The Specialist Committee on Stability

Final Report and
Recommendations to the 22nd ITTC

1. INTRODUCTION

1.1 Membership, Meetings and Organisation

Membership. The Committee appointed by the 21st ITTC consisted of the following members:

- Professor D. Vassalos (Chairman)
  University of Strathclyde, UK
- Dr. M. Renilson (Secretary)
  Australian Maritime College, Australia
- Mr. A Damsgaard
  Danish Maritime Institute, Denmark
- Dr. J.O. De Kat
  MARIN, The Netherlands
- Professor A. Francescutto
  University of Trieste, Italy
- Professor H.Q. Gao
  China Ship Scientific Research Centre,
- Professor M. Hamamoto
  Osaka University, Japan
- Professor J. Matusiak
  Helsinki University of Technology, Finland
- Mr. D. Molyneux
  Institute for Marine Dynamics, Canada
- Professor A. Papanikolaou
  National Technical University of Athens, Greece

Meetings. Five Committee meetings were held as follows:

- The Norwegian University of Science and Technology, Trondheim - Sept. 1996
- Osaka University, Osaka - Nov. 1996
- Heraklion, Crete - Nov. 1997
- Institute for Marine Dynamics St. John's, Newfoundland - Oct. 1998
- Australian Maritime College, Launceston, Tasmania - Jan. 1999 (Editorial meeting)

Organisation. The following working groups were established and chairmen appointed:

- Guidelines for model tests on intact stability (Hamamoto)
- Techniques for numerical simulation of intact stability (De Kat)
- Guidelines for model tests on damage stability (Molyneux)
- Techniques for numerical simulation of damage stability (Papanikolaou)
- Symbols and Terminology (Matusiak)

Liaisons. The following Committees and organisations have been contacted: Loads and Responses; Manoeuvring; Safety of High-Speed Marine Vehicles; Model Tests of High-Speed Marine Vehicles; Environmental Modelling; IMO (Revision of 1966 ICLL, Intact Stability, Harmonisation Group); WEGEMT; CRN; SNAME Technical Panel; EU Thematic Network - SAFER EURORO; SRA of Japan - Panel 71.

1.2 Recommendations of the 21st ITTC

The recommendations for the Future Work of the Committee made by the 21st ITTC were as follows:

- Examine the *techniques* for carrying out model tests to investigate capsize of *intact* and *damaged* ships and provide *guidelines* for such tests.
- Assess the methods available for numerical simulations of capsize of *intact* and *damaged* ships.

1.3 Contents of the 22nd ITTC Report

The following chapters detail the tasks undertaken by the Committee:

Chapter 2:	Background
Chapter 3:	State of the art Review of Intact Stability
Chapter 4:	State of the art Review of Damage Stability
Chapter 5:	Techniques for Numerical Modelling of Intact Stability
Chapter 6:	Techniques for Numerical Modelling of Damage Stability
Chapter 7:	Guidelines for Benchmark Tests
Chapter 8:	Conclusions and Recommendations
Chapter 9:	References and Nomenclature
Appendix A:	Guidelines for Experimental Testing of Intact and Damage Stability

2. BACKGROUND

2.1 General

Stability against capsizing in heavy seas is one of the most fundamental requirements considered by naval architects when designing a ship. The purpose of studying capsizing is to establish an understanding of ship behaviour in extreme seas and to relate this to the geometric and operational characteristics of the ship to achieve cost effective and safe operation. In an industry with progressively diminishing returns and an ever increasing emphasis on safety this objective is becoming ever more important. As a consequence, the research effort in this field over the last 10 years has expanded considerably, as indicated by the plethora of publications available in the literature and the large number of specialist international conferences, symposia and workshops which have been held.

Capsizing is a statistically rare event concerned with extreme behaviour of ships in waves. To assist in understanding what is a complex phenomenon, efforts have been directed towards identifying modes of capsizing and their inter-relationships based on the results of model experiments and numerical simulations. Research using scale models in realistic wave conditions, combined with theoretical developments in non-linear systems dynamics has led to improved understanding and insight on the nature of the capsize process. Mathematical and numerical models followed of increasing sophistication, capable of predicting with sufficient engineering accuracy the ability of the ship to resist capsize in a range of scenarios. A stage has now been reached where a combination of numerical and physical model testing provides powerful prediction techniques. However, despite the considerable progress achieved, the complexity of the problem at hand has meant prediction of capsize thresholds must still rely on a combination of theoretical, experimental, and intuitive approaches which lack internationally accepted standards. Safety against capsizing is currently assessed by a combination of the following:

- Deterministic rules - prescriptive regulations deriving from experiential and statistical data but which lack, in the main, solid foundations (IMO Intact Stability Code, SOLAS'95).
- Probabilistic rules – adoption of a framework of probabilistic description (IMO Resolution A.265) or of risk assessment methods (Formal Safety Assessment).

- Performance-based standards – use of numerical and or physical model testing to assess safety against capsizing based on the ability of a vessel to resist capsize in a given scenario, pertaining to vessel and environmental conditions (IMO SOLAS'95 Resolution 14).

Standards in these groups are often assumed to ensure an "equivalent" level of safety, but without any evidence to support this and with a serious attempt to demonstrate such equivalence totally lacking. Coupled to this is the lack of an effective translation of rules-based knowledge to safer ship designs, often a haphazard process shaped by the ingenuity of designers. This inherent weakness is exacerbated by the emergence internationally of a clear tendency to move from prescriptive to performance–based standards and to adopt first-principles approaches to safe ship design and operation. To overcome the aforementioned weaknesses and to respond to emerging needs for adopting first principles and performance-based approaches internationally, a concerted effort is required to assess the numerical and experimental methods currently available and to devise standard techniques and guidelines for assessing safety against capsizing as a matter of priority. ITTC has responded positively to this need by establishing the Specialist Committee on Ship Stability.

2.2 Questionnaire

The first step to achieving the above must derive from a thorough knowledge of the state of the art pertaining to availability of numerical "tools" and hydrodynamic facilities capable of assessing ship safety against capsizing. To this end, a questionnaire was prepared and circulated to all the ITTC member organisations which included questions on a wide range of capsize scenarios, involving intact and damaged conditions, water trapped on deck and cargo shifting. Respondents were asked to complete this questionnaire which included questions about their ability to model various capsize modes, the factors taken into account and the techniques used. ITTC members were also asked if they were willing to validate their computer programs for predicting extreme ship behaviour including capsize against standard sets of model experiments. Details of the candidate ships, for which systematic data pertaining to wide-ranging conditions are available, are described in chapters 7 and 8. A summary of the results received to date is given in Tables 1 and 2. The full questionnaire, including details of how to fill it out and submit it, can be found on the Australian Maritime College's web site at: *www.amc.edu.au/staff/events/stab2000/ittc.html*

2.3 Symbols

A comprehensive review of the symbols used by the major organisations with interest in ship stability including ITTC, IMO, and a range of journals, was conducted with a view to recommending a rationalised list of symbols to be included in the ITTC standard symbols. Unfortunately, the differences found are too great. Following careful consideration, it was considered inappropriate to make any harried recommendations at this stage before consulting in full all concerned and following a process of careful evaluation. It is strongly recommended that this be pursued with a view to finalise it in time to report at the 23rd ITTC.

3. STATE OF THE ART REVIEW OF INTACT STABILITY

3.1 General

Early work focused on resonant rolling motion in beam seas in the presence of beam wind. This lead to the adoption, in 1985, of IMO Resolution A.562, known as *Weather Criteria*, (Blagoveshchensky, 1932, Vassalos, 1985, Yamagata, 1959). This has been successful in ensuring adequate stability of conventional ships without any damage or forward

Table 1: Analysis of Responses to Questionnaire

Ref.	Organisation	Country	Max DOF	Capsize Modes Wave Crest	Broaching	Param. Rolling	Breaking Waves	Water Ingress	Other	Note	Solution	Method		Validation
1	AMC	Australia	6	1	1	1					time	hybrid	2-d	Yes
2	CSSRC	China	6	1	1	1		1	1	Resonant beam seas	time	non-linear	n/a	Yes
3	Dal-Tech	Canada	6	1	1			1			time	hybrid	3-d	Yes
4	DTMB	USA	6	1	1	1	1	1			time	hybrid	2-d	Yes
5	HUT	Finland	4	1					1	Cargo shift	time	hybrid	n/a	Yes
6	Krylov SRI	Russia	3	1		1					time	hybrid	2-d	Yes
7	MARIN	Holland	6	1	1	1		1			time	hybrid	3-d	n/a
8	Michigan U	USA	1						1	Dynamic roll	time	hybrid	2-d	Yes
9	Michigan U	USA	3						1	Dynamic roll	time	non-linear	2-d	Yes
10	MTG Marinetechnik	Germany	6	1	1	1		1			time	non-linear	2-d	Yes
11	MUN	Canada	6	1	1	1					time	hybrid	3-d	Yes
12	NTUA	Greece	6					1			time	hybrid	3-d	Yes
13	NTUA	Greece	4	1		1					time	hybrid	3-d	Yes
14	NRIFE	Japan	3						1	Beam seas	time	hybrid	2-d	Yes
15	NRIFE	Japan	4	1	1	1					time	hybrid	2-d	Yes
16	Osaka U	Japan	5			1		1			time	hybrid	3-d	Yes
17	RDIS	Romania	3	1		1					freq./time	linear	2-d	Yes
18	Strathclyde U	UK	3					1			time	hybrid	2-d	Yes
19	Strathclyde U	UK	6					1			time	hybrid	3-d	Yes
20	Strathclyde U	UK	6	1	1	1					time	non-linear	3-d	Yes
21	Technical U of Hamburg	Germany	6	1		1		1			time	hybrid	2-d	Yes
22	Tokyo U	Japan	3		1						time	linear	3-d	Yes
23	Trieste U	Italy	3				1				time	non-linear	2-d	Yes
24	Yokohama U	Japan	6	1							time	non-linear	2-d	No
25	SRI	Japan	6	1			1	1			time	non-linear	3-d	Yes
		Total		**16**	**10**	**13**	**3**	**11**	**5**					

Table 2: Summary Statistics

Overall Response			Number of d.o.f.						Solution Techniques			Hydrodynamics			Participation in Validation		
Total Replies	Countries	Organisations	1	2	3	4	5	6	Non- Linear	Hybrid	Linear	3D	2D	N/A	Yes	No	N/A
25	13	20	1	0	7	3	1	13	7	16	2	10	13	2	23	1	1

velocity and is now a part of the IMO intact stability code. In order to gain insight on the real nature of ship capsize, experimental procedures have included free running radio-controlled model tests in an open water area in natural wind-generated waves (Kastner, 1962, Oakley et al., 1974, Tsuchiya et al., 1977) and in artificial waves in model basins (Blume, 1990, Blume and Hattendorff, 1982, Grochowalski, 1989, Hamamoto et al., 1996, Ishida et al., 1990, 1993, Kan et al., 1990, 1994, Kawashima et al., 1979, Umeda et al., 1995, Yamakoshi et al., 1982). Some of the experiments conducted in HSVA and SRI involved comparative studies (Kan, 1990). The derived results clearly showed that a ship complying with the IMO criteria capsizes mainly in following and quartering seas but not in beam seas.

3.2 Modelling Capsize of an Intact Ship

The experience gained from the above experiments enabled researchers to develop representative mathematical models to describe non-linear ship behaviour in extreme waves. However, while standard models for seakeeping and for manoeuvring have been developed, a generally accepted mathematical model for capsizing has not yet been established.

Seakeeping behaviour is described in an earth fixed co-ordinate system where the ship travels at a steady speed with small amplitude motion. Manoeuvring in still water involves highly non-linear motion in the horizontal plane and is described in a body fixed co-ordinate system. However, since extreme ship motion likely to lead to capsizing involves a combination of what is traditionally described as seakeeping behaviour and manoeuvring behaviour, a mathematical model to predict such motion requires both earth fixed and body fixed co-ordinate systems. Mathematical models relate to two different problem areas: dynamics of ship motion using a combination of frequency domain techniques, time domain simulation and properties of non-linear systems; and the stochastic nature of wave excitation, including the identification of sea wave spectra and of encountered wave groups consisting of high waves necessary to cause capsizing. Combining outcomes from these approaches led to the adoption of the Guidance to the Master for Avoiding Dangerous Situations in Following and Quartering Seas by IMO in 1995 (MSC Circular 707). The guidance covers encountered wave group phenomena (Takaishi, 1982, 1994, Takaishi and Watanabe, 1997) and surf-riding (Kan, 1990, Makov, 1969, Umeda and Kohyama, 1990). Chapter describes specific techniques for the numerical modelling of capsizing.

3.3 Modes of Capsize

The pioneering work reported by Oakley et al., 1974, afforded a fundamental understanding of intact ship capsizing and formed the basis for subsequent research in this area. As a consequence, research efforts have focused mainly on three modes of capsize which are described below in some detail (De Kat and Thompson, 1998a, 1998b).

Static Loss of Stability. Loss of static stability refers to the quasi-static loss of transverse stability (associated with an excessive righting arm reduction) in the wave crest. This mode occurs typically at forward speed in regular or irregular following to stern quartering waves with low encounter frequencies. The ship can capsize when it experiences temporarily a critically reduced (possibly negative) righting arm for a sufficient amount of time, while the wave crest overtakes the ship slowly and the ship is surging or surf-riding periodically. For this mode of capsize to occur in irregular waves, one encountered wave of critical length and steepness is sufficient to cause the sudden catastrophic event. Experimental evidence can be found in Oakley et al. (1974) and Kan et al. (1990).

Dynamic Loss of Stability. A ship can lose stability dynamically in conjunction with extreme rolling motions and lack of righting energy under a variety of conditions. This major capsize mode may be associated with the following phenomena:

- *Dynamic Rolling:* This mode of motion occurs at forward speed in stern quartering seas, which can be of regular or irregular nature. Here all six degrees of freedom are coupled, where in addition to roll, surge, sway and yaw can exhibit large amplitude fluctuations. The motion is characterised by asymmetric rolling: the ship rolls heavily to the leeward side in phase with the wave crest (approximately) amidships and rolls back to the windward side in the wave trough, albeit with a shorter half-period and smaller amplitude. Due to the associated surging behaviour, the ship spends more time in the wave crest than in the trough, resulting in a periodic but asymmetric reduction in the crest and restoring (in the trough) of the righting arm. The roll period may exceed the natural roll period significantly. In the case of a capsize, the roll motion typically builds up over a number of wave encounters to a critical level, and the ship will usually capsize to leeward. Experimental evidence can be found in Kan et al. (1994), De Kat and Thomas (1998b) and Umeda et al. (1995).

- *Parametric Excitation:* Parametric excitation results from the time-varying roll restoring characteristics of a ship typically found in longitudinal waves. The periodic changes in static righting arm during the repeated passage of a wave crest followed by the trough can cause large amplitude roll motions. Roll motions occurring at approximately the natural roll period and simultaneously at twice the encounter period (encounter frequency equals half of natural roll frequency) characterise this mode of motion. The roll motion is of a symmetric nature and the maximum roll angles to port and starboard occur when a crest passes the midship area. The wavelength must be of the order of the ship length. In such circumstances, parametric rolling - also referred to as low cycle resonance - can result in capsizing. It can occur in regular and irregular waves. It has been observed in head seas (Dallinga et al., 1997), but parametric excitation in astern seas is typically more critical in terms of capsizing (Oakley et al., 1974). In particular, when a ship travels at the mean group speed in following seas, parametric excitation can occur during the passage (in a regular fashion) of a wave group with a sufficient number of encountered waves of critical height and length (De Kat, 1994). Experimental evidence can be found in Umeda, Hamamoto et al. (1995) and Hamamoto et al. (1996), for both regular and irregular waves. Analytical predictions have also been attempted (Boroday and Vilensky, 1997, Vilensky, 1995).

- *Resonant Excitation:* In principle large amplitude roll motions can result when a ship is excited at or close to its natural roll frequency. Roll resonance conditions are determined by the combination of GZ curve characteristics, weight distribution, roll damping, heading angle (e.g., beam seas), ship speed, wavelength and height. Experimental evidence can be found in Umeda, Hamamoto et al. (1995).

- *Impact Excitation:* Steep, breaking waves can cause severe roll motions and may overwhelm a vessel. The impact due to a breaking wave that hits a vessel from the side will affect the ship dynamics and may cause extreme rolling and capsizing (Dahle and Myrhaug, 1996). Possible damage to deck structures and subsequent water ingress are not considered here. This capsize mode is relevant especially to smaller vessels in steep seas. Experimental evidence can be found in Ishida and Takaishi (1990) and Ishida (1993).

- *Bifurcation:* In laboratory conditions, the roll response may jump from one steady state to another (larger amplitude) steady-state condition at the same frequency following a sudden disturbance. The experimental studies on these and other types of non-linear systems behaviour have so far been restricted to regular waves. An analytical approach to the behaviour in irregular waves indicates that bifurcations can persist also in narrow band seas (Francescutto, 1993). Experimental evidence can be found in De Kat and Thomas (1998b), Francescutto et al. (1994) and Kan et al. (1994).

Broaching. Broaching is related to course keeping in waves. Although there is no uniformly accepted mathematical definition of a broach, it represents the wave-induced undesired, large amplitude change in heading angle. A variety of broaching modes exist in regular and irregular waves:

- Successive overtaking waves (low speed);
- Low frequency, large amplitude yaw motions;
- Broaching caused by a single wave.

The first mode has been observed to occur in steep following seas at low ship speed, where the ship is gradually forced to a beam sea condition during the passage of several steep waves. The other modes occur at higher speed, typically at a Froude number Fn > 0.3. Experimental evidence of the first two modes can be found in De Kat and Thomas (1998b) and Oakley et al. (1974). The latter mode is usually characterised by quasi-steady surf-riding at wave phase speed and steadily increasing yaw angle. Experimental evidence can be found in De Kat and Thomas (1998b), Hamamoto, Enomoto et al. (1996) and Umeda (1998).

Other factors. Water on deck can occur in conjunction with (and hence influence) the capsize modes discussed above. Large amplitude relative motions and breaking waves can result in the temporary flooding of the deck, which from a stability viewpoint is relevant especially to vessels with bulwarks, such as fishing vessels (Hirayama et al., 1997, Shin, 1997, Yamakoshi et al., 1982). Free surface effects and sloshing can influence the ship motions (Francescutto and Contento, 1997). Furthermore, deck edge submergence results in loss of waterplane area and righting arm. If a bulwark is present, its submergence will influence the forces acting on the vessel (Grochowalski, 1989).

Wind does not necessarily influence wave-induced capsizing in astern seas. In beam waves, however, it may be important. Cargo shift as a consequence of large amplitude rolling and high accelerations can induce capsizing (Kawashima et al., 1979). A ship with bias due to shifted cargo is more prone to capsize than a symmetrically loaded ship (Cotton et al., 1996).

4. STATE OF THE ART REVIEW OF DAMAGE STABILITY

4.1 General

In the past, the ship damage stability problem has received little research attention, mainly because the numerical as well as experimental treatment of progressive flooding and capsize in a random seaway represents a very difficult undertaking. As a result quantitatively specific standards of residual stability have been introduced for the first time in the 1960 SOLAS Convention which only address the metacentric height (0.05m).

However, a number of major disasters involving a large loss of life have forced development in international regulations based either on deterministic or probabilistic approaches to assessing damage stability but ignoring in the main the physics of the problem at hand. At present, damage stability requirements for passenger vessels are generally based upon the deterministic principles introduced by the 1948 SOLAS Convention. Concerted action to address the water on deck problem of Ro-Ro vessels led to the next level of development involving the adoption of new stability requirements, notably SOLAS'90 as the new global standard and a regional standard known as the "Stockholm Agreement" to be complied to by the North West European Nations. Related to the latter and deriving from the uncertainties in the state of knowledge concerning the ability of a vessel to survive damage in a given seastate, an alternative route has also been allowed which provides a non-prescriptive way of ensuring compliance by performing physical model experiments (IMO SOLAS'95 Resolution 14). This represents a major development towards the adoption of performance-based standards by utilising state of the art knowledge to assessing ship safety against capsizing. The first major step in the development of probabilistic damage stability rules was the publication by IMO of Resolution A.265 for passenger vessels based on the work of Wendel (1960). These regulations used a probabilistic approach to assessing damage location and extent drawing upon statistical data to derive estimates for the likelihood of particular damage cases occurring and of surviving such damages. Lack of ability to determine the latter through a rigorous approach led to the adoption of experimentally derived results, carried out independently in the USA (Middleton and Numata, 1970) and the UK (Bird and Browne, 1973), to establish a simplified relationship between environmental and stability-related parameters for a damaged ship. This, in turn, allowed for estimates of the capsize resistance of a damaged ship in a given sea and for estimates of the associated probabilities. The next major step came in 1992 with the introduction of SOLAS B-1 containing a probabilistic standard for cargo vessels. Subsequently, IMO has focused on harmonisation of damage stability standards and this continues to date.

4.2 Modelling Capsize of a Damaged Ship

Numerical Simulation. Since the dynamic behaviour of the damaged vessel and the progression of the flood water through the damaged ship in a random seaway are ever changing, rendering the dynamic system highly non-linear, the technique used, of necessity, is time simulation. To this end, to study damage survivability effectively, developments have been directed towards: Damaged Vessel Dynamics; Water Ingress/Egress; Floodwater/Vessel Interaction.

Modelling has been attempted at various levels of complexity (De Kat, 1996, Papanikolaou, 1997, Vassalos and Turan, 1994, Vassalos 1998a) but the use of such a “tool” in its complete form, however, for routine design application is not within reach at present

Model Tests. In the recent past, especially after SOLAS'95 and the proposed model test method of IMO Resolution 14, a large number of experiments have been performed worldwide. Because of the originality and the extent of the obtained results, time is required to fully appreciate and systematically investigate the acquired knowledge. However, questions pertaining to the specification and uniformity of interpretation of the aforementioned model test method must be addressed on an urgent basis as it is currently being applied to ensure compliance of existing vessels with the Stockholm Agreement whilst discussions are underway for extending its application to new ships. Several issues have been raised relating to the preparation of the damage ship model, the simulation of the incoming seaway and the testing procedure (duration of the test, number of tests, initial conditions, etc.). It was considered, therefore, essential for the newly formed ITTC Stability Committee to address these issues and to put forward recommendations based on scientific principles and engineering know how with a view to facilitating its standardisation as its adoption by the international community, following discussions at the relevant committees of IMO.

The first impetus for systematically testing the capsize resistance of damaged ships followed the accident of the *Herald of Free Enterprise*. Model experiments by Dand, (1991), Schindler and Velschou (1994), Stubbs, et al. (1996) and Velschou and Schindler (1994) focused on the factors effecting side collision damage, similar to the work by Bird and Browne (1973). These experiments expanded the range of Ro-Ro hull forms tested to include modern Ro-Ro designs and investigated the effect of survivability enhancing devices such as internal bulkheads, flare, sponsons and buoyancy bags. The major change between this work and the work described by Middleton and Numata (1970) and Bird and Browne (1973) was that model motions were measured and video cameras were installed in the model to record the movement of water on the Ro-Ro deck. The study by Stubbs, et al. (1996) included measurement of depth of water on the Ro-Ro deck and relative motion at the damage location. The capsizing of the *Estonia* in 1994 provided the next stimulation for further interest in modelling damaged Ro-Ro ferry stability, focusing again on side collision damage in spite of the fact that both the *Estonia* and the *Herald of Free Enterprise* capsized with their hull intact with water entering the Ro-Ro deck from the bow door with the ships underway. Key contributions include Aanesland, (1996), Damsgaard and Schindler (1996), Ishida et al. (1996), Molyneux et al. (1997), Nattero and Blume (1996) and Noble et al. (1996). The techniques used were again an incremental development from the earlier work but this time more attention was paid to measuring the amount of water that accumulated on the Ro-Ro deck and the relative motion between the deck edge.

The most recent work on modelling of damaged Ro-Ro ferries has focused on understanding the factors that influence the vessel's ability to survive in waves, after it has been flooded (Harachuchi et al., 1998, Jost et al., 1998 and Vassalos 1998a). The models were instrumented to measure the amount of water collected on the car deck, with specific purpose to test the validity of the Stockholm Agreement. Other investigations addressed the effect of damage opening shape, number of degrees of freedom and wave slope on flooding rate and survivability, Vassalos, Conception et al. (1997). The shape of the damage opening and the nature of the edge of the damage, were both found to influence the results. In particular, it was noted that a rectangular opening, as prescribed by SOLAS regulations, would allow the vessel to survive a higher significant wave height than a damage opening with tapered sides and maximum width at the top. Similarly, if the damage opening has clean edges higher waves will be survived than if the edge of the hole has a plate bent back to prevent water draining off the deck. These studies are important information on the behaviour of the damaged ship in waves but most studies have only considered the simplest arrangements. The ability of the model to move freely during progressive flooding was also identified to be a major factor affecting survivability. Finally, flooding tends to be exacerbated with increased wave heights and smaller wave periods, as a larger number of higher crests would reach the deck level. It has been observed, however, that steep waves tend to diffract and break against the model side, thus giving rise to highly distorted crests that carry considerably less water. This is the reason why there seems to be a wave period resulting in maximum flooding.

One of the main results of systematic model experiments performed by Svensen and Vassalos (1998) and Vassalos, Turan et al. (1997) was the development of a semi-empirical relationship between the critical height of water on the deck, h, of damaged Ro-Ro ships and the significant wave height, Hs, of the operational sea state. Using these results in combination with numerical simulation results and calculations based on a Static Equivalent Method, Vassalos, Turan et al. (1997) suggested that the critical height of water on the Ro-Ro deck, measured from the mean sea surface, is proportional to $Hs^{1.3}$. Subsequent work on time-based survival criteria by Vassalos, Jasionowski et al. (1998) led to a modified relationship that includes the residual freeboard after damage: $h \propto Hs^{(0.97+0.46F)}$. These particular results are of great importance in that they present a exceedingly straight forward way of assessing capsize thresholds for passenger/Ro-Ro vessels when subjected to large scale flooding in a random seaway. In addition to experimental research addressing progressive flooding in a side collision damage scenario, three studies focused on flooding through open bow doors for a ship with forward speed (Dand, 1989, Noble et al., 1996 and Shimizu, et al., 1996). The techniques for this type of testing were slightly different to allow for forward speed, which in this scenario is of major significance. Dand (1989) focused on the physics of the water ingress into the car deck and on the effect of the accumulated water on the manoeuvrability of the ship. To investigate the latter a self-propelled, radio-controlled model was used. The car deck was empty but open to the waves. In the study by Noble et al.

(1996) models of two ferries were towed into head waves at different speeds, significant wave heights and trim conditions. The primary purpose of these experiments was to identify the safe limit for bow scooping. Water depth at the car deck, just inside the bow door, was measured using a sonic probe. A similar experiment was also undertaken by Shimizu et al. (1996) using a passenger Ro-Ro ferry model. It is interesting to note that the majority of experimental research described in the foregoing concentrated on a damaged model of a passenger Ro-Ro ferry, with initial condition representing final equilibrium after damage and drifting under wave action in beam seas. As a result, the range of hull form parameters has been relatively small. Notable exceptions are: Spouge (1986) who attempted to explain the loss of the *European Gateway* by a phenomenon he termed "transient asymmetric flooding"; Aanesland (1996) who investigated the effect of initial transients after damage; and Vermeer et al. (1994) who studied the motions and stability of Ro-Ro ships during the intermediate stages of flooding. The derived results, albeit inconclusive, tend to indicate that damage survivability is unaffected by initial transients with the exception of tests involving ships with marginal damage stability. Studies on the survivability of multi-hull vessels were also undertaken by Renilson and Manwaring (1998) and Vassalos et al. (1993).

5. TECHNIQUES FOR NUMERICAL MODELLING OF INTACT STABILITY

This chapter provides a discussion on numerical modelling aspects related to the capsize modes discussed in chapter 3. Furthermore, a general survey of relevant techniques for the prediction of large amplitude ship motions is provided. The bibliography addresses published recent research in this area with emphasis on current (1990s) developments.

Modelling of Capsizing. Even though there are many ship types, the focus of numerical stability research has been directed at conventional mono-hulls (general cargo, fishing, naval, Ro-Ro ships). Intact stability of unconventional ships, including high-speed craft, has been investigated mostly – if at all – experimentally and is being dealt with by the ITTC Committee on Model Tests of High-Speed Marine Vehicles and the Committee on Safety of High-Speed Marine Vehicles. Several numerical models have been developed for conventional ships but even in this case a rather large number of modelling simplifications are typically made. Table 3 summarises those aspects, which should be taken into account in modelling each capsize mode identified in chapter 3. Systematic studies on establishing the sensitivity of relevant factors can be found in De Kat (1990) and Umeda (1997).

As a generalisation, the techniques employed in the existing models can be classified as follows:

- Hybrid time domain
- Non-linear time domain
- Non-linear system dynamics
- Analytical
- Other (e.g., frequency domain; higher order Volterra method)

Aspects related to the more commonly used techniques are outlined next:

- *Hybrid Time Domain:* This type of modelling can deal with ship behaviour up to capsizing. While hydrodynamic forces are mainly linearly modelled, some non-linear terms essential to capsizing are added. As a result of non-linearities, these models have been used in the time domain with given initial conditions in spite of involvement of frequency domain techniques (Bandyopadyay and Hsiung, 1994, De Kat, 1990, De Kat et al.,1994, Hamamoto et al., 1992, 1994, 1995, 1996, 1997, Hua, 1992,

Table 3: Key Factors in the Modelling of Intact Ship Capsize

Modes Factors	Static loss of stab.	Dyn. rolling	Param. excitat.	Reson. excitat.	Impact excitat.	Bifur-cation	Broach.
Above water hull shape	✓	✓	✓		✓		
GZ curve (including large angles)	✓	✓	✓	✓	✓	✓	✓
GZ variation in waves	✓	✓	✓				✓
KM variation with speed (if appropriate)	✓	✓	✓				✓
Pitch quasi-static	✓						✓
All 6 d.o.f.		✓					✓
Heel/yaw coupling		✓					✓
Surge response	✓						✓
Roll Damping		✓	✓	✓	✓	✓	
Integration of wave up to free surface		✓	✓				✓
Resistance and propulsion characteristics		✓					✓
Bilge keels, anti-roll fins, skegs, etc.		✓	✓	✓	✓	✓	✓
Rudder and auto-pilot		✓					✓
Roll and sway				✓	✓	✓	

1990, De Kat et al., 1994, Hamamoto et al., 1992, 1994, 1995, 1996, 1997, Hua, 1992, Hua and Rutgersson, 1994, Neves et al., 1994, 1997, Oakley et al., 1974, Ottoson and Bystom, 1991, Renilson and Tuite, 1995, 1997, Tuite and Renilson, 1998, Vassalos and Maimun, 1994, Vassalos and Tsangaris, 1997). General aspects include:

- Linear potential flow theory for computation of diffraction and radiation forces: strip theory (Hamamoto and Munif, 1998, Nabergoj et al., 1997) or 3-d (Huang & Hsiung, 1994) with or without forward speed
- Hydrodynamic memory effect (Bailey et al., 1995, Hamamoto and Saito, 1992)
- Froude-Krylov forces obtained by integration of wave-induced pressure up to the undisturbed free surface for arbitrary body position
- Viscous effects (eddy shedding, drag): empirical model (Penna et al., 1997)
- Manoeuvring: empirical model
- Ship resistance: empirical model
- Motion control, lifting surfaces: can be included
- Course keeping: arbitrary auto pilot
- Waves: linear (regular or irregular)
- Wind effects: empirical
- Water on deck (Cardo et al., 1997, Francescutto and Contento, 1997, Huang et al., 1998, Huang and Hsiung, 1996a, 1996b, 1996c, 1997, Lee and Adee, 1994).

- *Non-linear Time Domain:* Non-linear time domain models are being developed to consistently take all elements into account. However, further developments are still required for practical use (Bass, 1997, Engle et al., 1997, Kring et al., 1997, Lin et al., 1994, Magee, 1997, Pawlowski and Bass, 1991, Shin et al., 1997, Zhu and Katory, 1998). General aspects include:

- Fully non-linear 2-d potential theory without forward speed effects (Contento, 1997, Tanizawa and Naito, 1998) or higher order potential flow theory with forward speed effects and wave resistance (Huang and Sclavounos, 1997, Sclavounos et al., 1997)

- Integration of hull pressure up to disturbed free surface for arbitrary body position.

- *Non-linear Systems Dynamics*

  This approach explores critical behaviour among the solution sets of a non-linear equation from given initial conditions. Thus, it can directly assess a critical condition for capsizing. For beam seas, the emphasis is placed on a relationship with chaos; for quartering seas, efforts have been concentrated into broaching.

  Beam seas - (Cotton et al., 1996, Donescu and Virgin, 1994, Falzarano, 1995, Kan 1993, Kan and Taguchi, 1990, 1994, MacMaster and Thompson, 1994, Nayfeh and Khdeir, 1986, Rainey and Thompson, 1991, Soliman, 1990, Spyrou et al., 1997, Thompson, 1997). General aspects include:

- Linear exciting forces
- Non-linear restoring forces or piece-wise linear restoring force (Belenky, 1998)
- Linearised or non-linear roll damping (Spyrou, 1998)
- Periodic motions
- One or more degrees of freedom (Falzarano, 1994, Nayfeh and Oh, 1995)
- Regular or Irregular waves (Lin and Yim, 1995, Jiang et al., 1994, 1996).

Quartering seas - (Spyrou, 1995, Spyrou, 1996a, 116b, 196c, 1997, Umeda, 1998, Umeda et al., 1997, Umeda and Renilson, 1992, 1994, Umeda and Vassalos, 1996). General aspects include:

- Linear potential flow theory for computation of hydrodynamic lift forces - slender body theory. (Ananiev and Loseva, 1994, Ananiev, 1995, Umeda, Yamakoshi et al., 1995)
- Linear Froude-Krylov forces
- Non-linear roll restoring moment: with or without wave effect
- Linear roll damping: with forward speed effect
- Manoeuvring: empirical model (Vassalos and Spyrou, 1990a, 1990b)
- Ship resistance and propulsion: empirical model
- Motion control, lifting surfaces: can be included
- Waves: linear (regular)
- Periodic motions and surf-riding equilibrium points
- 4 degrees-of-freedom model: surge-sway-yaw-roll with autopilot: quasi-static heave & pitch taken into account (Matsuda et al., 1997, Umeda, 1996).

- *Direct Probabilistic Assessment*

  This approach evaluates directly capsizing probability per second in irregular seaways without repeating random realisations.

  Beam seas - General aspects include:

- Phase plane method (Sevastianov, 1979, Umeda et al., 1992, 1993)
- Piece-wise linear method (Belenky, 1994, 1995)
- Markov process theory (Nechaev, 1994, 1995)

Quartering seas - General aspects include:

- Phase plane method (Umeda and Yamakoshi, 1994)
- Markov process theory (Haddara, 1974, Nekrasov, 1994, 1997)

The first two (time domain) techniques are in principle able to accommodate water on deck dynamics by coupling a CFD model of the fluid behaviour to the ship motion model. (Armenio et al., 1996).

Guidelines for experimental testing of intact stability are given in Appendix A.

6. TECHNIQUES FOR NUMERICAL MODELLING OF DAMAGE STABILITY

General. Existing numerical models cover the following aspects:

- *Pioneering model* (Vassalos and Turan, 1994)
- Side damage
- Non-linear sway-heave-roll motions
- Wind and wave excitation
- Regular or irregular waves
- Hull hydrodynamics: strip theory
- Internal water dynamics: static model
- Water ingress: hydraulic model
- *Advanced model*
- Side or loss of bow door (Chang, 1995)
- Nonlinear motion with 6 degrees of freedom with mass change due to water accumulation (De Kat, 1996 and Vassalos et al., 1997)
- Wind and wave excitation
- Regular and irregular waves
- Hull hydrodynamics: 3-d potential theory with memory effect (Huang and Hsiung, 1997, Papanikolaou et al., 1997, Vassalos and Letizia, 1995)
- Internal wave dynamics: sloshing model with Navier-Stokes equation (Armenio, et al., 1996) or shallow water equation (Chang and Blume, 1997); simplified dynamic model (Francescutto and Contento, 1997)
- Water ingress: Bernoulli's equation (Vassalos, Conception, et al., 1997)
- Nonlinear system dynamics: Chaos and bifurcation (Murashige and Aihara, 1998).

Numerical Modelling Techniques. The following areas have been identified as the main focus for mathematical modelling of the behaviour of a damaged vessel:

- *Damaged Vessel Dynamics*: A non-linear 6 d.o.f. seakeeping model that allows the vessel to drift as well as allows for changes with time in its mass, centre of mass, mean attitude, environmental excitation and hydrodynamic reaction forces.
- *Water Ingress/*Egress: An adequately accurate water ingress /egress model that allows for multiple-compartment flooding in the presence of oscillatory flows and at times of shear flows in extreme wave conditions is a prerequisite to undertaking any investigations on damage survivability.
- *Floodwater/Vessel Interaction*: A study of damage survivability involves two distinct but intrinsically interrelated and highly interacting processes, namely ship motion and flooding. The vessel motion influences considerably and directly the flooding process and conversely, flooding affects both the vessel motion and her attitude. It is essential, therefore, to take both phenomena into consideration when studying the evolution of either. However, the non-stationarity in the vessel motion introduced by the water accumulation coupled with the intermittence of the flooding process itself and the severe non-linearities in the ensuing dynamic system, demand great care in dealing with the many issues of this complex problem.

It is generally accepted that exact modelling of the fully non-linear behaviour of intact and damaged ships in waves is beyond the range of existing mathematical models. However, it seems that because of the quasi-static nature of the final phase of the capsize process of a flooded ship, existing, state of the art mathematical tools, properly accounting for the change of the vessel's hydrostatic characteristics due to flooding and large inclinations, can effectively contribute to the prediction and understanding of the capsizing process, as well as to the identification of relevant environmental and ship parameters leading to capsize. It is also understood, that state-of-the-art computer simulation programs, properly validated by systematic comparison with physical model test results, can eventually lead to a rational assessment of the damage stability of ships as a significant aid, if not "equivalent", to the current physical model testing of Ro-Ro passenger ships for compliance with the Stockholm Agreement (IMO SOLAS'95 Resolution 14).

A variety of models are in use for addressing the damage stability problem of ships in waves, particularly 6 d.o.f. models, as shown by Huang et al. (1996), Papanikolaou, (1997), Papanikolaou et al. (1997) and Vassalos et al. (1995 and 1997) and strip theory like, quasi 2-d approaches, as shown by Chang et al. (1997) and Vassalos et al. (1994). Both types of methods give satisfactory and useful results for practical applications. It is necessary to perform a systematic "benchmark" testing of existing methods and computer codes, available today on a world-wide basis, with the aim to determine the reliability of existing tools for practical applications. This is further discussed in chapter 8.

Modelling the Flooding Process. The modelling of the flooding process remains a critical issue, as pointed out by Vassalos et al. (1994 and 1997). Among other issues, to be reconsidered, both experimentally and theoretically, are the possible shapes of the damage opening. The values of the semi-empirical coefficients K used in mathematical models were reconfirmed to be about 1.1 for unidirectional and 0.7 for bidirectional flows, respectively.

To consider the effect of floodwater, present models use a quasi-static approach where the internal water surface is assumed to be horizontal and parallel to the external one. This assumption provides sufficiently accurate results at the final stages of capsize. However, in several cases, depending on the relative magnitude of the floodwater mass and the internal water depth, internal resonances and interactions with the overall ship dynamics will produce additional dynamic effects, which might significantly affect the ship motions and the vessel's survivability. Some evidence on this aspect, and methodology of approach is given by Papanikolaou (1997), and Papanikolaou et al. (1997).

Other approaches, suggested by Vassalos et al. (1997), were to build up a comprehensive database through a systematic series of model experiments, or to employ CFD techniques for describing the internal water mass motion, along with the ship motion simulation model. Finally, Chang et al. (1997), employed a shallow-water equations model in connection with Glimm's method to obtain a solution for the case of low fill depth compared to the tank width, however without an improved model for the water outflow. This gave good results only for small heel angles (less than about 25 degrees).

Guidelines for experimental testing of intact stability are given in Appendix A.

7. GUIDELINES FOR BENCHMARK TESTS

7.1 General

The aim of the comparative study, being co-ordinated by the ITTC Specialist Committee on Ship Stability, is the numerical benchmark testing of existing software tools, and of mathematical models in general, developed by ITTC member organisations and other qualified research institutions, on the intact and damage stability of two standard ships. The numerical results will be compared with available experimental data from collaborating institutions, and with experimental data with the eventual aim of establishing a state of the art in the field of available numerical methods and computer simulation programs for assessing a ship's dynamic stability in intact and damage condition under a variety of environmental and ship operating conditions.

7.2 Specification of Test Ships

Two test ships (Ships A & B) have been selected for the subsequent studies. Ship A, a 23,720 tonnes displacement containership, investigated using systematic model experiments at Osaka University (ship geometry and mass data, service speed and other particulars are given in Hamamoto, 1998). Ship B, a 12,000 tonnes displacement passenger/car ferry, known as “NORA”, studied using systematic model experiments at DMI, MARINTEK and the University of Strathclyde (ship geometry and mass data, service speed and other particulars are given in Vassalos, 1998).

7.3 Specification of Environmental Data

The specification of environmental data

refers to the definition of the benchmark incident wave conditions. Benchmark tests should be performed for the following conditions:

Regular Wave Conditions (Ships A & B).

- wavelength to ship length ratio: 0.25 to 3.00 in steps of (0.25)
- wave height to wavelength ratio: 1 to 25 (constant), alternatively, in addition, 1:20 and 1:30 for specific tests (see 7.1).

Irregular Seaway Conditions (Ship B).

- JONSWAP sea spectrum according to specifications related to the operation of Ship B.
- Significant wave height 4.0 m, peak period 8.0 sec., $\gamma = 3.3$.

7.4 Specification of Benchmark Tests

Initial Motion Studies on Ships A & B.

- *Initial Calm Water Studies*: Numerical Simulation of the time histories for 10°/10° Zig-Zag test and 35° Turning Manoeuvre for Ship A at $F_n = 0.25$, model experimental results provided by Hamamoto, 1998.

- *Seakeeping - Zero Forward Speed Case:* 6DOF Response Amplitude Operators (frequency domain techniques) or Time Histories (time domain techniques) of intact Ships A and B for varying wavelength, as specified in 7.3, and wave headings as follows: 0^0 (following seas), 15^0, 30^0, 45^0, 90^0, 135^0 and 180^0 (head seas).

- *Seakeeping - Non-Zero Forward Speed Case:* At service speed, 6 d.o.f. Response Amplitude Operators (frequency domain techniques) or Time Histories (time domain techniques) of intact Ship A, for $\lambda/L = 1.5$, wave headings as specified above and varying speed, namely $F_n = 0.20$, 0.30 and 0.40.

Intact Stability Studies on Ship A.

- *Non-Zero Forward Speed – Regular Waves Excitation:* Capsize simulation of intact Ship A for the following environmental and ship conditions:

- wave length to ship length ratio, $\lambda/L = 1.5$,
- wave height to length ratio $H/\lambda = 1/25$ (standard), study on the effect of change of wave height between 1/20 and 1/30,
- GM=0.15m (constant),
- Case A: Wave heading: 0^0 (following seas), Fn = 0.20 (capsize).
- Case B: Wave heading: 30^0 (stern quartering seas), Fn = 0.40 (capsize),
- Case C: Wave heading: 30^0 (stern quartering seas), but for Fn = 0.30 (non-capsize),
- Case D: Wave heading: 45^0 (stern quartering seas), Fn = 0.20 (non-capsize)

Damage Stability Studies on Ship B.

- *Zero Forward Speed – Irregular Seaway Excitation:* Capsize simulation of damaged Ship B in beam (90° heading) irregular seas (as specified in 7.3), zero forward speed. Ship loading according to KG boundary curve, damage opening according to SOLAS'95 Resolution 14. Relevant data can be found in Vassalos, (1998) for three characteristic cases: capsizing, marginal, non-capsizing.

An overview of the test cases described above is provided in Tables 4-7.

7.5 Deliverables

- Brief description of the method employed including modelling of floodwater (damage studies).
- Completed ITTC Stability Committee survey questionnaire.
- Grid/panelling details.
- Results for the initial calm water study: Manoeuvring test for Ship A, roll motion and rudder angle time histories.
- Results of zero speed case: 2 Ships x 6 RAOs (where applicable all 6 d.o.f.) x 7 wave headings (charts, tables and/or time history responses).

Table 4: Zero Speed Seakeeping Cases for Ships A & B (Intact Ship, Regular Waves)
[$H/\lambda = 1/25$]

λ/L Heading	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50	2.75	3.00
180^{0}	√	√	√	√	√	√	√	√	√	√	√	√
135^{0}	√	√	√	√	√	√	√	√	√	√	√	√
90^{0}	√	√	√	√	√	√	√	√	√	√	√	√
45^{0}	√	√	√	√	√	√	√	√	√	√	√	√
30^{0}	√	√	√	√	√	√	√	√	√	√	√	√
15^{0}	√	√	√	√	√	√	√	√	√	√	√	√
0^{0}	√	√	√	√	√	√	√	√	√	√	√	√

Table 5: Non-Zero Speed Seakeeping Test Cases for Ship A (Intact Ship, Regular Waves)
[$H/\lambda = 1/25$, $\lambda/L = 1.50$]

Fn⇒ Heading	0.20	0.30	0.40
180^{0}	√	√	√
135^{0}	√	√	√
90^{0}	√	√	√
45^{0}	√	√	√
30^{0}	√	√	√
15^{0}	√	√	√
0^{0}	√	√	√

Table 6: Intact Stability Test Cases for Ship A (Nonzero speed, Regular Waves)
[$H/\lambda = 1/25$ (1/20 – 1/30), $\lambda/L = 1.50$, GM = 0.15m]

Fn⇒ Heading	0.20	0.30	0.40
45^{0}	√ non-capsize		
30^{0}		√ non-capsize	√ capsize
0^{0}	√ capsize		

Table 7: Damage Stability Test Cases for Ship B (Zero Speed, Irregular Waves)
[JONSWAP Spectrum, Hs = 4.0m, Tp = 8.0sec, $\gamma = 3.3$, unidirectional (90^{0}, beam seas)]

KG⇒ Heading	KG1	KG2	KG3
90^{0}	√ non-capsize	√ marginal	√ capsize

- Results of non-zero speed case: 1 Ship x 6 RAOs (least requested information on roll, pitch and yaw responses) x 7 wave headings x 3 speeds (charts, tables and/or time history responses).

- Results on the capsizing of intact ship: 4 cases, with possible variation of wave height (3) providing in total a minimum of (4x3=) 12 cases (time history responses; least requested information on roll response - additional information on heave and pitch, where available).
- Results on the capsizing of damage ship B: 3 cases, with possible variation of KG (3) providing in total a maximum of (3x3=) 9 cases (time history responses; least requested information on roll response - additional information on heave and pitch, where available).

8. CONCLUSIONS AND RECOMMENDATIONS

8.1 General Technical Conclusions

Prediction of extreme behaviour of intact ships requires an approach, which involves a combination of seakeeping and manoeuvring models. The resulting level of complexity has made it necessary to develop prediction tools focused on specific modes of capsize rather than addressing the problem holistically.

Ship capsize in an irregular seaway is a rare event, necessitating tests of long duration to ensure statistically valid results. As a consequence, and to assist in understanding the many parameters influencing this complex phenomenon, most experimental work has concentrated on regular waves. Although many member organisations have developed experimental techniques they have been limited to specific aspects of capsize, particular to each facility and there have been scarcely any attempts to produce corroborative evidence to verify these techniques.

Numerical simulation models have been developed, capable of predicting with good engineering accuracy the behaviour of a damaged ship near the capsize region and hence capsize resistance when the ship is subjected to large scale flooding. A rigorous validation program is now required to enable these models to become useful engineering tools for design and regulatory purposes.

Modelling of the floodwater/vessel interaction in the general case still remains elusive.

A model test method has been proposed by IMO, which addresses a simplified scenario of side collision damage for Ro-Ro ferries. For this scenario a comprehensive set of data has been produced by a large number of facilities, which provides a strong basis to standardise model test techniques and validate numerical models. It is now necessary to generalise this procedure to cover other vessel types and damage scenarios.

8.2 Recommendations to the Conference

Adopt the proposed guidelines for experimental techniques for testing of intact and damage stability (Appendix A).

Encourage ITTC member organisations to participate in the planned benchmark programme.

It is strongly recommended that the Conference make every effort to attain observer status at IMO so that it can contribute to the scientific evolution of the regulatory process.

8.3 Recommendations for Future Work

Co-ordinate the proposed benchmarking programme, collate and assess the results to determine the capability of Member Organisations' to test (numerically and experimentally) intact and damage stability of ships for design and regulatory purposes.

Develop and validate generalised mathematical models to assess resistance against capsize of intact and damaged ships to be routinely used for design and regulatory purposes.

Monitor the implementation of the proposed experimental procedures for experimental testing of intact and damage stability.

Rationalise the symbols used routinely by relevant authorities in ship stability to enable a recommendation to be made to the 23rd ITTC and to IMO to encourage the adoption of standard symbols.

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9.2 Nomenclature

StabWshop	Int. Workshop on Ship Stability
CRN	Co-operative Research, Navy
STAB	Int. Conf. on Stability of Ships and Ocean Vehicles
JSNAJ	Journal of the Soc. of Naval Architects of Japan
TRINA	Trans. of the Royal Institution of Naval Architects
TSNAME	Trans. of the Society of Naval Architects and Marine Engineers
WEMT	West European Marine Technology Conf.
WEGEMT	European Association of Universities in Marine Technology and Related Sciences

10. ACKNOWLEDGMENTS

The committee would like to thank wholeheartedly all the organisations and individuals who contributed to the work of the committee over the last three years.

APPENDIX A: GUIDELINES FOR EXPERIMENTAL TESTING OF INTACT AND DAMAGE STABILITY

A.1 Guidelines for Model Tests on Intact Stability

Objectives. The fundamental objectives of these tests are to study the behaviour of a ship in extreme conditions and to determine threshold for capsizing and extreme motion.

In regular waves this will be presented as a function of the main parameters such as: KG, F_n, ψ, H_w/λ and λ/L, and in irregular waves as a function of the main sea state parameters, KG, Fn and ψ.

Model Building. The model hull should be complete up to the upper weather deck including forecastle and bulwarks and be sufficiently rigid with a smooth finish. The whole model should be watertight in order to protect the instrumentation. Watertight hatches with a clamp fastening for quick opening and closing are necessary for allowing easy access to the inside of model during the tests.

Superstructure. The influence of superstructure on the ship motion loading to capsize should be considered, taking into account appropriate regulations.

Appendages. Appendages related to ship motion should be fitted and the report should state which appendages were fitted during the tests.

Steering. It is necessary for the free running model to have a steering system, either manual steering or an autopilot. The characteristics of the autopilot and the steering system are to be clearly stated in the report.

Propulsion. It is necessary for the free running model to have a main propulsion system, including speed and direction control, reduction gear, shafting, propeller and a power supply system consisting of rechargeable batteries capable of confined operation in the motion of the model. Propeller characteristics should be stated in the report.

Scale. The model should be built to scale and should be large enough to contain the necessary instrumentation for propulsion system, steering system, ship motion measuring system and ballast adjustment.

$$W_m = W_S \left(\frac{L_m}{L_S} \right)^3$$

Experimental set up. Preference should be given to unrestrained model testing. When constraints are applied for particular tests, full details of the restraining system must be reported and care must be taken to avoid undesirable effects.

Instrumentation. The instrumentation system should be appropriate to the model and type of test carried out. For ship motion measurement preference should be given to non-contact measurement systems.

Calibration. In order to ensure accurate operation of instrumentation, calibrations must be carried out and reported, preferably following codes of practice conforming to ISO 9000 procedures.

Measurements. Motions of the model, propulsor and steering performance should be simultaneously measured and recorded as appropriate to the purpose of the test. Wave height measurements should be made with a wave probe fixed in the tank on open water. All quantities measured must conform to the recommendations of the ITTC Quality Control Group regarding uncertainty analysis. Tests should be recorded visually, either by film or video, preferably in a way allowing scaling of time.

Tank Dimensions. The seakeeping and manoeuvring basin with wave maker may be suitable for free running and captive model tests. The size and depth of the tank should correspond to the size of model and type of tests to be conducted to avoid blockage, reflection and unwanted bottom effects *etc*.

Wave Generation and Documentation. Regular or irregular waves can be used for the free running and restrained model tests. Tests should be carried out in regular waves to provide adequate data for a range of wavelengths from $0.75L_{WL}$ to $2.5L_{WL}$ and including extreme wave steepness up to 1/10. Tests in regular beam seas should be carried out to provide adequate data for a range of wave periods from $0.4T_\phi$ to $1.2T_\phi$ and including waves of extreme steepness. Tests should be carried out in irregular waves simulating a specific severe seaway on a predetermined course and speed. In the absence of information on specific spectrum data, an ITTC spectrum should be used.

Wind. The effect of wind pressure on the model may be taken into account in an appropriate way.

Ballasting/Loading. The model should be ballasted to the appropriate displacement and loading condition for the ship.

Centre of Gravity and Radius of Gyration. Weights should be adjusted to achieve the correct position of the centre of gravity and radius of gyration in the transverse and longitudinal directions. The method of doing this and the values of radii of gyration in roll, pitch and yaw should be included in the report. In the absence of more accurate knowledge a value of 0.4B should be adopted for the roll radius of gyration and $0.25L_{WL}$ for both the pitch and yaw radii of gyration.

Roll Decay Test. The roll decay test should be carried out to obtain the natural roll period T_ϕ and the damping coefficients of the model in the test condition at zero and forward speeds if appropriate. Full details of the experiment and all roll damping, including time histories, should be included in the report.

Propulsion Test. Where appropriate, the speed must be calibrated for smooth water by running the model along a measured distance. The resulting speed can be obtained as a function of propeller revolutions, which are to be held constant by the propulsion motor.

Autopilot Test. If applicable, the autopilot control system can be set up as a Proportional-Differential control circuit. Thus, the rudder angle δ is determined by the yaw deviation ψ from the prescribed course and the yaw rate $\dot{\psi}$ as follows:

$$\delta = C_1\psi + C_2\dot{\psi}$$

where, C_1 is the coefficient of rudder to yaw ratio, C_2 the coefficient rudder to yaw rate ratio and the model scale ratio $(C_2 / C_1)_m$ corresponds to the ship scale ratio $(C_2 / C_1)_s$ according to the relationship:

$$\left(\frac{C_2}{C_1}\right)_S = \left(\frac{L_S}{L_m}\right)^{1/2} \cdot \left(\frac{C_2}{C_1}\right)_m$$

Rudder response characteristics are to be reproduced correctly and reported.

Start-Up Condition. Prior to the start of the tests a datum for all instrumentation used must be established. This must be checked after completion of the tests if appropriate. Particular attention has to be paid to start up transients and the start up condition fully reported.

Duration of Test. In regular waves the number of waves encountered by the model should be large enough to reliably measure the motions of the model leading to capsize.

Number of Tests. Taking into account the nature of extreme ship motions, sufficient tests in irregular waves should be undertaken.

Model Test Method. The model in the specified loading should be floating in calm water and then encounter the generated wave train with the specified speed and heading. In the case of following and quartering seas, the model should be situated near the wavemaker first. After the wave train propagates enough in the model basin, the model propeller revolutions should be increased from zero to the specified value and the steering system should be activated where appropriate. In irregular waves, special attention should be paid to the modelling of encountered wave groups.

Capsize Time Series: In order to determine the causality for capsizing, the time series data should be recorded and analysed. The main items to be measured as functions of time are: model speed; roll angle; pitch angle; yaw angle; rudder angle; and wave height.

A.2 Guidelines for Model Tests on Damage Stability

Introduction. The majority of experiments carried out to date in this area have been for Ro-Ro passenger ships. However, the general principles should apply to any ship type. The purpose is to provide ITTC Member Organisations with a sound scientific basis for carrying out the tests. Note that these procedures do not consider selection of the ship or sea conditions to be tested.

Model Construction. The capsizing of a flooded model is a very demanding experiment. It requires models constructed to a high quality, with good strength and stiffness properties. It is particularly important to emphasise how difficult it is to construct a model to be used for these tests which is free from leaks. In addition, sections of the model must be watertight, and other sections of the model must flood and be drained. It is recommended that stiffness and flooding characteristics are tested and corrected prior to the start of any experiments.

Scale. Minimum model scale should be 1:40. In no case should the overall length of the model be less than 3.0 metres.

Hull and Deck. The model shall be complete up to the main deck, with the correct shear and camber on the deck. The hull shall be divided into compartments, with watertight bulkheads in between. The flooded compartments on the model must be geometrically similar, in terms of flooded volume and free surface areas, to those on the ship. Construction materials for the model must be selected to meet this objective. Care must be taken to build cross-flooding arrangements and other small diameter ducts sufficiently oversize to allow for free flow of water or air. Special devices, such as deck drains, should be scaled geometrically unless this results in dimensions being sufficiently small for viscous effects to be significant, when care must be taken to avoid scale effects. It is a good idea to fit transparent decks, to allow flooding or leakage to be observed.

Superstructure. The external geometry of the ship superstructure must be scaled, up to the point where it no longer influences ship motions at large angles of heel. In the case of a Ro-Ro ferry, the superstructure will be significant. The internal geometry of the floodable parts of the model superstructure must be geometrically similar, in terms of flooded volume and free surface area, to those on the ship. Construction materials for the model must be selected to meet this objective. The uppermost deck of the superstructure should be made of transparent material, so that water movement on the main deck can be seen. This arrangement also allows for adequate light, if video cameras are mounted inside the model, to view water movement on the main deck.

Appendages. Major appendages likely to have an effect on roll motion, such as bilge keels, must be fitted. Other appendages, such as: fin stabilisers, shaft bossings, rudders, propellers, skegs, bow thrusters etc. need not normally be fitted for experiments where the model is disabled and drifting.

Damage Opening. For testing associated with Resolution 14 of SOLAS'95 the damage opening is specified by the Convention. This results in a rectangular hole in the side of the hull and superstructure, with a triangular hole in the main deck. Otherwise it is recommended that the holes in the hull and superstructure have tapered sides, more representative of the damage caused by the bow of a ship. This means that the damage is wider at the top than at the bottom. It is assumed that the hull and superstructure damaged during the collision have been removed from the ship. Therefore, the edges of the damage should be sharp.

Cargo, Flooding and Permeability. In the case of Ro-Ro ferries, the models will be tested with the car deck empty, until more information is available concerning the flow around vehicles on the car deck. Also, it is assumed that the cargo has not shifted during the collision, or at any other time. Any downflooding through the main deck must be modelled accurately. Also, any cross flooding between floodable compartments must be modelled correctly. The permeability of floodable spaces below the main deck must be modelled correctly. If no information is available for a specific ship, then the following values are recommended:

- Void spaces	100%
- Passenger or accommodation spaces	80%
- Engine room	70%
- Machinery spaces	70%

Instrumentation: Minimum requirements for instrumentation are: time histories of wave height (close to the model); and roll angle. It is desirable to measure the additional parameters listed below:

- model motion and attitude in 6 d.o.f.
- relative motion between deck and wave surface at damage opening
- volume of water on car deck
- wave elevation near the wavemaker(s)

Power may be supplied to the instrumentation via an umbilical cable. It is not recommended to fit batteries inside the model, since these may become damaged during capsize. Similarly data may be recovered via an umbilical cable. Umbilical cables must not interfere with the motion of the model in any way. Radio telemetry is a good alternative system for data recovery from the model. All data should be stored as synchronised time histories, at a minimum sampling frequency of 20Hz. Video records of the experiments are also extremely useful for interpreting the results.

Calibration. All sensors should be calibrated according to ISO 9000 standards or equivalent. Any systems, which rely on data from combined signals, such as integration of depth of water on deck from point measurements, should be checked with known loads in static and dynamic scenarios.

Ballast and Weight Distribution. The fully instrumented model should be checked for its mass distribution properties.

The intact model must float in calm water at the operating draft and trim corresponding to the ship. If it is not practical to check these values in water then they must be checked in air by swinging the model as a pendulum. The radii of gyration for pitch and roll (in air) must correspond to the equivalent values for the ship. If these are not known then the following values may be assumed:

- Pitch	0.25 L_{WL}
- Roll	0.4 B

where, L_{WL} is the waterline length of the model and B is the maximum beam. These values must be checked by swinging the model in air, in a manner similar to that used for seakeeping experiments. Either a bifilar pendulum or a special frame can be used, depending on the standard procedure at the facility. Vertical centre of gravity must be correct, and must be checked by an inclining test. The natural roll period should be determined from a roll decay test. This should be done in an area where reflected waves do not influence the results. The natural roll period of the flooded model, with dry decks, must be determined from a roll decay test. Care must be taken not to flood the main deck during this test if the residual freeboard is low. It is also desirable to carry out an inclining test for the flooded model. This, however, can be difficult, if the model has inherently low stability or a very low freeboard after flooding. It is desirable to check the large angle stability of the model against the calculated values, at least up to the point of maximum righting moment.

Experimental Set-Up. It is documented that reduced degrees of freedom increase the flooding rate. Therefore, the model should remain free from restrains at all times during the testing.

Tank Dimensions. It is usual to carry out damaged stability model tests (especially for Ro-Ro Ferries) in towing tanks. The model should be no longer than 75% of the width of the tank. This is to minimise interference from waves reflected from the walls of the tank.

Wave Generation. Damage stability model experiments for design evaluation must be carried out in irregular waves. It has been observed that flooding and drainage patterns in regular waves are unrealistic compared to irregular waves. Wave signals must be random for a minimum period equivalent to at least 30 minutes for the ship (based on Froude scaling). Wave spectra used during the tests must be reported and matched with the nominal values over the full repeat period. As a minimum, measured values of significant height and peak period ($Tp=2\pi/\omega_p$) must be reported.

Wind and Current. Wind and current need not be modelled.

Start-Up Condition. The flooded model is positioned in the tank, approximately 15 metres away from the wavemaker(s). If this is not practical the model should be far enough away from the wavemaker(s) to avoid breaking wave transients which occur at the wavemaker. The best position for towing tank carriage is between the model and the wavemaker. Here it provides a solid structure for mounting gear to recover the model after capsize. It is also a good position for video cameras and observing the experiments. Prior to starting each experiment, the draft, trim and heel of the model must be checked. It is particularly important to make sure that there is no water in the buoyancy compartments at the start of a test. Data collection should start in calm water, before the waves reach the model. This provides a datum level for each signal.

Model Experiments. The model is allowed to drift under the action of the waves. If necessary, guide ropes can be fitted to the model. These are kept slack except for short times when they can be used to keep the model on course, and then released again. However, if the model has a natural tendency to drift at a steady angle, this must not be corrected.

The Specialist Committee on Stability

Committee Chair: Prof. Dracos Vassalos (Univ. of Strathclyde)
Session Chair: Prof. Hong-Cui Shen (CSSRC, China)

I Discussions

Contribution to the Discussion of the Report of the 22nd ITTC Specialist Committee on Ship Stability

By Masataka Fujino

First, I would like to highly appreciate intensive and comprehensive work done by the Specialist Committee on Stability.

Recently, IMO tends to adopt performance–based criteria or appreciate validation in the light of model experiment in towing tanks. As a result, in Japan, Ship Research Institute and National Research Institute of Fisheries Engineering have conducted many capsizing model tests as their major tankery work. However, experimental technique of such tests has not yet been established. Although that is one of the tasks of this Committee, the guideline presented in the Committee Report for damage stability, for example, is limited to RO-RO ship with side damage.

If the guideline for capsizing tests is established for wide range of ship-types and situations, Member Organizations can find new field for their commercial works.

This Specialist Committee has provided a way of benchmark test for validating numerical method for capsizing prediction. However, what we need now is to EXECUTE this benchmark test and then to RECOMMEND APPROPRIATE METHOD for practical use.

By Gregor Macfarlane, Australian Maritime College

I would like to thank the committee for an interesting report. The testing of ship models for stability is becoming an important issue and member organisations such as my own need advice and recommended standard procedures. I am therefore very pleased to see that the ITTC has now addressed this important issue.

My comments relate to the testing of intact ships in beam seas. We have been asked to do this for a couple of clients recently to determine the so called ‘roll back angle’ for use with the wind heeling criteria. It turns out this is often the critical factor governing the stability of ships – particularly high speed ships and warships. As a consequence, builders are increasingly putting pressure on us to predict the required value.

My question is: has the committee looked at this aspect of testing, and what technique do they suggest?

There appears to be two sets of guidelines – one for intact ships and one for damaged ships. The former concentrates on a self-propelled model in regular waves, and the latter concentrates on the influence of water ingress. Thus, neither appears to be directly applicable.

This is an important issue and it is essential that we get guidance from the ITTC as soon as possible.

Finally, although we are not currently engaged in damage stability investigations, I note the requirement for a model for such tests to be no smaller than 3m. On what scientific basis has this size been decided? I don’t see any evidence quoted in the literature for this and as the maximum size of model we can test is just under 3m this is of considerable concern to us.

Given all the unknowns assumed with such tests is this a reasonable restraint? Is it realistic to expect designers of relatively small high-speed craft to fund the testing of large scale models? They would certainly require the scientific community to justify such a statement which in the case of Australian designs would mean testing overseas with the associated substantial increase in costs. If we can not back this up with scientific evidence we will have a hard time justifying their extra costs.

We would be happy to contribute to an investigation into scale effects associated with these tests if it were to be coordinated by the committee. I believe this is going to be an important issue in the future, particularly for high-speed vessels, and it is therefore very important that the procedures adopted by the ITTC be as scientifically justifiable as possible.

By R.P. Dallinga, MARIN

I would like to provide the general comments to the SCS.

In order to trust a numerical code that aims at quantifying safety performance in terms of ship stability, the underlying mathematical model must be sufficiently general (to avoid the case-sensitivity of empirical models), sufficiently detailed (to capture the particulars of individual designs) and well validated. As yet there are no codes that satisfy all of the above requirements. When carried out properly, model tests still provide more reliable information on the performance of a ship in critical, extreme conditions than is the case for numerical codes.

Because the particular sensitivity of a particular design is far from obvious it is necessary that the environmental conditions be modelled as realistically as possible. This implies at least irregular waves with relevant characteristics (steepness, shortcrestedness, breakers) and, if necessary, modelling of wind and current (a physical current to obtain the related very steep waves). As long as the relevance of results from model tests in regular waves is uncertain as regards safety assessment, this method should not be promoted as an alternative, unless the aim is to provide validation material for numerical codes.

Capsizing in intact and damaged conditions is a very complex phenomenon. Existing test facilities may be insufficiently equipped to answer the demand for a quantitative safety assessment. If our community wants to demonstrate credible safety awareness it should not be satisfied with the limitations of (older) existing test facilities. As a minimum, a testing facility should have the following capabilities for carrying out a comprehensive intact stability assessment:

- tests with free running models in irregular, stern quartering waves;
- measurement of wave field in proximity of model;
- good control of wave properties as a function of time and location in basin.

Recommendations to the Specialist Committee on Stability

- ITTC should provide more detailed model test procedures for carrying out stability assessment for intact and damaged ships (more dedicated research may be needed before such procedures are finalised);
- ITTC should propose a methodology for selecting critical testing conditions (by

making use of e.g. numerical codes); for example: selection of critical sea state parameters, ship operating conditions and proper autopilot.

- In the case of testing for the possibility of ship capsizing or broaching in irregular seas, is it possible to specify a methodology to ensure that the ship meets the most critical wave conditions; there might be a role for testing in deterministic wave trains with specified critical properties.

By Ulderico Bulgarelli, INSEAN

a) In the frame of the analysis of strong non-linearities, that are characteristics of some problems in ship stability, generally standard perturbation methods have convergence difficulties. This is due to the use of harmonic generating functions (zero order solution) that are a bad approximation of the solution of the wished problem. A recent mathematical method proposes the use of non-harmonic and non-smooth generating functions. This method guarantees a very fast convergence of the perturbation proceedure. Are there any examples of the application of this procedure in ship stability?

References:

V.N. Pilipchuk, ‘Analysis study of vibrating systems with strong nonlinearities by employing saw-tooth time transformation’, Journal of Sound and Vibration, 1996, 192(1)

b) When analysing stability of ships the problem is frequently, especially for dynamic instability, controlled by factors of random nature not only concerning loads but for example, the eventual damage. In this case the concept of stability has a random character too. The mathematical theory of stochastic operators precises the probabilistic confidence about the system stability. Has this approach some chance of application in ship stability?

References:

Soong, ‘Random Differential Equations in Science and Engineering’, Academic Press, New York, 1973.

Schuss, ‘Theory and Applications of Stochastic Differential Equations’, Wiley, New York, 1975.

By Dr Strasser

There are in the appendix guidelines for performing model tests on stability and they are suggested by the committee to be interim. Can you tell us whether you want to see these guidelines in one paper (procedure) or two?

Additionally we would like to ask why you consider these guidelines as interim.

II REPLIES

Reply of ITTC Specialist Committee on Ship Stability to Professor Fujino

The committee would like to thank Professor Fujino for his kind words and for his highly relevant comments. As he rightly says the guidelines proposed by the committee on testing of damage stability are vessel specific and damage scenario specific. Problem specific approaches have traditionally been developed to circumvent the complexity of generalised models to address the overly complex and wide ranging problems associated with dynamic behaviour of ships in extreme conditions. The committee agrees with Professor Fujino that establishing guidelines and procedures for capsizing tests of other ship types will offer considerable scope for commercial work in test tanks in the future.

The work done so far in relation to the IMO resolution 14 of SOLAS ’95 can be used to demonstrate the level of expected involvement by test tanks in the furture. Eleven tanks in Europe have been involved (DMI, SSPA, HSVA, INSEAN, El Pardo, MARIN, Nantes, Haslar, MARINTEK, NTUA, Strathclyde) as well as IMD, SRI and Osaka Prefecture. In Northern Europe alone 150 – 200 Ro-Ro ship models are likely to be tested by 2002 and if the Stockholm Agreement model testing method is enforced in Southern Europe the number of tests may potentially rise to around 500. If, finally, the model test method becomes an international instrument for testing the survivability of new vessels, the implications on commercial tank testing will be long lasting.

Looking at the wider picture, recent developments in the probabilistic approach to assessing damage stability and survivability may necessitate extensive testing for developing new harmonised regulations, likely to involve all ship types. The imminent revision of the Load Line is also likely to lead to substantial testing for most ship types to support numerical results and proposals towards new rational criteria.

Notwithstanding rule development, a number of safety-critical vessels will continue to demand that increased attention is paid to improving their safety. Model testing of performance in extreme conditions provides the method for addressing this goal. This includes all small craft (leisure boats, fishing vessels, and offshore vessels) as well as naval vessels, containerships and bulk carriers.

Regarding Professor Fujino’s second point, the committee could not agree more and would welcome the opportunity to do this as well as the support of ITTC member organisations in making this possible.

Reply of ITTC Specialist Committee on Ship Stability to Mr Macfarlane

The committee would like to thank Mr Macfarlane for his contribution.

The “roll back angle” referred to is associated with the windward heeling angle used in the so called weather criteria for merchant and naval ships. This applies to the physical situation with the ship subjected to combined beam wind and beam seas.

Other than the heel angle specified by the relevant criteria there is no standard experimental procedure to determine this angle in an acceptable fashion.

One way forward could be based on dedicated research involving model tests in waves with the presence of wind in the relevant survival conditions. With the better physical insight obtained from these extensive tests it may be possible to arrive at a meaningful experimental procedure.

There were several factors which resulted in the selection of the required minimum scale for damage stability experiments.

Firstly, an analysis of past practice showed that models were all within this limit. Secondly, some work on modelling the flooding of the chain locker of a semi-submersible drilling rig suggested no significant scale effects on the flow for scales of 1:40 and 1:15. Finally, some very old work concerning scale effects on notched flow was used and is the strongest justification for the selection of the size. However, length selection was based on an assumed SOLAS damage length which is a function of ship length. The minimum Reynolds number to avoid scale effects gave a ship length of 2.7m, which was rounded up to 3.0m to give a safety margin.

The committee would like to thank Mr Macfarlane for his offer to help address this problem by carrying out specific experiments on this topic. It is only by carrying out this type of study that the proposed methods can be justified by sound scientific principles.

Reply of ITTC Specialist Committee on Ship Stability to Mr Dallinga

The committee would like to thank Mr Dallinga for his comments, and in particular for the recommendations.

We agree with his comment on the stability assessment based on more dedicated research on non-linear dynamics of ship motion and critical sea state leading to capsize. As he mentioned, capsizing in intact and damage conditions are very complex phenomena. This is what makes it necessary to investigate the critical modes leading to capsize.

Three typical modes have been referred to as follows:

Static loss of stability;
Dynamic loss of stability; and
Broaching to.

Static loss of stability is concerned with the reduction of the righting arm curve. It is possible to predict the reduction when the wave crest is amidships in a regular wave. This mode occurs when the ship is travelling at high speeds in following seas.

Dynamic loss of stability is concerned with the variation of the righting arm curve with relative position of the ship to the waves and the natural rolling period of the ship. It is possible to predict the critical waves for this in regular waves. This mode occurs in the low speed range.

Broaching is concerned with the directional stability of the ship travelling in following and quartering seas.

When a ship is travelling in following and quartering seas in irregular waves it encounters groups of successive high amplitude waves. These wave groups are similar to regular waves.

Capsizing in irregular waves is a very rare event and to investigate this fully to assess the probability of capsize for a vessel would be somewhat impractical. It is therefore necessary to establish deterministic wave trains – regular or otherwise, which can be used to assess a vessels resistance against capsizing. At present we are a long way from being able to specify such wave trains with confidence and the committee therefore agrees strongly with Mr Dallinga that this should be included in the recommendations to a future committee.

Reply of ITTC Specialist Committee on Ship Stability to Dr Bulgarelli

The committee would like to thank Dr Bulgarelli for his interesting discussion. Pertubation methods have been used frequently in ship stability problems. The ship dynamics has been generally represented by a single degree of freedom model, namely roll. The committee does not know of an application of non-harmonic nor non-smoothing generating functions in this context and are looking forward to the results of the approach Dr Bulgarelli suggests.

It is true that the random nature of both wave loading and damage events are important, however since wave frequency is much higher than the frequency of damage events the concept of conditional probability is normally used. Work on this has been published from time to time, but real numerical results and validation have not been sufficiently reported to recommend such methods for practical use.

The committee would be very interested in the results using the proposed method, and looks forward to hearing about this from Dr Bulgarelli in the future.

Reply of ITTC Specialist Committee on Ship Stability to Dr Strasser

The Committee would like to thank Dr Strasser for his comments, however at this stage feels that the guidelines are not sufficiently developed to be included as ITTC procedures, and must therefore remain ‘interim’. This is backed up by comments from other discussers to this report, who advocate further work in this area before this can be finalised.