ITTC Quality System Manual

Recommended Procedures and Guidelines

Procedure

Model Tests on Damage Stability in Waves

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Damage Model test Procedure

1. PURPOSE OF PROCEDURE

1.1 Purpose

This procedure provides the recommended practices for carrying out the model tests of a damaged ship in waves. The general purposes of damaged model tests are

1. To determine the probability of capsizing or the significant wave height that will cause the model to capsize over a fixed time period.
2. To understand the physics and behaviour of the motion of damaged ship and the flooding process and their effects.

The procedure is based on review of the damaged model experiments that include Ro-Ro passenger ship, frigate, cruiser and box-shaped barge. The general principles would apply to any ship type and it can be modified for special studies.

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 Ro-Ro 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 capsize criteria boundaries may be quite different.

1.2 General considerations

Model testing of a damaged ship in waves must consider ship motion and flooding dynamics. In general there exists a strong interaction between the ship motions and the flooding process. Ship motions are influenced by the amount of flood water and will have effects on flooding process, too. The whole process can be highly non-linear especially in case of large damage openings and compartments.

- Initial condition (flooded and transient)

It has been assumed previously that during the model tests the model would already be in a damaged state, flooded and stationary at the start of the experiment. This procedure now also considers modelling the transition from an intact hull to a damaged hull. The transition from intact to flooded condition may cause the significant dynamic behaviour of the vessels. In general, model experiments will be carried out in conditions corresponding to the most severe damage scenario that the vessel is expected to survive.

- Wave condition (regular and irregular wave)

Damage stability model experiments for design evaluation could be carried out in calm water, regular waves and irregular waves. The experiments in calm water and regular waves are carried out to investigate the fundamental flooding process, ship motions and the characteristics such as roll damping. The experiments in irregular waves are carried out to assess the damage survivability of a ship in a seaway. It has been observed that the characteristics of flooding process in regular waves is different and unrepresentative of that in irregular waves (Vassalos and Letizia, 1998).

- Wind loads

In view of the use of the instantaneous roll angle and mean heel angle in survivability criteria, it is recommended that the wind load acting on a ship must be considered. It is noted that fluctuating wind load may also affect the flooding process because the wind load result in motions.

- Air compressibility

Air compressibility effects must be considered when flooded compartments are not vented or are partially ventilated. The model may consist of multi-compartment configurations connected through doors, vents, down flooding and ducts.

Air compressibility may have influences on the flooding, especially for the case with trapped air in a compartment (none vented) and partially vented compartment where the vent area is small compared with water inflow opening area. When there is trapped air within compartments and it is anticipated to have an influence on the test result, it is recommended that some level of air venting is included. This will ensure a water level in the compartment equivalent to the water level in the full scale case. An alternative is to consider the model test in a depressurised towing tank. For the case of depressurized air tank test, the ambient pressure scale ratio should be lowered as the model scale ratio. The effect of air compressibility is investigated by numerically (Lee, 2015).

- Ro-Ro deck

In the case of Ro-Ro ferries or vessels with large open decks the models will be tested with the open deck empty until more information is available concerning the flow around cargo on deck. Also, it is assumed that the cargo has not shifted during the collision or at any other time.

For Ro-Ro vessels sloshing can be of importance. Sloshing is significant 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.

1.3 Special Requirements for Ro-Ro Ferries

Resolution 14 of the 1995 SOLAS conference includes an option that an Administration may, as an alternative to calculation of the damage stability properties of a Ro-Ro passenger ferry in waves, accept the results of model test carried out for an individual ship. The model tests must be in accordance with the model test method developed and amended by IMO, justifying that the ship will not capsize in an irregular seaway. This model test procedure is specified by the IMO. In the case of Ro-Ro ferries the ITTC procedure and associated guidelines are intended to supplement the IMO method with a technical explanation for the adopted methodology. They are not an alternative and any experiments carried out under Resolution 14 must satisfy all of the Administration's requirements regardless of the recommended ITTC procedure and guidelines.

2. DESCRIPTION OF PROCEDURE

2.1 Preparations

2.1.1 Model size

Principally, the model scale is selected according to the size of the vessel in relation to the size of the test tank and capability of the wave makers; the relationship between model size and basin and wave is described in ITTC Recommended Procedure 7.5-02 07-02.1 (Seakeeping Experiments). The typical model scale used in wave basins is around 1/60 with a model size around 4 to 6m. A review of model size shows the large range of scales from 1/20 to 1/ 100 (STAB and ISSW papers reviewed). It is recommended that the choice of model scale and model size for damaged ship model experiments are explained by considering the limitations of the wave basin, the desired wave conditions and the damage scenario.

A minimum model scale should be 1:40 and in no case should the overall length of the model be less than 3.0 metres. However, based on the reported experience of ITTC member organisations with respect to modelling of internal arrangements and fitting, it is recommended to consider a minimum length for the model of 4.0 metres.

2.1.2 Model design and fabrication

The model must be fabricated to a high accuracy. The accuracy may depend on the model size and model scale. For general model scale (50 ~70), the accuracy will be within ±1 mm in maximum beam and draught and ±2 mm on length over all with adequate strength and stiffness properties. Special care should be taken to ensure that the model is free from unintended leaks. It is recommended that the waterproof is tested if required prior to the start of any experiments.

The model should be an accurate representation of the hull up to the main deck with the correct sheer and camber on the deck. The hull should be divided into compartments by watertight bulkheads. The floodable compartments and all pertinent features influencing the flooding process should be geometrically similar, in terms of flooded volume and free surface areas, to those of the ship. The wall thickness in way of the flooded spaces should be checked and reported. Care should be taken with model scale selection to ensure when building cross-flooding arrangements and other small diameter ducts that they adequately sized (a minimum cross sectional area of 500 mm² is recommended) to allow for realistic flow of water or air. Special devices, such as deck drains, should be scaled geometrically unless this results in dimensions being so small that viscous effects are significant where an increase in size of drain should be considered.

The material of the internals of the model should be waterproof, and the part of inner hull that will be wet during the tests should be properly coated so that the material does not absorb water. The mass of model ship should be the same before and after test. It is recommended to fit transparent decks and bulkheads, to allow flooding to be observed and leakages identified.

Where appropriate, compartments should be properly vented to prohibit unwanted air trapping which would induce undesirable effects. In conventional towing tank conditions, the air compressibility effects should be minimised when applicable, it may be achieved by adding full or valve vents to allow venting to allow comparable water heights compared to the full scale case. For tests in depressurised conditions, all the air vents should be scaled by the geometrical scale ratio. The exception would be that water drops or air bubbles in small diameter pipes can block the required flow. In this case the diameter of pipe should be suitably increased.

The external geometry of the ship superstructure above the bulkhead (freeboard) deck should be modelled up to the point where it no longer influences model behaviour or the flooding process (heel angle of at least 30 degrees)

Any appendages likely to have an effect on roll motion, such as bilge keels, skegs, fin stabilisers, propellers/shafting and rudders should be fitted.

- Damage opening and compartments

The location and size of damage openings are 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, for damage size see for instance SOLAS 90 (MSC.194(80) regulation II-1/8.2.3.2). The opening typically spans 10-15% of the ship length. The height of the opening covers at least two floodable decks. The shape of the damage opening is a simple triangle, rectangle or trapezoid. More detailed guidance can be found in SOLAS 90 regulation II-1/8.4.1 or in MSC 76/23/Add.1.

Other rules/criteria may apply to naval vessels and high speed craft (see HSC code (2000)).

For standard IMO collision the damage opening shall have a trapezoidal shape, with a 15 degree slope from the waterline, so that the top of the opening is wider than the bottom. The width of the damage at the main deck should be at least that required by the SOLAS 90 regulation II-1/8.4.1. The main deck shall have a cut-out in the shape of an isosceles triangle with a height equal to $B/5$.

Surface and volume permeabilities of floodable spaces should be modelled correctly according to full scale. This can be accomplished by including foam blocks representative of major objects in the compartment. If no information is available for a specific non Ro-Ro vessel the following values for volume permeability should be used:

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

Member organisations with experience in model testing of damage stability for Ro-Ro passenger vessels use SOLAS-defined permeabilities adjusted to reflect the model construction and procedure described herein as follows:

- Void spaces 98%
- Passenger or accommodation spaces 98%
- Engine room/Machinery spaces 85%
- Store rooms 60%

Permeability can be modelled directly if the compartment and major objects are simple shapes such as blocks or cylinders. More complex shapes such as wing tanks may require volume calculations from model fabrication drawings or direct measurements. Direct measurements involve pouring a measured amount of water into the closed compartment until full.

For convenience, the model can be returned to the intact state by attaching a cover that closes the damage opening. All checking of the intact model may be performed with the damage cover in place. The checking of damaged model may be performed without the damage cover. This is recommended as it is a minor change between the intact and damaged model setups. It is not recommended to just check the intact model condition and then cut the damage opening.

2.1.3 Instrumentation

The instrumentation system should be appropriate to the model and type of test carried out. The use of a non-contact measurement systems is recommended when feasible. If the cables for sensor are connected to the model then these should be positioned to not alter the VCG or motions of the vessel in waves. The instrumentation should guarantee the measurement of all the pertinent parameters.

- Wave elevation,
- Model attitude and motion in 6 degrees of freedom,

- Relative motion between deck and wave surface at damage opening,
- Height of water in each flooded compartment.

All data should be stored as synchronised time histories at a minimum sampling frequency of 20 Hz. Video records of the experiments are also extremely useful for interpreting the results.

All sensors should be calibrated according to ISO 9001 or equivalent. Any systems which rely on data from combined signals such as integration of depth of water on deck from point measurements should be checked with known loads in static and dynamic scenarios.

2.1.4 Test preparation

Since flooding experiments 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 for instance when inspecting time traces of flood water height in certain compartments. Therefore it is recommended to check and document a number of basic properties before performing the model tests.

- Mass, trim, CoG, inertia

The fully instrumented model should have its mass distribution properties measured in the intact and damaged conditions.

As a first basic check, the trim and draught at calm water should match the displacement and location of the centre of gravity should be evaluated through an inclining experiment. In both intact and damaged conditions, the model should satisfy the correct displacement and draught marks (*T*A, *T*M, *T*F, port and starboard.) with a maximum tolerance in any one draught mark of ±2mm. The displacement and draughts can be calculated from a hydrostatics/static stability calculation. Draught marks forward and aft should be located as near FP and AP as practicable. 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).

The mass, position of the centre of gravity and the radii of gyration for pitch, yaw, and roll (in air) should correspond to the equivalent values for the ship. In the absence of more accurate knowledge a value of 0.35*B* to 0.45*B* for the roll radius of gyration, and 0.25*L* for both the pitch and yaw radii of gyration are generally used. The roll radius of gyration can also be estimated by:

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

where *B*, *H* and *T* are the beam, height and draft of the ship respectively and z_G is the height of the centre of gravity above the water surface.

These values should be checked by swinging the model in the air, in a manner similar to that used for seakeeping experiments. For roll, the natural roll period of the intact model can be used to confirm the transverse mass distribution is correct. The vertical position of the centre of gravity should be correct, and should be cheeked for the intact model by an inclining test or equivalent.

- Natural roll period and damping

The natural roll period and roll damping of the intact and damaged model should be estimated by doing free decay test in calm water.

There are some factors to be considered for free decay test. The initial amplitude is one parameter to affect the damping value. The free decay test must be carried out for small, medium and large amplitudes and damping values must be checked according to the initial amplitudes.

When a ship is damaged and may incline to one side, the free decay test should be carried out after the flooding finish and the flooding become steady state. It seems that the roll damping for damaged condition is different compared to intact because the hydrostatic and GM change and the position and wetted surface area is different with upright intact condition. So the free decay test also can be tested for starboard and port direction.

It should be realised that before and/or during roll decays with floodwater present in a multiple compartment configuration, up and down flooding and sloshing can occur which can make the resulting roll motion non-periodic and rather dependent on the initial roll angle.

The roll decay should be conducted in an area where reflected waves do not influence the model results. Care should be taken with the damaged model not to flood the main open deck during this test if the residual freeboard is low. It is also desirable to carry out an inclining test for the flooded model. This however, can be difficult if the model has inherently low stability or a very low freeboard after flooding. It is desirable to check the large angle stability of the model against the calculated values, at least up to the point of maximum righting moment.

2.1.5 Wave conditions

Model experiments are generally carried out in long-crested irregular waves. The regular wave and white noise wave test can be conducted for investigating the fundamental characteristics of motion and interaction effect.

The waves in the experiment should include wave spectra for the area of operation or as required by stability regulation. 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 :

$$H_{w1/3} \Big/ \left(gT_p^2 \big/ 2\pi \right) = 0.05 \tag{2}$$

is recommended as a guide.

Wave spectra should be measured along the length of the tank spanning the drift range of the model and with time duration of at least one experimental run or 30 minutes (full scale), whichever is the shortest. The wave realisation should be measured at constant speed along the path or alternatively three fixed locations should be used. Following the latter procedure the first measurement should be close to the model at the start of the experiment, at the wave-maker end of the tank, the second at the mid-point of the tank and the third close to the beach end of the tank.

Variation in $Hw_{1/3}$ between nominal and measured spectra should be within ±5% at each location and variation in T_p should be within ±5%. Moreover, deriving from ocean wave measurements, a maximum characteristic wave steepness of $H_{w1/3}/\left(gT_p^2/2\pi\right) = 0.05$ is recommended.

For determining a survival wave height, *i.e.* the wave height above which the capsize criteria are exceeded, a series of model test runs must be performed for a matrix of $Hw_{1/3}$ 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 model test run. 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 (or equivalent) 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 noted that the maximum wave height should be checked. Although the significant wave height of generated wave is satisfactory, the maximum wave height may larger than the expected height. This is usually observed in basins. The survivability and capsizing probability can be affected by maximum wave height. It is recommended that the maximum wave height is checked, if necessary should be calibrated by using different wave random seed number with keeping significant wave height and wave spectrum.

2.2 Execution of Procedure

2.2.1 Conditions

It is recommended that pre and post experiment calibrations are performed of the instrumentation system and documented.

For compartments that are to model trapped air it is important to return the water level in the compartment to the same initial condition following each run. This should be achieved through a pipe attached to the compartment that can be used to adjust the pressure in the compartment to the correct level without lifting and inclining the model in the water.

In the case of a test in depressurised air conditions, the ambient pressure should be recorded during all the test period.

It is desirable to include estimated additional heeling moments that are likely to be present in an emergency situation. These can be caused by mean wind forces, passengers gathered at the edge of the deck, lifeboat launching etc. For tests with Ro-Ro ferries, it is recommended that the model be ballasted to achieve 1 degree heel towards the damage side for practical purposes as recommended by MSC 76/23/Add.1.

- Model position

There should be a clearance of at least 1 metre between each end of the model and the tank wall, when the model is placed across the tank, in beam seas. The water depth in the tank should also be properly modelled so that waves of the desired characteristics can be generated.

The model should be positioned in the tank approximately 15 metres away from the wavemaker(s). If this is not practical the model should be far enough from the wavemaker(s) to avoid breaking wave transients which occur in the vicinity of the wavemaker. Prior to starting each experiment the draft, trim and heel of the model should be checked. It is particularly important to make sure that there is no water in the intact compartments at the start of a test. Data collection should start in calm water, before the waves reach the model. This provides a datum level for each signal.

- Forward Speed

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 model tests 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) cannot be modelled adequately. As a compromise the ship can be initially positioned in beam seas with zero drifting velocity. The wave height is slowly increased from zero to its nominal height through the use of a ramp function. During this ramp-up period the ship will assume its initial drifting velocity and heading angle.

- Damage opening

The damage opening may be closed initially and opened once the wave height has reached its nominal value. The initial transient flooding and associated heel can be simulated in this way but it is not necessarily representative of the actual transient when a collision or grounding occurs. The damage opening has been successfully modelled using a sliding door style mechanism or with a bursting rubber patch. Alternatively, the model tests can be started with the equilibrium amount of flood water on board and the corresponding equilibrium draught, trim and heel.

During the model tests 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.

If necessary, guide ropes can be fitted to the model on the centreline at the stem and stern, in a symmetric fashion and at a vertical height between the damaged waterline and the vertical centre of gravity. These lines are kept slack except for short times when they can be used to keep the model on course and then released again. However, if the model has a natural tendency to drift at a steady angle this should not be corrected.

- Number of test and repeatability

At least 10 experiment test runs should be carried out in irregular waves for each condition, i.e., combination of $\overline{KG}$, sea state, displacement, significant wave height etc. A different random wave realisation should be used for each experiment. The test period for each experiment run should be of duration such that a stationary wave state has been reached, but not less than 30 minutes in full-scale (based on Froude scaling). Multiple runs may be combined together to attain the minimum of 30 minutes full-scale data.

For model tests with transient flooding phase included, at least 10 experiment test runs should be performed with a duration sufficient for 30 minutes *after* reaching a steady state (in terms of the three minute average draught, trim, heel angles and drift velocity) to obtain extreme value statistics. In each of the 10 test runs a different wave realisation must be obtained.

Wave spectra measured during the tests should be reported and matched with the nominal values over the full 30 minute period.

The effect of wind loads on the model may be taken into account by using a fan system attached to the carriage or tank. If fans are being used care will have to be taken to ensure that the wind velocity is not affected by the position of the model. This probably means that as the model drifts down the tank the fans will have to move with the model in some way. Current need not be modelled.

2.2.2 Test 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 Hz):

- Average heel angle (over 3 minutes full scale), drifting velocity and heading relative to the wave direction.
- Ship motions (displacements, velocities and accelerations) in 6 degrees of freedom.
- Wave elevation at the positions within the test tank, 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 (if applicable).

Video of the ship motions in combination with the instantaneous floodwater levels and openings in the compartments is extremely useful for analysing the model test results.

2.3 Evaluation

The term capsizing refers to loss of buoyancy (sinking) as well as insufficient righting arm to keep the ship under a prescribed heel angle. A number of parameter can be used to define the survival boundary for a damaged ship and will be dependent on the requirements for the vessel. For example, the IMO (Resolution MSC 76/23) considers a RoRo ship to have capsized when the instantaneous roll angle exceeds 30 degs or when the 3-minute average heel exceeds 20 deg. For naval ships capsize criteria boundaries may be quite different

The model tested should be considered as surviving if a stationary state is reached for the recommended 10 successive test runs. The model tested should be considered to have reached unacceptably high roll when:

a) the maximum roll angle exceeds 30° against the vertical axis or

b) the mean roll angle exceeds 20°, averaged over a period of at least 3 minutes full scale

As these angles relate to the launching of life-boats in merchant ships, different limits should be considered for naval vessels which are subject to different stability standards.

Considering the possibly chaotic behaviour of flooding in irregular waves, the number of model tests and their duration should be documented. The level of confidence in 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):

$$p_c = \frac{N_c}{N} \tag{3}$$

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

$$\Delta p = \frac{2}{\sqrt{N}}\sqrt{p_c\left(1-p_c\right)}z_{(1-\alpha'/2)} \tag{4}$$

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:

$$p_c - \frac{\Delta p}{2} \le \mathrm{p} \le p_c + \frac{\Delta p}{2} \tag{5}$$

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

2.4 Documentation of experiments

The main model test 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 test 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.
- A description of the capsizing modes identified.
- Ship condition information including $\overline{GZ}$ curves with and without flood water at equilibrium condition.
- Roll decay 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.

The report of the results should include, as a minimum, the measured wave spectra and statistics ($H_{w1/3}$, H_{max}, T_p) of the wave elevation at the 3 different locations in the basin for a representative realisation. Analysis of the time series should include records of wave elevation, model attitude and motion in 6 degrees of freedom, relative motion between deck and wave surface at damage opening, height of water in each flooded compartment and of the drift speed.

3. PARAMETERS

3.1 Other parameters to be considered

Other features that should be considered for modelling of damaged ships are 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 flooding ducts, *etc*.

4. UNCERTAINTY ANALYSIS

All data measurement should conform to the recommendations of the relevant ITTC Procedures regarding uncertainty analysis. An uncertainty assessment of the experimental results is considered to be vital for the proper use of the experimental data. Since the flooding process can have a chaotic character, small differences in for instance damage opening size and location can have a large effect on the end result. Also for validation purposes uncertainty data is vital.

5. REFERENCES

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