ON THE PROBABILITY OF CAPSIZING IN TRANSIENT FLOODING CONDITIONS

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SUMMARY

This paper introduces an integrated approach for the probabilistic assessment of the damage ship survivability in transient flooding. The proposed approach is validated by investigating the behaviour of a passenger/Ro-Ro vessel in transient flooding by a numerical time-domain simulation method. The comparison of results of these two approaches leads to some significant conclusions regarding the applicability of the proposed procedure.

1. INTRODUCTION

Transient flooding phenomena are related to the initial stages of flooding of a damaged ship. They could be defined, in terms of time, as phenomena occurring in the time period required for the damage compartment to become fully flooded in case of a damage opening, starting from the intact ship conditions. The hydrostatic fully flooded condition is a theoretical limit sate that ships eventually reach when slowly moving in still water conditions. Practically, assuming the ship moving dynamically, the fully flooded condition might be achieved at certain time when the floodwater equals the amount of the static fully flooded condition.

The risks associated with the transient flooding are the large intermediate heeling angles that could lead the ship even to capsize, before it reaches a static equilibrium after damage and the prolongation of the time of ship exposure to wind and waves at undesired heeling angles. The latter risk is met especially in cases of slow flooding where a long time is required to complete the flooding.

During the transient flooding the ship generally moves under the action of the unbalanced floodwater moments and environmental forces. As the water flows into the damaged compartment and considering the compartment's geometry it will be first distributed in an asymmetric unbalanced way. Even in symmetrical spaces, free surface effects and the time lag observed from the instant of water passing the damage opening until it is spread to the whole compartment (noting the effect of internally fitted equipment), unbalanced distributions will arise causing heeling moments. Internal waves of floodwater as well as other dynamic phenomena increase the moments acting on the damaged ship, affecting her motions.

Therefore, the ship heeling in transient flooding is clearly a dynamic phenomenon. The ship heels under the action of various time dependent moments, absorbing potential energy to the extent available. The magnitude of ship's heel motion depends on the amount of the instantly flooded water related to the damage geometry, the ship's inertia and hydrostatic characteristics as well as energy dissipation components of ship's hull that act as damping forces on the ship, e.g. rudder, bilge keels. Because of the continuous kinetic-potential energy balance, the ship's mean position (especially here heel) deviates from the position it could reach, if moving hydrostatically. The heeling angles resulting from a hydrostatic analysis appear generally amplified and this fact should be considered in the transient flooding analysis.

As indicated in [7] the ship's maximum heeling angle during the transient flooding stage primarily depends on the strong non-linear character of the ship hydrostatics at intermediate stages of flooding, as shown in Figure 1, where the stable equilibrium of heeling angle is shown with respect to the floodwater mass and the *KG* values for a passenger/Ro-Ro ferry, having one symmetrical compartment damaged amidships.

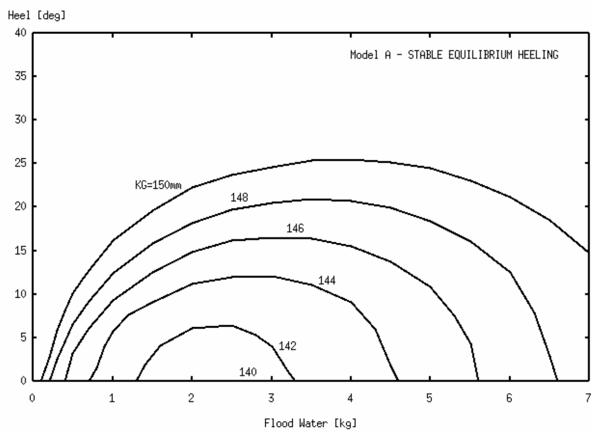

Figure 1 Stable equilibrium mapping

The above mapping becomes even more complicate for other compartment arrangements, e.g. assuming the existence of an intact double bottom or other internal compartments. This strong non-linear hydrostatic behaviour resulting from the presence of floodwater appears to decisively determine the ship's transient behaviour.

Based on the above observations, a simplified approach to the probabilistic assessment of ship's survivability in transient flooding is defined in the following that is based on ship's hydrostatic properties in intermediate stages of flooding. The proposed method, developed for the needs of the HARDER research project [1], is validated by carrying out a representative set of numerical simulations in transient flooding, which consider the full ship dynamics omitted in the suggested simplified assessment method.

2. THE SURVIVABILITY ASSESSMENT METHOD

The *GZ* curves for a discrete number of intermediate stages of flooding are assumed, as shown schematically in Figure 2. The *GZ* curve corresponding to the initial intact condition (stage 1) gradually changes as the water flows into the damage compartment up to the final fully flooded condition (stage N). The equilibrium angle is shown to generally change during flooding, but it might not.

The stable equilibrium angle $\theta_{e,k}$ at each stage is the angle that the inertia system of the flooded ship tends to. The instant moment that guides the ship towards the equilibrium depends on the ship and the floodwater characteristics, as well as the external wave and wind forces. In any case the equilibrium is a variable that determines the evolution of the motion.

As shown in the diagrams, for the intermediate stages the actual position of the ship will be determined by the varying hydrostatics as well as the other dynamic properties. From all these properties and factors the flooding rate has a dominant effect in the appearance of dynamic phenomena as will be shown in the following. If the flooding rate were very slow then the ship would move following the succeeding equilibrium angles $\theta_{e,k}$. Then the actual ship path towards the fully flooded condition would be determined through the trace of the equilibrium in succeeding stages. To the contrary, if a very fast flooding occurs the final fully flooded condition would be achieved faster, while the ship motion would lag in that case. Ship does not go to this equilibrium any more and the potential energy imbalance between instant equilibrium and current ship position would cause dynamic phenomena and some energy absorption by the ship. Other possible flooding situations are expected to behave between those two extreme cases of very fast and very slow flooding. Therefore, the flooding rate seems to determine the conditions that ship dynamics could raise.

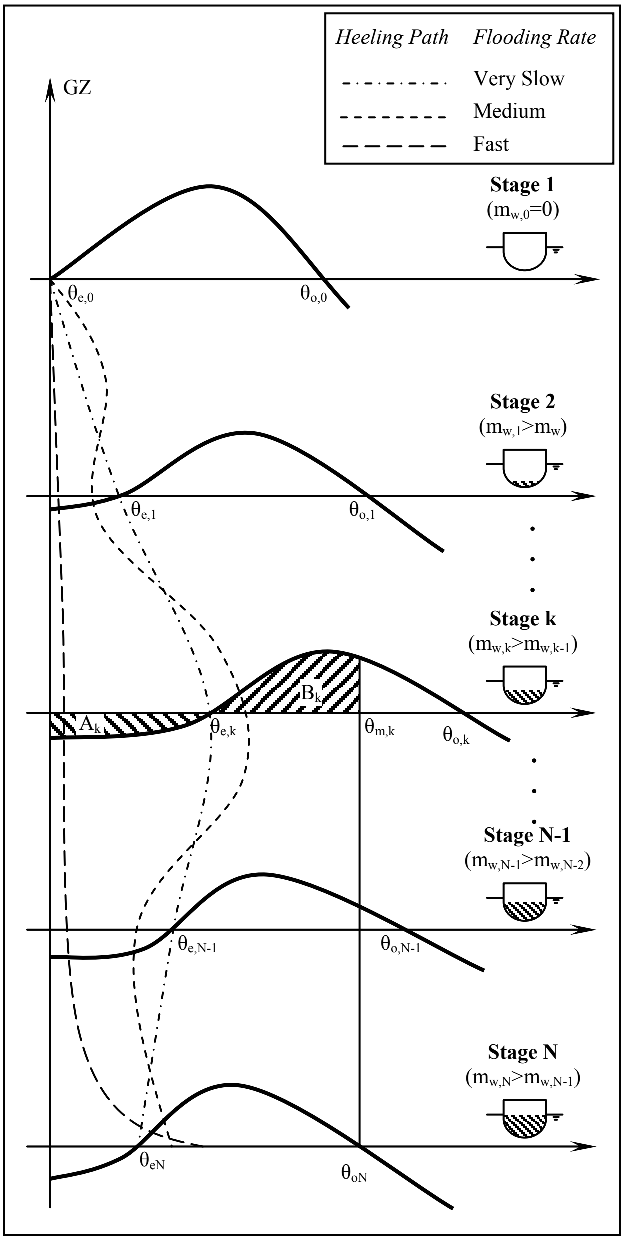

Figure 2 Transient flooding hydrostatics for survivability assessment

The flooding rate for a given damage compartment obviously depends on the damage opening, and the ship position. Damage opening is defined though the size, shape and position of the opening. All these characteristics of the damage opening are in principle unknown inserting a random variable in the probabilistic assessment of transient flooding. Statistical analysis of the existing casualties supported by more theoretical work based on numerical simulation are reported in the HARDER project [1], giving fully satisfactory information about the damage openings distribution, particularly in case of collision damage, correlating size and position of the openings. However damage shape, which has also a significant impact on the flooding rate, and the sensitivity introduced into the transient flooding by the strong non-linearity, still remain unknown variables in a probabilistic assessment approach.

Regardless how fast or slow the ship will pass through the intermediate stages of flooding, at each stage a potential energy could be available that makes ship to move towards the instant equilibrium. That energy is denoted by the symbol *A*, see Figure 2, and is the area of *GZ* curve between the initial equilibrium angle at intact condition and the instant equilibrium angle θ_e. As the ship moves it is expected to absorb a percentage *p* of the available potential energy *A*, which is denoted by *E*, so that *p=E/A*. When the ship passes by the equilibrium $\theta_{e,k}$, at any k-th stage, the percentage *p* could be something between 0 and 1.

In the lack of knowledge on the actual distribution of the absorbed energy it is assumed that it is uniformly distributed over the whole range of the available energy, as illustrated in Figure 3.

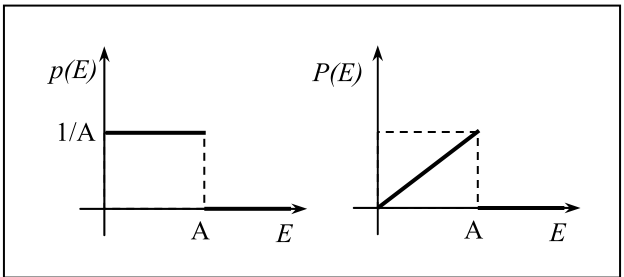

Figure 3 Probability density distribution (left) and cumulative distribution (right) of absorbed energy

In principle, the ship survives during the transient flooding if the energy absorbed can be supported by the restoring ship properties. In terms of hydrostatics, the ship survives when the energy *E* of the ship, when it passes through the equilibrium position, is less equal to the energy that corresponds to the residual stability area *B*. Other ways, the ship capsizes when its energy *E* is greater than *B*. The probability of those survival events, considering the distribution assumed above, then becomes:

$$P(E < B) = \int_0^B p(E)dE = \begin{cases} B/A & \text{for B} \leq \text{A} \\ 1 & \text{for B} > \text{A} \end{cases} \tag{1}$$

The uniform probability distribution for *E* incorporates all factors relating to the finally absorbed energy by the ship, namely inertia characteristics, damage opening, inflow rates and damping effects. The proposed uniform distribution might be improved by more accurate models once results of relevant experimental and numerical simulation studies are available. Some alternative approach to the herein adopted method is suggested in [8].

The maximum energy B_k that the ship is able to support in order to survive at each intermediate k-th stage, corresponds to the area under the *GZ* residual curve between the equilibrium angle $\theta_{e,k}$ and an angle $\theta_{m,k}$ defined as shown below.

$$\theta_{m,k} = \min\{\theta_{o,j}, j = k, N\} \tag{2}$$

where $\theta_{o,j}$ is the minimum of the vanishing and the down flooding angles of the j-th stage.

This definition of the $\theta_{m,k}$ angle introduces the constraint that the ship *should not take an angle greater than the minimum vanishing or down flooding angle appearing in later stages of flooding.* This requirement is imposed because if the angle becomes greater than the vanishing or down flooding angle of later stages then it is not ensured that the ship will be able to return to lower heeling angles in later stages, thus remain stable in later stages and survive.

Considering the above conditions, the next formula might be used for the survival probability in transient flooding, namely the *s* factor.

$$\boxed{s = \min\left\{1, \frac{\min\{B_j\}}{\max\{A_i\}}\right\}, \quad i = 1,\dots,k \quad and \quad j = k,\dots,N \quad and \quad k = 1,\dots,N} \tag{3}$$

Herein, *N* is the discrete number of intermediate stages that are taken into account and it is recommended to take $N = 5$, as illustrated below. Stage 1 is the intact condition and 5 the fully flooded.

Formulation (3) provides a method of survivability assessment correlating the capsize risk to the possible failure of energy balance during transient flooding. It considers an adequate number of controls of the energy balance at intermediate stages of flooding where possible instabilities might be hidden. The formula can be applied in a straightforward way by using easily calculated hydrostatic ship properties and enables the surveying of a great number of damage cases or alternative designs, as requested in the probabilistic damage stability assessment procedure.

3. APPLYING THE METHOD ON A Ro-Ro SHIP

The method described in the previous chapter is herein validated by applying it to a selected passenger/Ro-Ro ferry, while in the chapter following the theoretical results are compared with those of a large set of numerical simulations of transient flooding.

3.1 THE PASSENGER/Ro-Ro FERRY

The presently investigated passenger/Ro-Ro ferry has been experimentally tested earlier in transient flooding and published by Ma et al. [2]. The ship has been studied in model scale 1/60. Her principal particulars are listed in Table 1 and her body plan is shown in Figure 4.

	SHIP		MODEL	
Lpp	120.0	M	2000	mm
B	18.8	M	300	mm
D	10.0	M	167	mm
T	4.8	M	80	mm
Displ.	5900	tn	27	kg
KM	9.39	M	156.5	mm

Table 1 Main particulars of passenger/Ro-Ro ferry

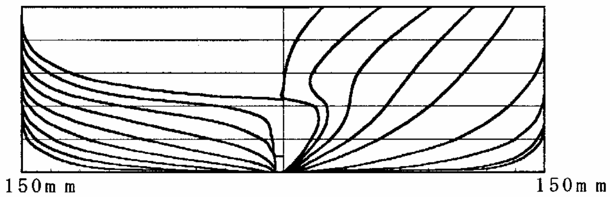

Figure 4 Body plan of the passenger/Ro-Ro ferry

In the studied damage case, damage is extending between stations 4.5 and 6 as shown in Figure 5. Compartment length is 1/6 of the model length and corresponds to the whole mid part of the hull, from side to side and from bottom up to main deck.

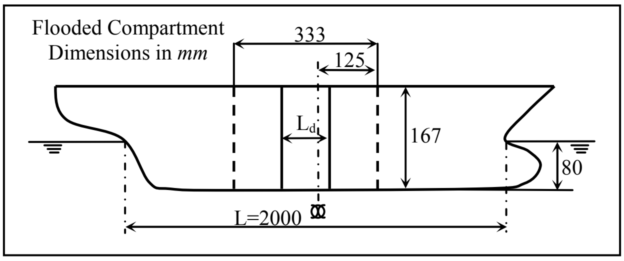

Figure 5 Damage compartment arrangement

3.2 DAMAGED SHIP HYDROSTATICS

The hydrostatic curves corresponding to the above damage case of the passenger/Ro-Ro ferry have been calculated for a set of *KG* values. High values of *KG* have been selected so that marginal stability conditions are reproduced. The following Figure 6 up to Figure 10 present the *GZ* curves for five different values of *KG*, namely 146, 148, 150, 152 and 154 mm, and for five stages of flooding each, namely 0, 25, 50, 75 and 100 % of the floodwater mass in fully flooded condition. This extended presentation of hydrostatics is useful for survey and helps understanding the different phenomena arising during the transient flooding.

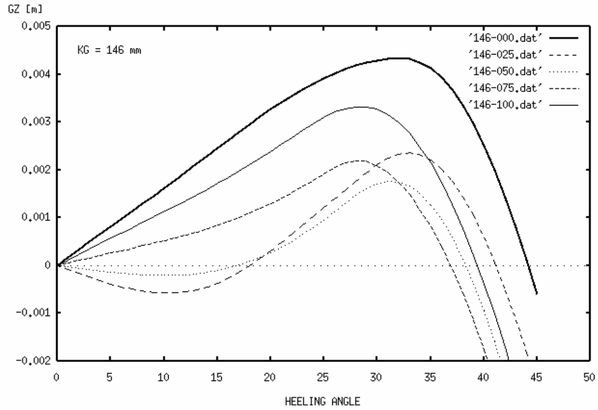

Figure 6 *GZ* curves for *KG* = 146 mm

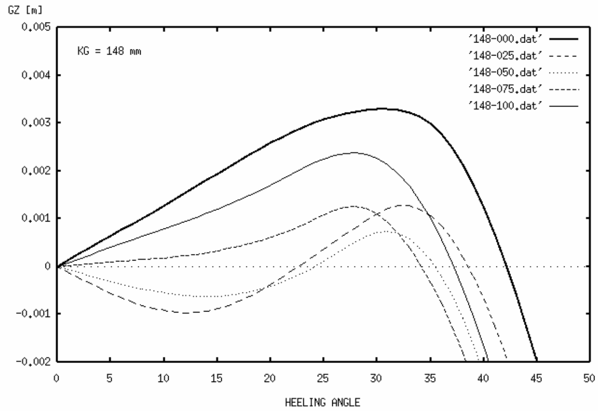

Figure 7 *GZ* curves for *KG* = 148 mm

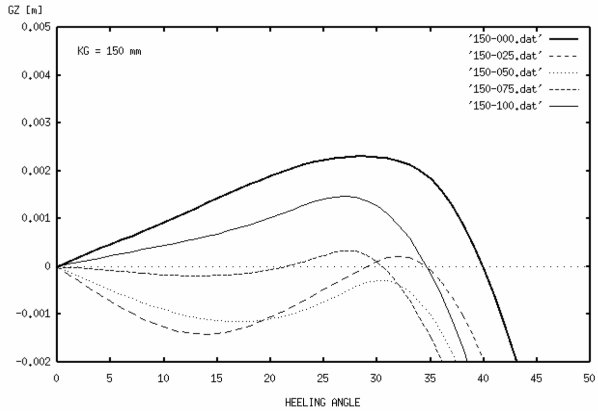

Figure 8 *GZ* curves for *KG* = 150 mm

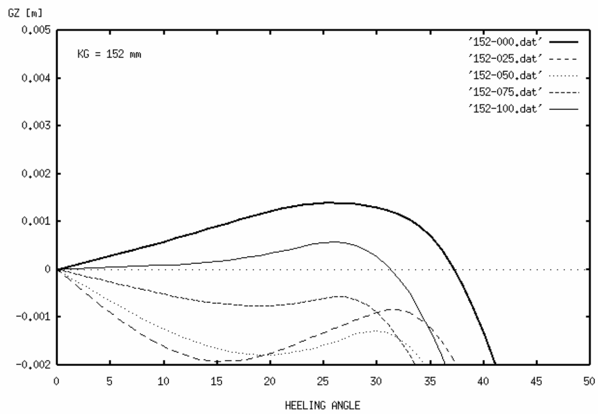

Figure 9 *GZ* curves for *KG* = 152 mm

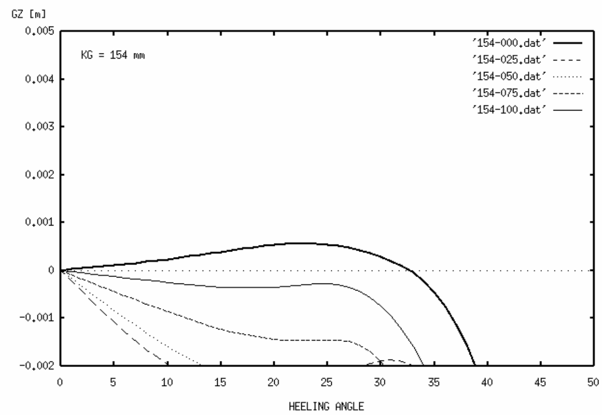

Figure 10 *GZ* curves for *KG* = 154 mm

GZ curves have been calculated letting the hull free to trim so that it better fits to the actual conditions expected. The intact condition is an even keel one while in the fully damaged condition a trim of 26 mm arises.

The last Figure 10 shows that the ship becomes purely unstable when it is flooded as for all flooded cases *GZ* becomes negative throughout its range. For the other *KG* values, Figure 6 up to Figure 9, the ship balances upright, when fully flooded, while for intermediate stages it may balance at different angles. Particularly, for *KG* = 150 and 152 mm, Figure 8 and Figure 9 respectively, there are intermediate stages for which the ship becomes purely unstable, although in the final flooding condition the ship is stable.

3.3 VESSEL'S SURVIVABILITY ASSESSMENT

Having gone through the marginal hydrostatics of the ferry its survivability in transient flooding is assessed herein by application of the proposed method. The method is based on that hydrostatic data and it is discussed how the method interprets the marginal conditions described above.

The survive factor *s* is calculated for each case defined by *KG* value and the results are summarized in the next Table 1. The calculated intermediate quantities are also presented for a clear review of the assessment process. The variables presented in the table are defined according to the Figure 2.

According to the listed table results, the first case of *KG* = 146 mm gives a survive *s* factor equal unit, in the second case of *KG* = 148 mm the *s* has been reduced to 0.33 while for the rest cases not any survivability is recognized. The vanishing of the last three cases is obviously related to the occurring unstable intermediate stages; see Figure 8 up to Figure 10. In the second case the final behaviour the ship is not such clear and the present method evaluates it with just 1/3 of events as survival.

Assessment of Survive Factor in Transient Flooding

Stage	m_w %	$\theta_{e,k}$ deg	$\theta_{o,k}$ deg	$\theta_{m,k}$ deg	A_k m*rad	B_k m*rad	$A_{m,k}$ m*rad	$B_{m,k}$ m*rad	$s_{a,k}$
KG	**146**	**mm**		**s**	**1.00**				
1	0	0.00	44.15	36.83	0.00000	0.00175	0.00000	0.00035	1.00
2	25	18.06	41.10	36.83	0.00012	0.00048	0.00012	0.00035	1.00
3	50	16.84	38.26	36.83	0.00004	0.00035	0.00012	0.00035	1.00
4	75	0.00	36.83	36.83	0.00000	0.00067	0.00012	0.00067	1.00
5	100	0.00	39.34	39.34	0.00000	0.00126	0.00012	0.00126	1.00
KG	**148**	**mm**		**s**	**0.33**				
1	0	0.00	42.11	34.12	0.00000	0.00121	0.00000	0.00008	1.00
2	25	22.61	38.47	34.12	0.00024	0.00016	0.00024	0.00008	0.33
3	50	24.17	35.36	34.12	0.00017	0.00008	0.00024	0.00008	0.33
4	75	0.00	34.12	34.12	0.00000	0.00030	0.00024	0.00030	1.00
5	100	0.00	37.14	37.14	0.00000	0.00083	0.00024	0.00083	1.00
KG	**150**	**mm**		**s**	**0.00**				
1	0	0.00	39.87	30.49	0.00000	0.00073	0.00000	0.00000	0.00
2	25	29.02	34.48	30.49	0.00044	0.00000	0.00044	0.00000	0.00
3	50	∞	∞	30.49	∞	0.00000	∞	0.00000	0.00
4	75	21.44	30.49	30.49	0.00005	0.00003	∞	0.00003	0.00
5	100	0.00	34.62	34.62	0.00000	0.00045	∞	0.00045	0.00
KG	**152**	**mm**		**s**	**0.00**				
1	0	0.00	37.17	31.28	0.00000	0.00047	0.00000	0.00000	0.00
2	25	∞	∞	31.28	∞	0.00000	∞	0.00000	0.00
3	50	∞	∞	31.28	∞	0.00000	∞	0.00000	0.00
4	75	∞	∞	31.28	∞	0.00000	∞	0.00000	0.00
5	100	0.00	31.28	31.28	0.00000	0.00013	∞	0.00013	0.00
KG	**154**	**mm**		**s**	**0.00**				
1	0	0.00	32.70	32.70	0.00000	0.00018	0.00000	0.00000	0.00
2	25	∞	∞	∞	∞	0.00000	∞	0.00000	0.00
3	50	∞	∞	∞	∞	0.00000	∞	0.00000	0.00
4	75	∞	∞	∞	∞	0.00000	∞	0.00000	0.00
5	100	∞	∞	∞	∞	0.00000	∞	0.00000	0.00

Table 2 Survivability assessment in transient flooding

Regarding the impact of $\theta_{m,k}$ on the *s* factor, it is generally observed that about 8 degrees reduction in the maximum heeling angle occurs. But a direct impact on the *s* factor is identifiable only for the case of *KG* = 148 mm and 50 % flooding case where a minor reduction of 1.24 degrees occurs.

Focusing still on the second case, it can be observed that the requirement of considering at each intermediate stage the maximum available energy in previous stages and the minimum residual stability in later ones, forms the final value of *s* = 0.33. In the absence of that requirement, and retaining the calculations on the current stages, *s* factor would equal 0.47 as results in stage 3. Thus, a reduction of 30% on the *s* factor results by the present requirement.

The above calculations are based on a five (5) stages analysis of the transient flooding. The results for a nine (9) stages analysis are given together with the five stages in the Table 3 below, where the convergence is obvious considering just the five stages.

KG [mm]	s-factor (N=5 stages)	s-factor (N=9 stages)
146	1.00	1.00
148	0.33	0.32
150	0.00	0.00
152	0.00	0.00
154	0.00	0.00

Table 3 Survive factor for 5 and 9 stages

It is noticed that present assessment has been applied to a symmetrical damage condition and identifies suffering in transient flooding when considering the non linear hydrostatics in intermediate stages of flooding (Figure 1), which are invisible in the final fully flooded conditions.

4. TRANSIENT FLOODING SIMULATION

The survivability assessed for the damaged ferry in the previous chapter was based on ship's hydrostatics omitting the dynamic effects and the related factors. It was assumed that the ship changes its condition from intact to fully flooded in a generally undetermined way. In this paragraph the ship's dynamics are introduced into the analysis of the transient flooding, using a numerical simulation method, and a comprehensive review of the obtained results so far can be obtained. The behaviour of the passenger/Ro-Ro ferry is simulated for a wide range of possible conditions, employing the numerical simulation method of NTUA-SDL and the results are analysed and compared to the ones derived by the *s* factor assessment method. The discussion of the comparative results reveals several aspects of the assessment method.

4.1 NUMERICAL SIMULATION METHOD

A brief outline of the employed intact and damaged ship motion simulation code CAPSIM and the underlying theory is provided next. More details can be found in [4], [5] and [6]. The simulation code has been developed at the Ship Design Laboratory SDL, of NTUA. It provides an efficient way to predict the motion of the coupled ship and floodwater system. The model is nonlinear allowing the consideration of large amplitude motions and the stability of the vessel in extreme environmental conditions.

The flooded ship is assumed as a two mass system consisting of the intact ship and the flooded water mass. The ship is considered as a rigid body having six degrees of freedom, while the flooded water is approximated by the lump mass concept, namely a mass being concentrated in its centre of mass. Floodwater is assumed moving over predefined surface domain [4], having two degrees of freedom. Considering also the change of mass of water in time, a suitable mathematical model for the motion of the inertia system, with nine degrees of freedom, has been formulated and implemented in the numerical code.

The motion of the inertia system is governed by the momentum conservation of the system masses under the action of external forces. The time rate of change of momentum has been suitably formulated considering the full non-linear character to the motion equations. The external forces are mainly the gravity and the exciting wave forces. The wave forces are treated in the framework of potential theory employing a three-dimension diffraction code, [3]. Non-linear roll viscous effects are assumed to depend on ship's roll velocity by use of the "equivalent linearisation concept" with the proportionality coefficient semi-empirically estimated. Hydrostatic forces are calculated by integration of pressure in the time domain over the instantaneously wetted ship surface, considering incoming waves and caused ship motions, and allowing the capturing of even complicated geometries by proper surface panelling.

The time rate of change of the floodwater has been approached by use of Bernoulli's equation and modified by a semi empirical, weir flow coefficient to account for the local flow effects at the damage opening.

4.2 NUMERICAL SIMULATION SETUP

A representative set of tests is defined covering a wide range of possible conditions that the given hull of the ferry might face in her service. The numerical tests should cover the range of those factors that determine ship's dynamics, such as the ship mass centre, mass distribution, damping and the damage opening.

The vertical distance of centre of gravity *KG* determines the ship hydrostatics and affects the natural roll period. Thus, five different values around its marginal stability area are selected to be studied, namely 146, 148, 150, 152 and 154 mm.

The spread of mass about longitudinal axis, as this is expressed through the roll radius of gyration i_{xx}, affects the natural roll period consequently the ship dynamics. Three different values for the radius have been selected for testing, covering the most usual range. These are given by the ratio i_{xx}/B = 0.35, 0.40, 0.45 where *B* the breadth of the model.

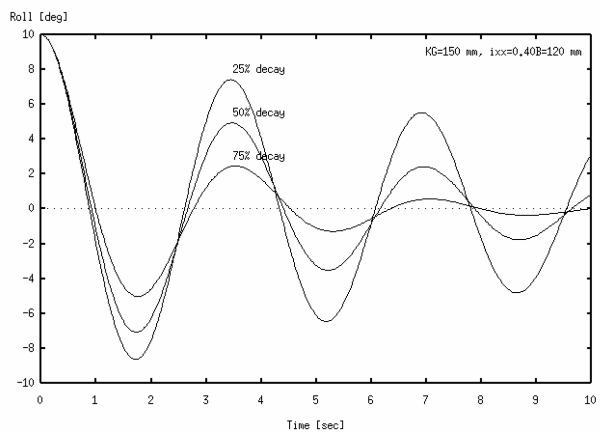

Figure 11 Free roll decay curves in varying damping

The ship damping, accounting for those phenomena dissipating energy, is selected to be such that causes specific decay. When the ship freely rolls, starting from a given initial heeling angle, three different values of damping are selected that cause 25, 50 and 75 % decay in roll amplitude in the first period, as illustrated in Figure 11 above.

In Figure 12 the probability distribution density for the longitudinal length of damage opening is presented, as this is derived from statistical analysis of existing casualties, within HARDER project [1].

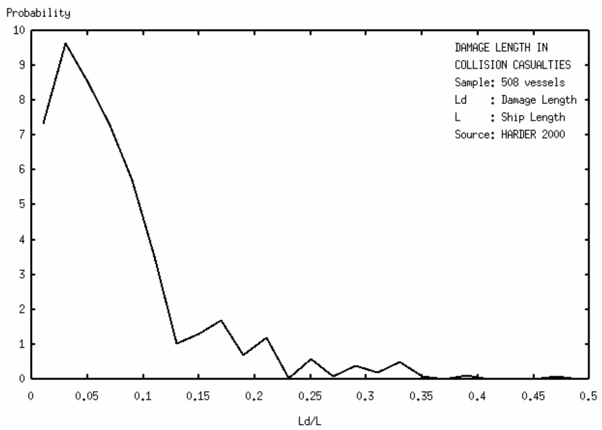

Figure 12 Damage length probability distribution

This diagram indicates that the major percentage of damage length is bounded under the 10 percent limit. These sizes seem to be the most probable while giving a probability trend towards the lower damages. Based on this, five different damage lengths L_d were selected for the study defined with respect to the ship length L. These are 0.5, 1.0, 2.0, 4.0 and 8.0 % of the ship's length, providing a sequence of lengths with double size from the previous one.

The vertical extent of the damage opening is herein considered unlimited, as in current SOLAS 90 regulations. This assumption has been imposed to avoid the effect of the lower edge of the opening, which drastically changes its position with respect to the sea free surface and complicates the assessment of the proposed method. The present specification of the opening does globally control the flooding rate with least effect of the damage shape itself.

Summarizing the selected conditions in Table 4, and taking all the possible combinations, a set of totally 225 numerical tests was defined.

Variable	1st	2nd	3rd	4th	5th	Cases
KG [mm]	146	148	150	152	154	5
i_{xx}/B	0.35	0.40	0.45			3
Damp % decay	25	50	75			3
L_d/L	0.5	1.0	2.0	4.0	8.0	5
				TotalTests		225

Table 4 Tests summary

Hence, the behaviour of the model of the passenger/Ro-Ro ferry was simulated for the above cases, letting the ship moving from an initial intact condition at time zero and releasing suddenly the damage opening. Then the water flows into the compartment through the opening and the ship motion is recorded for a time length of up to about 50 seconds in model scale and for all cases the behaviour of the ship regarding stability sensitive quantities are determined and analysed.

4.3 SIMULATION RESULTS

The set of results corresponding to the numerical tests are presented in this paragraph. In Figure 13 a collection of five tests for the roll motion is sampled. These tests correspond to a specific combination of KG, i_{xx} and damping while varying the damage length in its whole range.

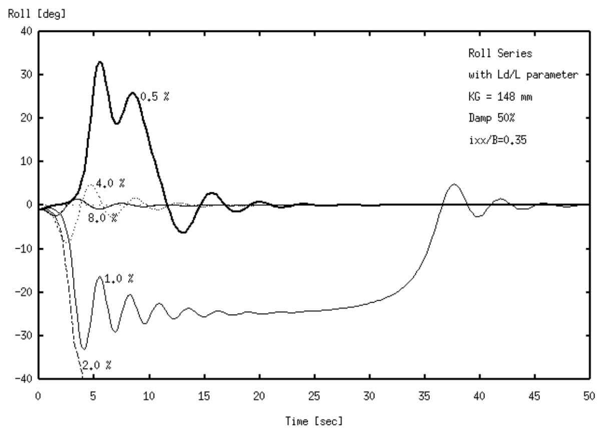

Figure 13 Sample of simulated roll time series

This comprehensive sample provides examples for all possible behaviours of the model. For the lower damage length, 0.5%, the ship obtains a large heeling angle, which after a short time of two oscillations vanishes again. For the greater length of 1.0 % the large heeling obtained is retained for a longer time before the ship comes back to the upright position. This response indicates the chance of a prolonged time of heeling in undesired angles during the transient flooding. In the 2.0 % case the ship capsizes rapidly in the first heeling. In the rest two tests, 4.0 % and 8.0 %, the model keeps the upright position with a slighter oscillation around zero.

In Figure 14 the survival factor s is presented as it results from the numerical simulation as well as the proposed probabilistic quasi-hydrostatic assessment method. It should be noted that the numerical simulation approach does not necessarily defines a statistical proper collection of tests such as the statistical approach of the s factor claims, to be directly comparable to each other. This comparison rather provides a strong evidence of how a wide range of possible events look like with respect to the herein applied theoretical approaches.

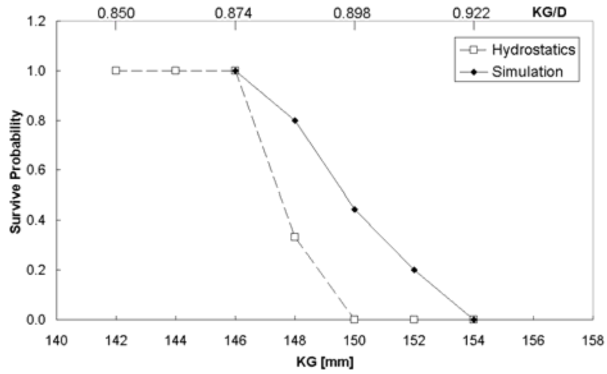

Figure 14 Transient flooding survivability vs vertical centre of gravity

As shown, both methods identify a limit *KG* value of 146 mm where the *s* factor is reduced for higher values. For the numerical simulations the reduction of *s* is less drastic, namely about one half compared to the hydrostatics approach. This transient area for the *s* factor corresponds to a $\delta KG/D$ ratio equal to 4.8 % for the simulation and 2.4 % for the hydrostatics. It seems that hydrostatical approach underestimates the survivability of the ship. However when looking at the ship's hydrostatics it is observed that unstable intermediate stages occur already from KG = 150 mm on. For that value the simulated *s* factor is 0.45. It seems that the ship is avoiding these intermediate unstable conditions when considering her dynamics. For example, at the next value of KG = 152 mm the model survived for all the tests of greater damage opening L_d/L = 0.08, while for all the others it didn't, indicating that when the flooding rate is high enough, as a result of a large opening, the ship passes in a fast mode through the unstable conditions and this short time is not enough for the ship to heel out in a no return angle. Consequently, the dominant factor for explaining the difference between the hydrostatics approach and simulation is the consideration of the unstable intermediate stages of flooding.

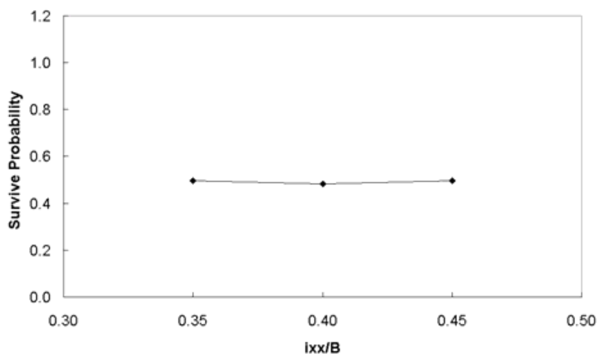

Figure 15 Transient flooding survivability vs roll radius of gyration

Another quite interesting result is presented in Figure 15, where the survive *s* factor is given with respect to the roll radius of gyration of the model. As it is observed that the survival behaviour of the model has no dependency on the radius of gyration. Although mass distribution affects the model dynamics it seems that other factors are quite more significant diminishing the influence of the radius of gyration.

Likewise, low dependency is observed for the *s* factor on the model's damping, Figure 16. Generally, an increase of survivability would be expected as the model damping increases. The results show this dependency but it is quite small effect, and, therefore this parameter could be considered of minor importance.

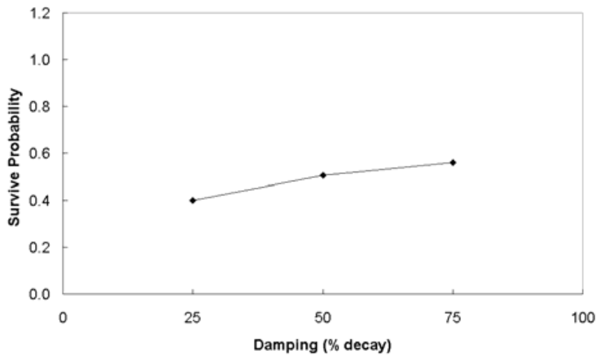

Figure 16 Transient flooding survivability vs damping

The dependency of the simulation results on the last test parameter, namely the damage length, is depicted in Figure 17.

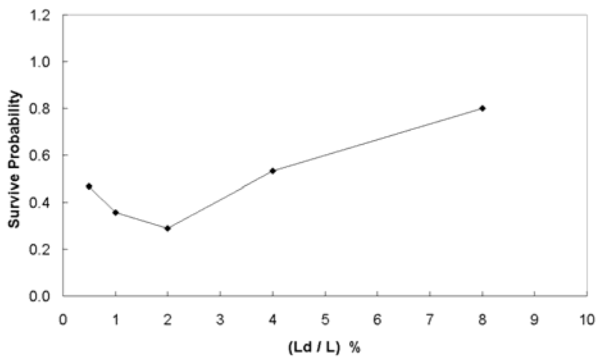

Figure 17 Transient flooding survivability vs damage length

Note that the model suffers for the smaller damages more than for the large openings. In other words, when transient flooding is lasting longer, the model is more prone to instabilities and possible capsize.

Figure 18 presents the mean flooding times against damage lengths as calculated in the simulations, indicating an increased bound of the transient flooding phenomena as the damage opening becomes larger. In this diagram flooding time is divided by natural roll period T_N.

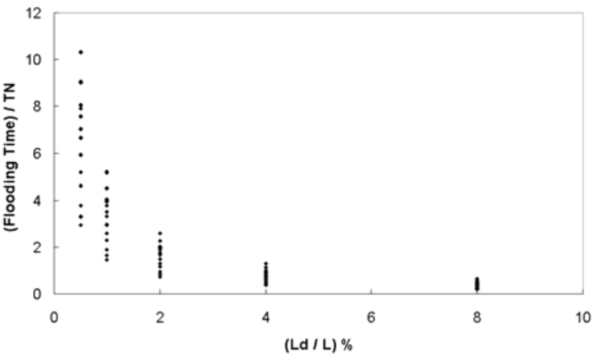

Figure 18 Flooding times vs damage length

In Figure 17 the minimum survivability is identified at about 2-3 % of the model length. This size is close to the damage length according to SOLAS'95 regulations for the study of damage stability by model tests (Res. 14).

Summarizing the above, it was observed that survivability in transient flooding shows a dependency primarily on the *KG* and damage length. Particularly for the damage length, length up to 10% of the damage opening seems to define transient conditions of importance in survivability aspects. The *KG* is taken into account, when hydrostatically analysing the problem of survival, while the damage length seems to be almost unpredictable within the above range, with a probability distribution almost uniform. Based on these observations, the presently proposed method for the assessment of survivability in transient flooding is found to be a rational way in considering the substantial factors of the transient flooding problem, taking into account the hydrostatics and considering in a random way the damage opening.

The basic assumption of uniform distribution on the absorbed energy *E* by the model is examined in the next Figure 19. In this diagram the maximum energy E_{max} absorbed by the model divided by the maximum available energy A_{max}, up to the time of E_{max} occurrence, is presented for all the survive tests. Tests are sorted in descending order with respect to the energy.

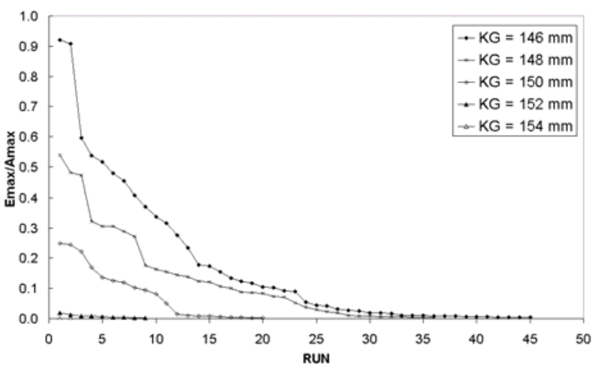

Figure 19 Ship's energy for survival tests

As shown, for each *KG* value there is a certain level of energy, which is not exceeded in survival cases. For greater levels of energy the model is capsizing. Considering now the energy distribution of each case determined by *KG*, within its survive domain, the next distribution, Figure 20, is derived accounting for the entire set of numerical model tests.

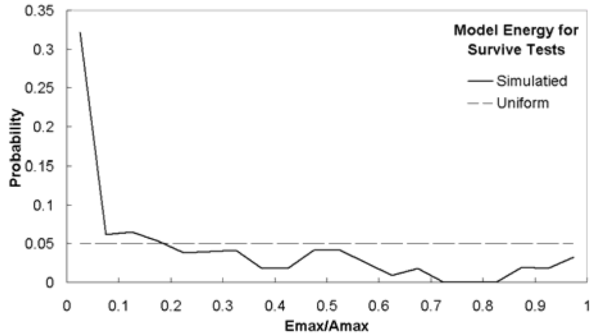

Figure 20 Ship's energy distribution for survival tests

It is observed that a significant probability at the lower energy percentages exists that exceeds the theoretical level of probability while for higher percentages there are lower simulated events than assumed theoretically. This difference resulting from the depicted distribution could be considered as a second factor that explains the results of the *s* factor vs. *KG* values presented in Figure 14. However the uniform distribution, although it seems conservative, it should be adopted when assessing transient flooding phenomena in safety evaluation procedures (and related regulations) unless another more efficient model is justified.

On the other hand the present analysis considers only the still water transient flooding excluding for the time being the effects of the waves or winds during the transient flooding that should be also considered as a part of transient analysis phenomenon. The most likely case that could happen in practice is that during an intermediate stage, where the ship adopts a heeling, it could change its heeling side e.g. from port to starboard, under the waves excitation. Obviously in that case, as the ship passes again through its initial equilibrium, it could absorb more energy from the available energy than predicted by the present simulations, thus, further reducing its survivability.

Furthermore, it is the authors' opinion that safety assessment procedures should properly validated and gradually improved, clearly identifying cases for which regulations set inordinate demands. Regulatory developments founded simply on the statistics of events, without deep understanding of the regulated ship properties, might lead to high cost in human lives, besides possible unnecessary penalties in ship's efficiency.

5. CONCLUSIONS

A theoretical integrated approach for the probabilistic assessment of survivability in transient flooding has been defined and proposed. This comprehensive method is based on the ship's non-linear hydrostatics in intermediate stages of flooding. The non-linear hydrostatics plays a substantial role for the estimation of the maximum ship's heeling angle in transient flooding. The method was validated investigating the behaviour a passenger/Ro-Ro ferry in transient flooding employing the numerical simulation method for the ship's motion and flooding of NTUA-SDL.

The assessment method seems slightly conservative, when compared with a direct numerical simulation method, a favourable feature in terms safety. This conservative property is bounded only to the higher marginal *KG* values. Implementation of the method proves to be practical and efficient.

The vertical distance of centre of gravity together with the damage length proved to be the dominant factors affecting the survivability of the ship at transient flooding. Smaller damage lengths favour the development of undesired heeling angles in transient flooding.

The simulation analysis has been based on still water transient flooding. Further simulations considering also the action of seaways are necessary to complete the investigation of the transient events.

6. ACKNOWLEDGEMENTS

Authors would like to acknowledge the support of this work by the E.C. HARDER project [1] dealing with the harmonization of probabilistic damage stability regulations and with the design development of new ship concepts of enhanced survivability. The opinions presented in the paper are solely of the authors.

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