ITTC Quality System Manual
Recommended Procedures and Guidelines

Procedure

Simulation of Capsize Behaviour of Damaged Ships in Irregular Beam Seas

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Simulation of Capsize Behaviour of Damaged Ships in Irregular Beam Seas

1. PURPOSE

This procedure is for carrying out numerical simulations of motion of a damaged ship in waves including the flooding process to predict the occurrence of capsizing. For a full capsize-risk assessment a definition of capsize is required in combination with an assessment procedure. These two items are outside the scope of this procedure.

The term capsizing of damaged ships refers to loss of buoyancy (sinking) after flooding as well as insufficient righting arm to keep the ship under a prescribed heel angle. For instance, the IMO (Resolution MSC.141(76)) considers a RoRo ship model to have capsized when the instantaneous roll angle exceeds 30° or when the 3-minute average heel exceeds 20°. For naval ships capsize definitions may be quite different.

Due to the complexity of physical model experiments, the aim is to use computational tools that yield the most reliable results to the extent possible. For simulations of damaged ships however, computational time requirements play a major role in selecting a suitable computational method. The large number of simulation conditions (damage size and location, ship loading condition, sea states, *etc.*) and required simulation time length for determining a reliable capsize-risk figure often prohibit the use of advanced methods such as CFD.

2. NUMERICAL METHODS

Simulation methods for a damaged ship in waves must combine ship motion in view of wave excitation and flooding dynamics. In general, there exists a strong interaction between the exciting waves, the ship motions and the flooding process. Ship motions are influenced both by the exciting waves and the amount of flood water and will have effects on flooding process, too. The whole process can be highly nonlinear, especially in case of large damage openings and larger ship motions. Hence, nonlinear time domain simulation methods are required.

The numerical method used for simulations of a damaged ship in waves should be capable of including:

- Time varying mass, inertia and restoring terms, as well as the varying CoG location,
- Large transient and large amplitude motions,
- Nonlinear hydrostatic restoring, which means the nonlinear dependence of restoring force with the heeling angle due to the several effects including the influence of flooding water in tanks/deck spaces, large amplitude rolling, time varied righting arm in wave.
- Nonlinear wave excitation forces, which means that the wave excitation force is not dependent on the incident wave height in a linear way due to several effects like the significant change of hull geometry under the incident wave profile and the nonlinear influence of the incident wave itself in relatively steep seas.
- Nonlinear hydrodynamic reaction forces, which means that the fluid force estimation from radiation forces due to ship motions and diffraction forces due to the interactions of ship with the incident wave needs to consider the influence of nonlinear boundary conditions at the ship body and water free surface, one of the typical influences being

that the added mass and damping coefficients depend on the significant change of hull geometry.

- Viscous effects, especially for roll damping
- Water on deck dynamics and coupling with ship motions
- Flood water dynamics, including flow between compartments and sloshing.

2.1 Accounting for the Inertia of Flood Water

Newton's Second Law states that the force (moment) on a body is equal to its time rate-of-change of momentum (angular momentum). For a body of constant mass (moment of inertia) this translates to $\vec{F} = m\vec{a}$, $\left(\vec{M} = I\, d\vec{\omega}/dt\right)$ However, for a variable mass body such as a rocket which is burning fuel and ejecting gas or a damaged ship in a seaway taking on and possibly discharging water, the $\vec{F} = m\vec{a}$ analogy is not correct, but in fact the time-rate-of-change of mass must be taken into account (Sommerfeld, 1952). As the force must remain independent of the coordinate system, a simple application of the rule for differentiation of the product of two functions is not correct—the contribution from the time-rate-of-change of mass term belongs on the left-hand side of the equation with the force. In the context of rocket propulsion, the time-rate-of-change of mass contribution is the equivalent of the thrust of the rocket motor, and the entire system must be looked at as a constant mass system. Similar analogies apply to the time-rate-of-change of moment of inertia.

If we represent the momentum of the vessel as $\vec{p}$ and the angular momentum as $\vec{L}$, where $\vec{p} = m\vec{V}$ and $\vec{L} = I\vec{\omega}$, with m the mass of the ship, $\vec{V}$ the velocity, I the moment of inertial tensor and $\vec{\omega}$ the angular velocity, then Newton's second law can be written as:

$$\begin{aligned} \vec{F} &= m\frac{d\vec{V}}{dt} \\ \vec{M} &= I\frac{d\vec{\omega}}{dt} \end{aligned} \tag{1}$$

When the mass and hence the moment of inertia are constant, then these equations reduce to the traditional $\vec{F} = m\vec{a}$ form. However, in the damaged condition, the vessel's mass and moment of inertia vary with time and the equations of motion must be written in the above form. Rewriting equation (1) to account for the intake or discharge of floodwater as for a closed system yields:

$$\begin{aligned} \vec{F} + \overrightarrow{v'}\frac{dm}{dt} &= m\frac{d\vec{V}}{dt} \\ \vec{M} + \overrightarrow{\omega'}\frac{dI}{dt} &= I\frac{d\vec{\omega}}{dt} \end{aligned} \tag{2}$$

where $\overrightarrow{v'}$ and $\overrightarrow{\omega'}$ are the relative velocity and angular velocity of the flooding (discharging) water relative to the vessel, respectively, with the same sign conventions on the flow velocities as for vessel motions. All of the quantities $\overrightarrow{v'}$ dm/dt and $\overrightarrow{\omega'}$ can be determined from analysis of the flow at the damaged opening. If there is flow between flooded compartments, then the flow between the compartments must be incorporated in a similar manner. The of dI/dt is somewhat more complex as it involves the actual shape of the compartment. The formulation and solution of the coupled ship-flood water motion problem was elaborated by Spanos et at. (1997) and Papanikolaou et al (2000).

The floodwater in a fully filled compartment is often treated as a part of the ship and treated as a solid. In rectilinear acceleration, the floodwater acts like a solid. In rotational acceleration however, the moment of inertia is smaller than that of a solid, because there is a part of water that does not rotate with the ship, see ITTC (2014). Lee (2014) shows the ratio of the moment of inertia of floodwater and that of solids for various shapes of compartments.

$$C_R = I_{Liquid}/I_{Solid}$$

where I_{Liquid} and I_{Solid} are the moment of inertias of the floodwater when treated as liquid and solid respectively.

The following, Figure 1 shows the shapes of compartment treated in his study.

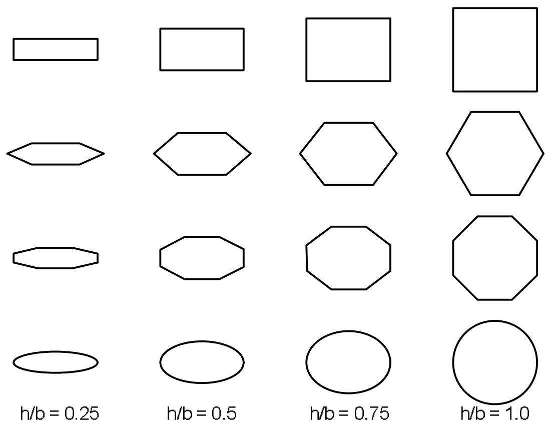

Figure 1 Various cross-section shapes of tanks useful for application from Lee (2014)

The inertias of the fluid in tanks of different aspect ratios and shapes, Figure 2, become small as the aspect ratio goes to unity. The solid lines of Figure 2 are analytical or numerical results while the dashed lines are an estimation formula that provide accurate results.

The approximate formula for the moment of inertia of the fluid in a tank given in Lee (2014) is:

$$I_{Liquid} = \rho k_e \frac{A^2}{\pi}\left(\frac{hb}{h^2+b^2}\right), \tag{3}$$

where A is the cross-sectional area of the tank, h is the height of the tank, b is the width of the tank, and k_e is given by the following:

$$k_e = \begin{cases} (\pi/4)^{1/2} & \text{for rectangle} \\ \left(\pi/2\sqrt{3}\right)^{1/3} & \text{for hexagon} \\ \left(\frac{\pi}{8(\sqrt{2}-1)}\right)^{1/4} & \text{for octagon} \\ 1 & \text{for ellipse} \end{cases} \tag{4}$$

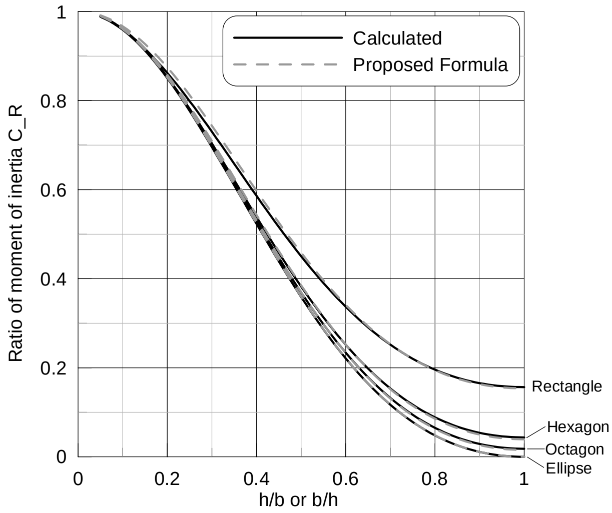

Figure 2 Moment of Inertia prediction of fully filled liquid for various shaped tanks; calculated and estimated from Lee (2014)

2.2 Additional Considerations

Nonlinearity is required to account for the changes in mean heel, draft and trim due to flooding. The principal axes of inertia may change as well due to the flood water mass. Water may appear on the weather deck. Furthermore, the method of determining the viscous reaction forces should be capable of dealing with a ship drifting in irregular seas.

In view of the use of the instantaneous roll and mean heel in survivability criteria it is recommended that unsteady wind loading be included in the excitation forces. It is noted that unsteady wind loads may also affect the flooding process through their effect on the heel angle.

Beside a method that includes nonlinear hydrodynamics, the effects of flooding must be accounted for. Air compressibility effects must be determined when the compartments are not or partially ventilated. For RoRo type ships, sloshing of flood water on large, open deck spaces is important. The method should be capable of dealing with multi-compartment configurations connected through doors, vents (down flooding) and ducts. The size of openings can be large and in and outflow of flood water may have a chaotic character. In this case some sensitivity analysis would be advisable.

Several types of flooding methods can be used, varying from fast methods based on Bernoulli's law to more advanced but complex CFD based methods, including SPH methods. Most times a compromise must be sought between fidelity and computational resources.

The free surface in tanks and flooded open spaces is often modelled by one of the following methods, in increasing computational cost order: (1) plane and horizontal; (2) plane and free movable (lumped mass models) (Papanikolaou and Spanos, 2002); (3) free by using of shallow-water-equations (Glimm, 1965; Chorin, 1976; Dillingham, 1981; Söding, 2002); (4) by blended methods using CFD for capturing the sloshing effects (Gao et al., 2011).

Most flooding methods are based on Bernoulli type equations. By using a pressure correction method air compressibility can be taken into account. Such flooding methods have been shown to yield accurate results for ships with relatively small compartments (no significant sloshing) and small openings, see Ruponen (2007).

However, for RoRo vessels sloshing can be of importance. This can be approximated by using the equivalent gravity angle approach (lumped mass models with a moving plane free surface). Better yet, shallow water equations can be used to account for sloshing, and should yield more accurate results, see Cho *et al* (2006), at the expense of a computational burden. Sloshing should be taken in to account when the natural frequency of the water motion in a flooded compartment $\omega_{nf} = \frac{\pi}{b}\sqrt{gh}$ is close to the frequency of the ship roll motion ω: $0.7\omega \leq \omega_{nf} \leq 1.25\omega$. Here h is the height of the water level and b is the width of the compartment.

Coupling the seakeeping method with CFD for flooded compartments is a logical next step. CFD methods are capable of dealing with highly complex and chaotic flows as well as sloshing and air compressibility. For relatively simple compartment configurations such methods have appeared recently, see Strassner *et al.* (2009). For the case of a Ro-Ro ferry in regular beam waves, Gao et al. (2011) presented a methodology for assessing the behaviour of a damaged ship in waves by coupling a seakeeping solver with a volume-of-fluid (VOF) solver. However, the computational burden seems still too high for application to ships with a complex compartment arrangement and for Monte-Carlo type simulations, *i.e.* performing a large number of time domain simulations. For example, a full capsize-risk assessment is estimated to require a simulation duration of 10,000 hours real time: 5 loading conditions, 10 damage positions and /or sizes, 20 sea states, 10 wave seeds and a 1 hour simulation duration. This means that the simulation tool should be faster than real time and that it must be used on multi-processor hardware.

Another feature that may be required for simulations for damaged ships is the ability to include effects due to:

- collapsing watertight doors and bulkheads,
- leaking (watertight and non-watertight) doors and bulkheads,
- counter flooding measures, for instance pumping ballast water in compartments,
- cross flow ducts,
- forward speed effects on water ingress at the instant the damage is created,

- flood water loads and loads in waves, for analysing the (weakened) ship structure,
- as well as air compressibility.

3. PREPARATION, SIMULATIONS AND ANALYSIS

3.1 Geometry

The discretisation of the hull form should be such that buoyancy and restoring forces can be accurately predicted. The calculated displacement and $\overline{GZ}$ curve should be within the accuracy of well-established hydrostatics software. Other hydrostatic data such as water plane area, block and prismatic coefficients are also useful checks on the geometry discretisation. A check on geometry errors by means of 3D surface plots is recommended. It is noted that besides hydrostatics, wave excitation forces are also sensitive to the geometry discretisation and the same discretisation error margin as for the $\overline{GZ}$ curve can be used: 2.5%. This should be verified by grid refinement.

According to IMO (MSC.76/23/Add.1), for Ro-Ro ships the superstructure should be included up to at least three superstructure deck heights above the bulkhead deck to include effects of reserve buoyancy, wave excitation and down flooding openings.

The correct mass, position of the centre of gravity and radii of gyration in the transverse and longitudinal directions corresponding to the data on the full scale ship should be used. In the absence of more accurate knowledge, a value of $0.35B$ to $0.45B$ for the roll radius of gyration, and $0.25L_{PP}$ for both the pitch and yaw radii of gyration are generally used. The roll radius of inertia for the intact ship can also be estimated by Eq.1 in ITTC Procedure 7.5-02-07-04.2.

Forces due to appendages such as rudders, skegs, bilge keels and fin stabilisers, affecting the roll motion and drift velocity should be included. For roll damping one is referred to the ITTC Procedure 7.5-02-07-04.5 on Numerical Estimation of Roll Damping.

The internal configuration should include all compartments, vents, other openings and cross ducts having an effect on flooding and air compression.

The volume permeability of floodable spaces should be modelled correctly. If no information is available for a specific ship, the ITTC Procedure 7.5-02-07-04.2 Model Tests on Damage Stability in Waves recommends volume permeability for non Ro-Ro vessels as follows:

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

For passenger ships, the ITTC Procedure 7.5-02-07-04.2 Model Tests on Damage Stability in Waves recommends volume recommends using SOLAS-defined permeability:

- Void spaces: 98%
- Passenger or accommodation spaces: 98%
- Engine room: 85%
- Machinery spaces: 60%

Special consideration should be given in the case of active buoyancy and stability recovery systems using inflatable devices (Chodankar, 2016, Zilakos I. and Toulios, 2018) or highly expandable foam (Vassalos et.al. 2016). Such systems may reduce significantly the permeability of a space over time following an accident. In order to capture accurately their impact to the floatability and the stability of the ship, the numerical simulation codes should model correctly: the timing and geometry of the inflation/expansion, the impact of the flood water pressure and air pressure build up due to potential blockage of vents, the impact of the position of the vessel (heel and trim) to the inflation/expansion process and any potential asymmetries resulting from them.

When CFD is used to determine flooding, the permeability can be accounted for by using simple shapes such as blocks or cylinders. When using Bernoulli-type flooding methods, the permeability can be specified when generating tank tables. Tank tables define the relation between the water level and the mass and centre of mass of the floodwater in a compartment. In practice, the permeability is usually not homogeneously distributed over the compartment volume, however this is generally neglected in Bernoulli-type flooding methods. It is recommended to describe the methodology applied to implement permeability.

Another feature specific for Bernoulli-type flooding methods is the need to use discharge coefficients (c_D). These coefficients relate the pressure difference over an opening to the flow velocity u_B through that opening and they were first discussed by Evangelista Torricelli (1643). Recent research has confirmed the values applicable to damaged ship numerical simulation (e.g. Ruponen, 2007):

$$u_B dA = sign(h_B - h_A) c_D \sqrt{2g|h_B - h_A|} dA \quad (5)$$

$$C_D = \frac{1}{\sqrt{1+K_L}} \quad (6)$$

According to Ruponen (2007), discharge coefficients typically have a value of C_D=0.60 to 0.70 for small openings. For larger openings, C_D values about 0.5 are usual. Note that discharge coefficients also depend on the shape of the opening and could be affected by scale effects, Katayama and Ikeda (2005). Furthermore, discharge coefficients are usually kept constant during the simulation, which is not always correct.

The location and size of damage openings is generally defined in the applied damage stability criteria. The location follows from either the most probable position or a worst location in terms of flooding effects, see for instance SOLAS 2009 (MSC.194(80) regulation II-1/8.2.3.2).

The opening width is typically 10-15% of the ship length. The height of the opening covers two floodable decks. The shape of the damage opening is a simple triangle, rectangle or trapezoid. More useful information can be found in SOLAS 90 regulation II-1/8.4.1 or in MSC 76/23/Add.1.

Other rules/criteria apply to naval vessels (Sarchin and Goldberg, 1962) and high speed crafts (see HSC code (2000)).

During the simulations, the instantaneous submergence of the opening must be determined, accounting for ship motions and wave elevation. If the vertical extent of the opening is large, a horizontal strip wise approach should be taken to deal with local pressures and velocities. For a large horizontal opening extent, variations in pressures and velocities can be taken in account by subdividing the opening in more than one part.

3.2 Preparations

Since flooding simulations in waves involve a number of complex physical phenomena with a sometimes chaotic nature, small differences in wave induced ship motions, damage openings, vents, doors, *etc.*, affecting the flooding process, may have large effects on the final result, *i.e.* to capsize or not to capsize. Furthermore, it is difficult to distinguish between cause and effect when inspecting for instance time traces of the amount of flood water in certain compartments. Therefore it is recommended to check and document a number of basic properties before performing the actual time domain simulations.

As a first basic check, the trim and draught at calm water should match the displacement and location of the centre of gravity within 2.5%. Next, the $\overline{GZ}$-curves for the intact and equilibrium damaged condition (calm water) should be compared with these from hydrostatic software packages. The differences in $\overline{GZ}$ should be less than 2.5% up to the point of vanishing stability.

Next, a zero forward speed roll decay simulation should be performed for the intact case to check the external roll damping. Initial amplitudes of 15 to 25 degrees are to be used. For the equilibrium damage case with a constant amount of flood water (closed damage opening) a roll decay simulation can be performed as well. It is recommended to compare the derived roll response for the intact and damaged cases with those from model tests on a similar ship and damage cases. This is of particular relevance when sloshing is expected to occur. When no experimental data are available more general validation data can be used, see Section 4.

It should be realised that before and/or during roll decays with flood water present in a multiple compartment configuration, asymmetric and up and down flooding can occur which can make the resulting roll motion non-periodic and rather dependent on the initial heel angle and potentially on how long the vessel was held at the initial heel angle. The procedure and results should be documented, especially differences between simulated and experimental roll response.

Generated tank tables should be visually inspected for inconsistencies and irregularities.

For the equilibrium damage condition in calm water, the water level in fully ventilated compartments extending through the water line should be equal to the water level outside the ship (sea level). For non-vented compartments, the air pressure should match the hydrostatic pressure at the opening.

It is also recommended that a sensitivity analysis on discharge coefficient values and compartment permeability be performed.

Furthermore, it is recommended to investigate the basic drifting behaviour (velocity and heading) of the ship under influence of a constant force, for instance a constant wind loading. Drifting in regular waves can be investigated as well (for instance for deterministic validation), but it should be noted that the drifting behaviour in regular waves can be markedly different from that in irregular waves.

3.3 Wave conditions

The simulations are generally carried out in long-crested irregular beam waves. Simulations and model tests have shown that the flooding process in regular waves can be different than and not representative of that in irregular waves. Therefore, it is recommended not to perform simulations in regular waves other than for better understanding and validation purposes. No data is available on the need to conduct simulations in short-crested seas and this should be subject to further investigation. The quality of the numerically generated waves may be not sufficiently good when using a boundary element method (BEM) and has to be checked to ensure they resemble real waves. The simulation method should be capable of including wave spectra for the area of operation or as required by rules. In absence of information on specific spectrum data, JONSWAP and ITTC (1978) spectra should be used (see ITTC Procedure 7.5-02-07-02.1).

A maximum characteristic wave steepness of $H_{1/3}/(gT_p^2/2\pi) = 0.05$ is recommended as a guide, $H_{1/3}$ being the significant wave height and T_P the peak period.

For determining the survival wave height, *i.e.* the wave height at which the capsize criteria are exceeded, a series of simulations must be performed for a matrix of $H_{1/3}$ and T_P combinations, selected from the wave statistics for the area of operation. For efficiency it is recommended to start with wave spectra at the expected survivability limit and to go upwards and/or downwards in wave steepness until the limit is well defined.

The wave signal generated from the spectrum should not repeat during a simulation. It is recommended to use randomly spaced frequency bands and to use one very narrow frequency band near the peak frequency. At least 100 frequencies should be used to discretise the long-crested wave spectrum. For short-crested spectra 100 frequencies times 25 wave directions are recommended for discretisation. It is recommended to check the autocorrelation of the generated wave elevation to ensure that it remains small for enough time and they do not show spikes that will indicate repetition.

3.4 Wind conditions

At zero speed (drifting), wind forces can be important as they have an effect on ship heading, drifting direction and velocity and thereby on flooding and heel angles. The wind velocity can be constant, properly specified by a given wind profile, or wind gusts and direction variations can be generated from multi directional wind velocity spectra. Wind load coefficients in six degrees of freedom can be obtained from wind tunnel experiments and CFD, or from empirical methods based on non-dimensional wind tunnel data. Examples are Isherwood (1972), Blendermann (1994) and Fujiwara et al. (1998).

3.5 Simulations

Forward speed effects at the instant that damage occurs can have an important effect on initial flooding (Herald of Free Enterprise, Estonia). However, starting the simulation with the condition (speed and heading) at which the damage is expected to occur adds more degrees of freedom to the problem and the effects of an instantaneous opening or damage at forward speed with another ship present (collision) can probably not be simulated adequately with the current state of the art. As a compromise and until more complete tools and more powerful hardware are available, the ship can be initially positioned in beam seas with zero drifting velocity. The wave height should be slowly increased from zero to its nominal height through the use of a ramp function. A similar ramp function can be used for the wind velocity. During this ramp-up period the ship will assume its initial drifting velocity and heading angle.

The damage opening may be closed initially and then opened once the wave height has reached its nominal value. The initial transient heel can be simulated in this way, but it is not very representative of the actual transient when a collision or grounding occurs. Alternatively, the simulation can be started with the equilibrium amount of flood water on board and the corresponding equilibrium draft, trim and heel. The damage opening then opens at the start of the simulation.

For damage model testing of passenger ships an additional heeling moment that is likely to be present in an emergency situation can be included. This can be caused by passengers gathering at the edge of the deck for lifeboat launching. For RoPax ferries a heeling moment resulting in a 1-degree heel angle towards the damage side is recommended by IMO-MSC 76/23/Add.1. It is noted here that heeling moments may already be present due to wind.

During the simulation the ship must be allowed to drift freely under influence of waves and wind. The damage opening should be facing the incident waves since experience indicates that this is generally worse than when the damage opening is at the leeward side. Nevertheless, for some critical cases the effect of having the damage opening at the leeward side should be investigated.

Per condition (displacement, CoG location, sea state, damage opening, *etc*.) at least 10 simulations should be performed with a duration sufficient for 30 minutes *after* reaching a steady state (in terms of the three-minute average draft, trim, heel angles and drift velocity) to obtain extreme value statistics. In each of the 10 simulations a different wave realisation must be obtained.

3.6 Simulation data

In order to analyse the possible capsizing process, the following quantities should be stored, as applicable, at a sufficient sampling rate (at least 20 divided by the natural roll period):

- Ship position in space.
- Average ship draught, heel angle, drifting velocity and heading relative to the wave direction.
- Ship motions (displacements, velocities and accelerations) in 6 degrees of freedom.
- Wave elevation at the reference ship CoG position, the relative wave elevation at the damage opening(s) and possibly at a number of positions at the deck edge.
- Wind characteristics (speed, direction and gradient profile) at the ship position.
- Floodwater mass and level in each compartment, flow rate through openings and air pressure for non-ventilated compartments.

Visualisation of the ship motions in combination with the instantaneous floodwater levels and openings in the compartments is indispensable for analysing the simulation results.

3.7 Analysis

Considering the possibly chaotic behaviour of flooding in irregular waves, the number of simulation runs and their duration should be documented. The level of confidence of estimated capsizing probability should be calculated by using the formula of a binomial probability distribution. A simple estimate of the capsizing probability, p_c, is a ratio of the number of capsizing events, N_c, to that of different realizations, N, as follows (from ITTC procedure 7.5-02-07-04.1, Model Tests on Intact Stability):

$$p_c = \frac{N_c}{N} \tag{7}$$

If p is the true capsizing probability, the confidence interval of capsizing probability can be calculated by the following equation:

$$\Delta p = \frac{2}{\sqrt{N}}\sqrt{p_c(1-p_c)}z_{1-\alpha'/2} \tag{8}$$

Here, $z_{1-\alpha'/2}$is the $(1-\alpha'/2)$ quantile of the standard normal distribution, which can be determined from the table of normal distributions and α' is the confidence level of the predicted capsizing probability. The range of error tolerance of the capsizing probability can finally be determined as follows:

$$p_c - \frac{\Delta p}{2} \le p \le p_c + \frac{\Delta p}{2} \tag{9}$$

with a probability of $1-\alpha'$

3.8 Capsize Band and Rate

Numerical simulations can be used to identify few distinct characteristics of the damaged ship. Capsize band is one of them. It was first introduced in the North West Research European Project (Vassalos et al., 1997) as “survival boundary”. It indicates a band within which the transition from “safe” to “unsafe” takes place (Papanikolaou et.al., 2010). It corresponds to one damage case for different loadings conditions and sea states. The band starts at the maximum wave height where no capsizes are observed (given certain uncertainty levels) and ends at that wave height where all realisations result in loss. The wave heights are plotted against the variation of the $\overline{KG}$ or the $\overline{GZ}$. An example is shown in Figure 3.

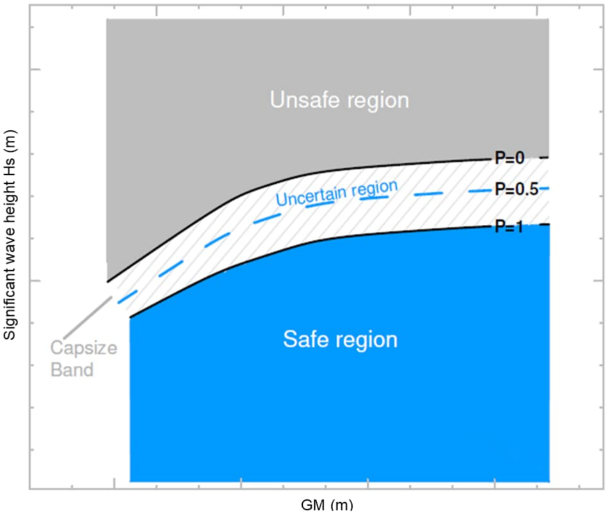

Figure 3. Capsize band with indication of safe (P=1_, uncertain and unsafe regions (P=0) (Atzampos, 2019)

Directly linked to the capsize band is the concept of "rate of capsize" (PF) (Papanikolaou et.al., 2010). It is actually the probability of capsize, given a sea state. As such, PF is 0 at the lower end of the capsize band and 1 at the upper end. An example is shown in Figure 4.

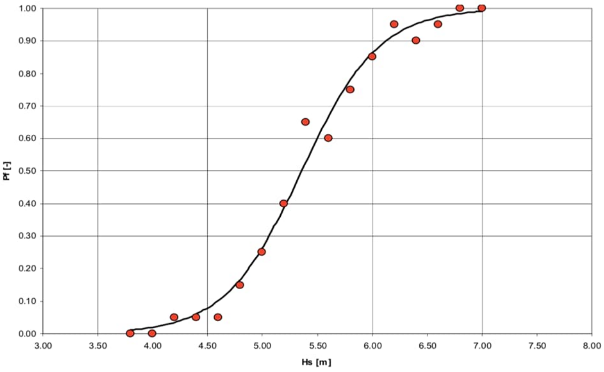

Figure 4. Capsize rate and fitted sigmoid (Papanikolaou et.al., 2010)

The capsize rate follows a sigmoid shape distribution and it depends upon the time of observation. As such, in case of a limiting case of infinite exposure, the capsize rate distribution will turn into a unit step function as indicated in Figure 5 for increased simulation times (Papanikolaou et al., 2013).

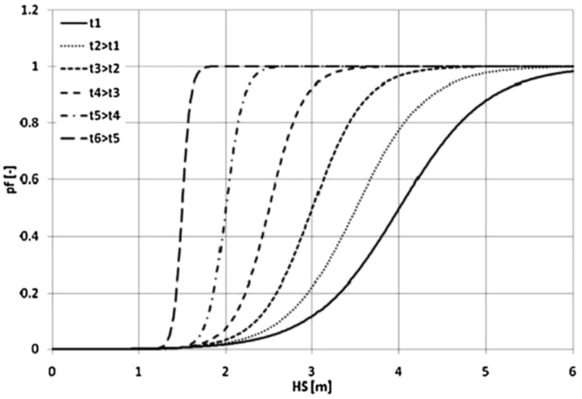

Figure 5. Contraction of the capsize rate with increased time of observation (Papanikolaou et al., 2013)

3.9 Critical Wave Height

The point of the capsize band where PF = 0.5 is the "critical wave height" (H_{Scrit}) and it is this value that is used by convention when referring to ship survivability (Tuzcu, 2003 and Papanikolaou et al., 2010). Tsakalakis et. al. (2010) observed that when the simulation time increases, the capsize band contracts towards its lower boundary (see Figure 5). Therefore, they propose that H_{Scrit} is defined as the highest sea state at which no capsizes are observed within 30-min runs.

The relationship between the stability parameters and the critical significant wave height has been discussed by Tuzcu and Tagg (2002). A concept for the calculation of the probability of survival, defined in SOLAS Ch. II-1 Regulation 7-2 as s-factor, is based on H_{Scrit}. It was proposed in the HARDER project (Tuzcu, 2003) according to the following formulation.

$$\begin{gathered} H_{\mathrm{Scrit}} = 4\frac{GZ_{\max}}{0.12}\frac{Range}{16} = 4s^{4} \\ \Updownarrow \\ s = \left(\frac{H_{\mathrm{Scrit}}}{4}\right)^{0.25} \end{gathered} \qquad (10)$$

The coefficients of 0.12 meters and 16 degrees resulted from regression analysis and they are referred in SOLAS as targeting values $GZ_{\max}$ and $Range$ respectively.

3.10 Time to Capsize

A significant output from the time domain simulations is the so-called “time to capsize” (TTC). Several researchers have proposed notions such as “survival time” (Jasionowski, 1999) or “time to sink” (Veer et al., 2002). Jasionowski et al. (2002) proposed the consideration of individual waves or groups as an integral element of the capsizing process. The capsize event is identified from the presence of the incidence of the critical groups. TTC is then calculated by the statistical analysis of the results. Veer et al., (2002) referred to the time required to reach specific SOLAS static criteria such as maximum roll of 30deg, mean roll angle of 20deg within 3 min and mean roll angle of 12deg. Spanos et al. (2007) differentiate between TTC and the “time to ship loss” that corresponds to the loss of adequate floatability or stability. Valanto (2006) proposed alternatively the term “time to flood” representing the time from the initiation of the water ingress and the steady state ensuing progressive flooding.

Atzampos (2019) underlines that TTC is fundamentally linked to the H_{Scrit} concept since it forms a boundary below which it is unlikely to observe capsizes. That conceptually forms an asymptote of the TTC distribution. Generally, TTC will decrease with the increase of the encountered wave height. Therefore, the TTC is inversely proportional to the difference between H_{Scrit} and the actual sea state.

3.11 Real-time Flooding risk evaluation

Vassalos et al. (2023) developed a framework for assessing the flooding risk in real-time and operational phases, building on the H2020 FLARE project's design phase framework. This operational approach uses high-fidelity methods for accurate flooding risk and PLL estimations. It introduces a probabilistic model compatible with the FLARE software by adjusting damage distribution sources and includes real-time PLL assessments during voyages based on damage and vulnerability databases, a step not required in the design phase. Furthermore, the framework proposes the development of dedicated databases for damage and survivability models post-collision, demonstrating the methodology's real-time applicability with a mock-up dataset. However, its full onboard application is dependent on precise onboard sensor data to address measurement uncertainties, indicating the current example is limited to theoretical error evaluations. Nonetheless, the methodology remains effective regardless of sensor inaccuracies or the surrogate models' estimated nature.

3.12 Machine Learning/Artificial Intelligence methodologies

Lourvos et al. (2023) developed a methodology combining two reasoning approaches, namely Machine Learning and Case-Based Reasoning, utilising pre-calculated databases for real-time damage scenario analysis. This methodology, validated for real-time use, requires simple, easily obtainable inputs, such as crew visual assessments. It accounts for uncertainty in predictions, especially regarding the survival factors. It demonstrates reliable results and the ability to extract key insights from extensive data. Both reasoning methods yield similar outcomes, with their benefits discussed and compared. The authors suggest further exploration into ML for dynamic, real-time damage stability assessments, highlighting the methodology's simplicity, effectiveness, and relatively low requirements for sensor data quality and computational power. Success largely depends on the extent of pre-calculated damage scenarios, offering a significant improvement over traditional, less flexible tools by incorporating a wide range of factors like weather and actual loading conditions without overburdening crew resources. It can be integrated into a decision support tool in flooding emergencies, as it was depicted in the H2020 Project SafePASS.

Mauro et al. (2023) developed a surrogate model to enhance real-time onboard risk assessment for ship collisions, utilizing SHARP software's Super-Element methods for efficient scenario generation. This approach, tested with approximately 4,400 damage cases, found forest tree models to offer the best fit, though multiple linear regression models were considered for their simplicity in real-time applications. Increasing the sample size, particularly by adding more types of colliding ships, could improve model accuracy without necessarily expanding the design of experiments (DOE). Given the uncertainties in calculating damage dimensions directly, multiple linear regression is recommended as an initial approach for developing onboard risk assessment tools. As the database grows with more detailed information, transitioning to forest tree models is suggested. Neural networks were noted to require significantly more data to outperform these models. The developed model can then be used in the real-time flooding risk assessment (see Vassalos et.al., 2023).

3.13 Documentation of simulations

The main simulation results should be presented as capsizing probabilities in irregular seas. They should be a function of the main ship characteristics and operational and environmental parameters. The number of simulation runs and their duration should be documented.

The report should also contain the following (where applicable):

- Loading condition, damage opening and internal arrangement. External configuration details including appendages.
- Differences in predicted and expected hydrostatics should be reported.
- A description of the capsizing modes identified.
- Ship condition information including $\overline{GZ}$ curves with and without flood water at equilibrium condition.
- Roll decay simulation time series and derived coefficients.
- Wave spectrum and wave characteristics.
- Initial conditions.
- Statistical analysis of the time series of wave elevation and ship motions in 6 degrees of freedom.
- Capsize Band and Rate analysis for critical damage scenarios
- Time to Capsize calculation for each critical scenario
- H_{Scrit} and corresponding s-factor

4. VALIDATION

In absence of specific model test data, the cases described below can be used for validation purposes.

Papanikolaou and Spanos (2004, 2008) presented results of the 24th ITTC and SAFEDOR project benchmark studies on the numerical prediction of damaged RoPax ships stability in waves in comparison to model experiments.

In van Walree (2007) and Ruponen (2006) benchmark model tests are described that can be used for validation. The case considered is a barge with small damage openings. Detailed experimental data are available.

Further validation data for these two cases is presented by Corrigan (2010).

Cho et al. (2009) present experimental results for a damaged cruise ship at calm water and in waves. Detailed data are available at the Stability in Waves committee.

Macfarlane et al. (2010) describe damage model tests on a destroyer with large openings. Special attention is paid to the transient roll immediately after the occurrence of the damage.

Begovic et al. (2013) presents a study on the experimental of motions for the well-known 5415 frigate hull in intact and damaged conditions. The experimental campaign is conducted for two models, 1/100 and 1/51 scale, at zero speed in head, beam and quartering seas. All experimental results for 1/51 model are presented as 1st and 2nd order RAO. The results show the changes in motion responses when a ship hull is in damaged condition. Furthermore, they highlight the model scale effects and demonstrate the comparisons between the tests in which the model may freely drift and those in which the mean position of the model is restrained. For damaged ship in free drift tests the damage opening orientation is varied and its effect on RAO and free drift velocity is commented. Gu et al. (2018) conduct a similar test, comparing experimental (using the 1/51 scale model) with CFD results. They investigate the impact of ingress and egress of floodwater and the interaction between the ship behaviour and water surface effect have on the ship motions and loads acting on the ship.

Manderbacka T. et al. (2015) conducted roll decay tests for one flooded compartment and transient abrupt flooding test for the box shaped barge model. The tests were conducted to obtain information on the flooding process for the development of numerical tools and to provide validation data. Propagation of the flooding water inside the compartment, at a dam-break type abrupt flooding, was studied by tracking the surface of the flooded water. The internal layouts of the flooded compartment on the roll damping and roll motions has been analysed based on the measurements.

Ruth et al. (2019) present the opportunities and challenges of using CFD for simulating the damage stability of cruise ships in waves, based on the experience gained in the joint industry project eSAFE.

Rupponen et.al. (2022a, 2022b) present an international benchmark study on simulation of flooding and motions of damaged ropax and cruise vessels that was conducted within the EU Horizon 2020 project FLARE, using new dedicated model tests as a reference. The test cases include transient flooding in both calm water and in irregular beam seas, as well as gradual flooding and capsizing in beam seas. The studied damage case is a two-compartment collision damage, and the studied intact metacentric height values were lower than the statutory requirements to achieve also capsize cases. Numerical results were carefully compared against measurement data from the model tests. In transient flooding cases the capsize conditions were generally detected well by most codes.

5. LIST OF SYMBOLS

A	Cross-sectional area of the tank,	m^2
$\vec{a}$	Vector of linear acceleration,	m/s^2
B	Beam,	m
b	Width of the tank or compartment,	m
C_D, c_D	Discharge coefficient	
C_R	Ratio of the moment of inertia of floodwater and that of solids	
$\vec{F}$	Force on a body,	N
$\overline{GM}$	Metacentric height,	m
$\overline{GZ}$	Righting arm,	m
$GZ_{\max}$	Maximum of GZ curve	
g	Gravity acceleration,	m/s^2
H_{Scrit}	Critical wave height	m

$H_{1/3}$	Significant wave height,	m
h	Height of the tank or water level,	m
I	Moment of inertia of a body,	$\mathrm{kg\cdot m^2}$
I_{Liquid}	Moment of inertia of floodwater, when treated as liquid	$\mathrm{kg\cdot m^2}$
I_{Solid}	Moment of inertia of floodwater when treated as solid,	$\mathrm{kg\cdot m^2}$
$\overline{KG}$	Vertical position of the center of gravity,	m
$\vec{L}$	Angular momentum	$\mathrm{kg\cdot m^2/s}$
L_{PP}	Length between perpendiculars,	m
$\vec{M}$	Moment of a body,	$\mathrm{N\cdot m}$
m	Mass a body,	kg
N	Number of realizations	
N_c	Number of capsizing events	
$\vec{p}$	Momentum of a body,	$\mathrm{kg\cdot m/s}$
p_c	Capsizing probability	
T_p	Spectral peak (modal) period,	s
t	Time,	s
u_B	Flow velocity,	m/s
$\vec{V}$	Vector of linear velocity,	m/s
$\overrightarrow{v'}$	Vector of relative linear velocity of flooding (discharging) water,	m/s
z	Quantile of standard normal distribution	
α'	Confidence level	
Δp	Width of confidence interval for an estimate of capsizing probability	
ρ	Density of water,	$\mathrm{kg/m^3}$
$\vec{\omega}$	Vector of angular velocity,	$\mathrm{s^{-1}}$
$\overrightarrow{\omega'}$	Vector of relative angular velocity of flooding (discharging) water,	$\mathrm{s^{-1}}$
ω_{nf}	Natural frequency of the water motion in a flooded compartment,	$\mathrm{s^{-1}}$
ω	Frequency of the ship roll motion,	$\mathrm{s^{-1}}$

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