 3.5 Difference of Survival Boundary in Comparison to the Basic Test 1

Participant	Test 2 Lower (by 1.0 m) KG	Test 3 Longer Waves	Test 4 Higher (double) Roll Damp.	Test 5 Lower (half) discharge coefficients
P1	0.40	0.31	0.02	0.57
P2	0.50	1.25	0.00	-0.25
P3	0.75	-0.50	0.00	0.00
P4	0.50	-0.75	N/A	N/A

The numerical estimations of survivability of the benchmarked ship were most sensitive to the ship loading condition and the spectral periods of the incident waves, while less sensitive to the assumptions made for the discharge coefficients. No conclusions could be derived for the effect of the viscous roll damping as the present results appear to contradict the conclusions from the earlier benchmark studies, suggesting an increased importance for the values of the semi-empirical roll damping coefficients.

Independent of the successful prediction of the survival wave height boundary by two codes, the rating of the overall performance of the benchmarked codes could not be concluded, as verification of the reasons for the inferior performance of the other codes is still pending.

Further details and background information about the benchmark study, its conditions and activities can be found in Papanikolaou and Spanos (2008), as well as on the webpage www.naval.ntua.gr/~sdl/sibs. The final results of this study would be reported by SAFEDOR in a forthcoming IMO-SLF paper.

3.4 Benchmark Testing of Numerical Codes of Time-to-Flood

Introduction. The ITTC Stability in Waves committee has conducted two benchmark studies on numerical methods for the prediction of time to flood of damaged ships in a seaway. Both studies were completed under the coordination of the 25th ITTC committee and were performed at the request of the SLF Sub-Committee of the IMO. The studies have contributed to the assessment of the state of the art of numerical methods. Results of the studies have been and will be reported at the 50th and 51st sessions of the SLF Sub-Committee (Walree 2007: Walree and Carette, 2008a). Furthermore, results have been presented at the ISSW 2007 and 2008 workshops, see Walree and Papanikolaou (2007) and Walree and Carette (2008b).

The development of a structured approach to benchmark testing was a key feature in the benchmarking process. Several comparisons of predictions for the time-to-flood and motions in calm water and in waves, obtained from running the participating numerical codes, have been reported for progressively more complex scenarios.

The initial intention was to carry out a benchmark study for an existing cruise ship. Unfortunately, the data for a realistic cruise ship with a complex internal geometry were not readily available to the Committee. Therefore it was decided to split the work in two phases as follows:

1. A benchmark based on a barge for which detailed model test data is available;
2. A benchmark based on a realistic passenger ship with complex internal geometry.

Benchmark Study Phase 1. The objective of the benchmark study was to establish the current capabilities and weaknesses in predicting, qualitatively and quantitatively, the time-to-flood for a simple configuration of compartments in a barge-like hull form. Besides time-to-flood, related quantities such as motions and flooding volumes in compartments were compared with experimental results.

The barge that was used as the basis for the study has been tested at the Helsinki University of Technology (TKK, formerly HUT), see Ruponen (2006b). The model was box shaped with tapered bow, stern and bilges. The model scale was 1:10 with a model length of 4 m, see Table 3.6 and Figures 3.3–3.5. The model was instrumented with water level sensors in the eight floodable compartments to obtain detailed information on the flooding process. Two pressure sensors were located in the two lower, double bottom compartments. The floodable compartments were located forward of amidships so as to introduce a trim angle and thereby encourage progressive flooding.

Table 3.6 Main Particulars of Barge Model

Length over all	4.000 m
Breadth	0.800 m
Height	0.800 m
Design draft	0.500 m

Block coefficient	0.906
Volume	1.450 m^3

Six flooding cases were tested in the experiment, four of which were selected for the benchmarking study. The experimentally derived discharge coefficients were used in the simulations. The details of the experimental configurations are described by Ruponen (2006b).

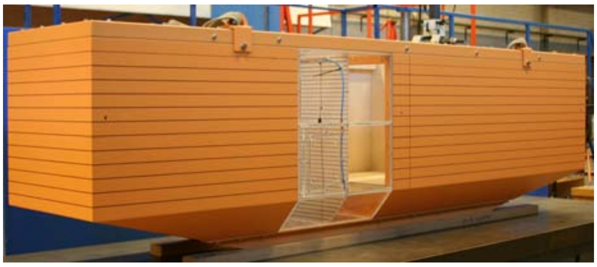

Figure 3.3 Barge Model at TKK

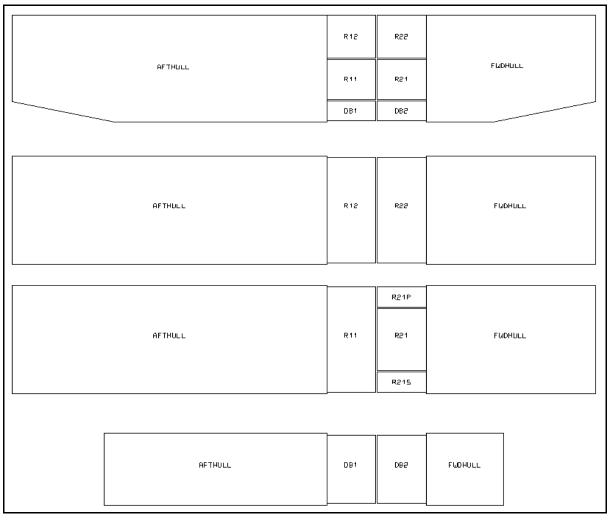

Figure 3.4 Barge Configuration

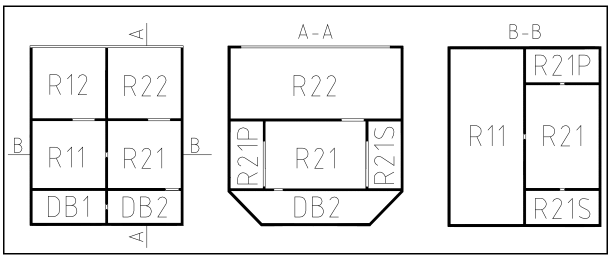

Figure 3.5 Internal Compartments

The following organizations participated in Phase 1 of the benchmark study:

1. Ship Stability Research Centre (SSRC), United Kingdom.
2. Helsinki University of Technology (TKK), Finland.
3. Maritime Research Institute Netherlands (MARIN), The Netherlands.
4. Maritime and Ocean Engineering Research Institute (MOERI), Korea
5. National Technical University of Athens (NTUA), Greece.

In the presentation of the results the participants are referenced to anonymously as C1 to C5.

All of the codes tested incorporate time domain simulation methodologies and can predict ship motions in six degrees of freedom. The codes are applied for conventional ship hulls at zero or normal operating speeds.

Froude-Krylov forces are based on the integration of the undisturbed wave pressures over the instantaneously submerged hull and superstructure portions. Radiation and diffraction forces are generally based on strip theory or a 3D frequency domain panel method. This frequency domain information is used in the time domain by means of convolution integrals. The hydrodynamic force components that are influenced significantly by viscosity are modelled semi-empirically.

The flooding methods use relatively simple hydraulic models. The basic Bernoulli equation is used to determine the water ingress through damage openings. The flow rate through an opening is related to a pressure difference over the opening and a semi-empirical discharge coefficient. This approach is also applied to the progressive flooding between ship compartments through open doors, ducts, collapsed bulkheads, etc. None of the codes take into account sloshing effects. The water surface in compartments is either assumed to be horizontal at all times, or a local gravity angle is applied such that the water surface is still planer but not necessarily horizontal.

Plots showing comparisons between the experimental (Test) and simulation results (C1 through C5) are shown in Figures 3.6 through 3.16 (Test 03). Water level heights in the compartments are denoted by H-x where x stands for the compartment identification. The pressure in the double bottom compartment DB1 is denoted by P-DB1. Sinkage and trim are denoted by heave and pitch, respectively.

Water level results from Code C1 are only defined between the instants that the level starts to rise and that the compartment is filled. Otherwise a zero value is given.

In Code C2 a very low atmospheric pressure is present and so this method cannot be applied correctly at model scale. The ambient air pressure is fixed in the code and cannot be changed and therefore the effects of air compressibility are likely to be underestimated.

The results for Codes C3 and C4 do not include pressures, as air compressibility is not taken into account in the simulations. The compartments are assumed to be fully ventilated.

The results for the individual compartments for Code C5 have been grouped into larger compartments: DB1+DB2 and R21+ R21S+R21P. Results for grouped compartments cannot be compared directly to the results for the individual compartments.

In some of the codes it was possible to use the experimentally determined discharge coefficients; in other codes a fixed discharge coefficient has been used.

The external damage opening for this test case was present in the bottom of compartment DB2 and allowed to progressively flood into the other compartments. Compartment DB1 was not ventilated; all other compartments were ventilated to some extent.

For the non-ventilated compartment DB1, the results show that Code C1 overestimates the air pressure effects, C3 and C4 do not account for air pressure while the Code C2 result is closest to the experimental flooding rate. For the ventilated compartment DB2, the agreement is better. Code C3 results lag behind the experiment result, but Code C4 results show good comparison.

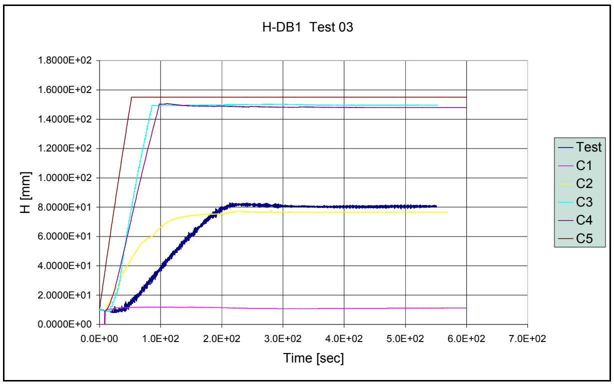

Figure 3.6 Water Level for Compartment DB1

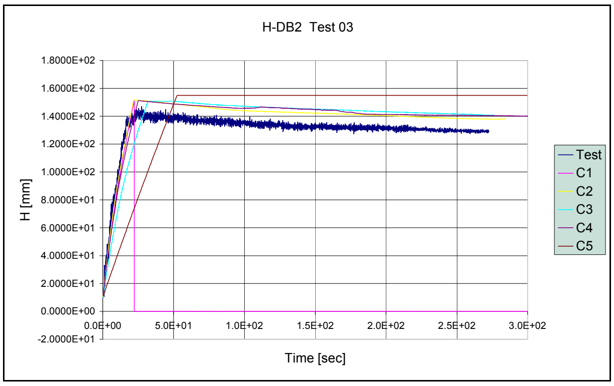

Figure 3.7 Water Level for Compartment DB2

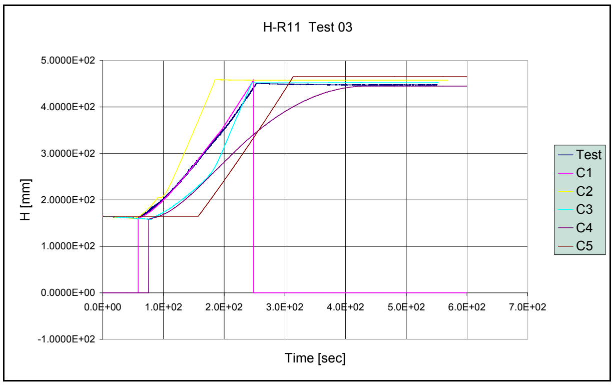

Figure 3.8 Water Level for Compartment R11

For the R11, R21, R21S and R21P compartments located on top of the double bottom, the Code C1 result is very close to the experiment result, C2 shows a flooding rate that is too high while C3, C4 and C5 lag behind the experiment result.

For the top compartments R12 and R22, Code C2 results show flooding too early compared to the experiment result, C1 and C3 results are close to the experimental values. Code C4 predicts no flooding in these compartments. C5 lags behind for R12 and R22.

The pressures in compartment DB1 are well predicted by Code C1, while C2 shows again a steeper pressure rise than measured in the experiment.

The results for the water level comparison are also reflected in the heave and pitch curves: the heave and pitch rates for C2 are too high but the steady values are well predicted. Code C1 results are close to the experimental values while C3 results also show high heave and pitch rates and somewhat high steady values. This is a contradiction to the general under prediction of the flooding rates for C3. For Code C4, both heave and pitch are under predicted, which is in agreement with the general under prediction of flooding rates. Code C5 finally predicts the heave quite well while the pitch is slightly underestimated.

In conclusion, the prediction of flooding rates, especially for unventilated or partially ventilated compartments shows large variations. Differences are found between experimental and simulation results and between the results from the different simulations. Code C1 performed generally well throughout.

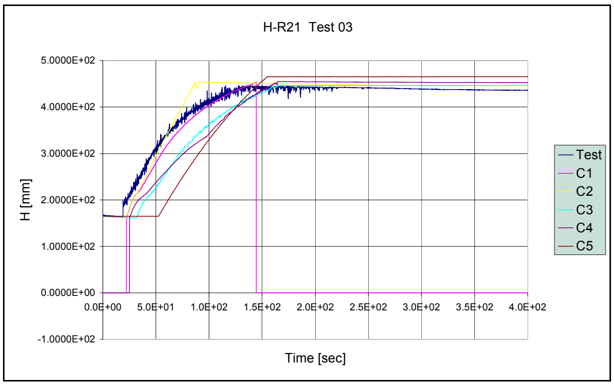

Figure 3.9 Water Level for Compartment R21

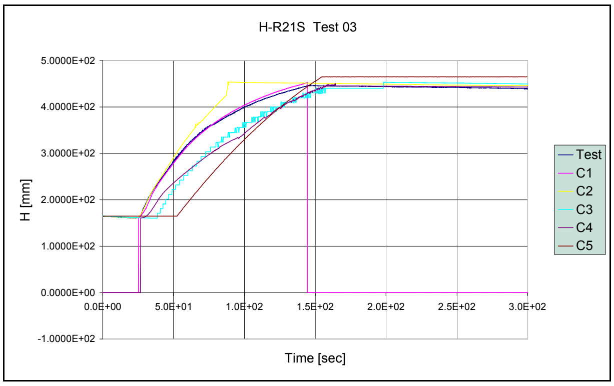

Figure 3.10 Water Level for Compartment R21S

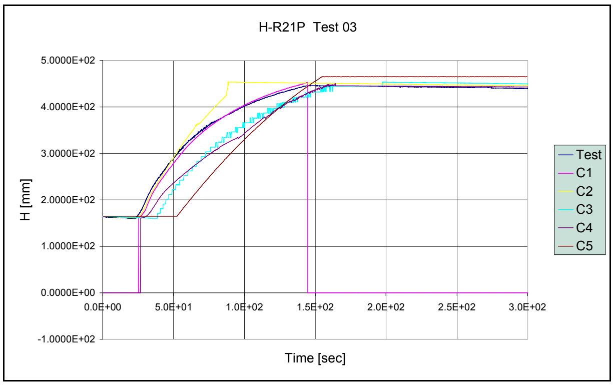

Figure 3.11 Water Level for Compartment R21P

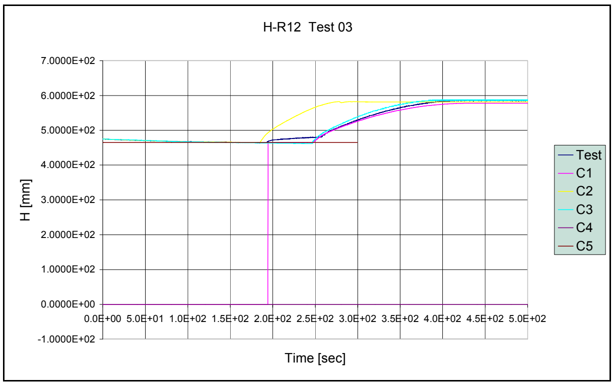

Figure 3.12 Water Level for Compartment R12

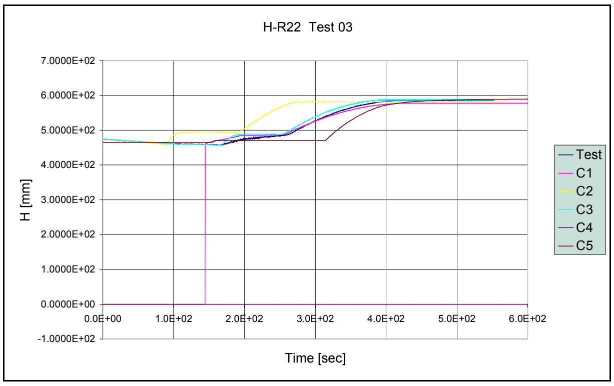

Figure 3.13 Water Level for Compartment R22

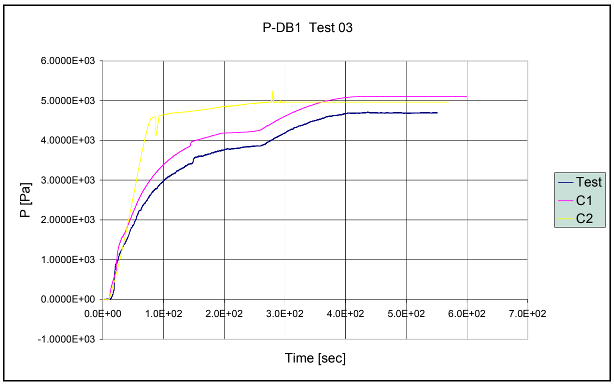

Figure 3.14 Pressure for compartment DB1

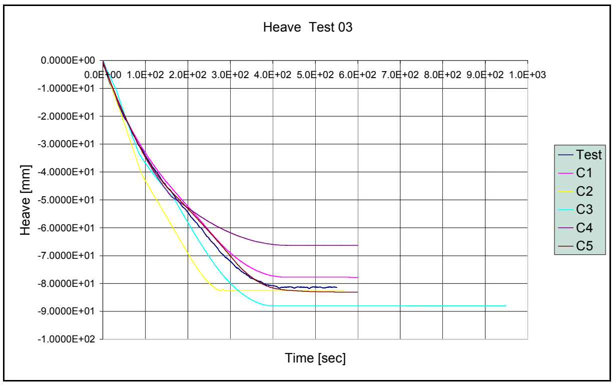

Figure 3.15 Heave of the Barge

At the same time, differences in local flooding rates on the total flood water mass apparently cancel out, since the equilibrium position is reasonably well predicted by most codes.

As such, reasonable time to sink predictions appear feasible by most of the present codes, at least for ships having a relatively simple internal geometry and interconnection between flooded compartments under calm water conditions.

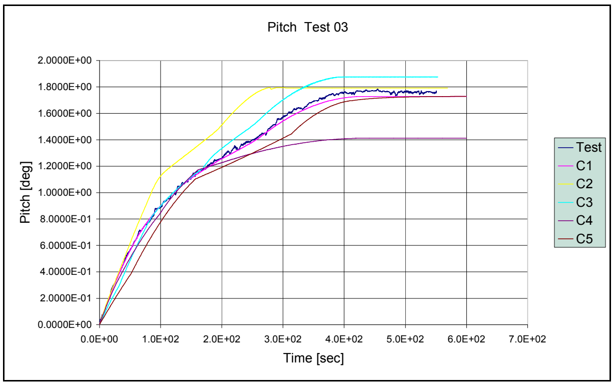

Figure 3.16 Pitch of the Barge

Comparative Study Phase 2. The objective of Phase 2 of the study was to establish the current capability and weaknesses in predicting, qualitatively and quantitatively, the time-to-flood for complex configuration of compartments in a typical passenger ship. The study was limited to a comparative study of numerical results since there currently is no public domain experimental data available to conduct a true benchmark study. Besides time-to-flood, related quantities such as ship motions and flood water masses in compartments were compared. Due to the complexity of the simulations required and the restricted time constraints, only two participants completed this study.

Table 3.7 Main Ship Particulars

Mass	56542	[ton]
Lpp	247.7	[m]
B	35.5	[m]
T	8.3	[m]
GM	2.0	[m]

The hull form and the internal compartment layout used here were kindly provided by SSRC, see Table 3.7 and Figures 3.17 and 3.18. The only appendages present were a set of bilge keels with length 75 m and height 0.5 m.

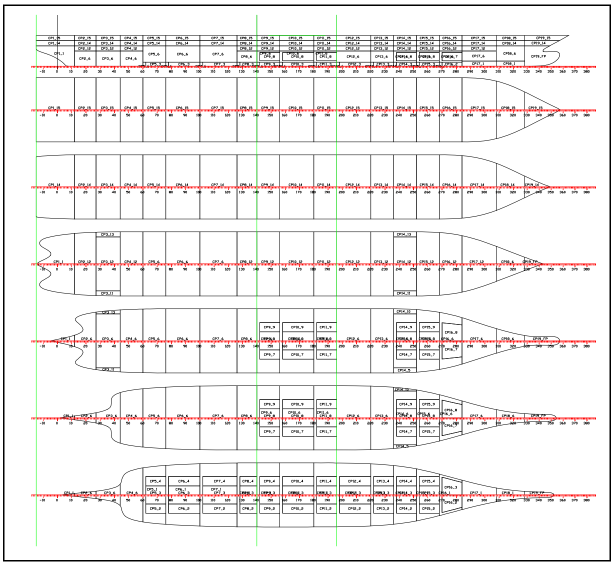

Figure 3.17 Passenger Ship Compartments

In total 142 compartments were present with 84 openings in horizontal and vertical direction. Most of the compartments were subject to flooding.

The ship was freely drifting (zero initial forward speed) for all simulations. No wind forces were taken into account. All six modes of motion were free, i.e. no mode was restricted. The initial position of the ship was such that the wave direction was on the starboard side of the ship (90 deg from stern), i.e. the damage faced the incident waves.

The damage length was set as 0.03*Lpp+3m. The damage height equalled the depth of the ship while the damage depth was B/5.

The shape of the damage was triangular in top view, pointing into the ship with depth B/5. Two damage positions were chosen;

D1: centre at frame 100 (aft of midship)
D2: centre at frame 180 (midship).

Both damage positions were at the starboard side of the ship. The damage length was extended across two compartments. Discharge coefficients were determined by each participant.

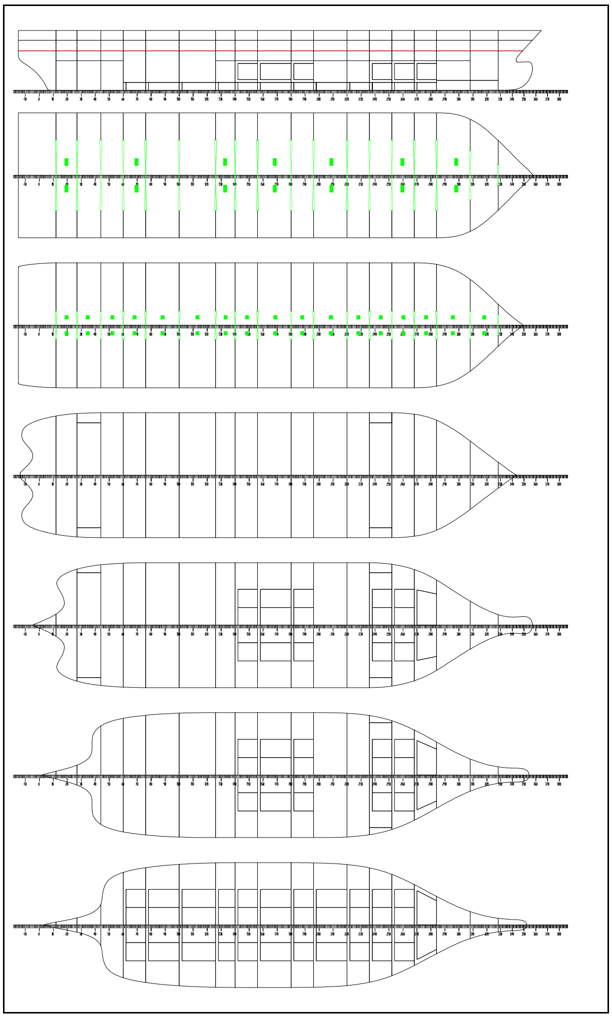

Figure 3.18 Passenger Ship Openings

The following Simulations were requested for the Intact Vessel:

- Four sea states, long-crested seas
- Ten wave seeds (wave realizations).
- Simulation duration 1800 sec.
- One loading condition.

The following were done for the Damaged Vessel:

- Two damage positions, D1 and D2.
- Five sea states.
- Ten wave seeds (wave realizations).

- Simulation duration until mean heel angle is constant but at least 1800 sec.
- One loading condition.
- Additional calm water runs.
- Additional runs with fixed heading angle and specified discharge coefficient.

The following organisations participated in phase II of the benchmark study:

- Ship Stability Research Centre (SSRC), United Kingdom
- Maritime Research Institute Netherlands (MARIN), The Netherlands

In the presentation of the numerical simulation results, the participants are referenced anonymously as A and B.

Both codes incorporate time domain simulation methods and can predict motions in six degrees of freedom. The codes are applied to mono-hulls at zero for normal operating speeds. Froude-Krylov and restoring forces are based on the integration of the undisturbed wave pressures over the instantaneously submerged hull and superstructure. Radiation and diffraction forces are generally based on strip theory or a 3D frequency domain panel method. This frequency domain information is used in the time domain by means of convolution integrals (retardation forces). The hydrodynamic force components that are influenced significantly by viscosity are generally determined semi-empirically. Part of the second order wave drift forces are included by determining the non-linear Froude-Krylov forces.

The flooding methods use relatively simple hydraulic models. A modified Bernoulli equation is used to determine the water ingress through damage openings. The flow rate through an opening is related to a pressure head and a semi-empirical discharge coefficient. This approach is also applied to the progressive flooding between ship compartments through open doors, ducts, collapsed bulkheads, etc. The flooded compartment water surface is either assumed to be horizontal at all times, or movable due to the coupling with the ship motion, but still planer. Air compressibility effects can be taken into account.

Preliminary results were published by Walree and Carette (2008b). A selection of time to flood results is presented as obtained from code B.

Following the ITTC recommended procedure for damage stability in waves, the survival limit of the ship is defined as either an instantaneous roll angle of 30 degrees or a three minute average roll angle of 20 degrees.

On reviewing the results for Code B, the roll and damage mass are not always constant near the 1800 seconds limit and the criteria can be exceeded during longer duration simulations, especially for aft damage case D1. Typical examples are shown in Figures 3.19–3.22. In each Figure, results are shown for five wave realisations. Figures 3.19 and 3.20 show the three minutes average heel angles versus time, while Figures 3.21 and 3.22 show the three minute average flood water mass versus time.

It can be seen that for damage case D1 (aft damage) and Hs = 4m significant wave height, the survival limit is reached in about 2500 to 3000 seconds. Damage case D2 (mid ship damage) is less critical in these conditions.

On reviewing the preliminary results from Code A, they show that the three minute averaged values for roll and damage mass are constant near the 1800 second simulation duration. Therefore, Code A simulations stop here and the criteria are never exceeded. At the time of reporting the results were still under investigation to determine the significant differences between the results from the two codes.

Based on a preliminary analysis of results, it is concluded that for the most severe flooding and sea conditions there were considerable differences in the results from the two codes for the time to flood for a large passenger ship with complex interior layout. The true performance of the current codes can only be evaluated when accurate experimental model benchmark data are available for comparison.

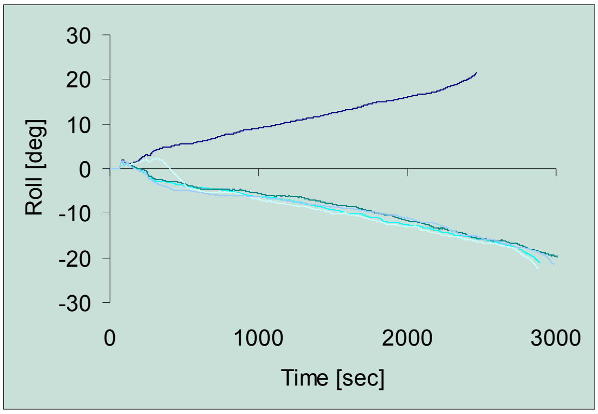

Figure 3.19 Roll Versus Time, Hs = 4 m, Damage Case D1

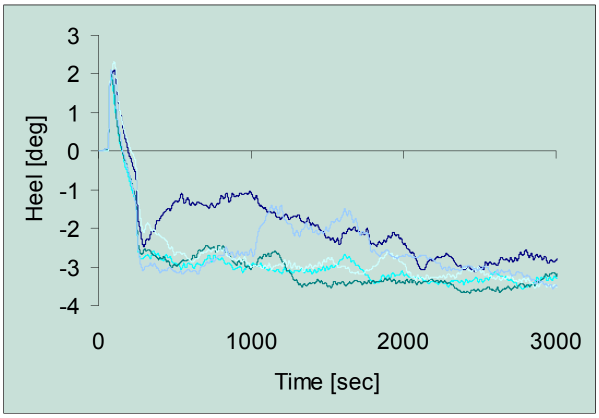

Figure 3.20 Roll Versus Time, Hs = 4 m, Damage Case D2

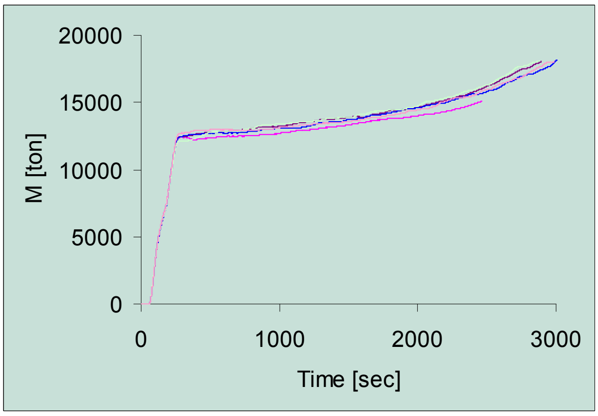

Figure 3.21 Flood Water Mass Versus Time, Hs = 4 m, Damage Case D1

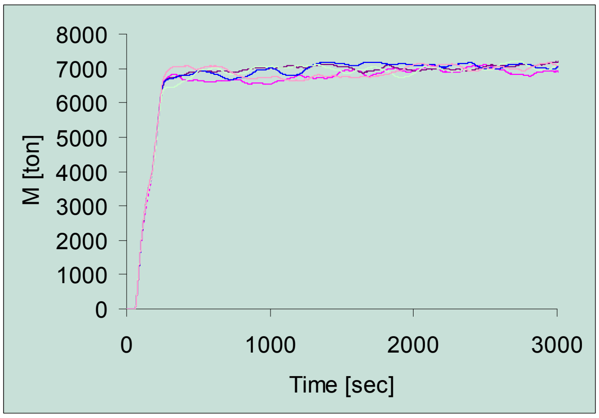

Figure 3.22 Flood Water Mass Versus Time, Hs = 4 m, Damage Case D2

4. STABILITY SAFETY ASSESSMENT

In this chapter, only current work on intact stability safety assessment is reviewed, because mainly performance-based approaches to intact stability are discussed during this term at the navies and IMO.

4.1 Review of Techniques for Naval Ships

Existing Naval Stability Standards. With few exceptions, the navies of the world are still employing hydrostatic based stability criteria that reflect growths or extensions of the works of Rahola (1939) and Sarchin and Goldberg (1962). Although static based criteria are currently used there is recognition of the need to further develop the stability criteria to incorporate hydrodynamics and performance based approaches.

There have been a number of recent papers and reports relating to the subject of dynamic stability assessment for naval vessels, cf. Alman, et al. (1999), McTaggart (2000), McTaggart and de Kat (2000), and Hughes (2006). Many of these have been motivated by the work of the Naval Stability Standards Working Group (NSSWG) a collaborative effort between the Royal Australian Navy, the Canadian Navy, the Royal Netherlands Navy, the British Royal Navy, the US Coast Guard, and the US Navy.

In 2003 NATO initiated an effort to develop a goal based standard for naval vessels that could guide navies and classification societies in the development of rules for naval vessels. The intent was to develop regulations for naval vessels that paralleled the IMO regulations for commercial vessels. (IMO regulations do not apply to naval vessels.) In 2007, NATO issued several documents relating to standards for classing naval vessels, all under the umbrella of a *Naval Ship Code* (NATO, 2007a). The introduction to the *Naval Ship Code* states, “The overall aim of the Naval Ship Code is to provide a framework for a naval surface ship safety management system based on and benchmarked against IMO conventions and resolutions that embraces the majority of ships operated by Navies.” The code further goes on to state “. . . it therefore contains safety related issues that correspond in scope to that which is covered by IMO publications but which reflect the fundamental nature of naval ships.” Rudgley et al. (2005) provide an overview of the process and the overall philosophy for the development of the *Naval Ship Code*.

The *Naval Ship Code* is composed of ten chapters:

Chapter I	General provisions
Chapter II	Structure
Chapter III	Buoyancy and Stability
Chapter IV	Machinery Installations
Chapter V	Electrical Installations
Chapter VI	Fire Safety
Chapter VII	Escape, Evacuation and Rescue
Chapter VIII	Radio communications
Chapter IX	Safety of Navigation
Chapter X	Carriage of Dangerous Goods

Chapter III, Buoyancy and Stability, deals with dynamic stability and capsize. This chapter was developed in the second half of 2006 by a study group composed primarily of representatives from: Australia, Canada, Italy, Netherlands, Spain and the United Kingdom, with input from the Naval Stability Standards Working Group (NSSWG). In parallel to the *Naval Ship Code*, NATO produced another document, *Guide to the Naval Ship Code* (NATO 2007b). The discussion of Chapter III in the Guide states “Due to the variety of available Naval Standards on stability and on-going work in other bodies to understand the dynamics of the stability problem and the measure of safety provided by current standards, it was decided not to develop another detailed quasi-static stability standard.” Thus, the *Naval Ship Code* provides only the most generic guidance with regard to dynamic stability and capsize.

The Buoyancy and Stability chapter is divided into eight “Regulations.” numbered 0 through 7. Regulations 1–7 are subdivided into four sections: Functional Objectives, Performance Requirements, Verification Methods, and Definitions (optional). Four of these Regulations (0 Goal, 1 General, 4 Reserve of Stability, and 7 Provision of Operational Information), explicitly mention capsize or dynamic stability. The Regulation 0 Goal specifically states:

1 The buoyancy, freeboard, main sub-division compartment and stability characteristics of the ship shall be designed, constructed and maintained to:
  .2 Provide adequate stability to avoid capsizing in all foreseeable intact and damaged conditions, in the environment for which the ship is to operate, under the precepts of good seamanship;

The “Performance Requirements” listed under Regulation 1 General further elaborate:

4 The ship shall:
  .1 Be capable of operating in the environment defined in the Concept of Operations Statement;
  .2 Have a level of inherent seaworthiness including motions tolerable by equipment and persons onboard, controllability and the ability to remain afloat and not capsize;”
  .3 Be designed to minimise the risk faced by hazards to naval shipping including but not limited to the impact of the

environment causing dynamic capsize, broach or damage to crew and equipment, . . ."

.4 Be provided with operator guidance, as required in Regulation 7 Operator Guidance, to facilitate safe handling of the ship.

The "Verification Methods" section of Regulation 1 General states:

6 Verification that the ship complies with this chapter shall be by the Naval Administration.

7 The burden of verification falls upon the Naval Administration. All decisions that affect compliance with the requirements of this chapter shall be recorded at all stages from concept to disposal and these records must be maintained throughout the life of the ship.

Thus the *Naval Ship Code* contains no specific dynamic stability or capsize criteria nor does it specify any procedures by which a vessel can be determined to be in compliance with the Code. Neither Regulation 4 Reserve of Stability nor Regulation 7 Provision of Operational Information provides any additional detail on how the requirements are to be met, this is left to each countries naval authority.

The *Naval Ship Code* provides a standardised 'goal based' framework, which allows each naval authority to use its own current static based or a performance based standard to provide verification of a ship's ability to meet the overall stability goals defined in the code.

Developments Relating to Standards for Navies. Among other topics, the NSSWG has been examining existing naval stability standards with respect to a dynamic stability assessment. Hughes (2006) presents preliminary results of this study. In the study a wide variety of static stability metrics (16 in total) for 12 naval vessels have been correlated against a dynamic stability assessment performed using an older version of the FREDYN time domain simulation program. The correlation coefficients for many of these criteria parameters (e.g. GM, GZ_{max}, $GZ_{30°}$, ϕ_{range}, $A_{0°\text{-}40°}$, $A_{0°\text{-}\phi_{range}}$, etc.) were all higher than 0.8 (the majority were higher than 0.9, many were close to 0.99). However, there was no static stability parameter or criteria that had the highest correlation coefficient across all 12 ships. This indicates that the current static-stability-based naval stability standards are not significantly deficient, at least for conventional naval ship designs. However, it should be noted that there is no means of telling how much safety margin any of these ships have.

The NSSWG is continuing its assessment of existing naval stability standards. It is anticipated that the FREDYN correlation will be repeated with an updated version of the code. However, this will require substantial computational effort and will not be undertaken lightly.

One navy that has been identified as applying dynamic stability criteria is the US Navy. Based on some model tests of tumble-home hull forms in the late 1990s, it was found that the criteria of DDS 079-1 (US Navy 2003a) did not provide the equivalent margin against capsize for tumble-home ship designs as it does for the traditional wall-sided and flared designs. Therefore, an intensive effort was instituted in 2000 to develop a dynamic-stability-based standard. This standard is codified in two documents. The first document is a succinct statement of the criteria (US Navy 2002) and the second document provides the actual implementation of the standard. US Navy (2003b) is the current version of this second document, which is an annex to the primary standard. The primary standard, the first version of the implementation document has in fact been incorporated in the American Bureau of Shipping (ABS) Naval Vessel Rules (NVRs).

The US Navy dynamic stability criteria are a relative criteria whereby the new vessel design is assessed against an existing naval vessel designed for an equivalent mission. This ensures that a frigate is not judged against an aircraft carrier, or vice versa. The dynamic stability criterion has five components, which are as follows:

(a) The annual probability of capsize without wind effects, for the appropriate range of sea states, when multiplied by a margin of 1.10, is less than or equal to that of the equivalent mission benchmark ship.
(b) For each sea state, the capsize probability shall be determined for the specified range of modal periods. The worst-case capsize probability for each sea state /modal period multiplied by a factor of 1.10 shall be less than or equal to that of the worst capsize risk for the benchmark ship taken in the same sea state over the same range of speeds, headings, and modal periods.
(c) In any given sea state it is shown, on the capsize and broaching risk polar diagrams, that regions of high capsize probability, 60 percent or higher, are not adjacent to regions of high broaching probability, 60 percent or higher.
(d) Regions of zero capsize probability, as shown on a capsize risk polar diagram, do not transition to regions of 80 percent or higher capsize probability over a 5-knot range of speed or 15° heading change.
(e) There shall be no region of 100 percent capsize probability in the defined mission sea states.

These criteria are applied over a range of sea states and modal periods. The sea states range from 5 to 8, with sea states 7 and 8 being subdivided into 3 significant wave heights, each of which has 3 modal periods. For each significant wave height and modal period, an assessment of capsize probability is performed over a range of speeds, 0 to 30 kt in 5-kt increments, and headings, 0° to 180°, in 15° increments. For each speed-heading combination, 25 30-minute simulations are performed in a different realization of the sea state being investigated, resulting in up to 12-1/2 hours of simulated operation at each speed-heading combination.

Component (a) of the US Navy dynamic stability criteria is intended to see that the over-all capsize risk is acceptable. Component (b) ensures that the capsize risk in all of the sea states is not excessive, by limiting it to being no worse than the worst risk for the benchmark ship. Component (c) is intended to ensure that the ship has a region of the speed-polar plot where it can operate without having to choose between having a high risk of either capsize or broach, while (d) ensures that there are no locations where the ship transitions too rapidly in speed or heading from safe operation to high risk of capsize, and finally, (e) ensures that there are no absolutely unsafe areas on the capsize speed-polar plot where the ship has a 100 percent probability of capsize.

The implementation document has four components. The first defines the code to be used for the assessment and the physical model against which the code will be validated. The second component defines the process for setting up the computational-model of a ship for the dynamic stability simulations. The third component defines the code validation process against model tests and the criteria for the validation process. Finally, the last component provides the details of the capsize risk assessment.

The motivation for the US Navy employing a relative capsize risk assessment approach was the recognition that the simulation tools were not absolutely accurate, but it was assumed that the biases of the employed computer code would be independent of the details of the hull form and the environmental conditions. There are two major weakness of the US Navy relative capsize criteria. The first is that there is no way of knowing what levels of safety or margin against capsize the benchmark ship has. The second relates to the assumption that the computational tools will have a uniform bias against all hull forms, actually it has been found that this is not true.

To supplement the relative capsize-risk assessment methodology described, the US Navy is also investigating a methodology for assessing annual and lifetime capsize risk based solely on regular wave-capsize model tests. This methodology relies on mapping the model test based capsize probabilities onto the joint probability distribution of a given wave length and period in a given sea state and modal period. This joint probability distribution is based on the work of Longuet-Higgins (1957). The results of these calculations indicate that the lifetime capsize risk for a typical naval vessel are on the order of a fraction of one percent. Intuitively, this seems to be a reasonable absolute lifetime capsize risk. However, many issues relating to the linear superposition of nonlinear experimental results via the decomposition of nonlinear seas by means of a joint probability distribution need to be resolved regarding this methodology.

4.2 Review of Techniques for Merchant Ships

The Revision of the Intact Stability Code. The intact stability requirements for cargo and passenger ships, which are covered by the Intact Stability (IS) Code (IMO, 2002) have undergone a large revision process in the last five years.

The IS Code contains design criteria and other recommendations to be verified in a range of loading conditions. The revision process at International Maritime Organization (IMO), started in 2001 (SLF44/INF.6, 2001), concerned the need to update and tune some coefficients of the Weather Criterion in view of its excessive effect in determining the limiting vertical centre of gravity for ships with large values of the beam-over-draft-ratio.

To resolve these issues, a series of experiments (Fujino, et al., 1993, Francescutto, et al., 2001) were conducted for the evaluation of the roll-back angle ϕ_1, under the action of beam waves (for details see Francescutto, 2004).

This change was considered a good opportunity to update the IS Code's foundations, putting them on a more physical basis, through the development of new performance based criteria (PBC) originally intended to replace the older prescriptive criteria.

The following tasks have been completed by IMO:

- An alternative procedure for the assessment of compliance with Weather Criterion with an experimental basis;
- The restructuring of the IS Code making part of it mandatory;
- The refining and minor modifications to IS Code;
- And the revision of MSC Circ. 707 (MSC/Circ.707, 1995).

The Alternative Way of Assessment of Weather Criterion Using an Experimental Basis. The original limits on the ship parameters used to set-up the Weather Criterion were identified as:

- Beam over draft ratio smaller than 3.5;
- Height of centre of gravity above waterline to draft ratio between -0.3 and 0.5;
- Roll natural period smaller than 20 s.

The development of an alternative assessment for ships with parameter values outside this range was later extended to all ships with the authorisation of the Administration and was given high priority.

Using studies reported in SLF47/6/18 (2004) and SLF49/5/5 (2007), an interim guideline for the alternative assessment of compliance with Weather Criterion with an experimental basis was produced and is contained in MSC.1/Circ.1200 (2006), whereas the explanatory notes are given in MSC.1/ Circ.1227, (2007). This allows the evaluation of the roll-back angle ϕ_1 by means of experiments conducted on a scale model of the ship, evaluated in regular beam waves having the steepness table corrected in the low frequency range as in Fig. 4.1. In the case of vessels with large roll periods, for example greater than 20 s, it is not possible to test models at the required size and nominal wave steepness in most model basins. This required the development of a procedure for the evaluation of the maximum roll amplitude in large amplitude waves starting from the experimental results in low amplitude waves.

This extrapolation is a delicate part of the procedure; two different methodologies were developed and can be accepted; the first substantially reproducing the procedure used in the original development of Weather Criterion, while the second is based on the parameter identification technique. At the same time it is also possible to evaluate the wind parameters (constant wind and gust levers) through combined experiments.

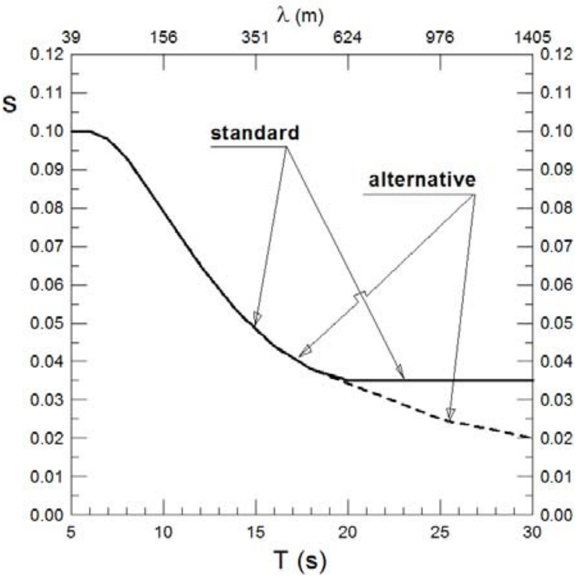

Figure 4.1 Wave steepness as a Function of Roll Natural Period as in Standard Weather Criterion and as Adopted in the Alternative Assessment with an Experimental Basis

For the combined tests, the above-water topsides are tested in a wind tunnel to measure the resultant wind force and the height of its point of application. Once this is known, the under-water hull is tested in a towing tank (drift tests) investigating the drift speed required to give a hydrodynamic reaction equal to wind force and identifying the depth of its point of application. Simplified tests are possible to determine the dependence on the transverse inclination and the assumption of half draft (present value) for the point of application selected for the hydrodynamic reaction.

The interim guidelines allow any combination of partial procedures for wind/ rolling. The results of the worked example reported in the Explanatory Notes MSC.1/Circ. 1227, (2007) seem to indicate that the limiting metacentric height has a non-negligible spreading. This is principally connected with the different results in terms of the wind lever, due to the fact that the drift test analysis gives a very high position of the centre of hydrodynamic reaction (around waterline and eventually above waterline). These results are awaiting confirmation (Ishida, et al,, 2006, Umeda et al 2006c).

Restructuring IS Code Making Some Parts Mandatory. Although presently an IMO recommendation, several parts of the IS Code are mandatory in many instances. However, their particular status allowed some alternatives presently included in the rules adopted by several Administrations. At MSC78, on the basis of a formal safety assessment study (MSC78/24/1, 2003), it was decided to restructure the code into three parts:

- Part A, containing "design criteria applicable to all types of ships" to become mandatory;
- Part B, containing recommendations for certain types of ships;
- Part C containing symbols and terminology and explanatory notes.

This task was accomplished at SLF50 in 2007 with the proposal to make part A mandatory both under SOLAS and ICLL to accelerate its entering into force.

IS Code Present Situation**.** There were other pending issues connected with the fact that the mandatory IS Code made the adoption of some alternatives currently used by Administrations not possible. The most important is connected with the required minimum value for the angle of maximum righting lever. During the discussion made at SLF50, the application of the Offshore Supply Vessels rule, allowing the reduced angle of maximum righting lever down to 15 deg, with an increase of dynamic stability (area under GZ curve) up to the maximum, was considered a viable alternative. In the course of the discussion, the problem of the equivalent level of safety was raised.

The Equivalent Level of Safety. The safety level guaranteed to ships complying with the stability criteria is generally unknown. In addition, it is clear that it is unequally distributed among different ship typologies and even inside a given ship typology, it appears to be strongly dependent on ship size. A study conducted by Umeda and Yoshinari, (2003) on the capsizing probability in beam waves of a sample of ships marginally complying with the provisions of Intact Stability Code revealed that the capsizing probability is spread in a wide interval covering many orders of magnitude. Only the development of performance-based criteria can allow a resolution of this problem.

Operational Guidelines to Avoid Dangerous Phenomena in Waves. Together with the intact stability criteria, IMO has developed operational guidance for avoiding dangerous phenomena in following and quartering waves (MSC/Circ. 707, 1995).

A new MSC Circular (MSC.1/Circ.1228, 2007) ship-independent and of qualitative nature was developed with the following changes:

- Simplification, to avoid excessive and partly unjustified warnings to the master;
- The inclusion of the consideration of parametric rolling in head waves.

The formulation of ship-specific guidance was left for future developments.

Future Developments: Performance-Based Criteria (PBC). At SLF50 the International Intact Stability Code was concluded by the Sub-Committee and successively approved by MSC as the 2008 IS Code. The need for the development of new criteria, based on more realistic physical approaches was stressed. Following important submissions by several delegations and in particular by Japan, the Netherlands and the USA (SLF50/4/4, 2007) and relevant comments by Italy (SLF50/4/12, 2007), an updated plan of action was made. This does not merely constitute a return to the original scope of the revision of the Intact Stability Code, since in the meantime the levels of knowledge and consciousness of the possibilities and limits of simulation procedures have greatly improved. This is also due to the second "cooperative benchmark experiment" launched by 24th ITTC calling for comparison of predicted basic quantities with high quality experimental results. This action was motivated by the substantial failure in the capability of simulation codes to quantitatively simulate the global extreme behaviour of ships in rough weather shown during previous benchmarks. Following this outcome, ITTC could proceed in the development/ revision of the procedures for testing and simulation, which are expected to play a major role in future development of PBCs.

The following distinctions were made at SLF50 (SLF50/4/4, 2007; SLF50/4/12, 2007) regarding the stability problems:

In relation to the consequences:
- Partial stability failure
- Total stability failure

In relation to the modes:
- Restoring arm variations problems, like parametric rolling and pure loss of stability
- Stability under dead ship conditions
- Manoeuvring-related problems in waves like broaching

In relation to the implementation:
- Probabilistic versus deterministic PBC
- Probabilistic versus deterministic parametric criteria

In relation to the needs:
- Guidelines for the development, use, and benchmarking of direct simulation tools;
- Guidelines for alternative model testing, in a way similar to that already followed in the case of Weather Criterion (MSC.1/ Circ.1200 and MSC.1/Circ.1227);
- Simplified physically sound semi-analytical models addressing, separately, particu-

lar phenomena.

The Updated Plan of Action. At SLF50 a rational updated plan of action was decided:

- Develop vulnerability criteria to identify the possible susceptibility of a ship to partial (excessive roll angles/accelerations) or total (capsizing) stability failures for each mode.
- Develop procedures for direct assessment of:
  1 Stability failures under dead ship conditions;
  2 Stability failures in following seas associated with matters related to stability variation in waves, in particular reduced righting levers of a ship situated on a wave crest;
  3 Stability failures caused by parametric resonance, including consideration of matters related to large accelerations and loads on cargo and stability variation in waves; and
  4 Stability failures caused by broaching including consideration of matters related to manoeuvrability and course keeping ability as they affect stability;
- Develop:
  1 Standard requirements for on-board guidance;
  2 Criteria for certain types of ships; and
  3 Implementation plan for incorporating a new generation intact stability criteria into the IS Code as well as parametric (simplified) criteria.

The idea of vulnerability criteria is of paramount importance in the frame of developing criteria to improve ship safety, or making safety improvement more "cost-effective" against modes of failure not covered by present criteria. It could avoid the need for indiscriminate generalized application of heavy computational or experimental procedures.

Once developed, the new generation of stability criteria could indeed be applied to certain ships that due to their typology and/or size, could be more susceptible to hazards not, or insufficiently, covered by the existing criteria, as assessed by way of a "vulnerability criteria."

Progress in the Development of Numerical Methods. Reviewing the results of the comparative studies conducted during previous two terms by the ITTC Specialist Committee on Ship Stability in Waves, it appears that the progress in the development of simulation codes obtaining the physical model characteristics from other sources (captive experiments), progressed faster than that of the fully hydrodynamic simulation codes, where all or most of the physical model characteristics are calculated by the code itself.

As far as the beam sea case is concerned, the introduction of a capsize index and the evaluation of the probability of capsizing under the action of stochastic beam wind and waves is presented (Bulian and Francescutto, 2006a; SLF49/5/5, 2006; Paroka and Umeda, 2006). The approach constitutes a stochastic generalization of present Weather Criterion with improved physical basis.

Concerning the longitudinal/quartering waves case, an attempt to validate numerical simulation of parametric rolling is presented in SLF/49/5/7 (2006). However, further validation of numerical modelling are required to realize direct assessment as an alternative means to the prescriptive criteria in the Intact Stability Code.

In SLF49/5/2 (2006) and SLF49/INF.3 (2006) a probabilistic intact stability criterion for parametric rolling and pure loss of stability phenomena is presented. It is based on the definition of a Capsizing Index by a procedure based on the fact that the significant wave height should allow that the residual area under the still water righting lever curve from the maximum angle to the point of vanishing stability during one simulation exceeds three times the standard deviation of that area obtained from several simulations. In SLF50/INF.2 (2007) an improved approach is presented.

Considering parametric rolling in general, it seems that the predictions of a threshold and amplitude above threshold may be of acceptable accuracy when regular waves are considered (Bulian and Francescutto, 2006b; Hashimoto et al., 2008). However, further research is needed as far as the irregular wave case is concerned.

Analytical formulae for the prediction of asymmetric surging and surf-riding in pure regular following seas, which often forerun broaching, were presented in Spyrou (2006). A methodology for the direct assessment of surf-riding in regular stern quartering waves was presented in Umeda, et al. (2006a). The document suggests that numerical predictions without captive model test data for each subject ship are potentially conservative.

Progress in the Development of Experimental Methods. The development of experimental assessment procedures relies on having reliable procedures for the simulation of large amplitude motions and capsizing; or at least for the evaluation of relevant quantities connected to "conventional" assessment rules. These procedures should be standardized following the guidelines indicated by ITTC.

A notable example of progress in this direction is the development of the experimental procedure for the alternative assessment of Weather Criterion. However, roll damping is still a current problem, both in prediction and in model/full-scale transfer.

Progress in the Development of Probabilistic Methods. For quantifying the probability of broaching in irregular waves Umeda et al (2007) proposed a methodology by integrating a joint probability density of local wave height and wave period within the deterministic danger threshold and validated it successfully with Monte Carlo simulations in the time domain.

During the EU project SAFEDOR a novel methodology for probabilistic assessment of various types of ship instability (in the "short-" as well as in the "long-term") has been developed, exploiting the groupiness characteristic of high waves (Themelis and Spyrou, 2007). The setting of warning and failure levels has been proposed. The methodology caters for the probabilistic part of a risk-based assessment.

The application of first- and partly second-order reliability methods (FORM and SORM) to estimate extreme ship motions and capsizing was considered by Jensen (2007), Kogiso and Murotsu (2008) and Spanos, et al. (2008).

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 General Technical Conclusions

Intact Stability. A state-of-the-art review has been carried out concerning experimental techniques to model extreme motions, broaching and capsizing of intact ships in waves, including parametric rolling.

The Procedure 7.5-02-07-04.1 "Model Tests on Intact Stability" has been updated and extended to cover head-sea parametric rolling. Experimental data for future benchmark testing study of time domain codes were identified.

Damage Stability. State-of-the-art reviews have been carried out concerning numerical and experimental techniques to predict extreme motions and capsizing of damaged ships in waves with particular focus on the prediction of time-to-flood calculations.

Responding to the request from the IMO, prediction capabilities of numerical codes for time-to-flood have been investigated. First a comparative study on a flooded barge was executed and distinct differences between prediction models and experimental results with respect to flooding rates are found. Second, complex geometry data of a large passenger ship were provided and the relevant numerical runs were executed for evaluating time-to-flood predictions.

Supported by the EU project SAFEDOR, a benchmark study on the prediction of extreme motions and capsizing of damaged RoPax ships in waves has been conducted. The numerical estimations of the survival wave height were found to be sensitive with respect to the ship loading condition and the periods of the incident waves, while less sensitive with respect to the assumptions for the discharge coefficients. No conclusions could be derived for the effect of the viscous roll damping. Two of the benchmarked methods did show satisfactory prediction capability, but overall performance calls for further improvements of employed methods and codes.

Stability Safety Assessment. A state-of-the- art review has been carried out concerning intact stability safety assessment methods. Regarding naval ships, one navy has already implemented performance-based intact stability criteria. For merchant ships, the IMO implemented a procedure for the alternative assessment of the weather criterion on an experimental basis and prepared a plan of action for the development of performance-based criteria.

5.2 Recommendation to the Conference

Adopt the revised Procedure 7.5-02-07-04.1 "Model Tests on Intact Stability".

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6.2 Nomenclature

CFD	Computational Fluid Dynamics
DOF	Degrees of Freedom
ICLL	International Convention on Load Lines
IMO	International Maritime Organization
ISSW	International Ship Stability Workshop
MSC	Maritime Safety Committee
OC	Osaka Colloquium
OMAE	International Conference on Offshore Mechanics and Arctic Engineering
PBC	Performance Based Criteria
RINA	Royal Institution of Naval Architects
SiW	Specialist Committee on Stability in Waves
SLF	Sub-Committee on Stability and Load Lines and on Fishing Vessels Safety
SNAME	Society of Naval Architects and Marine Engineers
SOLAS	International Convention for the Safety of Life at Sea
SPH	Smoothed Particle Hydrodynamics
STAB	International Conference on Stability of Ships and Ocean Vehicles
VOF	Volume of Fluid