The Specialist Committee on Stability in Waves

Final Report and Recommendations to the 26th ITTC

1. INTRODUCTION

1.1 Membership and meetings

Membership. The Committee appointed by the 26th ITTC consisted of the following members:

- Professor M. Renilson (Chairman) AMC, Australia
- Mr. A. Peters (Secretary) QinetiQ, Haslar, UK
- Professor W. Y. Duan Harbin Engineering University, China
- Dr. P. Gualeni University of Genoa, Italy
- Assoc Professor. T. Katayama, Osaka Prefecture University, Japan
- Dr G. J. Lee MOERI, Korea
- Professor J. Falzarano Texas A&M University, USA
- Dr. A. M Reed Carderock Division, Naval Surface Warfare Centre, USA
- Dr. F. van Walree Maritime Research Institute Netherlands

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: Maritime Research Institute Netherlands (MARIN); Osaka Prefecture University; NSWC; HSVA; Science Applications International Corporation and Seoul National University.

Meetings. Four Committee meetings were held as follows:

- College Station, USA - February 2009
- Genoa, Italy - November 2009
- Wageningen, NL - June 2010
- Gosport, UK - February 2011

1.2 Tasks from the 25th ITTC

- Update the state-of-the-art for predicting the stability of ships in waves, emphasizing developments since the 2008 ITTC Conference. The committee report should include sections on:
  - The potential impact of new technological developments on existing ITTC procedures,
  - New experimental and extrapolation methods and the practical applications of computational methods to stability predictions and scaling,
  - The need for R&D for improving methods of model experiments, numerical modelling and full-scale measurements,
  - The development of vulnerability criteria and assessment methods for intact ships considered by the IMO and navies,
  - Validation issues.
- Write a section of the committee report describing various cases and methods for numerical prediction of capsizing. This section shall serve as a framework for future development of procedures for numerical predictions of capsizing of ships.
- Develop procedures for the prediction of capsizing of a damaged ship in irregular beam waves:
  - Refinement of existing ITTC experimental procedure; and
  - Development of numerical procedure.
- Carry out a benchmark test study of

numerical codes for predicting onset and the magnitude of parametric roll in head seas by using experimental data selected by the 25th Committee and identify crucial elements for accurate predictions.
- Review numerical techniques for assessing the survival time of damaged passenger ships and identify experimental data for their validation.
- Develop a procedure for numerical estimation of roll damping moment of intact and damaged ships.
- Cooperate with the IMO SLF subcommittee correspondence group on the development of new generation intact stability criteria allowing the use of data and knowledge collected by the ITTC.

2. STATE OF THE ART REVIEW

2.1 Review

During the past several years several major efforts have been on-going in ship stability research. The most well known references in this area are the International Stability Conference and Workshops. The last Stability Conference occurred in St. Petersburg, Russia in 2009 (Degtyarev, 2009) and the last two stability workshops occurred in Korea in 2008 (ISSW, 2008) and another at MARIN in the Netherlands in 2010 (Walree, 2010). In addition during the last several years the Society of Naval Architects has been sponsoring a Dynamic Stability Task Group (DSTG) (Bassler, 2009). This group has met a number of times over the last several years and has been in the process of developing a report which will address the most relevant aspects of ship and floating offshore platform stability. In addition, the International Maritime Organization (IMO) has undertaken a revision of the intact stability code. The prescriptive part of this revision is now complete and development of a performance based criteria is underway. (see *e.g.*, Francescutto and Umeda, 2010).

Research in ship stability has evolved into two distinct areas: analytical studies; and computer simulation studies with many investigations involving both areas. The research has also diverged into naval vessels and merchant ships which includes fishing vessels. With regards to naval vessels the Cooperative Research Navies Group (CRN) coordinated by MARIN has been the focal point. The IMO’s Stability and Load Lines and Fishing Vessels (SLF) subcommittee has been the focal point of international cooperative research efforts relating to merchant ships and fishing vessels. Furthermore, there are several national research programs and independent research groups which are active around the globe.

The SNAME Dynamic Stability Task Group (DSTG) report (Bassler, 2009) divided ship stability into the following nine aspects 1) Fundamental Principles and Definitions; 2) Dynamic Behaviour of Hull Forms; 3) Floating Offshore Platforms; 4) Modelling the Physics of Dynamic Stability; 5) Numerical Modelling of Dynamic Stability; 6) Probabilistic and Risk-Based Assessment Methods; 7) International Regulations and IMO Initiatives; 8) Naval Regulations and Standards; 9) Operator Guidance and Human Factors. Sub-working groups were formed in each area and an extensive hundred plus page report was produced. In all of these topic areas significant progress has been made and continues to be made in documenting the existing literature and highlighting progress which has been made and shortcomings which need to be addressed.

One of the more notable chapters in the SNAME DSTG report is “Modelling the Physics of Dynamic Stability,” written by a sub-group chaired by Prof. Spyrou at National Technical University of Athens (NTUA). This area includes both physical modelling and analytical studies. Numerous references in both areas have been included. In addition to this extensive report there have also been several oral presentations given at the SNAME Technical and Research (T&R) sessions at the SNAME Annual Meeting over the past several years (SNAME, 2009 and 2010). Overall this report represents an extensive effort by a large number of experts in the field. Although not the final word on this topic, it represents a significant contribution to the field and the final report will be a valuable reference of the work in ship stability.

The 2008 International Ship Stability Workshop in Korea (ISSW, 2008) had 24 papers in nine sessions in the following areas: Numerical Prediction of Intact Stability (3); Parametric Roll Prediction (3); Ship Behaviour in Following/Quartering Waves (3); Probabilistic Assessment of Intact Stability (3); Numerical Prediction of Flooding and Damage Stability (3); Design System Considering Damage Condition (3); Operational Stability Safety (1); Probabilistic Assessment of Damage Stability (3); and Ship Accident Investigation (2) This broad range of topics sessions and the papers in each represent a significant contribution to the ship stability literature. The work on numerical and analytic investigations of intact stability dominates ship stability research, although parametric rolling is also deemed important.

The 2009 Ship Stability Conference in St. Petersburg Russia (Degtyarev, 2009) consisted of three keynote lectures in the following topic areas: historical; a naval perspective; and an industry perspective. In addition, there were 18 sessions dealing with a wide range of topics, including: 1) Offshore Structures and Sea-Based Aviation; 2) Rules and Criteria 1 — IMO New Generation Criteria; 3) Accidents Investigation; 4) Rules and Criteria 2 – IMO Development; 5) Damage Stability 1, 2 & 3, 5) Intact Stability in Following and Quartering Seas; 7) Intact Stability (Roll Damping and Deck in Water); 8) Non-linear Dynamics 9) Safety Assessment & Environmental Aspects; 10) Parametric Rolling 1 & 2; 11) Operational Aspects; 12) Computational Aspects of Stability Evaluation; 13) Probabilistic Methods in Dynamics of Ships; 14) Workshop on Benchmarking of Numerical Tools; 15) Design for Safety and Design for Safety Integrated Toolbox 1&2. The work on numerical and analytic investigation of intact stability continues to dominate the ship stability research although probabilistic methods are becoming increasingly important. The large number of sessions in a wide range of topic areas and the significant numbers of papers presented represent an important contribution to the ship stability literature. One of the more notable keynotes papers of this conference was the paper by Reed (2009) which discussed the "US Navy's perspective on ship stability research." This paper is important because it summarises the various efforts the US Navy has undertaken over the past several years to investigate various aspects of vessel dynamic stability as it relates to naval hull forms. The most significant topic discussed in this paper was the validation, verification and accreditation of numerical codes. These aspects are particularly important for highly nonlinear large amplitude rolling response leading to capsizing. In the paper several unique methods to compare numerical and experimental results are presented.

The 2010 Ship Stability Workshop at MARIN (Walree, 2010) had 11 sessions on the following topics: Goal Based Stability Standards (Intact); Goal Based Stability Standards (Damage); Special Problems; Risk Based Analysis Methods; Naval Ship Stability; Safety of Damaged Vessels; Developments in Intact and Damage Stability Modelling; Operational Safety; Roll Damping; Flooding of Damaged Ships and Parametric Roll. The wide range of topics of the various sessions and the papers in each represented a significant contribution to the ship stability literature

One of the more notable papers from this meeting included one by Francescutto and Umeda, (2010), describing the "Status of the Next Generation of Intact Stability Criteria Development". This paper is significant because it addresses efforts at the IMO to develop the next generation of ship stability criteria which not only includes an updated prescriptive criteria but also performance based criteria for advanced hull forms. This paper gave an update on both the prescriptive and performance based aspects of the new IMO intact ship stability code. The prescriptive part of the code is complete but the performance based aspect is still under development and will be so for several years. The performance based aspects will bring together the broad range of research that has been undertaken in this field over the last few years and is therefore still being defined.

This field of research has continued to mature over the last several years. Several new sub-areas have also developed over the intervening period which includes the study of the unique features of floating offshore platforms versus displacement hulls and the probabilistic approaches. These, and other areas such as the study of nonlinear dynamics and bifurcation analysis, will continue to evolve and reach maturity where practical analysis of ship stability can be undertaken using these advanced mathematical methods.

2.2 The potential impact of new technological developments on existing ITTC procedures

The major technological developments over the past several years have involved improvements in computational predictions from both a hydrodynamic and a probabilistic view point. Improvements in these aspects have also impacted model testing procedures creating new demands with respect to both accuracy and capability of model testing facilities. In order to focus on what are the most important parameters affecting stability several researchers have investigated the systems sensitivity to various parameters. The strongly nonlinear behaviour of large amplitude ship rolling motion requires an understanding of nonlinear dynamical systems analysis techniques.

In Vidic-Perunovic, *et al.,* (2011), the influence of the GZ calculation method on parametric roll prediction is described. Das, *et al.,* (2010), describes mathematical modelling of sway, roll and yaw motions in order to determine the sensitivity of coupling on numerical simulation results. Long, *et al., (*2010), estimates the survival probability of a ship in beam seas using the safe basin concept. Neves, *et al.,* (2009), describes nonlinear coupling of unstable ship motions in head seas using bifurcation analysis and studying the erosion of the safe basin. Falzarano, *et al.,* (2010) uses the safe basin concept to study the combined steady state and transient response of a vessel as affected by varying amounts of damping and periodic and random wave excitation. Ahmed, *et al.,* (2008), describes an investigation into parametric roll resonance in regular waves using a partly nonlinear numerical model. Vidic-Perunovic and Juncher, (2009), describe the effect of instantaneous volume changes and speed variations on parametric rolling. The development of these and other advanced analysis techniques will most certainly continue over the next several years. With the continued development of advanced analysis techniques, the use of physical model testing in order to validate mathematical models for large amplitude nonlinear motions will also continue to grow. Moreover, the additional demands on the experiments with regards to the quality of the description of the phenomena will also continue.

2.3 New experimental and extrapolation methods and the practical applications of computational methods to stability predictions and scaling

There are numerous aspects of experimental and extrapolation methods and the practical application of computational methods to stability prediction and scaling. One of the most important aspects is the accurate prediction of full scale roll damping. Roll damping forms a significant aspect of model testing that must be properly understood in order for accurate capsize predictions to be made. In this report an ITTC Procedure for an empirical prediction technique for roll damping is discussed (see section 7).

Over the past few years this has been studied extensively by several research groups empirically, experimentally and computationally. New methods of analysing experimental roll decay data will be needed in addition to numerical methods of predicting roll damping. These three aspects of roll damping prediction will continue to complement each other.

In Jang, *et al.,* (2010), a method is described for recovering the functional form of the nonlinear roll damping of ships from a free-roll decay experiment using an inverse formulism. Accurately determining the form of roll damping from experiments is an important aspect of predicting full scale damping from model test results. In, Falzarano, *et al.*, (2004a), a method to extrapolate full scale roll damping from model tests results is presented.

Prediction of full scale roll damping using computational fluid dynamics is a major opportunity for the ship stability community. Studies by Bassler and Reed (2009), for example, have highlighted the importance of accurately predicting the damping for large amplitude rolling motion as affected by rapid changes in hull form as the ship rolls.

2.4 The need for R&D for improving experimental methods, numerical modelling and full-scale measurements

In order to improve the likelihood of ships capsizing in extreme environmental conditions, better hydrodynamic predictions are needed.

In Minnick, *et al.,* (2010), a method is described to measure wave kinematics in a wave basin. This method and similar methods are an effort to improve wave kinematics in order to improve ship-motion predictions and validation. In order to validate numerical codes it will become increasingly important to have detailed flow field measurements of experiments.

In Bassler, *et al.,* (2010), a method to evaluate ship response in heavy seas is presented. In the proposed method, critical wave groups are defined and used to separate the complexity of the nonlinear dynamics of ship response from the complexities of a probabilistic description of the response. The modelling of realistic random waves in new ways will continue to be an important aspect of both numerical prediction and physical model testing.

Other methods which have great promise in ship stability experiments and full scale measurements are the so-called system identification methods. In Crider, *et al.,* (2008), kinematic extraction (system identification) of full scale data from a cruise ship is used to develop a physical model and simulate motions which occurred during a large amplitude rolling incident. The result of this study was a reasonable explanation of why the event occurred and this and similar techniques will continue to be used in future accident investigations. Other system identification techniques have been utilised to study complex physics in, for example, the transit draught stability studies of a large semi-submersible (Falzarano, *et al.*, 2004b). The transit draught of a semi-submersible is typically at very low freeboard with the top of the lower pontoon alternatively dry and awash. This results in significant changes in the waterplane and therefore the hydrostatic and hydrodynamic restoring forces and moments. System identification techniques have the potential to separate out linear and nonlinear effects so that they can be analysed and scaled individually. The development of these and similar system identification techniques for large amplitude ship-motion studies will most certainly continue. These techniques can be particularly useful in analysing model test results and specifically in comparing to component wise numerical predictions.

2.5 The development of vulnerability criteria and assessment methods for intact ships considered by the IMO and navies

Vulnerability criteria and assessment methodologies are a recently identified aspect of ship stability which bridges the gap between pure prescriptive criteria and time consuming and expensive numerical simulation which requires validation by model testing. These performance based criteria most certainly use analytical results improving upon simplified prescriptive criteria but generally not high fidelity numerical simulation or model testing.

Belenky, *et al.,* (2008), describes each of the United States, Japanese and Dutch positions with regards to a performance based ship stability criteria. This was originally published as an IMO SLF paper. It gives a glimpse into the current status of part of the IMO efforts to develop performance-based criteria.

In Bulian, (2010), a probabilistic procedure to check vulnerability to pure loss of stability in long crested following waves is described. The development of complex probabilistic prediction techniques such as described in this paper will surely continue. Belenky and Bassler, (2010), describe procedures for early-stage naval ship design evaluation of dynamic stability considering the influence of the wave crest. This, and similar simplified techniques, may become part of the IMO performance based intact stability criteria. In Nielsen and Jensen, (2009), numerical simulations of the rolling of a ship in a stochastic sea are evaluated by use of the Monte Carlo Simulation and First Order Reliability Method. This paper represents a development of formal reliability assessment methods from ship structural analysis applied to ship stability and the further development of such methods will continue.

2.6 Validation issues.

The validation of a numerical tool dealing with ship motions in extreme wind and waves is really a great challenge requiring an extensive and comprehensive methodology, Grochowalski and Jankowski, (2009). It is vital that the validation is not only in the form of final motions but also in terms of hydrodynamic forces. A very comprehensive assessment of several numerical codes in terms of time histories for different force components is provided by Belknap and Telste, (2008). In Belknap *et al.,* (2010), a further analysis is performed which provides a comparison of body-exact force computations for large amplitude motions for two geometrically non linear 2D potential flow solutions and high fidelity CFD solutions. An additional set of detailed experimental data for validation is provided by Fullerton *et al*., (2008), specifically in terms of forces and moments experienced due to large roll motions.

3. NUMERICAL PREDICTION OF CAPSIZE

When a ship capsizes it is the result of the simultaneous influence of ship dynamics, environmental circumstances, operational profile and human behaviour.

Investigation of ship performance in terms of capsizing implies a definition of a comprehensive methodology where the numerical simulation of the motions is only a component. This fact may, in principle, influence the specification of the numerical tool itself. Due to the non-ergodic nature of capsizing, the question is posed of how a tool based on Newtonian physics (cause and effect based) can be used to study a phenomenon characterised by a strong lack of repetition. The statistic characterisation and probabilistic treatment of the phenomenon in relation to the environment must also be addressed.

The fact that capsizing is a rarely occurring event creates a significant challenge for verification and validation tasks. There are many sources of uncertainties from both experimental testing and the numerical model. The selection of adequate exposure time and number of test repetitions are therefore critical issues. The requirement for long simulation time or multiple repetitions requires significant attention to the computational efficiency of the numerical tool. In Section 6.4, Table 6.2 provides different possible levels of performance in relation to the selected numerical approach.

3.1 Distinguishing the modes of capsize

The analysis of the capsize prediction problem in terms of the different ways of capsizing has been examined by previous ITTC committees. Given the level of complexity of the whole problem, the development of prediction methodologies has historically focused on specific modes of capsizing, rather than addressing the problem holistically. This historical approach gave rise to several research streams, with in depth specialisation of some authors within a specific mode of stability failure. In parallel, the interest in a more comprehensive approach and a more complete prediction tool has always existed. This represents the present and future framework where all the activities should converge in order to tackle the challenge of a holistic answer to the problem. For example, a numerical methodology which is not confined to a single specific mode of stability failure has been recently presented in Belknap and Reed, (2010), where great attention is paid to both accuracy and computational efficiency.

A possible way of grouping the various capsize mode cases is derived from SLF, 2008:

- Parametric rolling
- Synchronous rolling
- Broaching-to
- Surf-riding
- Dead-ship condition
- Pure loss of stability

Other more synthetic schemes are given in Belenky, *et al.*, (2008a) and IMO, (2008). In the following, a brief review of numerical tools for parametric roll and loss of stability, broaching and surf-riding and dead ship condition in beam seas is given.

Beside the short literature review, with the aim to be effective in mentioning the main features of numerical tools able to deal with each specific mode of failure, two summarising tables are given; one for ship related issues, Table 3.1; and the other for the environmental scenario description, Table 3.2.

3.2 Numerical tools for evaluating capsize modes

Parametric roll and loss of stability are usually treated together since they both derive from the restoring variation problem whilst travelling in longitudinal seas. In recent literature where these phenomena are investigated, only parametric roll has gathered significant attention and only passing reference is made to "loss of stability." The particular interest in parametric rolling is evident in Spanos and Papanikolau, (2009a) and (2009b), where performances of fourteen numerical simulation methods are investigated. A notable difference in the capabilities of the tools is demonstrated, related primarily to the variety of the technical approaches used. On reviewing the set of results from all the numerical codes together, the ability to correctly predict the parametric roll behaviour is considered low, even though some methods performed rather well. The main critical issues are related directly to the prediction of large amplitude wave hydrodynamics and modelling complex wave profiles, like oblique wave groups.

The methods used for parametric roll prediction are generally non-linear time domain, mainly based on a potential flow approach like strip theory or a three dimensional methodology. The numerical tools range from single degree of freedom (DoF) to more complex 6-DoF models. Motions and their possible coupling, which must be taken into consideration, are intrinsically considered using parametric roll physics.

Great attention is often paid to the evaluation of the restoring terms variation due to the wave profile and the coupling with vertical motions (Ahmed, *et al.*, 2008; Spyrou, *et al.*, 2008; Umeda, *et al.*, 2008). It has been recognised that an important effect is the surge motion, which should be included in order to accurately account for ship speed variation due to incident wave longitudinal force and the possible restoring force variation (Ogawa, 2009a, Vidic-Perunovic, *et al.*, 2008).

Significant importance is also given to non-linearities in the damping term of the calculation. Numerical tools are often based on renowned formulations available in literature and in some cases on actual tuning directly derived from experimental tests (Yang *et al.*, 2008; Shigunov, *et al.*, 2009; Ribeiro and Soares, 2009, and Hong, *et al.*, 2009). Comparisons among different approaches are given in Hashimoto and Umeda, (2010), where it was concluded that the estimation methods of the roll damping significantly affect the prediction of parametric roll and further study on this topic is still required.

Most of the applications for parametric roll prediction are in regular waves and only a few applications take into consideration the irregular wave problem or are ready to address it in the near future (Chang, 2008).

In Chapter 5, the results of the recent benchmark study on parametric roll are presented.

Table 3.1 Main features for numerical implementation in terms - ship related issue

SHIP RELATED ISSUES			
MODE OF FAILURE	IMPORTANT ISSUES	DESIRABLE ISSUES	OTHER ISSUES
PARAMETRIC ROLL (in head/following sea)	Time varying in roll restoring term; Time varying Froude-Krilov forces Roll damping; Natural frequency in roll;	Variation of speed in the wave;	Variation of heading; Roll wave excitation; Water on deck;
SURF-RIDING/ BROACHING	Longitudinal forces; Wave yawing moment; Rudder yawing moment;	Roll/yaw coupling; Auto-pilot; Manoeuvring model; Roll restoring term;	Roll wave excitation; Water on deck;
DEAD SHIP CONDITION	Roll wave excitation; Roll wind excitation; Roll damping; Roll restoring moment; Roll natural period; Water on deck;	Heading; Wave drift force; Wind drift force;	Manoeuvring model;
PURE LOSS OF STABILITY	Varying in roll restoring term;	Longitudinal forces;	Roll damping; Natural frequency in roll;

Surf-riding and broaching phenomena have also been investigated and there is literature presenting evaluation tools for surf riding and broaching. The tools are often strongly dependant on non-linear dynamic system analysis with great attention to the surf-riding threshold, since, in principle it can be considered a prerequisite for a possible broaching occurrence (Wu and Spyrou, 2009; Maki, *et al.*, 2010).

An approach to evaluating this is the 4-DoF surge-sway-yaw-roll manoeuvring model (Maki and Umeda, 2009). There is still the problem of properly defining physical components in the formulations with relation to their real influence on the phenomena. An example is Sadat-Hosseini, *et al.*, (2009), where an investigation is performed of the wave induced surge force evaluated with different approaches, including experimental, Froude-Krylov prediction and CFD, but without any significant change in the instability map. In the same reference, free running CFD simulations are performed showing reasonable agreement with experiments for surf-riding, broaching and periodic motion prediction using the tool.

Another interesting demonstration of the application of CFD is presented in Carrica, *et al.* (2008) for the ONR tumblehome hull form with auto-pilot in regular and irregular seas, where the importance of the rudder and autopilot influence on broaching behaviour is demonstrated. However, in addition to the substantial computational effort required for these simulations, it is noted that significant validation activity is still required for general seakeeping and large amplitude motions of CFD applications.

The satisfactory quantitative prediction of the tendency of a ship to surf-ride and broach in following/quartering seas should still be characterised as a research goal (Spyrou, 2009). In the same paper, the capability of a non-linear, time-domain, 3-D potential flow method (LAMP-3) to deal with surf-riding and broaching was performed with consistent results. A less computationally intensive version of the potential flow code was then developed to deal with the continuation method with the future aim to characterise surf-riding and broaching in irregular waves.

In Umeda and Yamamura, (2010), a numerical simulation code with a surge-sway-yaw-roll model in the time domain and a PD autopilot is discussed. The tool is applied in order to define the deterministic dangerous zone of stability failure due to broaching in various regular waves, with a wide range of wave steepness's and lengths. The paper also calculates the failure probability due to broaching in irregular waves using the deterministic dangerous zone together with Longuet-Higgins' probabilistic wave theory.

<u>A classic beam seas (dead ship)</u> scenario is treated in the literature using a "split time" approach Belenky *et al*., (2009). Conventional numerical simulation of large amplitude ship motions in irregular waves is used for the "non-rare" time scale, and statistical methods are used to treat the "rare" part of the problem. This approach allows the study of ship capsizing without having to directly simulate it. An application in beam waves without wind is given in Belenky, *et al., (*2008b). The large number of numerical simulations is performed using a time-domain three dimensional non-linear potential flow method (LAMP). A verification of self consistency is carried out using a differential equation in roll with a piecewise linear representation of the non-linear restoring term, for which a more detailed description is given in Belenky, *et al.,* (2009).

In general, a significant increase has been observed in the application of CFD codes in an attempt to capture viscous flow effects. This is critical for the realistic evaluation of the damping moments which are recognised as very influential on stability behaviour, especially for roll in beam seas and parametric rolling (Kim, *et al.,* 2008; Yu and Kinnas, 2008).

A method for large amplitude roll damping evaluation is presented in Bassler, *et al.,* (2010a), based on modelling the extreme physical changes that occur. Examples of when these physical changes occur are bilge keel emergence or deck-edge submergence. To provide useful insight into the physical phenomena, experimental measurements are carried out with special attention to bilge keel emergence (*e.g*., Bassler, *et al.,* 2010b).

In Katayama, *et al*., (2010), a specific investigation into damping components due to bilge keels is addressed with the proposal of empirical formulae. An efficient computational approach to predict forces on bilge keels, based on non-linear unsteady low aspect ratio lifting surface theory, has been developed and (initially) validated (Greeley and Petersen, 2010). Another approach for possible application in numerical tools is presented in Pawłowski, (2010a). The method is based on the approximation of free roll, using the instantaneous values of the logarithmic decrement of damping.

Table 3.2 Main features for numerical implementation - environment related issues

ENVIRONMENT RELATED ISSUES			
MODE OF FAILURE	IMPORTANT ISSUES	DESIRABLE ISSUES	OTHER ISSUES
PARAMETRIC ROLL (in head and following sea)	Wave length; Wave steepness; Encounter frequency; Wave groupiness; Wave spreading;	Non-linearities in the ship-wave interface;	
SURF-RIDING/BROACHING	Wave length; Wave steepness;	Non-linearities in the ship-wave interface;	Wave spreading;
DEAD SHIP CONDITION	Modal period and groupiness of waves; Wave steepness; Non-linearities in wave breaking; Wind and gustiness effects;	Wave spreading;	
PURE LOSS OF STABILITY	Wave length; Wave steepness; Encounter frequency;	Non-linearities in the ship-wave interface;	

Environmental related issues. The influence of high, steep and possibly breaking waves or groups of large waves is presented in Bassler, *et al.*, (2009b), where an experimental technique to generate extreme wave groups in irregular waves is proposed. However, the difficulty involved in the validation of a numerical tool dealing with ship dynamics is noted. This is due to the necessary accuracy required in the comparison between the numerical and experimental realisations.

A method using wave groups, which are critical to ship response in heavy seas, is presented in Bassler, *et al.*, (2009a). The principal idea is to enable separation of nonlinear dynamics of ship response from the probabilistic description for the response. This separation may be achieved by considering irregular waves as a series of wave groups, which are capable of producing the desired test conditions, interlaced with intervals of relatively benign waves. The non-linearity of the response therefore only becomes important during the duration of the key wave groups, while the initial interval of benign waves are only required to provide the initial conditions prior to encountering the wave group.

The inability of potential flow to model extreme free surface problems, including breaking waves, requires an approach that includes viscous effects which are able to treat the two phase air-water problem, capturing the interface between them, (Westphalen, *et al.*, 2008). Two commercial RANS codes are applied to this problem in the paper with promising results.

A new approach for obtaining irregular wave trains is presented based on Stokes wave interaction up to the third order. Kinematics of breaking waves is not covered by concurrent analytical wave theories. To overcome this problem, the instantaneous wave profile (last converging approximation solution before breaking) obtained with a potential flow theory is assumed to initialise the flow domain of a RANS code that has the ability to continue the calculation up to the breaking point. The simulation behaviour is in good agreement with the observations from the physical tank experiments (Clauss, *et al.*, 2008).

Numerical simulations for breaking waves have been investigated focusing on URANS formulation, the LES/LWS formulations and the corresponding closure modelling. A possible breaking criterion for use in potential flow simulation is presented in Hendrickson and Yue, (2008).

In the context of the environmental influence on capsize, the predominant focus is still on the wave. However, the effect of the wind has been shown to be of great importance (Ogawa, 2009b; Mousaviraad, *et al.*, 2008; Shen, *et al.*, 2008). The coupled wind-wave effect is in fact pursued as the more correct way to tackle the environmental context while developing a numerical tool dealing with large amplitude motions. This is going to be one of the future challenges in parallel with the ship hydrodynamic behaviour prediction.

4. PROCEDURE FOR PREDICTING THE CAPSIZING OF A DAMAGED SHIP IN IRREGULAR BEAM SEAS

4.1 Refinement of model test procedure

The Procedure 7.5-02-07-04.2 "Model Tests on Damage Stability in Waves" has been developed based on the experiences of experts and published literature. Advances in experimental techniques and recent results of experiments at various model scales and in scaled air pressure lead to the following refinement of the current procedure:

- An uncertainty assessment of the experimental results is considered to be vital for the proper use of the experimental data. Since the flooding process can have a chaotic character, small differences, for instance, in damage opening size and location, can have a large effect on the end result. Also, for validation purposes uncertainty data is vital.
- Normally, model tests are performed under atmospheric pressure. For models with compartments that are not fully vented, there may be a significant effect on the flooding due to the air pressure at model scale. This should be further investigated.
- A related issue is the use of ventilation openings at model scale to make sure that the compartments are fully vented, *i.e.* to prohibit air trapping. Justification of such measures seems to be lacking, in particular for watertight compartments. This should also be further investigated.

4.2 Numerical test procedure

This procedure is intended for carrying out numerical simulations on a damaged ship in beam seas to determine the occurrence of capsizing. The procedure addresses:

- Demands on numerical methods to deal with the non-linearities involved and the flooding process.
- Demands with respect to the discretisation of the ship geometry in the numerical method.
- Wind and wave conditions.
- Simulation preparation, initial conditions, duration of simulations and simulation data.
- Determination of probability of capsize.
- Documentation of simulations.

Due to lack of experience and proper data, this numerical test procedure does not address a number of items which are deemed to be of importance for the capsize probability of damaged ships drifting in beam seas. These items include:

- The amount of detail required for modelling the internal geometry of the ship. This is especially true for ships with a large number of small cabins, for instance cruise ships. This item also includes issues associated with non-watertight bulkheads, where there is some flow, but it is significantly restricted.
- How to deal with the inertia due to the flood-water mass. When the opening is small, the flood-water mass can be assumed to move with the ship, hence its mass and added inertia should be added to that of the ship. In the case of large openings, flood water will flow in and out of the ship as the ship moves. In that case the flood water mass will add only partially to the ship inertia.
- The lack of data on leak and collapse pressures for water tight doors and bulkheads, which may be essential for the

survivability of ships.

- The effects of forward speed on initial flooding directly after damage or openings occur.

It is recommended that these items be addressed by the next ITTC Stability in Waves Committee.

5 PARAMERIC ROLL BENCH MARKING STUDY

5.1 Background

The Stability in Waves Committee was assigned the task of conducting a benchmark of numerical simulation methods for the prediction of the parametric rolling of ships in head seas. Participants in the study were to be qualified organisations from both inside and outside the ITTC.

This study aimed to evaluate numerical simulation methods currently employed for the prediction of the parametric rolling of ships in waves and to assess the current level of accuracy of the relevant numerical prediction methods and computer codes by comparison with model experimental data.

This study was designed to capture the capabilities of the benchmarked numerical methods for ship responses in realistic random sea conditions. The performance of the methods for the selected loading and wave conditions was assessed in comparison to relevant experimental data as well as with respect to the relative performance of each participating method.

The study comprised the simulation of the behaviour of a containership in three wave steepness cases in longitudinal head waves at one ship loading condition. For the selected conditions, the excitation of roll motion is expected as a result of parametric resonance. The simulated motions in 6-DoF were to be recorded and submitted for review to the study coordinator.

5.2 The ship model

The vessel chosen for the study was a model of a C11 class container ship, MARIN Model 8004-2 (Levadou and van‘t Veer, 2006; Paulling, 2007, MARIN, 2005, 2009). MARIN provided the hull definition for the study, which was supplied to the benchmark participants in three formats. The fully appended hull was tested, with propeller and rudder. The ship was free to move in 6-DoF. Thus, the ability of the simulation to maintain course and heading was an integral part of the benchmark.

The model is a 55th-scale model of a notional 262m container ship. Its full-scale principal dimensions and mass properties are provided in Table 5.1. Figure 5.1 provides the plan view, profile and body plan of the vessel. Figure 5.2 provides a photograph of the overall model, including the modelling of containers on deck.

The container ship is fitted with a single horn-type rudder and a single 5-bladed propeller. Figure 5.3 provides a photograph of the stern configuration, including propeller and rudder.

Table 5.1 Main particulars and mass properties of the vessel

Designation	Symbol	Magnitude
Main particulars		
Length between perpendiculars	L_{PP}	262.0m
Breadth	B	40.0m
Depth	D	24.45m
Draught moulded on FP	T_F	11.719m
Draught moulded on AP	T_A	12.856m
Displacement weight	Δ	76020t
Centre of gravity fwd of station 0	LCG	122.78m
Centre of gravity above keel	KG	18.40m
Transverse metacentric height	GM_T	2.075m
Transverse radius of gyration in air	k_{XX}	16.73m
Longitudinal radius of gyration in air	K_{YY}	62.55m
Natural roll period	T_ϕ	25.2s

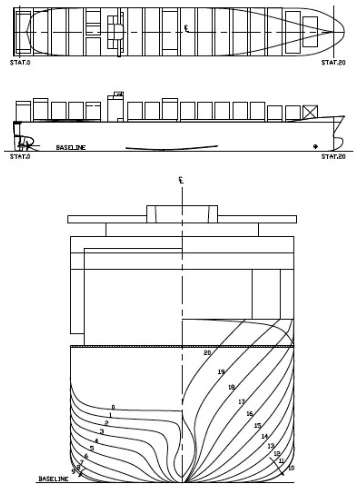


Figure 5.1 General Arrangement and small scale body plan for MARIN model 8004-2 (MARIN, 2009).

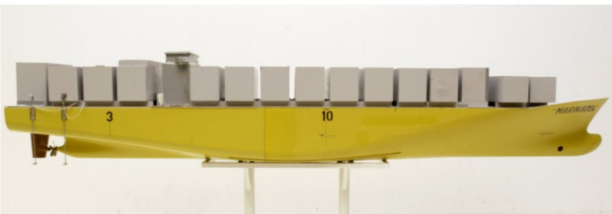


Figure 5.2 Side view of MARIN model 8004-2 (MARIN, 2009).

Figure 5.3 Stern-Quarter view of MARIN model 8004-2 showing rudder and propeller (MARIN, 2009).

The actual propeller used on the model was a Wageningen B-Series 5.59 propeller. Its characteristics were provided to the participants both graphically and as a table.

The ship model was fitted with bilge keels that were aligned with the streamlines on the hull. Participants were provided with a table giving the gross parameters of the bilge keels, and a drawing of the bilge keels with an embedded table that provided their placement along the girth of the hull. The bilge keels can be seen in Figures 5.1 and 5.2.

The model was fitted with a simple PID autopilot that operated based on the model's heading, yaw rate, and lateral position. Although it is not traditional to most autopilots, the sway component was used to keep the model located in the middle of the basin during the runs.

5.3 Parametric roll benchmark cases

Three runs at 5kts in random head seas of differing significant wave height for the same wave modal period comprised the parametric roll benchmark experiments. The conditions for the three parametric roll runs that are being benchmarked are provided in Table 5.2.

Wave spectra with phase information that could be used to reconstruct the wave train time histories at the model CoG position were provided, as were time histories of the actual encountered heights for each run. These wave heights were measured nominally 349m (full scale) forward of station 10 on the centreline (nominally in the sense that the distance is correct on the average, because the surge motion of the model is not taken into account).

Table 5.2 Tests in irregular head seas

MARIN test no.	Wave conditions	
	Significant wave height [m]	Peak period [s]
307001	4.125	14.4
307002	3.5	14.4
307004	5.25	14.4

For the parametric roll runs, the model was positioned approximately 8.25km full-scale

(150 m model scale) from the wave maker and the wave maker was started. When the waves reached the model, the model and carriage were brought up to speed, and the model proceeded along the tank under the control of the autopilot; tracked by the carriage. Data collection commenced once the model had reached a mean steady speed.

During all tests, the model was self-propelled at a propeller RPM that was the equivalent of 5kts full scale in calm water. (The resistance curve, required for the simulations of these cases, was provided to the participants). Connections between model and carriage consisted only of free-hanging wires for relay of measurement signals and to supply power. These cables did not restrict the motions of the model significantly.

MARIN's Basic Measurement System was used for the data acquisition, with a sample rate of 100Hz.

Figure 5.4 to Figure 5.9 show the encountered wave and roll time histories for Runs 307001, 307002 and 307004. As can be seen, the wave elevation time histories increase moderately from Run 307002 to Run 307001 to Run 307004. The roll for Run 307002 is negligible; while Runs 307001 and 307004 both show the occurrence of significant parametric roll.

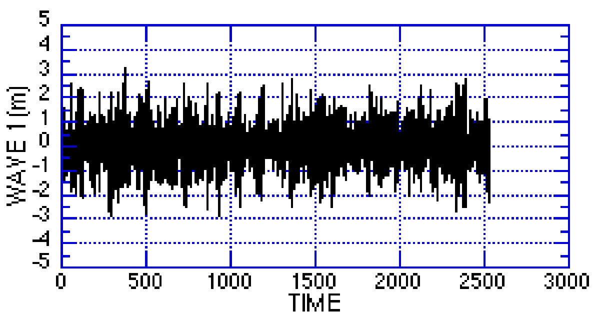


Figure 5.4 Wave time history for MARIN model 8004-2, Run 307001

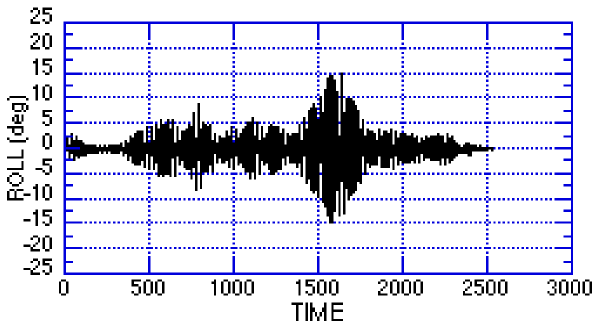


Figure 5.5 Roll time history record for MARIN model 8004-2, Run 307001

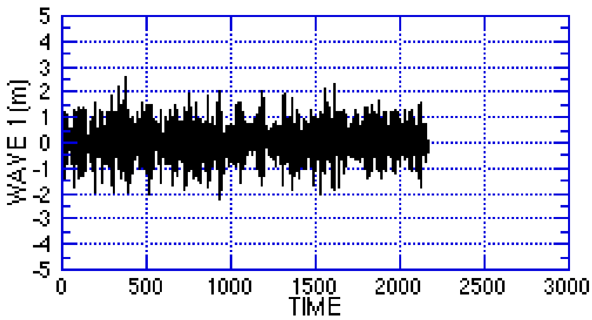


Figure 5.6 Wave time history for MARIN model 8004-2, Run 307002

5.4 Benchmark Simulation

Comparisons of the simulations of parametric roll with the experimental results were to be made based on the statistics of the simulated waves and of the predicted 6-DoF motions; and where possible, on comparisons of the actual 6-DoF motion predictions. For the three cases that were to be compared, participants were asked to perform one set of simulations using the "default" roll damping model from their simulation tool. If the participant "tuned" their roll damping against the roll decay data, a second set of simulations using that tuned roll damping were to be provided.

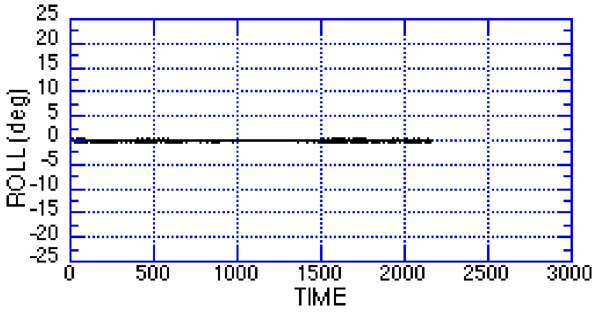


Figure 5.7 Roll time history for MARIN model 8004-2, Run 307002

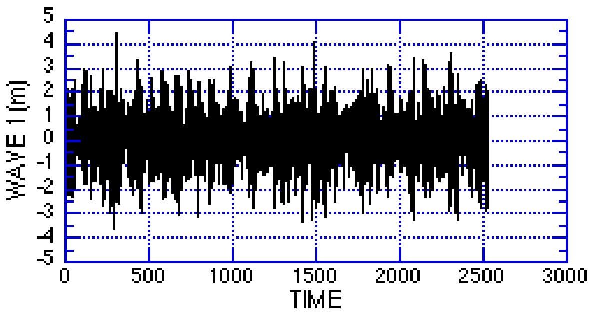


Figure 5.8 Wave time history for MARIN model 8004-2, Run 307004

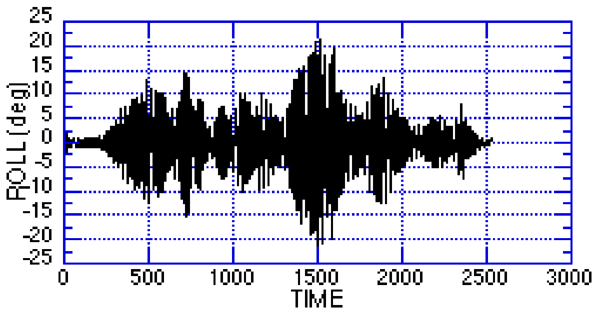


Figure 5.9 Roll time history for MARIN model 8004-2, Run 307004

Initially, ten organisations indicated an interest in participating in the benchmark study, and ultimately six organisations provided results predicted using seven different computer codes. The six organisations and their computer codes are listed in Table 5.3.

Brief descriptions of these computational tools are provided below. With the exception of ROLLSS, all of the codes are blended codes that compute the exact nonlinear Froude-Krylov exciting forces due to the incident wave and the exact hydrostatic restoring forces over the instantaneous wetted surface of the vessel, and employ linear computations of the radiation and diffraction forces for the vessel up to the mean waterline. ROLLSS employs a different blending where all forces except for those in roll are calculated linearly. The descriptions, with references, are as follows:

Table 5.3 Organisations participating in the benchmark study and their respective computer codes

Organisation	Code(s)
David Taylor Model Basin (NSWC/CD)	FREDYN, v9.8
HSVA	ROLLSS
MARIN	FREDYN, v10.1
Osaka University	OU-PR
Science Applications International Corporation	LAMP 3
Seoul National University	SNU-PARAROLL, WISH

FREDYN v9.80 and v10.1 (Kat and Paulling, 2001; Hooft, 1987) simulates the dynamic behaviour of a steered ship subjected to waves and wind. All 6 DoF are computed in the time domain, where the motions can be large up to the point of capsize. Non-linearities arise from rigid-body dynamics with large angles and fluid flow effects. A linear strip theory approach is used to compute the hydrodynamic forces acting on the hull.

ROLLSS (Söding, 1982; Kröger, 1986; Petey. 1988; Brunswig, *et al.,* 2006) is a code for simulating parametric rolling. The pitch, heave, sway and yaw motions are computed by a linear strip method, and the surge motion by a simple nonlinear approach. The roll motion is computed nonlinearly in the time domain using the righting arm curve for static stability in waves.

OU-PR (Osaka University simulation program for Parametric Rolling) (Hashimoto and Umeda, 2010; Hashimoto *et al.*, 2011) is a time domain program for predicting parametric rolling in regular and long-crested irregular waves, which uses 3-DoF coupled with a heave-roll-pitch model. The 2-D radiation and diffraction hydrodynamic forces are calculated for the submerged hull with the instantaneous roll angle taken into account. The roll radiation force is calculated at the natural roll frequency and those in vertical modes (heave and pitch) are at the peak of the mean wave frequency.

Linear and quadratic roll damping is determined from results of a roll decay test if available. Otherwise, they are determined by Ikeda's semi-empirical method.

LAMP 3 (Lin and Yue ,1990; Shin, *et al.*., 2003; Lin, *et al*., 2006; Yen, *et al.*, 2008, 2010) predicts the motions and loads of a ship operating in a seaway. The wave-body hydrodynamic forces are calculated using a 3-D Rankine potential flow panel method with a linearised free-surface boundary condition in the time domain, while forces due to viscous flow and other "external" effects such as hull lift; propulsors; and rudders are modelled using other computation methods, or with empirical or semi-empirical formulas. LAMP's calculations include 2nd and higher order "drift" forces in the horizontal plane (Zhang, *et al.*, 2009). These drift forces play an important role in the horizontal-plane motions for the prediction of course keeping in waves.

SNU-PARAROLL (Kim and Kim, 2010b; Kim and Kim, 2011) employs a linear impulse-response-function approach to compute the radiation and diffraction forces. The impulse response function approach converts the frequency-domain solution from a 3-D panel code into the time domain. In this method, the conversion is limited to the radiation force. The excitation force includes the nonlinear Froude-Krylov and restoring force and moment on the instantaneous wetted surface as well as the linear diffraction force. The wetted surface is defined as the hull surface wetted by the body motion and the incident wave.

WISH (computer program for nonlinear Wave-Induced loads and SHip motion) (Kim, *et al.*, 2009; Kim and Kim, 2010a&b) is a three-dimensional Rankine panel method used to study nonlinear roll motions. In this method, the total velocity potential is decomposed into three components: the basis flow; the incident wave; and disturbance velocity potentials. In this weakly-nonlinear approach, the disturbed component of the wave and velocity potentials are assumed to be small. The kinematic and dynamic free surface and body boundary conditions are linearised. The basis flow-wave induced motion terms are hard to compute, since they require second derivatives of the basis flow. In WISH, the second-order differentials are converted to first-order differentials using Stoke's theorem.

5.5 Benchmark comparisons

Statistical methodology. The motions that have no restoring force (surge, sway, and yaw) can be significantly affected by the actions of the autopilot and the propulsion algorithm. Taking advantage of the fact that these effects will, in general, be at a much lower frequency than the wave encounter frequency, the surge sway and yaw motions were decomposed into "low-frequency" and "wave-frequency" components, to separate the manoeuvring and autopilot related contribution to the motions from the direct response to the wave excitation.

The analysis of the results consisted of statistical analysis of the wave elevation and the 6-DoF motions. The statistical quantities that are computed are given below:

1. Mean value: $\bar{u}$ (MEAN)

$$\bar{u} = \frac{1}{N}\sum_{n=1}^{N} u_n \qquad (5.1)$$

where u_n is the nth sample of the signal and N is number of samples.

2. Variance of the Mean: V_M (VAR MEAN),

$$V_M = V\frac{1}{N}\sum_{i=-N+1}^{N-1}\left(1-\frac{|i|}{N}\right)\bar{R}_{|i|}, \qquad (5.2)$$

where $\bar{R}_i$ is the ith value of the normalised autocorrelation function of the signal and V is the variance of the signal.

3. Variance: $V\,(=\kappa^2)$ (VAR),

$$V = \frac{1}{N}\sum_{n=1}^{N}\left(u_n - \bar{u}\right)^2 \tag{5.3}$$

4. Variance of the Variance: V_V (VAR VAR),

$$\mathrm{V}_V = V^2 \frac{2}{N}\sum_{i=-N+1}^{N-1}\left(1-\frac{|i|}{N}\right)\bar{R}_{|i|}^2, \tag{5.4}$$

used to compute a confidence interval for the value of the variance.

Based on the ideas and method of Belenky, *et al.,* 2007, the computation of the variance of the mean (V_M) and the variance of the variance (V_V) allows the computation of confidence bounds for the mean and variance of the experiments and computations. The computation of V_M and V_V requires the normalised autocorrelation function $\bar{R}(t)$ of the measured or computed response.

The normalised autocorrelation function can be computed directly from the signal or from the spectrum of the signal. If $\bar{R}(t)$ is computed directly from the signal, $\bar{R}(t)$ must be truncated due to the loss of statistical confidence in the function's values for large lags. The computation of $\bar{R}(t)$ from the spectrum requires that the spectrum be smoothed before $\bar{R}(t)$ is computed.

The recommended method for computing $\bar{R}(t)$ is from the spectrum. The autocorrelation function is the cosine transform of the spectrum, so it can be computed as follows:

$$R(t) = \int_0^\infty d\omega\, S(\omega)\cos\omega t. \tag{5.5}$$

The normalised autocorrelation function $\bar{R}(t)$ is produced by dividing the autocorrelation function $R(t)$ by the approximate variance $V'\,[=R(0)]$, so that $\bar{R}(0)$ is identically equal to 1.

$$\bar{R}(t) = \frac{1}{V'}R(t) = \frac{1}{R(0)}R(t). \tag{5.6}$$

This normalisation is required to account for the computational and/or truncation errors that are likely to accrue in the computation of the spectrum and the autocorrelation function from the spectrum, which result in a difference between the approximate variance $V'\,[=R(0)]$ and the true variance of the signal, V.

The spectrum of the encountered wave train, complete motions (heave, roll, and pitch) and wave-frequency decomposed motions (surge, sway, and yaw) are computed in the usual manner using Fourier transforms. As seen in Figure 5.10, this spectrum will be quite jagged; and the normalised autocorrelation function computed from this jagged spectrum will not continuously decrease for large lag times.

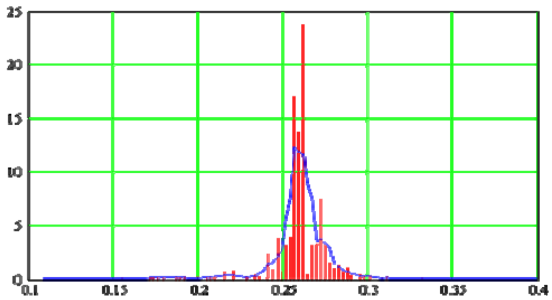


Figure 5.10 Raw roll spectrum and roll spectrum smoothed with 5-point boxcar filter.

Smoothing the spectrum before computing the normalised autocorrelation function improves the quality of $R(t)$ and reduces the growth of the envelope for large lag times. The smoothing can be performed by using a digital filter, or more easily by means of a "boxcar" filter, a simple 5-point running average filter that sets the new value of point n to be the average of the 5 points centred about point n. The spectrum smoothed with a 5-point boxcar filter is shown in Figure 5.10 and the resulting normalised autocorrelation function is given in Figure 5.11. A boxcar filter with more points (7, 9 or 11) produces a smoother spectrum and better looking autocorrelation function, Figure 5.12, but has little effect on the computed values of V_M and V_V.

Once the normalised autocorrelation function has been computed, it is straightforward to compute the variance of the mean, V_M and variance of the variance V_V of the measured or computed signal, using equations (5.2) and (5.3), respectively.

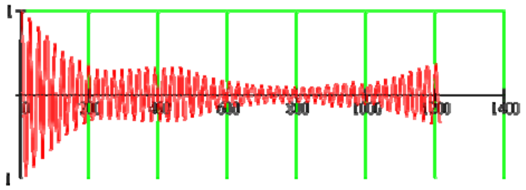


Figure 5.11 Normalised roll autocorrelation function from raw spectrum.

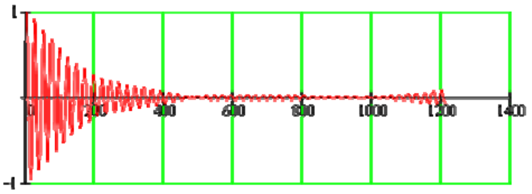


Figure 5.12 Normalised roll autocorrelation function from spectrum smoothed with 5-point boxcar filter.

Comparisons. Although all participants provided the statistics for the waves and all 6-DoF of motion, the allotted space does not allow all of the results to be presented. Thus, only the wave and roll statistics are being provided. Figure 13 shows the variance of the wave-time histories from the experiments and each of the predictions along with the corresponding 95% confidence bands. Figure 14 shows similar results for roll. On these plots, the experiments are denoted by “Ex” and the predictions have been randomly assigned the letters “A” to “G”.

Examining the variance of the wave height shown in Figure 13, it is seen that the variance of the wave heights is consistent with the experimental results for all three runs. Additionally, all of the predictions are well within the 95% confidence band of the experimental results.

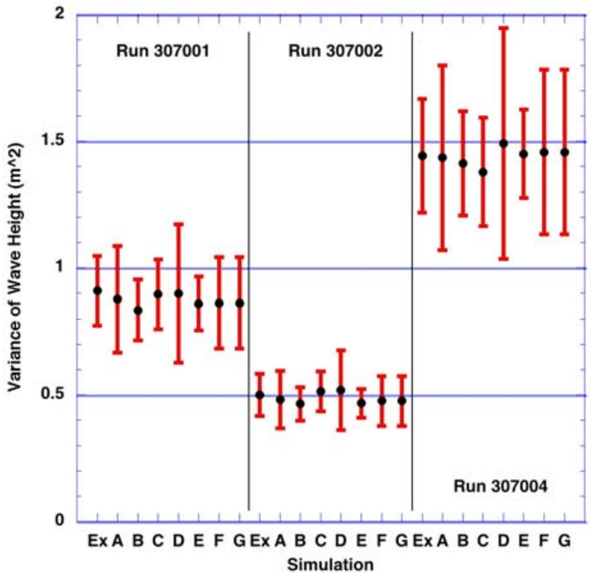


Figure 5.13 Variance of wave height with 95% confidence bands for MARIN model 8004-2, runs 307001, 307002, and 307004, as predicted from the experiments (Ex) and computations (A–G).

The statistics for roll shown in Figure 14 exhibit much less agreement between the predictions and the experimental results.
For Run 307002, only methods F and G show any notable roll response. None of the experiments or computations except for F and G have any significant variance of the variance.

In the case of Run 307001, the experiments show significant variance and 95% confidence bands, while methods B, F, and G show significant variance and have significant 95% confidence bands. None of the other methods show either any variance or 95% confidence bands. In fact the upper 95% confidence limits for the predictions by methods A, C, D and E are below the 95% confidence band for the experiments. Methods B, F and G have 95% confidence bands comparable to that of the experiments, which overlap the experimental 95% confidence band, statistically all of these results are the same.

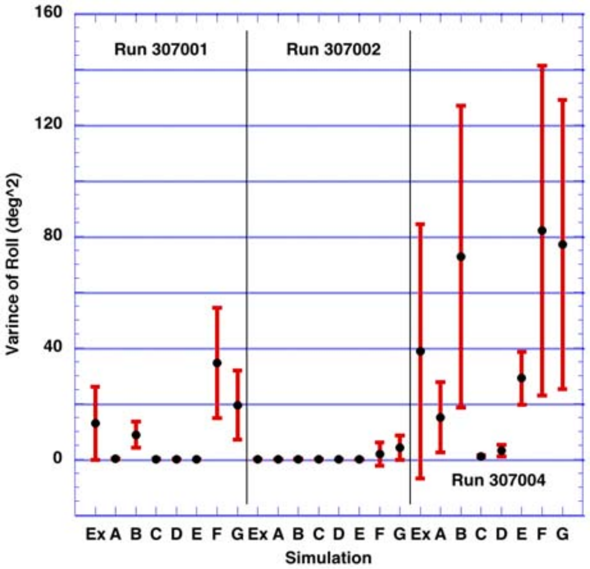


Figure 5.14 Variance of roll angle with 95% confidence bands for MARIN Model 8004-2, Runs 307001, 307002, and 307004, as predicted from the experiments (Ex) and computations (A–G).

The results for Run 307004 are different from both of the previous runs. The experimental results show a lower 95% confidence limit, which is negative, an impossibility, which indicates that the usual normal distribution assumptions are not applicable. (The same comment applies Methods F and G in Run 307002). In fact the 95% confidence band limits must be computed assuming a truncated normal distribution, and this will lead to upper and lower limits of 89.5deg^2 and 2.7deg^2, respectively. With the exception of method C, the variance of all of the predictions are within the 95% confidence band of the experiments, and are statistically equivalent.

5.6 Benchmark conclusions

The results of the SAFEDOR Parametric Roll Benchmark (Spanos and Papanikolaou, 2009b) provide no confidence bands, but show levels of scatter in the range of roll predictions consistent with those seen in Figure 5.14. They also have more participating codes and more cases. Thus the scatter in the variance of the predictions should not have been unexpected.

Belenky and Weems, (2011), have conducted a study where they used LAMP 2 to predict the head-sea motions of a C11 class container vessel, looking for parametric roll. They produced 50 realisations of the same JONSWAP spectrum, where each realisation consisted of 1500s of data. They then computed the 95% confidence interval for the roll variance for each individual realisation and for the ensemble of all 50 realisations. Figure 5.15 shows the variance of the roll along with the confidence interval for each individual run and for the ensemble of 50 runs.

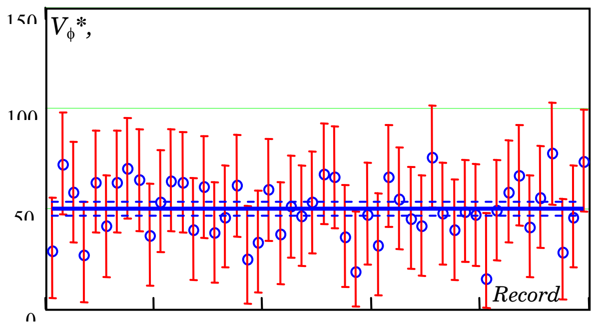


Figure 5.15 Estimates of variance values of records and ensemble (from Belenky and Weems, 2011)

Figure 5.15 shows the degree of variability that can occur from run to run. The variance of the first and second realisations differ by more than a factor of two (29 deg^2 vs. 72 deg^2), and the largest and smallest vary by a factor of five (15 deg^2 vs. 77 deg^2). As can be seen, the ensemble confidence band is significantly narrower than those of the individual records.

The reason for the dramatic differences in the variance of the records is the fact that parametric roll is a consequence of a group of waves of length close to the ship length and a speed-heading combination that results in an encounter frequency that is twice the roll natural frequency. The practical implications of this are that an individual record contains little statistically independent data. Thus, these waves have a narrow spectral peak that results in an autocorrelation function that does not decay quickly with lag time.

To characterise the solution to this problem, Belenky and Weems, (2011), went on to study the number of records that must be ensemble averaged in order to produce a "tight" statistical characterisation of the variance of the roll. This is demonstrated in Figure 5.16, where the convergence of the variance of the ensemble and its confidence interval is shown as a function of the number of records included in the ensemble average.

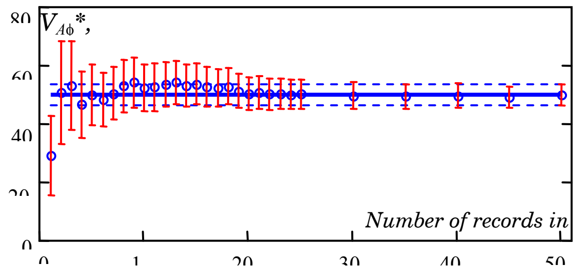


Figure 5.16 Convergence of ensemble estimate of variance (from Belenky and Weems, 2011)

As can be seen, after approximately 20 records there is little change in either the variance or the confidence band for the ensemble, and there is significant convergence after as few as 4 or 5 records. Thus, from a practical perspective, as few as 7 to 10 realisations should produce usefully convergent results.

In principle, this problem can be overcome by producing significantly longer records, but in general, this is not realistic. It is a manifestation of what Belenky and Weems call practical non-ergodicity, "meaning that several independent records must be used in order to devise any judgment on the statistical characteristics of the parametric roll response." To characterise the solution to this problem, Belenky and Weems went on to study the number of records that must be ensemble averaged in order to produce a "tight" statistical characterisation of the variance of the roll. They examine the convergence of the variance of the ensemble and its confidence interval as a function of the number of records included in the ensemble average. They found that after approximately 20 records there was little change in either the variance or the confidence band for the ensemble and there was significant convergence after as few as 4 or 5 records. Thus, from a practical perspective, as few as 7 to 10 realisations should produce usefully convergent results.

From the perspective of the benchmark study, this indicates that it is not possible to draw any conclusions regarding the performance of any simulation method from a single realisation. One may conclude that those methods that have very narrow confidence bands on their results are probably not fully capturing the physics of parametric roll. For either experiments or computations, it will take the results from 7 to 10 realisations at the same significant wave height to determine convergent results. Further, as converged statistical results are obtained, more sophisticated means of comparison than the variance of the roll amplitude (such a roll exceedance rates with the appropriate confidence bands) should be used to compare methods.

6 REVIEW OF NUMERICAL TECHNIQUES FOR ASSESSING SURVIVAL TIME OF DAMAGED PASSENGER SHIPS

The behaviour of a damaged passenger ship is affected by three main mechanisms:

Flooding process and floodwater dynamics;
1. Ship motion in waves; and
2. Interaction between floodwater and ship motion.

6.1 Flooding process and floodwater dynamics

Flow through openings. In most damaged model studies, the simple hydraulic model often referred to as the orifice equation is regularly used. The equation can be drawn from Bernoulli's equation for steady flow. The general form of the formula of flow rate is as follows:

$$q = C_D \rho \int \sqrt{2\Delta p / \rho}\, dA \quad \text{for an area opening} \tag{6.1a}$$

and

$$q = C_D \rho A \sqrt{2\Delta p / \rho} \quad \text{for a point opening} \tag{6.1b}$$

where C_D is the discharge coefficient for the opening (White, 1979).

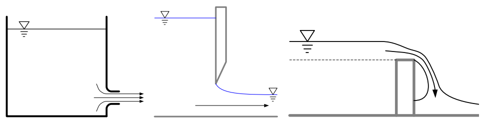

(a) orifice (b) sluice gate (c) weir

Figure 6.1 Various types of flow through openings

There can be various flow types through openings used to model the flow inside the ship including: small opening; sluice gate type flow; and weir type flow as shown in Figure 6.1.

In most damaged model simulation studies, the point opening is used. If the area of the opening is small, this has been shown to produce a reasonably good approximation of the flow. However, if the area of the opening is large, the pressure difference varies across the opening and water and air flow can take place at the same time.

For the case of a large opening and other types of opening, equation (6.1a) can be used for the calculation of flow, and can be altered easily to calculate the water flow and air flow through a large opening at the same time. Ruponen, (2007), reviewed the techniques for this situation.

For the validation of the calculation of flow through an opening using simple hydraulic model, van't Veer and Kat, (2000), presented validation results for this flooding model for an engine room and accommodation compartment. Katayama and Ikeda, (2005), have also performed experimental studies for the flow through damaged openings.

Air compression and flow. Air is compressible in nature. The ideal gas state equation or adiabatic process equation can be used for the modelling of air compression. In many damage simulation studies, the air is treated as free to vent, *i.e.*, it is free to flow freely to the outside. This is due to the complexity of the ventilation system, as van't Veer, *et al.,* (2004), noted that the modelling of all possible air ducts in a passenger ship is very difficult to achieve.

In the 1990s, the effect of air compression on the flooding process was taken into account in many studies; Vredeveldt and Journée, (1991), Vermeer *et al., (*1994), Journée *et al.*, (1997), and Xia *et al.,* (1999). Palazzi and Kat (2002) have studied the flooding of a damaged frigate with airflow taken into account and concluded that the effect of air should be included since it can have significant effects, especially in the transient flooding phase. They noted that this may be a significant effect on the flooding even in model test as indicated in section 4.1.

For the calculation of cross-flooding arrangements, Peters, *et al*., (2003), showed that the effects of air pipes can be significant due to the compression of air that delays the equalising flooding to the undamaged tanks.

There are situations where down flooding inside a ship occurs, such as flow through stairways, and where there is an opening at the bottom of a compartment. The higher pressure in the lower compartment can block the water flow. In reality, the water drops through and bubbles are exchanged through the opening. The bubble rising speed and bubble size are crucial for the exchange. This is shown in Figure 6.2.

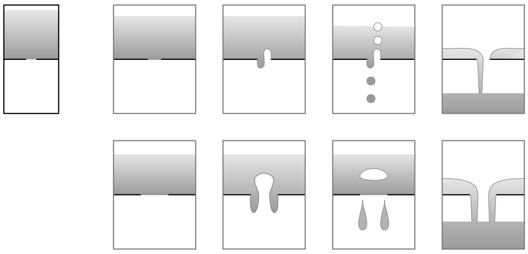


Figure 6.2 Concept drawing for water drops and air bubbles exchange

The air bubble shape and rising speed are modelled well in the text book of Clift, *et al.,* (1978) covering various radii of curvature of air bubbles. They analysed results from model experiments as shown in Figure 6.3 and gave the relationship between the rising speed and the size of the bubble. However, further investigation is required into the behaviour of large bubbles for application to the flooding of damaged ships.

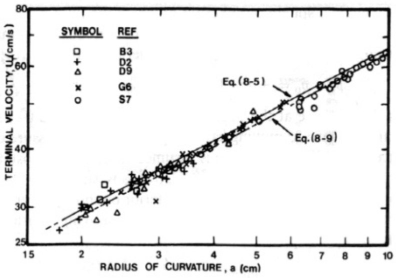


Figure 6.3 Rise velocity of spherical-cap bubbles (Clift *et al.*, 1978)

Floodwater dynamics (including CFD). In the early stage of the flooding calculation, Spouge, (1986), used a semi-empirical formula to calculate the position of the centre of gravity of the floodwater as a function of time. Later, Sen *et al*., (1987), used a calculation method for the position of the CoG of the floodwater with the assumption that the free surface remains horizontal. This method is now widely used for damage simulations. The dynamic effect was included by a so called 'lumped mass' concept. In this method the floodwater is treated as a concentrated mass and the possible track of location of the CoG is pre-calculated. The equation of mass movement is then coupled with the ship motion (Papanikolaou *et al.,* 2000, 2002).

Many attempts have been made to use CFD schemes for the simulation of the floodwater dynamics in the flooded compartment. With the existence of free surfaces, VOF RANSE methods have been used for the floodwater dynamics in Cho *et al*., (2005), Gao *et al*., (2009), and Strasser *et al*., (2009). More recently the SPH method was used (Perez-Rojas *et al*., 2009, Shen *et al*., 2009). These studies showed that CFD can be applied to model the floodwater dynamics and the results have shown that it is sufficiently accurate, suggesting that the CFD method is promising for the future. However, due to the mesh complexity and significant computational requirement, so far CFD methods have only been applied to one or two compartment problems. Currently it appears that the CFD methods can only really be used for limited cases with small numbers of compartments.

Progressive flooding. In analysing the flooding with a large number of compartments, the successive flooding across the compartments, door collapse and sometimes structure collapse must be taken into account.

For the collapse and leakage of watertight doors, SLF 47/INF.6(2004) suggests a practical assessment of how semi-watertight and non-watertight doors can be treated in time-domain flooding simulations. The practical assessment of the integrity of semi watertight fire or joiner doors indicates that the most important factor is to determine the leakage and the collapse pressure threshold, but there is a lack of proper data for carrying out a realistic numerical simulation as indicated in section 4.2.

In the calculation of progressive flooding between the compartments, the main difficulty is that there is no direct equation to calculate the pressure in the compartment fully filled with water. So the indirect method which calculates the pressure has to be used assuming that the assumption that the mass conservation law is satisfied. Ruponen, (2007), used the pressure correction method in which the pressures are calculated iteratively until this assumption is satisfied. However, this significantly increased the complexity, resulting in some convergence issues.

6.2 Damaged ship motions

Dynamic motion. The 2-D strip method or 3-D panel method have been used to calculate the radiation elements of the problem, with direct pressure integration used for the non-linear restoring force. Most studies calculate the ship motion in 6 DoF. The roll viscous damping is usually added by the use of empirical formula. However, one issue is that the linear memory effect function, *i.e.* added mass and wave damping, is used even for the large amplitude motion and heeling conditions. In order to address this problem, Belknap, *et al.,* (2010), introduced the body-exact strip theory work of Bandyk, (2009), in which he used the non-linear time-domain potential method that tracks the body and free surface to calculate the hydrodynamic disturbance forces.

The ability to calculate vessel motions in the time domain using CFD has only been possible in recent years. The equations of motion of a ship are now routinely included in CFD codes. The CFD technique is now being applied to the manoeuvring problem and to vessel motions in waves.

Wave effect. The Froude-Krylov force can be calculated by direct pressure integration over the wetted surface in the time-domain. However, many studies have used the frequency-domain results of the diffraction force for their time-domain calculations. It is not clear whether it is appropriate to make use of these in time-domain calculations, because the frequency-domain results are for the normal seakeeping condition, linear and upright condition, so this may not be adequate for simulation of damaged ship motions.

The non-linear diffraction force has been calculated in the time-domain by Lee *et al.,* (2006). They used the strip-wise cross flow drag that is related to the manoeuvring coefficient, and good agreement was shown with the results from a captive model test; however, the motions in waves were over-estimated.

6.3 Interaction between floodwater dynamics and ship motion

The effect of the floodwater on the ship motion can be calculated in one of two ways: the added weight concept; or the added force concept.

Added weight concept. The floodwater can be treated as an added weight with a moving centre of gravity which changes the location of the ship's overall centre of gravity. Many studies have been undertaken using this concept. Special care should be taken to ensure that as the total mass of the ship is changed, so the inertia forces should be changed also and that the floodwater does not experience a negative vertical acceleration. When this behaviour occurs the results are not valid.

Added force concept. The added force concept is where the forces due to the floodwater are treated as external forces. In this concept, the forces due to floodwater should be calculated using instantaneous acceleration, rather than gravitational acceleration, and by integrating pressure at the compartment wall.

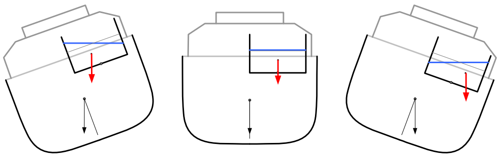
Interactions. There are three methods of modelling floodwater-ship motion interaction as shown in Table 6.1.

Table 6.1 Three models of interactions

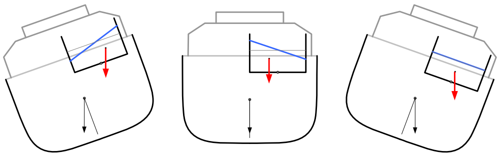
	Floodwater treatment	**Interaction concept**
Quasi-static	static	added weight
Quasi-dynamic	dynamic	added weight
Dynamic	dynamic	added force

The floodwater dynamics can be predicted using various models ranging from second order ordinary differential equations through to CFD.

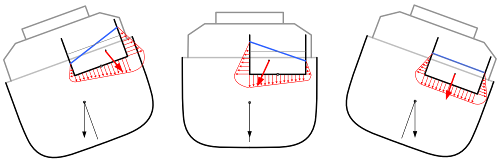
The concept of these three models can be drawn as shown in Figure 6.4.



(a) quasi-static(free surface horizontal)



(b) quasi-dynamic(dynamic free surface)



(c) dynamic(dynamics free surface, fluid pressure force)

Figure 6.4 Concept of floodwater and ship motion interaction

Figure 6.5 is an example of typical motions predictions obtained using the three different methods of modelling floodwater-ship motion interaction. As can be seen, for low frequency there is little difference in the motion, meaning that the three concepts agree well for the case of slow flooding processes in calm water. When approaching the natural roll frequency of the ship, the behaviour shows quite a difference between the three methods. Predictions using the quasi-static model result in a lower natural frequency compared to predictions using the other two models. Predictions using the quasi-dynamic and dynamic model result in very different motions at higher frequencies which are potentially due to the strong interaction between the floodwater and ship motion.

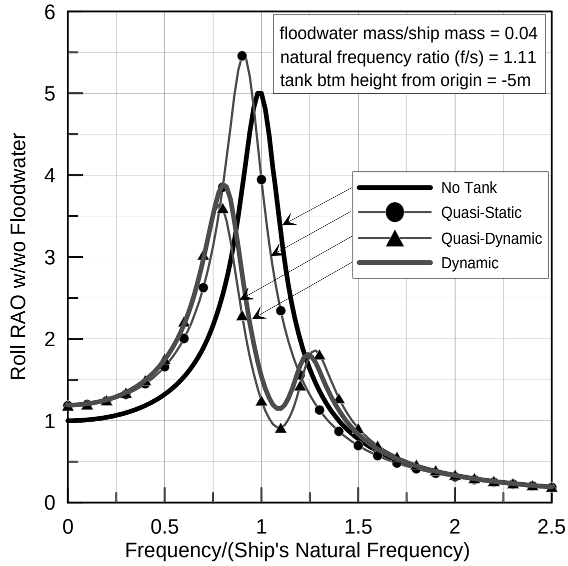


Figure 6.5 Typical roll RAO of ship with floodwater tank

6.4 Calculation time

Depending on the methods and the computing power adopted to calculate the behaviour of a ship in the time domain, the real time to calculation time ratio (T-T ratio) varies in the range of 10^{-2} to 10^{3} typically. In order to be able to conduct Monte-Carlo simulations or to obtain realistic probabilities, a large number of cases is required, *e.g.*, 300 (test scenario) x 5 (wave case) x 10 (independent repeat or design alternative case) = 15,000 cases. Allowing 1 hour full scale time for each case, this equates to 15,000 hours (1.7 years in real time). For a method which can achieve a T-T ratio of 10^{-2} this would be 1 week real time. The typical T-T ratio for 1 CPU is shown in Table 6.1.

Cho *et al.,* (2005) reported that it took 200 computer hours using 1 million cells to calculate the flooding of an engine room. It seems that about one million cells in RANSE or one million particles in SPH are necessary to simulate the floodwater dynamics in a large compartment. However most studies do not report the computing time required.

Table 6.2 Typical time-time ratio (T-T ratio)

T-T ratio (log scale)	Typical method	Usage
-2	Potential + calm water	Monte-Carlo or probabilistic study
-1	Potential + Wave	
0	Real time	Simulator
2	Potential + RANSE Flooding	
3~	Totally RANSE	Analysing of phenomenon

6.5 Assessing survival time

The time a ship survives after flooding occurs due to damage is a design objective, *e.g.*, for passenger ships through SOLAS regulations (safe return to port). The purpose of these regulations is to design a ship in such a way that its essential systems remain operational so that it can return to port and/or can be evacuated.

In order to assess the survival time, two approaches are predominantly being used. One is based on the survivability term derived from the SOLAS probabilistic method and the other is based on direct calculation using numerical simulation.

For the probabilistic approach to assess the survival time, Pawłowski (2008, 2009) proposed a relation between the survival time and the probability of survival (survival factor s). The factor s is a function of hydrostatics (maximum GZ value and range of positive stability) and the equilibrium heel angle after damage. Recent studies on the capsize band concept and survival factor, s, were conducted by Tsakalakis, *et al.* (2010) and Pawłowski (2010b). The capsize band separates sea states with low and high capsize probabilities. The capsize band concept enables a quick assessment of the capsize risk and hence the survival time, but also has inherent uncertainties.

To assess the survival time using numerical simulation it is necessary to model the actual scenario of the accident or a probabilistic distribution of the damage extents. Smith and Heywood (2009) proposed accidental damage templates without frequency for naval vessels for assessing the survivability. Spanos and Papanikolaou (2010) described a method to assess the survival time by means of direct numerical simulations. The probability distribution for the survivability is derived from Monte Carlo type simulations for a matrix of loading conditions, damage openings and sea states. Moderate to rough waves are considered (1.5 to 4.0 m significant wave height respectively) and damage openings according to ship collision statistics. Combining the probability density function of the sea states yields the time dependent survivability for the damaged case under consideration.

6.6 Experimental data for validation

There are currently a limited number of model test data sets openly available for vessels with a large number of damage compartments. There is, first, the difficulty of modelling accurately large numbers of compartments required for a passenger ship. Secondly experiments that are conducted are of particular ships and therefore not made publically available.

Käallströom *et al.*, (2009) analysed the sinking sequence of MV *Estonia*, combining the numerical and model tests. This study aimed to enlighten the sinking process for that vessel.

Ypma and Turner (2010) proposed a step-by-step method for validation of a numerical simulation with model tests. The procedure gradually enlarges the degrees of freedom over a number of steps as follows:

1. Component and interface verification;
2. Vessel roll damping;
3. Vessel hydrostatics;
4. Fully constrained;
5. Forced motions;
6. Moving mass; and
7. Unconstrained analysis.

Macfarlane, *et al.,* (2010) conducted a model test to analyse the transient phase. They investigated the experimental repeatability and the effect of KG on the intermediate and final roll angle. They reported that there were roll angle differences up to 4 degrees during the intermediate stage in the repeatability test.

Ruponen (2006) performed an experimental study of the progressive flooding of a box-shaped barge. The results were used for the benchmark study of numerical simulations in ITTC (see the 25th ITTC report of the Specialist Committee on Stability in Waves). Many other researchers refer to these results for the validation of their numerical simulations.

Cho *et al.*, (2009, 2010) performed an experimental study on the flooding of a cruise ship. The model had two damaged compartments: one is the same shape as that used by Helsinki University, except with a double bottom; and the other located at the bow of the ship. The hull form was provided by SSRC. In this study, the flooding model tests were performed with and without waves (regular and irregular waves).

7 ROLL DAMPING PROCEDURE

The objective of the procedure 7.5-02-07-04.5 “Numerical Estimation of Roll Damping” is to provide an overview and guidance of current roll damping estimation methods for use in stability calculations, without the need for experimental data. The procedure has been developed based on a survey of ITTC member organisations and based upon the experiences of domain experts and published literature.

One roll damping estimation method presented is a component discrete type method, which was reviewed in the reports of the seakeeping committee of the 15th and 16th ITTC Proceedings. The method is composed of wave, frictional and eddy making components. These components were developed from a theoretical and experimental background based on the hydrodynamic characteristics under periodic motion and provide an equivalent linear roll damping. This method was originally proposed for the conventional displacement type of monohull vessels; however, it has now been extended for use with high speed slender vessels, barge vessels, small hard-chine vessels and multi-hull vessels. With the inclusion of additional components, it can also be suitable for planning craft and damaged ships and all of them are discussed in detail in the procedure.

For the equivalent linear roll damping, methods of how to treat the non-linearity of roll damping are explained. However, it is difficult to apply an equivalent linear damping to a situation which is completely different from its theoretical and experimental background, like a time-domain simulation in irregular seas. Therefore, time-domain numerical calculation techniques such as the use of CFD are now desired. Developments in CFD have increased rapidly in recent years and the accuracy is continuously improving. The report by the Specialist Committee on CFD in Marine Hydrodynamics can be referred to for techniques for CFD roll damping calculations.

The final chapter of the procedure provides a literature review which present experimental data for validation of the roll damping components for several type of vessels at model scale and one at full scale vessel. Model test procedures are also introduced in order to validate a numerical roll damping tool.

8 IMO LIAISON

The Committee has made available experimental data on parametric roll of a C11 class container ship available to IMO. The data have been obtained through MARIN who performed the tests as part of a research program on the effects of variation of hull form on the likelihood and magnitude of parametric roll. Details on the results can be found in Levadou and van’t Veer (2006).

The experimental data are made publicly available through the web site of the IMO-SLF

Intercessional Correspondence Group on Intact Stability (ISCG) (**Erro! A referência de hiperlink não é válida.**). The Committee has reviewed draft reports of the ISCG. The reports describe methodologies for vulnerability criteria and direct stability assessment for the following stability failures:

- Quasi-steady stability variation in waves in following/stern quartering seas;
- Parametric resonance due to stability variation in waves;
- Dead ship conditions: roll; and
- Broaching, manoeuvrability and course keeping ability.

A summary of methodologies submitted by the various ISCG members is given in Table 8.1.

Table 8.1 - Methodologies by ISCG members

Stability failure mode	Level 1	Level 2	Level 3	Level 4
Pure loss of stability	Japan, United States	United States Japan	Germany Japan	Germany
Parametric roll	Italy, Japan, United States	United States Japan, ROK	Germany, Japan, ROK	Germany
Surf-riding/ Broaching	Japan, Poland, United States	Japan, United States	Japan	Japan
Dead ship Condition	Italy, Japan	Italy, Japan	Italy, Japan, Germany	

The methodologies range from:

Level 1: Simple but with a relatively large margin. For example; use only the Froude number to assess the broaching risk.

Level 2: More sophisticated by direct calculation. For example; use time domain simulation techniques or analytical bifurcation analysis, together with a comparison of wave induced and rudder induced yaw moments.

Level 3: Direct stability assessment; Use a method based on a combination of deterministic simulation and probabilistic wave theory.

Level 4: Operational guidance; Use the results from Level 3 analysis for ship dependent operational guidance.

The ITTC-SiW comments focused on the absence of wave conditions for some of the Level 1 vulnerability criteria and on the absence of quality control (validation and verification) on the numerical codes used for direct stability assessment.

9 CONCLUSIONS AND RECOMMEN-DATIONS

9.1 Technical conclusions

1. A comprehensive state-of-the-art review has been undertaken concerning the development of vulnerability criteria and assessment methods. This review has reinforced the importance that such methodology reflects the mechanism involved with the physics of extreme ship motions leading to capsizing *i.e.*, extreme sensitivity to initial conditions, critical behaviour, stochastic nature of the motions in a realistic seaway and coupling of roll to other degrees of freedom.

2. A state-of-the-art review has been carried out concerning the different modes of capsize behaviour. It has been concluded that among the numerical tools, it is possible to find some dealing with specific modes of capsizing and some others able in principle to capture all of them. The recent interest in the subject has

raised a new development activity definitely in the direction of the treatment of the capsizing in a way not confirmed to a single specific mode of ship stability failure.

3. Investigation of ship performance in terms of capsize implies a definition of a comprehensive methodology where the numerical simulation of the motions is only a component of the methodology. Progress is being made regarding this methodology for the stability assessment of both intact and damaged ships, but has not yet reached maturity.

4. In order to predict the motions in waves of a damaged ship in the time domain greater understanding is required of a number of important issues. These include; the air compressibility; inertia of flood water mass; effect of forward speed; short crested waves; non watertight boundaries; two phases flows; and bubble dynamics.

5. It is essential to better understand uncertainties associated with the results from experiments and simulations of parametric rolling in realistic irregular seaways. It is also necessary to develop a quantitative technique which reflects the nature and magnitude of the phenomenon.

6. The results of the parametric roll benchmark study, which, for the first time, include confidence bands, show significant scatter in the predicted roll variance, but the vast majority of the results are within the 95% confidence band of the experimental results. These results are consistent with previous parametric roll benchmark studies, and indicate that insufficient data is being accumulated either experimentally or computationally to produce reasonable confidence bands.

7. Some useful experimental data exists for the validation of flooding mechanisms. However no such experimental data is publically available for the validation of survival time of vessels with complex interiors, such as passenger ships.

8. The committee has:

a. Developed the procedure for the numerical estimation of roll damping 7.5-02-07-04.5;

b. Developed the procedure for the numerical procedure for the simulation of capsize behaviour of damaged ships in irregular beam seas 7.5-02-07-04.4; and

c. Provided refinements to the existing ITTC experimental procedure on prediction of the capsizing of a damaged ship in irregular beam waves.

9.2 Recommendation to the conference

Adopt the revised Procedure 7.5-02-07-04.5 “Numerical Estimation of Roll Damping”.

Adopt the revised Procedure 7.5-02-07-04.4 “Numerical Simulation of Capsize Behaviour of Damaged Ships in Irregular Beam Seas”.

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6.2 Nomenclature

DoF	Degrees-of-Freedom
CFD	Computational Fluid Dynamics
CoG	Centre of Gravity
CPU	Central Processing Unit
DoF	Degrees of Freedom
ICLL	International Convention on Load Lines
IMO	International Maritime Organisation
ISCG	Intercessional Correspondence Group
ISSW	International Ship Stability Workshop
LES	Large Eddy Simulation
MSC	Maritime Safety Committee
OC	Osaka Colloquium
OMAE	International Conference on Ocean, Offshore and Arctic Engineering
ONR	Office of Naval Research
PBC	Performance Based Criteria
RANSE	Reynolds Averaged Navier-Stokes Equations
RAO	Response Amplitude Operator
RINA	Royal Institution of Naval Architects
SiW	Specialist Committee on Stability in Waves
SLF	Sub-Committee on Stability, Load Lines and Fishing Vessels Safety
SNAME	Society of Naval Architects and Marine Engineers
SOLAS	International Convention for the Safety of Life at Sea
T-T	Ratio of calculation time to real time
SPH	Smoothed Particle Hydrodynamics
STAB	International Conf. Stability of Ships and Ocean Vehicles
URANSE	Unsteady Reynolds Averaged Navier-Stokes Equations
VOF	Volume of Fluid