On The Time to Capsize of a Damaged RoRo/Passenger Ship in Waves

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ABSTRACT

The time to capsize of a damaged RoRo/Passenger ship in waves has been analysed by a numerical simulation procedure, consisting of a nonlinear hydrodynamic method for the simulation of motion and flooding and a statistical simulation method to account for the variability and uncertainty of the various parameters affecting the complex behaviour of the damaged and flooded ship in waves. The probability distribution for the time to capsize has been derived. It is shown that there appears to be no practical time margins for the safe evacuation of RoRo-Passenger ships in the determined non-survival conditions. The results also suggest that the ship, which is complying with current damage stability requirements (SOLAS 90), will always capsize in the presence of waves, which are higher than a critical wave height, the so-called *survive limit*, and her overall survival time is determined by her *survive boundary*.

KEYWORDS

Time-to-capsize; Time-to-flood; damaged ship; survivability; numerical simulation; passenger ship safety

INTRODUCTORY INFORMATION FOR AUTHORS

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INTRODUCTION

In case of ship accidents resulting to sinking, the survivability of people onboard depends on the time required and being available for their safe evacuation and abandonment. The required time is determined by the duration of the evacuation and abandonment, which is affected by a variety of factors, like the number of people onboard, the internal ship arrangements and ways to muster stations, the ship motions, the live saving equipment, the visibility conditions (day or night) etc. The available time corresponds to the time until the ship loss, which reflects the resistance of the ship to capsize/sink, and is a property of the principal ship geometry mass and stability characteristics, her watertight subdivision and the environmental conditions.

A straightforward *assessment of the risk* of people onboard (in case of loss of watertight integrity) is based on the comparison of the time required for the people to safe evacuate and the time available up to the ship loss for a range of possible damage scenarios. Differently, estimating the time for the people to safely evacuate (by a proper evacuation study) and setting it as a requirement, then the time for the ship loss could be controlled by appropriate *risk based design measures* (and possibly additional operational measures), namely by minimizing the related risk, *Vassalos et. al* (2000).

In this context, IMO, *MSC.78* (2004), has introduced performance based criteria for the safety of the 'large' passenger ships, namely that of three (3) hours over which the ship is required to "remain habitable" after damage or safe return to the port under her own power. The explicit timeframe for habitability has been later revised, *MSC.80* (2005), to the "required time for safe evacuation and orderly abandonment" to better reflect the particulars of each vessel. These criteria determine the casualty thresholds, namely the extent of damage that a ship could sustain and they are being used by IMO in the development of appropriate requirements. Such developments imply the capability of managing the time for the ship loss after damage, which is an area of current and future intensive research that still needs time to become part of a standard design practice and eventually form a mature regulatory component.

In the framework of a holistic risk-based design procedure, as currently studied in the research project *SAFEDOR* (2005-2007), focused research on methods for the estimation of the time to capsize of passenger ships and the assessment of related risk has been conducted by the authors and some fundamental results of the related investigations are herein presented and discussed.

These results regard the time to capsize of a damaged RoRo/Passenger ship in irregular seaways due to flooding. The effect of the random waves on the time to capsize and its dispersion has been investigated on the basis of systematic numerical simulations of the ship in critical stability conditions. The criterion of three (3) hours habitability has been used as a reference time for the evaluation of the ship's capability to remain afloat and upright after damage. In the sense of IMO regulations, the study ship cannot be considered a 'large' passenger by size (Lpp=170 m); however, recent discussions at IMO, *MSC.82* (2006), have extended the safe return to port considerations to smaller passenger ships, hence relevant considerations apply also to the present one.

SHIP LOSS DUE TO FLOODING

The various flooding stages of the ship, which may lead to the physical or conventional loss of ship, are briefly revisited in order to facilitate the subsequent discussion.

Conventional and physical ship loss

Assuming a ship complying with current SOLAS damage stability requirements (SOLAS 90), the loss of her watertight integrity due to collision, and the damage extent within the range of current regulations, leads to the flooding of ship's internal spaces and the development of a new equilibrium, in principle with reduced transverse stability and floatability. Thereafter and in presence of waves, the ship may loose her transverse stability or floatability due to further accumulation of seawater and to capsize or sink. The latter process might last for a long time or lead to a fast ship loss depending on the ship however the prevailing wave conditions.

The damaged ship is said to be lost when it first loses her *floatability* or *stability,* and the corresponding time is the *time to ship loss*.

The *loss of floatability* occurs when the total floodwater mass, which entered the ship through any opening on her shell, equals the residual buoyancy related to the ship's loading condition in question. Apparently, loss of floatability does not mean concurrent full submergence of the ship. A delay will result due to the time required to flood the superstructures. So, *sink* is considered as the disappearance of the ship from the sea surface.

The *loss of stability* occurs when the ship first fails to comply with the transverse stability requirements, whereas it may physically *capsize* on a later time. For the present investigation the *capsize* event has been literally considered as the ship turn over.

Subjective time to ship loss

Theoretically the available time for evacuation of the people on board would be equal to the time to ship loss. However, in reality, the available time for evacuation is considerably reduced, because of the subjective perception of the passengers on the remaining time until the physical loss. This is rather evident in the sink of the RoRo/passenger ferry EXPRESS SAMINA, as noted by *Papanikolaou et. al* (2003), where the survivors testified as time to sink a considerably varying time between 20 and 45 min. In that accident the flooding caused rapidly a large heeling, hence most of the passengers tried (and many managed) to abandon the ship at the very early stage, though the disappearance of the ship from the sea surface happened about 50 minutes after the damage.

Flooding stages

In the ship flooding, two mechanisms can be identified that of the flooding due to hydrostatic head difference at the damage opening(s), which dominates the *flooding in calm water*, and that of flooding due to waves and ship motion, called *flooding in waves*. In terms of timing, both mechanisms start developing simultaneously after the damage incidence, hence, complicating the distinction of their impact on the stability of the ship.

It is used to refer to the flooding in calm water as *transient flooding,* while any stage between the start and the completion of transient flooding as *intermediate stage* of flooding. When the transient flooding has been completed, namely the damaged spaces have been fully flooded, the ship might continue be flooded due to waves action. This flooding stage is called *steady state* in order to distinguish against transient flooding.

Progressive flooding, namely the sequential flooding of adjacent spaces, is encountered during the otherwise transient flooding of multi-spaces. Progressive flooding could be triggered even in steady state flooding, due to the wave-induced and the floodwater-induced motion of the ship. In cases of highly compartmented internal arrangements, like passenger and cruiser ships, and in absence of wide spaces, like the car deck, the progressive flooding is governed by the hydrostatic flooding in calm water, whereas the waves' effect is limited, especially when the damage opening is limited too, *Papanikolaou et al* (2003).

The variety of the flooding stages of a damaged ship is illustrated in Figure 1.

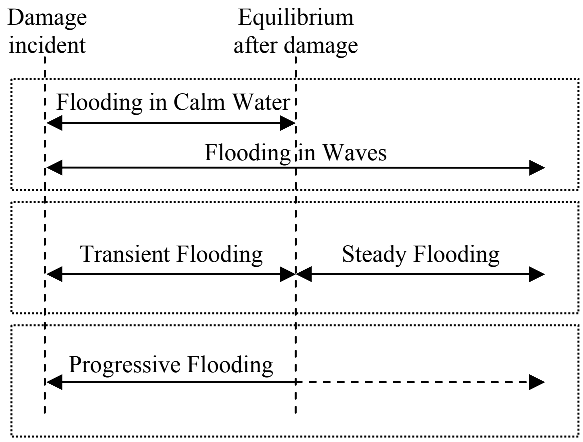

Figure 1 Flooding stages of the damaged ship

NUMERICAL SIMULATION PROCEDURE

Numerical Statistics

The time to capsize is a probabilistic quantity depending on several random variables that affect the flooding of the damaged ship in waves. The environmental conditions, waves and wind, the ship loading, the damage size, shape and location of the damage opening, the compartmentation and the status of the interconnecting openings (namely open or closed water-, weather- or splash-tight doors etc), all define a wide set of random variables and uncertain parameters that characterize the probabilistic nature of the flooding and the related time of specific events, like capsize.

To deal with above randomness the statistical method of Monte Carlo combined with a deterministic numerical hydrodynamic simulation for the ship motion and flooding is applied. The numerical hydrodynamic simulation program runs for a set of ship and environmental data, which have been specified randomly, to produce a single realization, a numerical test, of the damaged ship's flooding. The conducted numerical test may or may not result to capsize. The maximum time for the simulation has been set to three (3) hours in ship scale. For the next test, the simulation parameters are randomly updated by a Monte Carlo controller and the simulation process is repeated. The procedure keeps on until a sufficient number of numerical statistics has been gathered (convergence of statistical results) enabling a statistically reliable assessment. These statistics practically define the basis of the present investigation and reveal the nature of the time to flood/capsize problem.

Time domain simulation method

The numerical simulation method applied herein for the calculation of the time to capsize of the damaged ship is a nonlinear time domain numerical method for the coupled problem of the motion and flooding of the damaged ship in waves. The motion is defined with six (6) degrees of freedom. The hydrodynamics of the problem are based on a linear potential theory, whereas a variety of important non-linear terms of ship's equations of motions are considered, like the excitation by large amplitude regular or irregular waves, the exact wetting of the body geometry below and above the still waterline and its impact on ship's restoring, semi-empirical nonlinear viscous damping as well as sloshing effects due to moving fluids internally to the vessel or trapped on the deck, *Spanos* (2002). The employed random waves are considered to follow a Gaussian process and are generated by a *Longuet-Higgins* model for both long and short crested waves. The flow through the openings is approached in a stationary way, a hydraulic model that is based on a modified Bernoulli equation, assuming that the flow rate is governed by the difference of the water head in neighbouring spaces interconnected with an opening(s).

The simulation method has been extensively tested and validated with comparisons to experimental measurements for a variety of cases and conditions, *Spanos et. al* (2002), *Spanos* (2002), *ITTC* (2002), (2005), thus it can be considered rather reliable and robust.

However, the high accuracy achieved by use of this method is computationally demanding. The computational performance could be improved when interested in specific probability levels, instead of analyzing the full behavior of the damaged ship as herein questioned. This might be achieved by application of probabilistic methods (like first or second order reliability methods FORM/SORM) as appropriate for the estimation of the time to capsize T_{CAP} to exceed threshold times.

The RoRo/Passenger Ferry

The RoRo/Passenger ferry employed in the present investigation, has been previously investigated by *ITTC* (2002) and (2005). The main dimensions are given in Table 1 below, both in full and model scale, as the calculations have been executed in the model one.

Table 1: Main dimension of the investigated RoRo/Passenger ship, source: ITTC (2002)

	Full Scale	Model Scale	Units
Scale	1:1	1:40	

L_{BP}	170.00	4.25	m
B	27.80	0.695	m
T	6.25	0.156	m
Displ.	17300	0.270	tn
D_{CAR}	9.00	0.225	m
KG	12.50	0.313	m

The basic damage case has been defined assuming a damage opening of 8.10 m longitudinal length (acc. to SOLAS Part B, Ch.II-1, Reg. 8.4), an unlimited vertical extension and triangular penetration of B/5. This damage case corresponds to the worst-case according to SOLAS'90 regulations. The opening is located about amidships resulting to a flooding of two adjacent compartments. For this damage case the equilibrium angle in calm water equals 3.2 degrees to port due to an asymmetry of the damaged compartments, as shown in Figure 2.

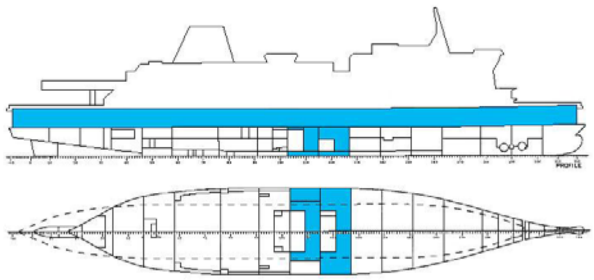

Figure 2 Two compartments damage case, source: ITTC (2002)

TIME TO CAPSIZE FOR THE DAMAGED FERRY

The numerical simulations account for initial conditions regarding the damage in calm water, zero speed and the damaged compartments below waterline being fully flooded. In that way any transient flooding effects were bounded and flooding in waves was dominant. The simulated beam waves were long-crested and deduced from a JONSWAP spectrum with the peak period randomly ranging between 3.5 and 6.0 times of square root of Hs and the peak enhancement parameter γ randomized between 1.0 and 4.0.

The typical behavior of the roll motion, for the non-survival tests, namely those leading to capsize of the vessel by the time of three (3) hours, is that shown in Figure 3. The vessel gradually heels under the effect of the accumulated floodwater on the car deck until the critical conditions were developed and then the vessel capsizes in a few wave periods.

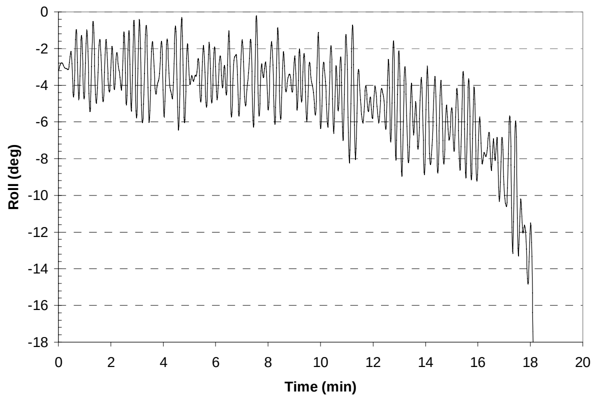

Figure 3 Sample roll time series of capsize test

The Survive Limit

The dependence of the time to capsize on the wave height is plotted in Figure 4. There, the time to capsize T_{CAP} is systematically recorded for selected values of the significant wave height Hs. For example, for Hs = 2.50 m the time to capsize ranges from 30 min (0.5 hr) up to 140 min (2 hrs and 20 min), with a mean value around 60 min (1 hr). When Hs equals 2.00 m none capsize occurred within 180 min (3 hr) simulation. The symbol shown at 180 min is to remind the execution of those tests.

The results of Figure 4 clearly demonstrate the presence of a limit wave height at 2.00 m where below that the T_{CAP} is infinite and above it the T_{CAP} converges asymptotically to the limit. This is actually a critical wave height corresponding to the studied damage case. We call this critical wave height the survive limit and distinguish it from the survive boundary, which is the lower boundary of the transition area between fully safe and unsafe conditions as pointed in Figure 4. Apparently, both survive (lower) and capsize (upper) boundaries in the transition area asymptotically converge to the survive limit. The existence of the survive limit is explained from the fact that a least and finite wave height is necessary for the flooding of the car deck, which stands above the water line at the height of the damage freeboard.

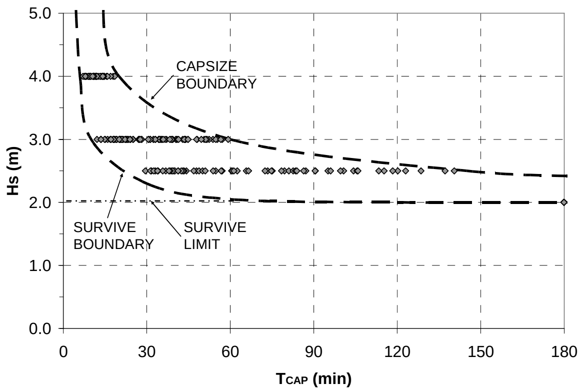

Figure 4 Time to capsize vs wave height

The boundaries recorded in Figure 4 for the RoRo/Passenger ferry are similar to boundaries for the Large Passenger ship as reported by Van't Veer (2004), where differently, the progressive flooding through a complicated internal arrangement was the prevailing flooding process. The fundamental difference of the boundaries between these two types of ship (RoRo/Passenger and cruiser) is the area between the survive boundary and the survive limit, which results rather small for the RoRo/Passenger ship compared to the Large Passenger. This rather small area evidences the substantial limited margins for the control of the time to capsize for the RoRo/Passenger ships.

When the waves are slightly higher than 2.0 m, namely between 2.0 and 2.50 m, a wide dispersion for the time to capsize occurs, revealing the rather random character of the flooding process as well as the reduced predictability at these conditions. When the waves are even higher then an abrupt reduction of the T_{CAP} is observed, with the time range becoming narrower and the mean value restricted to about 15 min (for Hs = 4.0 m).

Figure 5 samples the evolution of the mean value and the standard deviation over the sequence of the numerical simulation tests for the two cases those of Hs = 4.00 m and Hs = 2.50 m. The statistical convergence for the higher wave height of 4.00 m is apparent, whereas a slower (or even lack of) convergence is observed for the lower wave height of 2.50 m.

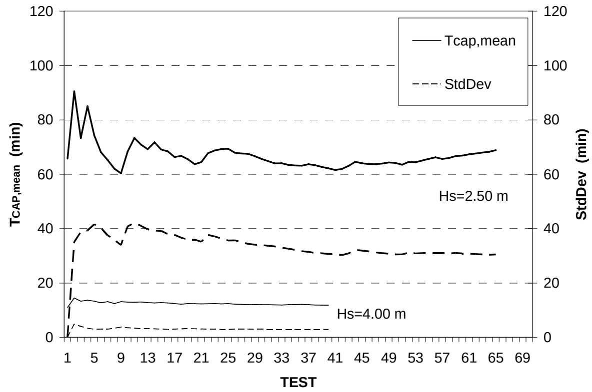

Figure 5 Mean value and standard deviation of T_{CAP}

In view of the damage stability of the RoRo/Passenger, the above findings are well correlated to the results of an investigation by *Vassalos* and *Papanikolaou* (2002) on the survive capacity of SOLAS'90 ships, which has been estimated on the basis of numerical and physical tests for a large sample of about thirty RoRo/Passenger ships, and was found about Hs=2.5 m. That estimation was actually based on the 30 min *survive boundary* (following Stockholm Agreement test procedures), as can be observed in Figure 4. Evidently, the ultimate survive capacity of the ship, namely regardless timeframes, is lower than 2.5 m, namely equal to 2.00 m, determined by the *survive limit*.

Parametric Investigation

To better observe the effect of the parameters that participate in the definition of the damage case on the time to capsize a parametric study has been conducted where the basic parameters have been changed to define four additional tests series, the Series 2 up to 5. For Series 2, the length of the damage opening has been reduced to the half-length of that of the basic Series 1. The vertical center of gravity has been increased by 30 cm for Series 3, with a proportional reduction of GM. The pitch has been fixed for Series 4 in order to cancel any possible *dead water* on deck, which may result in presence of trim and which drastically affect the stability of the vessel, *Pawlowski* (2006). In the last Series 5 the height of the car deck, the freeboard accordingly, has been reduced by 0.50 m.

For each of the above test series a similar procedure to Series 1, the basic case, has been applied for the generation of numerical statistics, which are shown in Figure 6.

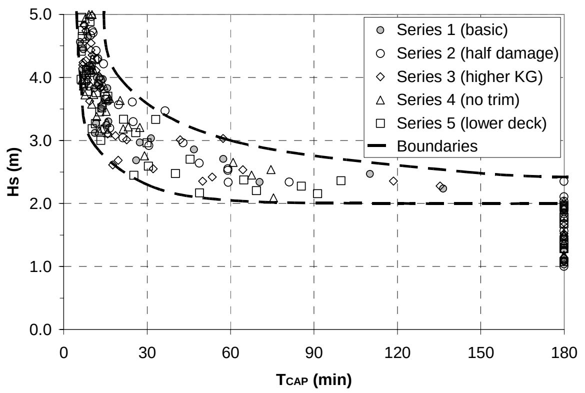

Figure 6 Numerical statistics for time to capsize

The above mess of results reveals an important fact, namely that none of the studied changes alters substantially the survive boundary results as determined from the basic damage case. The survive limit of 2.00 m is still recognizable, with the time to capsize converging asymptotically to this limit and all the tests below that wave height are survivals within three (3) hours.

PROBABILITY OF TIME TO CAPSIZE

Probability derivation

In order to derive a robust probabilistic formulation of the time to capsize for the damaged RoRo/Passenger ship in waves the numerical statistics of all the test series, as defined above, have been taken into account.

The derived statistical probability density of the time to capsize together with a corresponding regression analysis approach, are presented in Figure 7.

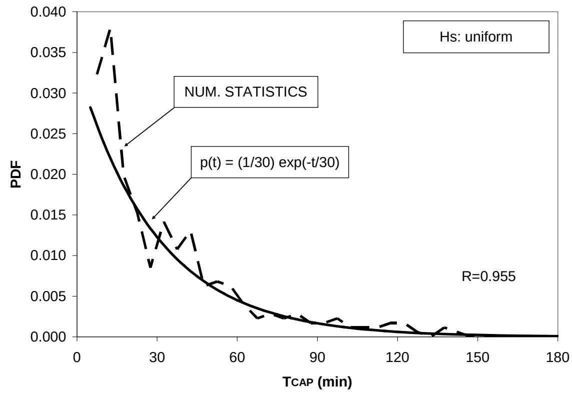

Figure 7 Probability of Time to Capsize of the RoRo/Passenger in waves, with Hs uniformly above survive limit

It is remarkable that the regression curve corresponds to an exponential probability distribution over the time to capsize T_{CAP} in min. The parameter defining the distribution equals (1/30), relating the time to capsize to a characteristic time of 30 min, which independently happens to be equal to the regulatory time for the safe evacuation of SOLAS'90 ships. In probabilistic terms this parameter determines the average capsize rate in the set conditions. Hence, the expected time to capsize for the RoRo/Passenger ship flooded in waves, is predicted to be one capsize every 30 min.

The above derived probability distribution has been based on a *uniform distribution* of the significant wave height Hs over the range considered, namely between the survive limit and 5.00 m. If another perspective of the time to capsize is considered, for example that corresponding to some particular wave statistics, then this probability needs to be modified accordingly.

Specifically, if the conditional probability of T_{CAP} for a certain wave height value Hs is considered, then this probability can be easily derived from the data of Figure 4. Such distribution varies around a mean value with definite width and has zero density for low capsize times. Apparently, it substantially deviates from the exponential probability distribution of Figure 7, and the exponential distribution proposed earlier by *Jasionowski*

(2006) for the conditional probability of T_{CAP} for certain Hs.

Another perspective of more general interest is to apply the wave height distribution recorded in collision events, as it has been introduced by the E.U. research project HARDER (2000). According to this distribution the probability of wave height gradually decreases in the higher wave height values, see *Tagg* (2002). When applying such distribution, the numerical statistics inherently change and the probability of the time to capsize results to that presented in Figure 8.

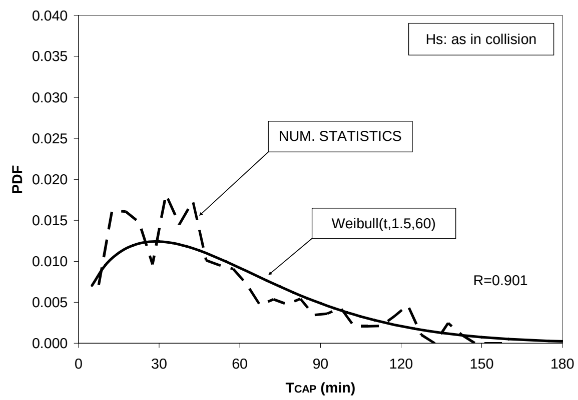

Figure 8 Probability of Time to Capsize of the RoRo/Passenger in waves, with Hs as in collision events

This probability distribution can be approached by a Weibull distribution with the two parameters a=1.5 and b=60. In comparison to the uniform distribution of the wave height applied in Figure 7, it shows that the lower waves, which are closer to the survive limit and are correlated with the wide range distributions of T_{CAP}, contribute more than the higher waves that correspond to shorter times T_{CAP}. As a result, the probability for a zero time to capsize vanishes with a relevant shift of the probability mass towards longer times.

Survive for long time

The above probability distributions for the time to capsize T_{CAP} have been derived through a pure numerical statistics approach and express the perspective of T_{CAP} for a damaged RoRo/Passenger ship in waves, in the first case assuming a uniform distribution of the wave height and in the second, assuming the waves to be distributed more realistically according to historical data of the waves during the collision events. According to these results the probability of a ship to remain upright for a certain time after the damage and waves be higher than 2.00 m (the survive limit) can be estimated as figured in Table 2.

Table 2: Probability to capsize in late times

	T_{CAP} later than	30 min	1 hr	2 hr	3 hr
Waves	Uniform	36.8 %	13.5 %	1.80 %	0.20 %
	collision statistics	70.2 %	36.8 %	5.90 %	0.55 %

According to these numbers the differences between the two cases assumed, are practically limited within the first hour period after damage incidence. After the first hour, the two distributions converge to zero and practically to each other. The probability to survive for long times after damage, namely after three (3) hours, and in presence of waves higher than the survive limit, is quite small practically negligible.

Considering that Table 2 provides the conditional probability of capsize in waves higher that 2.00 m and that the probability of waves higher than 2.00 equals 10% according HARDER project, the expectations after the damage are: in 90% of the damage cases the ship will survive (because Hs < 2.00 m), and in 10% she will not survive (Hs > 2.00 m). Where that 10% is further analyzed into 6.3% capsize within the first hour, 3.1% within the second hour, and just 0.6% to capsize later than 2 hours. It is reminded that the derived results have been based on the criterion of actual capsize instead of other conventional capsize criterion (e.g. loss of stability or exceeding a certain roll angle), hence, the estimated probabilities form an upper boundary for the expected times to capsize.

CONCLUSIONS

The present investigation has shown the critical character of the *survive limit* on the survivability of a damaged RoRo/Passenger ship. The ship will survive any case in which incident waves are below the survive limit, and will eventually soon or late capsize any case over this limit.

The time the ship takes to capsize in non-survival cases, is reduced rapidly with the increase of the wave height above the survive limit. This rapid reduction has been found to be quite independent of the basic assumptions on the ship loading condition, the damage opening and the depth of car deck. These findings suggest that the RoRo/Passenger ferry disposes apparently no practical time margins for safe evacuation and abandonment.

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