

## TOWARDS THE PERFORMANCE BASED APPROACH FOR STABILITY OF CRUISE VESSELS

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### Abstract

This paper is aimed at providing information on intact stability and damage survivability assessment of cruise ships in relation to recent developments in safety standards. The recent trend in the cruise market advocate safety issues, in particular those pertaining to *large passenger ships* (LPS). The paper presents some of the results from numerical and model tests that were obtained during recent projects undertaken by the ship stability centre (SSRC) including the FP5 EU projects covering various passenger ship types. Furthermore, the application of current and future *Intact Stability Code (IS Code)* and *Damage Stability Regulations* for passenger ships is demonstrated, while highlighting the drawbacks and the need for development of a performance based assessment.

### 1. INTRODUCTION

The rapidly growing cruise market with available techno economical advances is putting pressure on cruise operators to have bigger ships to accommodate larger number of passengers and crew in a single voyage. This trend is very promising in terms of the future of the cruise market. The safety regulations, however, in particular, intact stability code and damage stability regulations, which are applied to passenger ships, are lacking behind these fast developments. The stability and safety issues become core issues as the number of people on board such ships reaches to 5000-6000 and the existing rules do not cover satisfactorily dimensional ratios that modern cruise vessels exhibit.

This fact forced many maritime authorities, researchers, and operators to take a close look at the stability and safety issues of large

passenger ships. Advances in science and technology should be directly accommodated within regulatory regimes. In other words, regulatory regimes should set regulations addressing acceptable level of safety on the basis of pertinent risk. This paper looks at some of the issues regarding the recent developments including performance-based approach for stability of cruise vessels.

#### 1.1 Brief review of the recent developments

In response to the new trend with large passenger ships, the Maritime Safety Committee (MSC) held its 74<sup>th</sup> session in June 2001 and set out a series of *guiding philosophy*, *strategic goals* and *objectives* that were aimed at guiding and directing the development of a future regulatory framework related to the safety of large passenger ships. The overall *guiding philosophy* is later approved, together



with strategic goals and objectives, in 45<sup>th</sup> session of SLF [1]. The guiding philosophy consists of the following points:

- The regulatory framework for the prevention of a casualty must set *proactive* measures.
- LPS should be designed for survivability in a way that in the event of an accident, passengers and crew can stay on board as the ship proceeds to *safe refuge*.
- The regulatory framework should permit alternative designs and arrangements in lieu of the prescriptive regulations provided that at least an *equivalent level of safety* is achieved.
- LPS should be crewed, equipped and have sufficient arrangements to ensure the *safety of persons on board* for survival in the area of operation, taking into account climatic conditions and the availability of Search and Rescue (SAR) functions.
- LPS should be crewed and equipped to ensure the *health safety, medical care and security* of persons on board until more specialised assistance is available.

One of the strategic goals outlined in SLF 45 has a significant importance for the development of a new regulatory framework to implement performance based safety measures. The strategic goal proposed states that the future regulatory framework should be:

*“Developed in such a way that assessing alternative designs and arrangements so as to ease the approval of new concepts and technologies which provide a level of safety at least equivalent to that provided by the prescriptive regulations”*

During 45<sup>th</sup> session of the SLF-Sub Committee, the following regulatory gaps were identified in relation to LPS:

- characterisation of survivability of the ship,
- structural integrity of the ship after damage,
- raking damage issues for future ships.

In addition to the above developments during the review of the Intact Stability (IS) Code in SLF45, some concern was expressed over the effect of Weather Criteria [5] on LPS, and some modifications were proposed. The proposed interim modifications will be discussed in this paper.

With regard to damage stability, under the current IMO affords of harmonising cargo and passenger ships subdivision and damage stability regulations into one probabilistic-based set promises a better assessment methodology. The SDS working group under IMO has been pending the issue until the FP5 EU project HARDER delivers their proposal on this matter. It is expected that HARDER project results will be discussed in due course and will possibly be adopted at 2004 SOLAS conference. The potential effect of the harmonised regulations on LPS will be covered in later sections of this paper.

## 2. PERFORMANCE BASED APPROACH

The design stage must be regarded as the first step to achieve safety, not only from the point of view of compliance with regulations but also, as an opportunity to establish a safety level that will last as long as the life-cycle of the ship. To achieve this, the safety assessment approach must aim at measuring the performance of a vessel in true operational conditions as realistically as possible. Therefore, the performance-based approach can be regarded as the only means to provide this.

The will to do that has already been demonstrated for Ro-Ro passenger ferries through implementation of a regional agreement, known as STOCKHOLM Agreement. The implementation of Resolution 14, which deals with survival assessment of Ro-Ro passenger ferries through physical (scaled) model experiments constituted an alternative to prescriptive regulations. As it was

stressed in MSC 75, the demonstration of safety performance of a LPS is set to be the future regulatory regime.

The performance-based approach involves assessing a given vessel in a given set of environmental and operational scenario on the basis of her performance in terms of:

- floatability,
- stability,
- capsize resistance,
- dynamic responses,
- damage flooding,
- passenger comfort,
- passenger survivability,
- parametric rolling,
- manoeuvring,

and so on. However in order to achieve this, utilisation of the following means are important:

- numerical simulations,
- numerical methods,
- scale model experiments,
- full scale trials.

In the field of Intact and Damage Stability, the use of the above methods is becoming a common practice nowadays for design on a voluntary basis. For instance, it is worth noting that in SLF45, the Sub-Committee also agreed that other means of demonstrating compliance with the requirements of any part of the future revised IS code might be accepted. This is on the condition that the method chosen to be shown to provide an equivalent level of safety by means of the following methods:

- numerical simulations of dynamic behaviour,
- physical model testing,
- full-scale trials

## 2.1 Numerical simulations and methods

After so many years of extensive research and development work in modelling ship hydrodynamics in sea waves, the use of numerical simulations for certain aspects of marine hydrodynamics are increasingly recognised as a convenient tool and a permanent part of the modern ship design practices for assessing ship behaviour in realistic seagoing conditions. The number of applications that are acceptable in regulatory purposes are still limited but increasing. The practical use of numerical simulations in industry for design and performance assessment is very wide due to its obvious advantages.

On the other hand numerical methods are being developed with the aim of providing assessment tools based on the first principles, like Static Equivalent Method (SEM). The SEM method has been developed at SSRC to predict critical survival sea state -in the form of significant wave height- for vessels with large undivided deck close to sea level. The SEM model is capable of predicting with good accuracy the critical sea state as it has been validated by using model tests and numerical simulations for wide range of vessels [14], [15].

The utilisation of probabilistic based regulations -for example *Formal Safety Assessment*- require development of assessment methods like SEM, in order to obtain quality information effectively. Numerical simulations and methods offer significant advantage as to provide accurate information effectively; therefore they are becoming an essential part of modern design procedures.

Seakeeping performance can be assessed for both intact and damaged ships in given environmental conditions as an alternative to model experiments and full-scale trials. This



has been demonstrated very widely for intact vessels and in recent years for the upgrading of Ropax vessels and new Ropax designs. The biggest advantage of numerical simulations and numerical methods is that they are far cheaper and less time consuming than scale model and full-scale experiments. Although they offer immense advantages, universal issues like validation, verification of codes, as well as accreditation of software are the biggest issues that slowing the use of advanced numerical tools and methods widely.

## 2.2 Physical model experiments

Physical model experiments are being used extensively in other fields of marine technology. In the field of intact and damage stability, however, until recently, physical model experiments primarily have been used for research or accident investigation purposes. It took a long time to recognise model experiments as to demonstrate safety compliance within regularity regime. The introduction of Resolution 14 of SOLAS 95 conventions has established a new perspective to the safety assessment by allowing for the first time to demonstrate Ro-Ro passenger ferries survivability through model experiments. Although it is merely an alternative to static stability calculations that considers water on deck, a significant number of ferry operators have already chosen the model experiment route to demonstrate safety equivalence. Currently, these regulations were only applicable to Ro-Ro vessels operating in Northwest European waters but extended to for whole EU waters with necessary modifications. Furthermore, modified model test procedures for new Ropax vessel and purpose designed model tests for HSC are already in IMO in the form of resolutions or proposals.

## 2.3 Full scale trials

The demonstration of compliance with passenger evacuation requirements is a good example for full-scale experiments/trials. As it is intuitive that the use of full-scale experiments/trials can be costly and time consuming, however, in the absence of numerical simulations and methods it becomes an inevitable choice.

## 3. INTACT STABILITY

Provisions of Intact stability are similar for most of the conventional mono-hulls, however there are several issues arising for Large passenger ships. It was mentioned earlier that cruise ships with large numbers of passengers require not only more accommodation spaces but also large public spaces to accommodate leisure activities on board. As a result, the need for more space force superstructure of the cruise vessels to be bigger. The direct effect of this is most visible with issues like weather criteria and parametric rolling.

### 3.1 Weather criteria

In severe wind and rolling criteria, commonly referred to as “Weather Criterion”, the ability of a ship to withstand the combined effects of beam wind and rolling should be demonstrated for each standard condition of loading, see (Figure 1). The weather criteria requires that *area b should be equal to or greater than area a*.

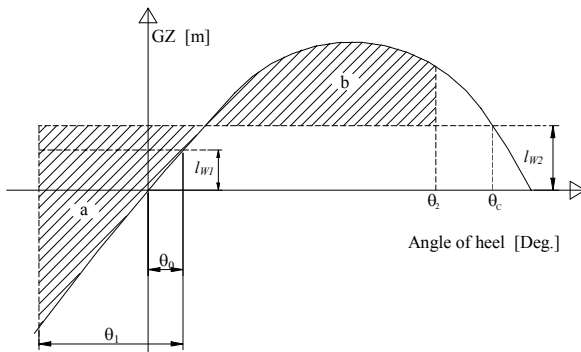


Figure 1: Weather Criterion

The angles and the main parameters in Figure 1 are defined as follows:

- ( $\theta_0$ )=angle of heel under action of steady wind;
- ( $\theta_1$ )=angle of roll to windward due to wave action;
- ( $\theta_2$ )=angle of downflooding ( $\theta_f$ ) or  $50^\circ$  or ( $\theta_c$ ) whichever is less;
- ( $\theta_f$ )=angle of heel at which openings in the hull, superstructures or deck-houses which can not be closed weathertight immerse. In applying this criterion, small openings through which progressive flooding cannot take place need to be considered as open;
- ( $\theta_c$ )=angle of second intercept between wind heeling lever ( $lw_2$ ) and GZ curves.

$$l_{w2} = \frac{PAZ}{1000g\Delta} \quad (\text{m}), \quad (1)$$

$$l_{w2} = 1.5l_{w1} \quad (\text{m}), \quad (2)$$

$$P = 504 \text{ N/m}^2 \quad (3)$$

where:

A= projected lateral area of the portion of the ship and deck cargo above the waterline ( $\text{m}^2$ )

Z= vertical distance from the centre of A to the centre of the underwater lateral area or approximately to a point at one half the draught (m)

$\Delta$ = displacement (t)

G=  $9.81 \text{ m/s}^2$

The angle of roll ( $\theta_1$ ) should be calculated as:

$$\theta_1 = 109kX_1X_2\sqrt{rs} \quad (4)$$

where:

k=1.0 for a round-bilged ship having no bilge or bar keels

k=0.7 for a ship with sharp bilges

k=As shown in Table 2 for a ship with bilge keels, a bar keel or both

$X_1$ = factor as shown in Table 1

$X_2$ = factor as shown in Table 1

s= factor given as based on T, as shown in Table 2

Table 1: Values of factor  $X_1$  and factor  $X_2$

B/d	$X_1$
$\leq 2.4$	1.0
2.5	0.98
2.6	0.96
2.7	0.95
2.8	0.93
2.9	0.91
3.0	0.90
3.1	0.88
3.2	0.86
3.4	0.82
$\geq 3.5$	0.80

$C_B$	$X_2$
$\leq 0.45$	0.75
0.50	0.82
0.55	0.89
0.60	0.95
0.65	0.97
$\geq 0.70$	1.0

$$r = 0.73 \pm 0.6 \text{ OG/d} \quad (5)$$

where:

OG= distance between the centre of gravity and the waterline (m) [ in formula (5); + if the centre of gravity is above the waterline, -if it is below ]

D=mean moulded draught of the ship (m)

Rolling period ;

$$T = \frac{2CB}{\sqrt{GM}} \quad (\text{seconds}), \quad (6)$$



where:

$$C = 0.373 + 0.023 (B/d) - 0.043(L/100)$$

L= waterline length of the ship (m)

B= moulded breadth of ship (m)

d= mean moulded draught of the ship (m)

$A_k$ = total overall area of bilge keels, or area of the lateral projection of the bar keel or sum of these areas (m<sup>2</sup>)

GM= metacentric height corrected for free surface effect (m)

Table 2: Values of factor k and factor s

$\frac{A_k \cdot 100}{L \cdot B}$	k	T	s
0	1.0	≤ 6	1.000
1.0	0.98	7	0.098
1.5	0.95	8	0.093
2.0	0.88	12	0.065
2.5	0.79	14	0.053
3.0	0.74	16	0.044
3.5	0.72	18	0.038
≥ 4.0	0.70	≥ 20	0.035

### General Problems With The Weather Criterion

$\theta_1$  is dependent on various parameters that could influence the outcome significantly. These parameters such as the natural roll period (T), presence and size of bilge keels, Beam/draught ratio and location of vertical centre of gravity from waterline are included by using empirical relations based on the experience gained some 40 years ago.

The factor s is dependent on the roll period where T is changing between 6 and 20 seconds while s is varying between 0.10 and 0.035 respectively.

There are various drawbacks with this relation. The first one relates to the rolling period which is predicted empirically with the largest period being 20 seconds, but with modern passenger ships periods may even go up to 30 seconds.

Furthermore, it is reported that the period calculated using the empirical formula (6) given above and that measured from model tests, or full scale trials do not match. The empirical formula (6) provides a smaller period, which increases ( $\theta_1$ ) artificially. For instance, for the case ship presented in this paper, the roll period calculated from the empirical formula (6) is 2 to 3 seconds smaller than the model test measurements depending on GM.

Another point is that the empirical roll period is decreasing with increasing GM, which in turn increases  $\theta_1$  under steady wind. This contradicts the knowledge that the higher the GM the better the stability is and therefore the ship should be heeling to lesser heel angles under steady beam wind.

The Weather Criterion includes only passive damping measures such as bilge keels through the k value, but it does not have the provision for active fin stabilisers or free surface tanks. Most of the passenger ships are equipped with very effective active fin stabilisers. Lack of provision for such damping devices again influences  $\theta_1$  adversely.

The range of B/d values which influences the X1 value does not cover modern passenger ships. IMO weather criterion covers the B/d range between 2.4 and 3.5, while the proposal submitted by Italian delegation to IMO at SLF45 [9] indicate that B/d values of their test ships are varying between 3.98 and 4.65. Similarly the case vessel in this paper has a B/d value between 4 and 4.36. It clearly shows that weather criterion does not cover the modern cruise vessels and this artificially increases the ( $\theta_1$ ).

If all these very relevant parameters are taken into account properly ( $\theta_1$ ) may be reduced by 50% and this can be regarded as a very realistic and practical estimation. This would eliminate most of the failure cases for cruise vessels and

passenger ships to comply with the *weather criterion*.

### Proposed Alterations To Weather Criteria At SLF 45

A number of member states at IMO expressed their concern about the unrealistic estimation of the rolling period for certain ships. As a result, two documents were submitted (SLF 45/6/3 and SLF 45/6/5) [3] in support of altering the estimation of the rolling period as well as the coefficients “r” and “s”.

It has been suggested that the rolling period value measured by model experiments, numerical calculations or full-scale trials may be used instead of the empirical formula. In addition to this the proposed amendment of the “r” and “s” factors as follows:

$$r = 0.73 \pm 0.6 \frac{\overline{OG}}{d} \text{ but not greater than } 1 \quad (7)$$

Table 3: Proposed values of factor “s”

T [sec]	s
≤ 6	0.100
7	0.098
8	0.093
12	0.065
14	0.053
16	0.044
18	0.038
20	0.032
22	0.028
24	0.025
26	0.023
28	0.021
≥ 30	0.020

### Application of The Modified Weather Criterion To The Case Ship

For the case studies presented in this paper a cruise vessel is used with main parameters as shown in Table 4. The roll period for GM of 2.0 m is measured at 17.97 seconds while the

period is calculated as 15.93 second using the empirical formula in the weather criterion [2, 5].

By using the roll period from the model tests as well as the proposed modified r value, the  $\theta_1$  values are re-estimated. By taking the above mentioned calculated roll angle values into consideration, the limiting GM values for the modified IMO Weather Criterion are calculated and compared with the original values in Figure 3.

Table 4: Main Characteristics of the case ship

L <sub>OA</sub>	294.00 m
L <sub>BP</sub>	272.00 m
B	32.2 m
D	10.80 m
d	8.00 m
Displacement (even keel)	45176.0 tonnes
Intact Design GM (even keel)	2.000 m
Windage area above WL	10062 m <sup>2</sup>

According to the new proposed modifications to IS code pertaining to the Weather Criterion there is a small difference in the resulting limiting GM curve, but as the comparison clearly shows the limiting curve becomes less severe, and just complies with the regulations. It appears that the non-compliance problem is encountered mainly for lighter draughts. However, it is the authors’ view that although the proposed modifications improve compliance, it still does not reflect the true compliance of the vessel as not all possible drawbacks are accounted for.

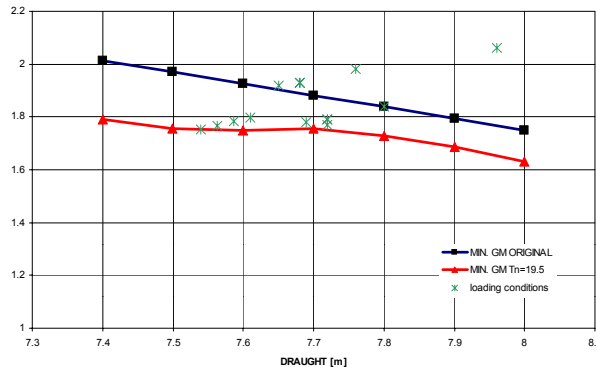


Figure 3: GM limiting curve according to the IMO Weather Criterion

#### 4. DAMAGE STABILITY AND SURVIVABILITY

With respect to the damage stability regulations for passenger ships, SOLAS conventions have been applied to almost 99% of the passenger ships fleet worldwide. The use of probabilistic based Resolution A.265(VIII) has been limited to very few vessels since its introduction in 1974. Therefore, the flaws that are associated with deterministic regulations still hold.

The biggest problem comes from statutory damage size and extent imposed. Although minimum safety compliance is deemed to provide sufficient means for survival, there is no consideration given to the damages beyond prescribed cases. Therefore the risk of potential hazards due to unaccounted damages beyond mandatory damages poses a potential danger to large cruise ships. As a result, the use of probabilistic based regulation is regarded as the future standards not only for cargo ships but also for passenger ships. Due to obvious reasons, special consideration must be given for the survivability of LPS in the cases of large-scale flooding as well as minor damage issue.

#### 4.1 Probabilistic damage stability assessment

The basic principles embodied in probabilistic damage stability assessment are quite simply expressed, with two main assumptions being vital to the calculations procedure outlined as follows:

- There is a probability that the flooding is confined to a particular compartment, or group of compartments, as characterised by factor “p”, and factor “v”.
- There is a conditional probability, for flooding as described above, that the survivability is estimated, as referred factor “s”.

The main concept of the probabilistic damage stability assessment is the determination of a subdivision index A as follows:

$$A = \sum p_i \cdot s_i \cdot v_i \quad (8)$$

For the  $i^{\text{th}}$  damage considered the following factors hold:

$p_i$  is the probability of having damage to zone under consideration,  
 $s_i$  is the probability of survival  
 $v_i$  is the probability that the space above a horizontal subdivision will not be flooded.

Generally speaking factor “p” is obtained through past accident data available. The new updated damage database is provided by EU-FP5 project HARDER. It consist of damage data cards from:

- The old IMO damage database
- Updated IMO damage statistics
- Data from several of the classification societies
- Data collected by some of the National Authorities.



Alternatively probability of having a particular damage can be derived from probabilistic analysis of collision damages through numerical simulations. This can be achieved by taking into account various parameters like struck and striking vessel parameters and structural characteristics, loading conditions, ship velocities, collision angle, sailing routes and traffic density, etc. These parameters can be gathered in a Monte Carlo simulation where the probability distributions for collision damages can be derived, for example see Lutzen M. (2001)[13]. Notwithstanding, the most difficult issue is the prediction of the probability of survival for a given damage scenario. The HARDER project has developed a suitable framework for rational assessment of survival within the probabilistic assessment framework [12]. The probability of survival for a given damage scenario is obtained from two main factors as follow:

$$S_i = S_a \cdot S_w \quad (9)$$

Where :

$s_w$  = the probability of survival from effect of waves,

$s_a$  = the probability of survival from all other effects then water accumulation on deck and wave dynamics.

The HARDER project has recently proposed harmonised regulations for cargo and passenger ships. The results will be made public soon, while some of the results have already been disseminated [12].

#### Advantages of Probabilistic based Assessment

The major advantages of a probabilistic based assessment method, in particular for cruise vessels, can be expressed as follows:

- Consideration of all possible damage scenarios including large scale flooding,
- Safety level achieved can be expressed

quantitatively,

- It can be extended to new ship design concepts,
- Required level of safety can be set on the basis of pertaining risk,

#### Disadvantages of Probabilistic-based Assessment

It is intuitive to say that the biggest disadvantage of the probabilistic-based damage stability assessment method is the number of passenger ships that were built according to probabilistic regulations. This gap, in terms of real life applications, does not disprove the concept but faces us with arguments, which are not facts but rather speculations. Nevertheless the following can be regarded as potential issues to be discussed for cruise vessels with in probabilistic-based regulations:

- Minimum statutory level of survival; to say up to how many compartment survival is required to have  $s=1$ ,
- Minor damage consideration,
- Survival time,
- Passenger survival assessment,
- Structural failure assessment,
- Inclusion of on-board safety systems,

However, these issues can easily be addressed within a probabilistic-based framework with the help of performance-based assessment methods.

#### **4.2 Large scale flooding**

As a result of a changing attitude towards safety by designers and cruise operators, it is becoming common procedure to identify potential problems and hazards even if they are not covered by today's mandatory rules. One of the important issues for LPS regarding damage survival is *large scale flooding*. Since the Titanic accident, it is well understood that in



the event of a damage accident unless there is a major risk of sinkage or capsizing, the safest action for passengers is to remain on board the ship as the evacuation and launching of survival craft have further risks. Even the modern day accidents, like the Estonia disaster demonstrated clearly that, most of the passengers lost their life due to hypothermia as life rafts failed to protect them properly.

In the case of massive damage where the ship sinks or capsizes quickly, then survival time is not an issue. However, if the ship survives the initial flooding and if there is progressive flooding due to internal openings, failure of watertight doors, pipes etc, it becomes extremely important to determine the extent of the progressive flooding and the time to sink/capsize accurately so that the correct course of action can be taken.

Large passenger vessels, whether watertight or non-watertight, are highly compartmentalised ships with many openings (see, Figure 4) and corrective action in the case of progressive flooding can change the outcome significantly. However, it is important to determine how to model these internal compartments and openings, and which approach to use for the progressive assessment of large scale flooding, which may occur in calm seas or in waves.

Traditional Naval Architectural software can only determine the final outcome due to the prescriptive rules. Furthermore, if the compartment is not fully watertight (door is not watertight, or there is a small opening etc), all the subdivisions, which may provide additional buoyancy, permanently or temporarily, are omitted from the modelling of internal geometry. This influences the outcome of the damage. In reality, the opening may be at the centre line and well above the waterline.

Therefore unless there is large roll and flooding these compartments can provide significant reserve buoyancy.

Most passenger ships should comply with standard two compartment damages (the exception is 1 compartment standard ships). On the other hand probabilistic rules (existing and future harmonised probabilistic rules) consider multiple compartment damages up to 24% of the ship length so that vessels which can survive any damage conditions are rewarded with a better Stability Attained Index. It is also a well known fact that damages occur very often beyond the SOLAS damage definition.

In the following, two different approaches are examined. The first one is the stability assessment of large scale damages beyond SOLAS 90 using the standard stability software and considering final equilibrium. It should be emphasised that in standard stability calculations all the compartments which are not watertight due to openings or non-watertight bulkheads etc. are not included in the calculations and therefore they do not contribute to the buoyancy and stability of the vessel.

The second approach is the assessment of large scale progressive flooding, which may occur as flooding can not be controlled due to failure of watertight doors, stairs, pipes etc. This can be examined by using first principles approach (PROTEUS is used) and by modelling the more realistic damage opening and all the internal compartmentation including the openings in as many decks as practically possible. By doing this it is possible to model the true flooding process and predict the behaviour of the vessel, including the time it takes to sink if no preventive action is taken.

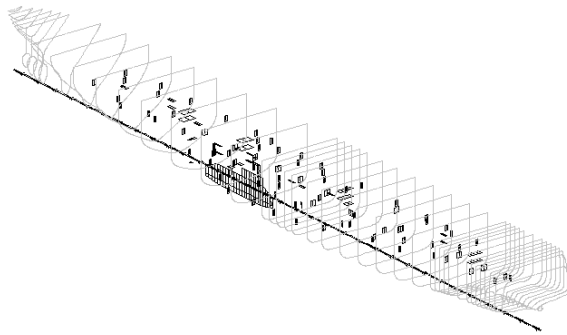


Figure 4: Typical internal openings in a cruise vessel.

### Investigation of 3-Compartment Damages

A case study was carried out for 3-compartment damages to investigate the residual stability of the vessel according to the standard static calculations. The case presented here is for design draught and even keel condition.

The study demonstrated that in the majority of the 3-compartment damage cases the cruise vessel fails to comply with SOLAS damage standards (it should be re-emphasised that 3-compartment damage is beyond SOLAS damage stability standards). More precisely, out of 18 3-compartment damage groups along the vessel length, 10 fail to comply with SOLAS standards. In 6 out of these 10 damages that fail, the ship capsizes due to lack of residual stability and the other 4 cases fail by big a margin for multiple reasons but the ship floats as it has still residual stability. The rest of the cases comply with current standards with varying margins.

As it can be seen in Figure 5, with 3-compartment damage, there is a significant reduction in KG limiting curve and as the draught increases this reduction increases. At around design draught, limiting KG collapses completely as the cruise vessel loses its

reserved stability and capsizes (Figure 6).

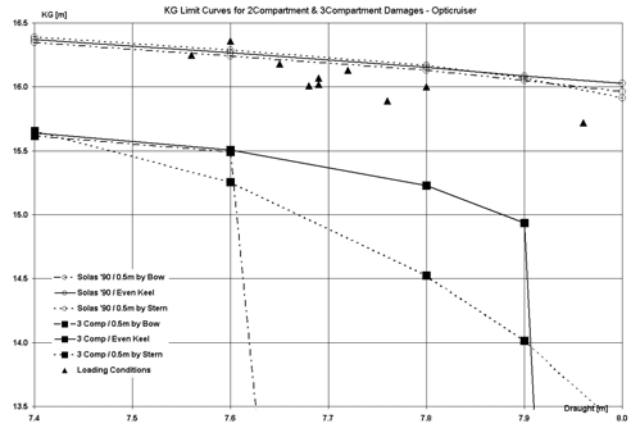
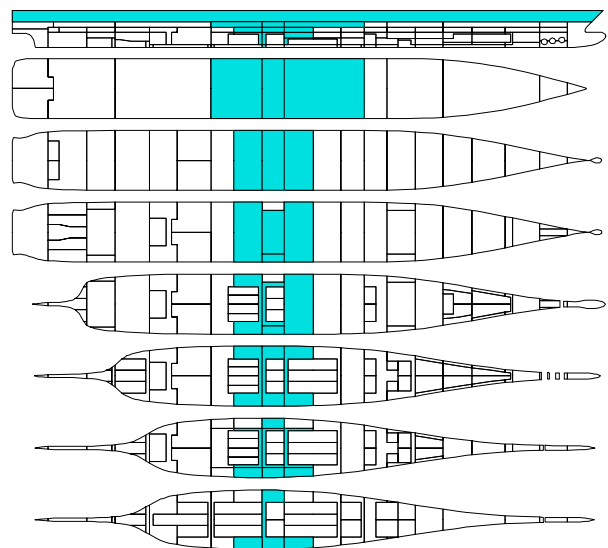
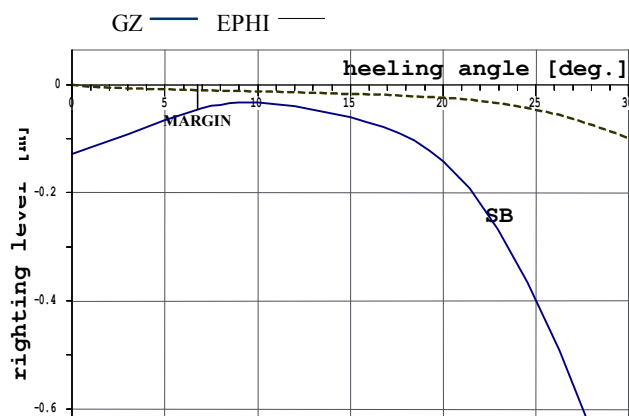


Figure 5: Limiting Curves for 3 compartment damages

In comparison, modern ROPAX vessels which evolved after the Estonia disaster have better residual stability for flooding beyond SOLAS. For instance the case vessel ROPAX tested by SSRC demonstrated very good resistance against capsize for either all the 3 compartment damages (complied with SOLAS standards) or the standard 2 compartment damage + Inner hold damage beyond B/5 [3, 4, 7].



(a)



(b)

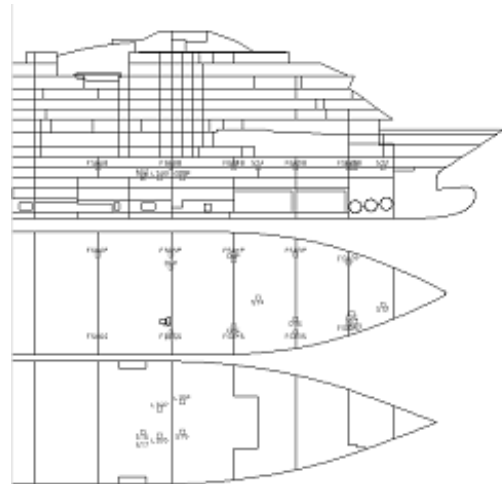
Figure 6: a) 3-compartment damage case, b) Capsize due to lack of reserved stability

However, one point should be mentioned that, cruise vessels, unlike ROPAX vessels, have greater compartmentation and subdivisions above the waterline, which may not be watertight according to SOLAS but in reality they keep the water out, providing buoyancy or delaying progressive flooding. Therefore, these vessels in reality will float unless there is a major flooding due to failure of some watertight openings or due to very large damage penetration, and this should be taken into account in stability calculations.

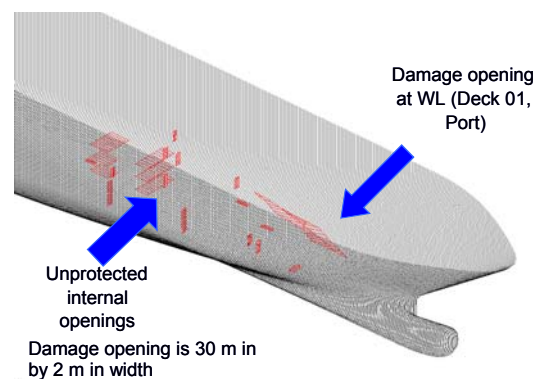
### Large Scale Flooding Using First Principles Approach

In the investigation of large scale progressive flooding, using first principles is extremely important to predict accurately the behaviour of the vessel as well as accurate time. Time based investigation will provide the information in terms of how long sinkage will take, and where the critical flooding takes place so that necessary actions can be taken either to prevent the flooding or to evacuate the passengers. For this study all the internal subdivisions whether watertight or not are modelled together with the openings in all decks. Two example cases are

presented to demonstrate the usefulness of first principles approaches.



(a)



(b)

Figure 7: Large Scale Flooding using First principal approach; (a) critical openings, (b) definition in simulation model

### Example 1:

A case study was carried out to compare the results from time simulation and standard damage stability calculations. In this damage case two compartments were damaged due to collision opening while various internal openings are left unprotected.

Due to the unprotected/unattended internal

openings upflooding is taking place through all the openings and if no corrective action is taken, this upflooding will continue. Eventually the ship will sink as the flooding spreads to the adjacent compartments and the ship will be lost as predicted by static calculations [A standard Naval Architectural Package, Figure 7(a) and the numerical simulations, Figure 7(b) (PROTEUS)]. However, the difference is that time simulation predicts that even without any corrective action it takes more than two hours for the vessel to sink. This is an extremely important point as the simulation provides very useful information to the captain so that appropriate actions can be taken to deal with the safety of passengers without taking any unnecessary risk.

### Example 2:

Another example given below is the effect of internal compartments on the survivability and the active control of flooding in 4m significant wave height. It is assumed that 4 compartments are damaged and various WT doors are left open. The damage opening has a similar area to SOLAS opening but the vertical extent is kept limited but extended longitudinally.

As soon as damage occurs the WT doors are closed from the bridge but it takes an average 20 seconds to close the WT door completely. This is converted to equivalent 15 seconds in the simulation as the area of the opening is decreasing due to the closing doors. As Figure 8 demonstrates the vessel heels to 24-27 degrees and remains in the same condition since all the watertight doors are closed and there is enough reserve buoyancy above the waterline to keep the vessel floating.

However, if in addition to closing the WT doors, the heeling tanks are filled to reduce the heeling, the ship responds to this active control and heels back from 24-27 degree port to 14 degrees starboard making the vessel more

stable and remains there during the rest of the simulation.

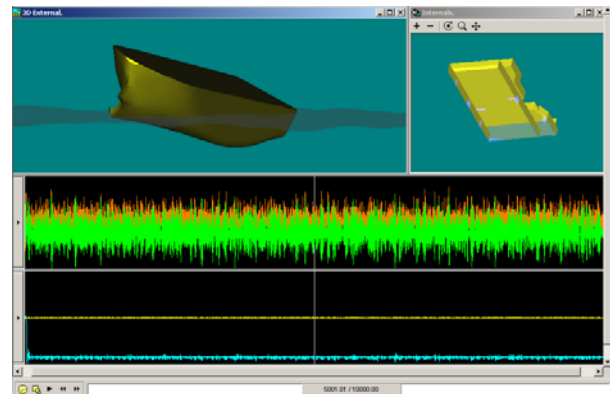


Figure 8: large scale flooding, WT doors are closed after 15 seconds, simulation time 3 hours, heeling 24-27 degrees to port

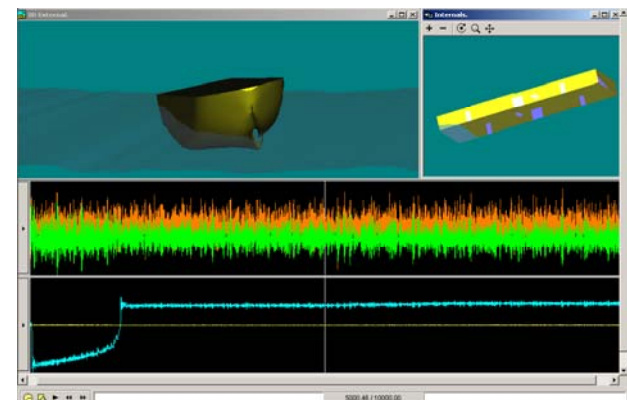


Figure 9: large scale flooding, WT doors are closed after 15 seconds, heeling tanks are filled to reduce the heeling, simulation time 3 hours, heeling 14 degrees to starboard

These examples can be extended but in general based on the comparative analysis between static and dynamic assessment, it clearly indicates that the level of survivability predicted by numerical simulations is higher than the estimation from static analysis. Although the vertical upper limits of the damage openings ensure buoyant spaces above the damaged regions, these buoyant spaces can be flooded internally through lifts and stairwells, which in general are located close to



the ship's centreline. The ship thus survives large roll amplitudes without flooding the upper parts of the hull.

It is likely that results from static stability calculations would have been closer to those of simulations, should these have been performed including more of the ship's buoyant and floodable volumes above the freeboard deck

## 5. CONCLUSIONS

In the wake of principles outlined by MSC, momentous research activities on LPS have been initiated throughout academia, regulatory bodies and the marine industry already. However, work must be consolidated in the best way possible to ascertain good level of effectiveness and quality in the stability considerations highlighted in this paper. Some of the research study demonstrated in this paper constitute performance-based assessment tools and methodologies. They are increasingly becoming regular design applications. Nevertheless the safety regulations should include or allow their wider use in regulatory purposes.

As far as the Weather Criterion is concerned, it is obvious that major updating is required as it does not represent modern passenger ships. Empirical formulae do not necessarily provide accurate results but thankfully IMO is starting to allow these parameters to be determined using more scientific methods. It is the author's view that the interim modification proposed at IMO for the Weather Criterion should be further studied to eliminate the artificial non-compliance problem of Passenger ships with this Criterion.

Results clearly demonstrate that the cruise vessel has very good damage stability and survivability characteristics for standard SOLAS damages. However, for Damages beyond SOLAS the vessel's stability may be

problematic. Based on the derived results, it is suggested here that cruise vessels should at least achieve floatability with any 3-compartment damages. This can be achieved easily without penalties on the functionality of the vessel, if such detailed assessments are carried out at the design stage.

It must be noted that the majority of the results from the simulations for large scale flooding demonstrate clearly the importance of modelling buoyant and floodable volumes above the freeboard deck both for numerical simulations and for static stability calculations. Furthermore, these case studies also demonstrate the usefulness of the active control systems and procedures on the survivability of passenger ships.

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