# Damaged Ro-Pax Vessel Time to Capsize

Heng Ran, *SSPA Sweden AB*, heng.ran@sspa.se

Ingvar Rask, *SSPA Sweden AB*, ingvar.rask@sspa.se

Carl-Erik Janson, *Chalmers University of Technology*, carl-erik.janson@chalmers.se

**ABSTRACT**

The time for a RoPax vessel (M.S. Estonia) to capsize after a hull breach event is investigated with both physical model experiments and computer based time domain simulations. A two compartment side damage is modelled and a series of tests at stationary head wind/wave is performed. A parabolic inflow velocity model is developed to simulate water ingression through the damaged opening. A two dimensional multi-model sloshing model, composed by a non-linear pendulum model near resonance and an acceleration ratio model at non-resonance, is used for calculating ingressed water transverse center of gravity in the damaged compartment and on car deck.

**Keywords:** *damaged, time to capsize, ingression, sloshing*

## 1. INTRODUCTION

Damaged ship stability and manoeuvre-ability are important for life and cargo safety on board a ship. Model tests and computer based simulations have been carried out at SSPA for a RoPax vessel, M.S. Estonia, to study the time and probability to capsize in different sea states.

The study started with testing a 1:40 RoPax vessel model in SSPA's manoeuvring and seakeeping basin. Meanwhile, a simulation programme is being constructed on SSPA's indoor manoeuvring and seakeeping software SEAMAN II. In this software, water ingression, progressive flooding and sloshing are integrated with ship motions in time domain simulation.

Model test is always a good way for damaged ship stability research. However, there are some limitations. For example, the size of the basin limits the towing distance. There is a requirement in damaged ship manoeuvring and seakeeping simulation software. Damaged ship stability related topics, such as water ingression, progressive flooding, sloshing in tank and sloshing on deck are focused during this research project.

According to the latest ITTC proceeding from the Specialist Committee of Stability in Waves, higher accuracy CFD methods are currently difficult to integrate with ship motion simulations for large deck area, multi-tank configurations. There is appearance of particle methods, showing the ability to model sloshing behaviour. However, the computational cost is expensive, which makes it not practical for full integration with ship motion simulations.

Godderidge, et al. (2012) constructed a rapid sloshing model by simulate internal fluid system as a pendulum. This model is adapted for sloshing simulation at resonance.

The ship motions, time to capsize, tow line force are measured and recorded during the model test. These results are used to validate the simulation software.

## 2. EXPERIMENT OBJECT AND SCHEME

### 2.1 Ship model main data

The experiments are carried out with a model of a RoPax vessel. The model is manufactured in scale 1:40. The main data of full scale ship at the intact loading condition are given in Table 1.

The model was equipped with two fixed rudders, propellers and bilge keels. The length of the forward bilge keel is 35.2m and the aft bilge keel is 13.6m. The height of the bilge keels is 0.6m.

Table 1: Main data of the intact ship.

| **Parameter** | **Unit** | **Value** |
|---|---|---|
| Length, Lpp | [m] | 137.4 |
| Breadth, moulded | [m] | 24.2 |
| Draft, aft | [m] | 5.61 |
| Draft, forward | [m] | 5.17 |
| Displacement | [$m^3$] | 12 046 |
| Block coefficient | [-] | 0.683 |

### 2.2 The hull damage

The side damage is caused to the model according to SOLAS damage opening standard (2004) by means of a V-cut in the hull from bottom to top. A two-compartment damage was modelled. There is water ingression to both car deck and compartment under car deck. The depth of the cut is B/5 = 4.84m and the length is 0.03L+3m = 7.12m. The position of the centre of the damage is 37.8m forward of aft perpendicular, see Figure 1.

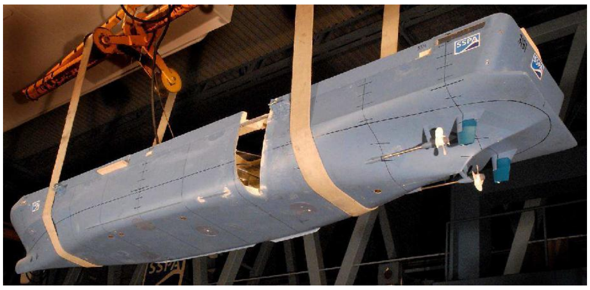

Figure 1: V-cut damage.

The trim angle of the damaged ship is 0.45 degrees relative to the intact ship and the heel angle is 4.0 degrees towards the port side. During model tests, damaged compartments below car deck are flooded with water. There is no obstruction longitudinally along the car deck. Water ingression and progressive flooding on car deck are the main cause of ship sinking in high wave situation.

### 2.3 The towage system

The length of the towing wire is 800m and the weight in air is 10kg/m corresponding to 8.6kg/m in water for a steel wire. Due to space limitation in the model basin, a truncated towing system has to be designed. The configuration of the system is shown in Figure 2. The system is calibrated and compared with the corresponding full scale catenary characteristics. Stationary ship with no propulsion is modelled during the test. In the working range of the wire, the truncated towing system agrees well with the full scale system.

### 2.4 The test scheme

A test starts with the model secured to the carriage by means of stretched cords at a position 20m from the wave generators. The air propeller is started and the model is released. The position of the towing point is adjusted in such a way that the model will be kept in a position with the measuring range of the device for measuring the six degrees of freedom.

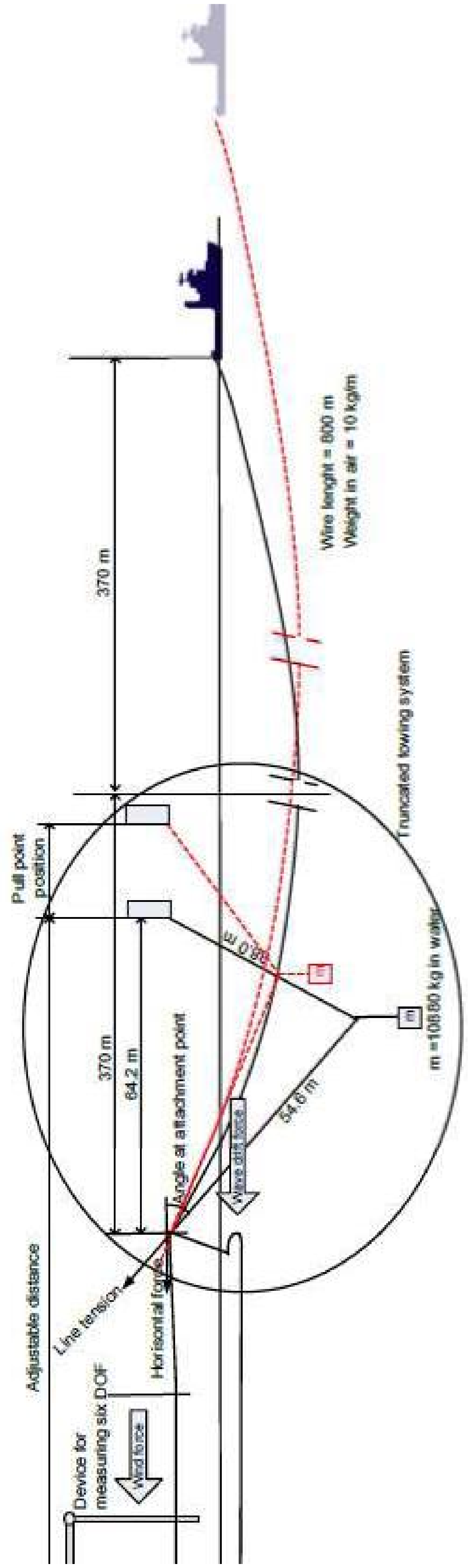


Figure 2: Model test set up.

motion of the model. When the model is in a stable position the wave generators are started

The different wave components are successively sent away towards the model; with the shortest waves first. In such a way that the wave spectrum will be fully developed when all wave components reach the position of the model. Shortly before this the data logging system are started.

A test is interrupted when the average heel angle exceeds 20 degrees or when the duration of the test exceeds 30 minutes full scale time.

The model is then secured to the carriage and drained from the water. In order to be sure that there is no water left in the model before the next test, the trim and heel are checked in a static measurement.

## 2.5 The Tested Cases

A series of tests are carried out for static ship at sea with significant wave height of 3.5m, 3.75m, 4m, 4.25m and 4.5m. For each wave height, a wind force in the same direction as the wave is calibrated according to the relation between wind speed and wave height recommended by ITTC. The series of tests comprised repetitions in order to create sufficiently consistent relative frequency distribution of the time to capsize.

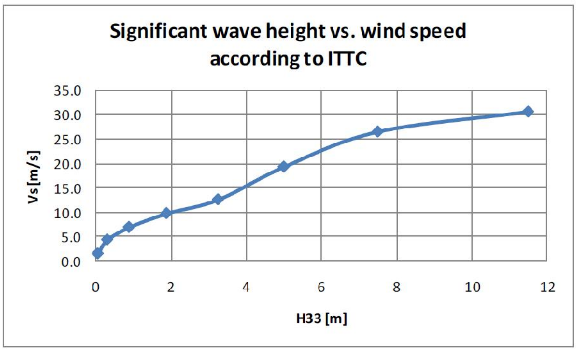


Figure 3: ITTC wind-wave diagram.

## 3. MATH MODEL FOR SIMULATION

The simulations are carried out with SSPA manoeuvring and seakeeping simulation program SEAMAN II, under different wind, wave conditions. SEAMAN II is a PC based time domain non-linear simulation tool for predicting ship motions both in calm water and in different weather situations. It covers the ship dynamics in all six degrees of freedom, including both first and second order wave forces.

### 3.1 Wave Model

The wave model is primarily adopted from conventional strip theory based on Lewis in SEAMAN II program. The sectional data is given in the form of section areas, beams, and draughts, and in the form of section off-set points. The section off-set points are used for pressure integration.

The first order wave force comprise linear damping, restoring forces, wave exciting forces and forces due to pressure integration. The second order wave force is calculated with the equation given by O. M. Faltinsen and A. E. Løken (1987).

### 3.2 Wind Model

SEAMAN II program allows simulation to be carried out at arbitrary wind conditions, comprising constant wind, as well as wind velocity varying around a pre-set mean value according to a certain wind spectra.

The wind spectra used for wind gusts is a Davenport spectrum consisting of five sinusoidal components, each representing a specific frequency and amplitude.

### 3.3 Constant Velocity Water Ingression Model

When calculating inflow rate through the damage opening, two types of inflow velocity models are constructed for result comparison.

The constant velocity water ingression model assumes that water enters the damage opening with same velocity.

$$qin = vin \cdot opening\_area$$

Where,

*vin* – inflow velocity, m/s

$$vin = v_{wave} - v_{ship} + \frac{2}{3}\sqrt{2 \cdot g \cdot hw}$$

$V_{wave}$ is the decomposed horizontal wave particle velocity in ship beam direction. This variable is very much related to the ship instantaneous yaw angle. $V_{ship}$ is the reversed ship transverse speed at damage centre. It comprises ship transverse speed at ship centre of gravity and transverse velocity due to yaw motion. Hw is the water head height at the damage opening.

### 3.4 Parabolic Velocity Water Ingression Model

When calculating inflow rate through the damage opening, the parabolic water ingression model assumes that the flooding velocity varies along ingression water line with a step size of 0.5m. The ingressed volume through the opening area per second is derived by summation along the h-axis in Figure 3. The thickened curve represents the flow velocity profile.

$$qin = \sum_{istep=1}^{nstep} vin \cdot opening\_area_{istep}$$

Where,

$$vin = v_{wave} - v_{ship} + \sqrt{2 \cdot g \cdot (hw - h)}$$

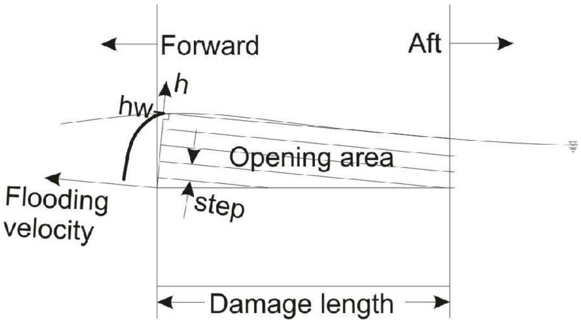


Figure 4: Flooding velocity parabolic profile.

### 3.5 Sloshing at Non-resonance

Acceleration ratio method is adopted to calculate cases at non-resonance situation, where the free surface of ingressed water changes moderately.

Certain assumptions are made when applying the method. In the programme, the car deck of the RoPax vessel is divided into twenty sections. During each time step, the sloshing phenomenon is simulated for each section in transverse two-dimensional plane. The free surface is assumed to be straight in the transverse plane. The slope of the free surface is calculated with the instantaneous accelerations.

The fundamental principle of acceleration ratio method is fluid static pressure. In ship transverse plane shown in Figure 5, the pressure at certain location below internal water free surface is a function of the location.

$$P(y,z) = \int \frac{\partial P(y,z)}{\partial y} \cdot dy + \int \frac{\partial P(y,z)}{\partial z} \cdot dz \quad (1)$$

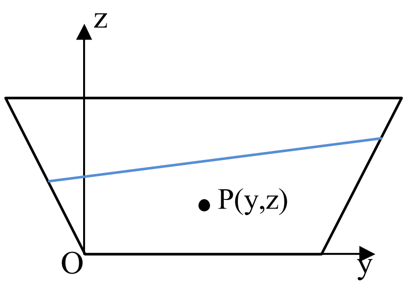


Figure 5: The coordinate system of car deck cross section.

The total force acting on a fluid particle of volume is due to pressure and gravity. According to Robert W. Fox (1985, p 75), in rectangular coordinates the component equations are:

$$-\frac{\partial P(y,z)}{\partial y} + \rho \cdot g_y = \rho \cdot a_y \quad (2)$$

$$-\frac{\partial P(y,z)}{\partial z} + \rho \cdot g_z = \rho \cdot a_z \quad (3)$$

Substituting the partial derivative components in the first equation derives:

$$P(y,z) = -\rho \cdot a_y \cdot dy + \rho \cdot (g_z - a_z) \cdot dz \quad (4)$$

On the internal water free surface:

$$P(y,z) = 0 \quad (5)$$

Gravity acceleration points downwards, i.e. opposite to z-axis in the transverse coordinate system.

$$g_z = -g \quad (6)$$

Therefore, on free surface equation 4 becomes:

$$\frac{-a_y}{g + a_z} = \frac{dz}{dy} = \text{Free surface slope} \quad (7)$$

Internal free surface intersects car deck walls at two inter section points. The coordinates of these intersections points are calculated based on the cross section geometry, volume of water ingression, and free surface slope. The centre of gravity of ingressed water is derived using the coordinates of intersection points and tank corner points.

### 3.6 Sloshing at Resonance

Pendulum model is adopted from Godderidge, B. et. al. (2012) to calculate sloshing cases near resonance, where the free surface of ingressed water is assumed to deform greatly due to resonance effect. The natural frequency of the water in a rectangular compartment is calculated with equation 8.

Given by linear theory, the natural frequency is related to the filling level of the compartment and compartment dimension along beam direction. Since water level changes during the simulation, the natural frequency is calculated at each time step. ±20% of natural frequency is selected as the prerequisite to initiate pendulum model.

$$\omega_n = \sqrt{\frac{g\pi}{L} \cdot \tanh\left(\frac{h}{L}\pi\right)} \qquad (8)$$

A pendulum models the sloshing fluid as a single moving mass. This mass point carries out simple pendulum movement under the excitation of ship side motion.

Based on Newton's second law, the angular acceleration of the pendulum swinging around virtue attachment point is presented with three terms, namely damping force, restoring force and body force.

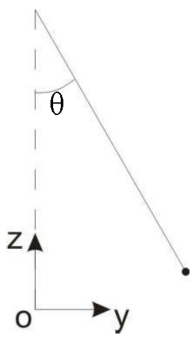


Figure 6: Pendulum model

$$\ddot{\theta} = -\beta_3\dot{\theta}^3 - \beta\dot{\theta} - \frac{g}{l}\sin(\alpha\theta) + (A_T - A_E - A_C) \qquad (9)$$

Where,
β – damping coefficient;
g – gravity;
l – pendulum length;
α – coefficient in displacement function, 1.0225;
$A_T$ – Excitation force induced term;
$A_E$ – Euler force induced term;
$A_c$ – Centrifugal and Coriolis force induced term;

## 4. EXPERIMENT AND SIMULATION RESULTS

Experiment results focus on probability, and simulation results focus on motion of the ship.

### 4.1 Probability of Capsize

A series of model basin experiment in head-on waves are performed for the stationary ship model. The test programme is shown in Table 2. Since the ship survived in all the cases at 4.0m wave height, model tests for 3.5m and 3.75m wave height were performed for once each.

Table 2: Model test programme.

| $H_{1/3}$ [m] | $T_p$ [s] | Number of tests |
|---|---|---|
| 3.50 | 7.48 | 1 |
| 3.75 | 7.75 | 1 |
| 4.00 | 8.00 | 10 |
| 4.25 | 8.25 | 10 |

The probability of capsizing within half an hour as function of significant wave height is shown in Figure 7.

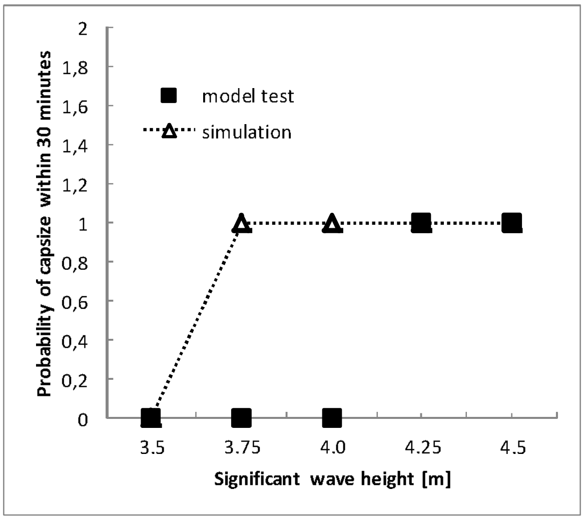


Figure 7: Probability of capsize.

The simulation results indicate that capsize for the RoPax vessel happens at 3.75m significant wave height. This result is 0.5m lower than the experiment result.

### 4.2 Inflow Velocity Profile Influence

In the simulations, the water ingression velocity is modelled with the inflow velocity profile as described in section 3.1. This influences the time to capsize greatly, as compared to a constant inflow velocity model. Figure 8 demonstrates the time to capsize using two different water ingression math models and during model test.

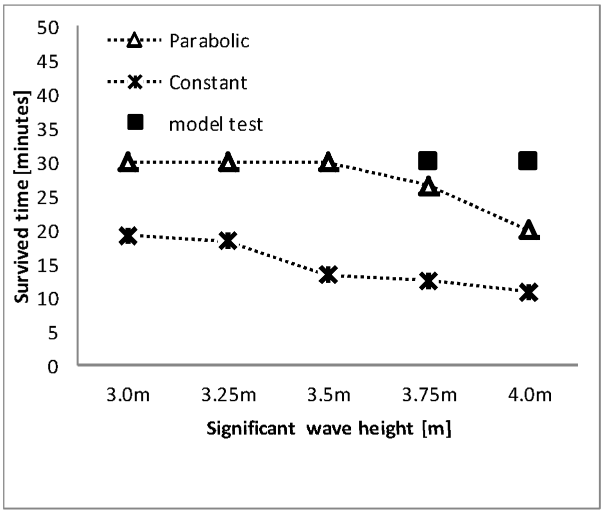


Figure 8: Survived time.

With constant inflow velocity math model, the simulated ship capsized in less than 30 minutes for all cases. The graph illustrates that parabolic inflow velocity profile method improves the accuracy of the simulation programme.

## 5. CONCLUSION

Model basin experiments result shows that the tested RoPax vessel with side damage opening, could survive in 4.0m wave for over 30 minutes.

Computer based time domain simulations resulted 0.5m lower in surviving wave height for the same ship and damage. The water ingression parabolic velocity profile model improves the simulation accuracy.

## 6. REFERENCES

ITTC. The Specialist Committee on Stability, 2008, "Proceeding of the 25th ITTC", Final Report and Recommendations, Vol. II.

SOLAS. Consolidated Edition, 2004, "International Convention for the Safety of Life at Sea", Chapter II-1, Regulation 8.

Godderidge, et al., 2012, "A rapid method for the simulation of sloshing using a mathematical model based on the pendulum equation", Computers and Fluids, Volume 57, p. 163-171

Robert W. Fox, Alan T. 2004, "Introduction to Fluid Mechanics", Third edition, New York, Wiley.

Ottosson, et al, 2008, "Research Study on the Sinking Sequence of MV Estonia.", research report, SSPA.

Odd M. Faltinsen, et al. 2009, "Sloshing", Cambridge University Press.

## 7. ACKNOWLEDGEMENTS

The research leading to these results has received funding from the European Community's Seventh Framework Program (FP7/2007-2013) under grant agreement no. 218532 (project FLOODSTAND). The financial support is gratefully appreciated. The European Commission and the authors or their organizations shall not in any way be liable or responsible for the use of any knowledge, information or data presented, or of the consequences thereof.