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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 on a damaged ship in beam seas to predict the occurrence of capsizing. For a full capsizing-risk assessment a definition of capsizing is required in combination with an assessment procedure. These two items are outside the scope of this procedure.

The term capsizing refers to loss of buoyancy (sinking) as well as insufficient righting arm to keep the ship under a prescribed heel angle. For instance, the IMO (Resolution MSC 76/23) considers a RoRo ship to have capsized when the instantaneous roll angle exceeds 30 deg or when the 3-minute average heel exceeds 20 deg. For naval ships capsizing definitions may be quite different.

Generally the aim is to use computational tools that yield the most reliable results. For simulations for 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 capsizing-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 and flooding dynamics. In general there exists a strong

relation between the ship motions and the flooding process. Ship motions depend on the amount of flood water mass and in turn, flooding depends on the ship motions. The whole process can be highly nonlinear, especially in case of large damage openings. 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 terms and CoG location,
- Large transient and large amplitude motions,
- Nonlinear hydrostatics,
- Nonlinear wave excitation forces,
- Nonlinear hydrodynamic reaction forces, including roll damping,
- Nonlinear viscous reaction forces,
- Water on deck dynamics, and
- 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 $\vec{F} = m\vec{a}$ ($\vec{M} = I d\vec{\omega}/dt$)

However, for a 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

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in fact the time-rate-of-change of mass must be taken into account. 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:

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

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:

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


where \vec{v}' and $\vec{\omega}'$ 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 \vec{v}' , dm/dt and $\vec{\omega}'$ 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 evaluation of dI/dt is somewhat more complex as it involves the actual shape of the compartment.

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, 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. 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.

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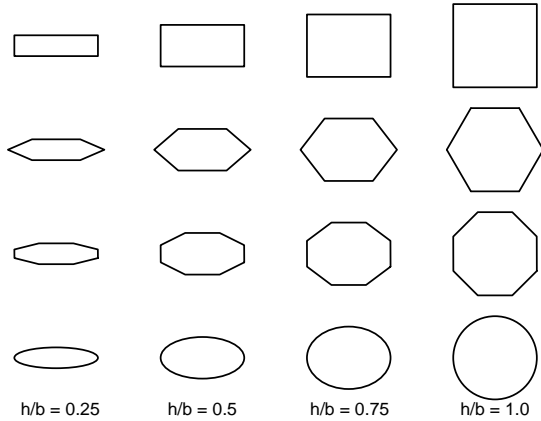


Figure 1 Various cross-section shapes of tanks useful for application from Lee (2014)

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.

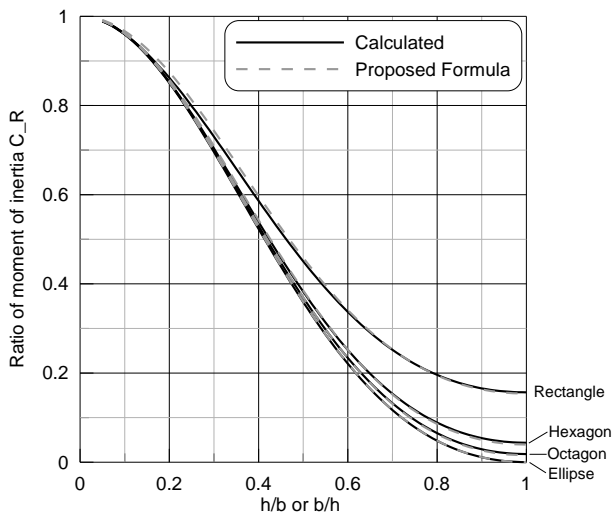


Figure 2 Moment of Inertia prediction of fully filled liquid for various shaped tanks; calculated and estimated from Lee (2014)

The approximate formula for the moment of inertia of the fluid in a tank given in Lee (2004) is:

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

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:


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

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 beam 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.

Apart from 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

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(down flooding) and ducts. The size of openings can be large and in and outflow of flood water may have a chaotic character.

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.

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. 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), yet 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 capsizing-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 preferably is 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, *etc.*
- 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.

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. A three-dimensional panel discretisation is recommended in lieu of a discretisation based on sections. The calculated displacement and \overline{GZ} curve should be within 2.5% of that 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

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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 can also be estimated by:

$$k_{xx} = \sqrt{\frac{1}{12} (0.4 B + H)^2 + 0.6 B^2 + H^2 - T - 0.5H - z_G}^2$$

where B , d and T are the beam, depth and draft of the ship respectively and H_{CG} is the height of the centre of gravity above the water surface.

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.

Surface and volume permeability's 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's as follows:

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


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

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

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's 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.

Another feature specific for Bernoulli-type flooding methods is the need to use discharge coefficients. These coefficients relate the pressure difference over an opening to the flow velocity through that opening. Discharge coefficients typically have a value of $C_D=0.60$ to 0.70 for small openings, see Ruponen (2007).

The location and size of damage openings is generally defined in the applied damage stability criteria. The location follows from either the

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most probable position or a worst location in terms of flooding effects, see for instance SOLAS 90 (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 detailed 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 for instance naval vessels and high speed craft (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 capsizes or not to capsizes. 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 damping 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,

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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 validation purposes. No data is available on the desirability to conduct simulations in short-crested seas and this could be subject to further investigation.

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 for limited fetch and ocean waves, respectively. A maximum characteristic wave steepness of $H_{W1/3}/(gT_p^2/2\pi) = 0.05$ is recommended as a guide.

For determining the survival wave height, *i.e.* the wave height at which the capsizing criteria are

exceeded, a series of simulations must be performed for a matrix of $H_{W1/3}$ 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.

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 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

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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 life boat 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.

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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):

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

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

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

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:

$$p_c - \frac{\Delta p}{2} \leq p \leq p_c + \frac{\Delta p}{2}$$

with a probability of $(1-\alpha)$.

3.8 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.


4. VALIDATION

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

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.

In Spanos and Papanikolaou (2008) a validation study of several codes is presented based on model tests on a Ro-Ro ship.

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

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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.

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