# Flooding simulations of ITTC and SAFEDOR benchmarks test cases using CRS SHIPSURV software

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**ABSTRACT**

SHIPSURV is a project of the Cooperative Research Ships (CRS) community, devoted to the development of tools and methodologies for the assessment of the survival capability of a ship after damage. This paper describes results obtained during one task of the ongoing validation process of the developed tool Pretti-flooding, which couples a seakeeping code with a progressive flooding simulation module. The task consisted in simulating test cases of the ITTC benchmark (flooding of a box shaped barge in calm water) and test cases of the benchmark carried out in the SAFEDOR project (determination of the survival wave height for a damaged RoPax in waves).

**KEYWORDS**

Damage stability; progressive flooding; numerical simulation.

## INTRODUCTION

The SHIPSURV project of the Cooperative Research Ship community aims at providing ship designers and operators with a methodology to identify which measures can be taken to increase the survivability of a damaged ship experiencing flooding after an accident such as grounding or collision. One of the major objectives was to develop and validate a numerical tool for the prediction of the damaged ship motion and internal loads on a seaway. In this purpose, a flooding simulation tool was developed by MARIN with funding of the CRNav (Cooperative Research Navies) and has been made available to the CRS community via a collaboration agreement signed between the CRNav and the CRS SHIPSURV working group. Then a validation process of this software, called Pretti-flooding, has started.

One of the first validation tasks consisted in performing numerical simulations for test cases defined in previous flooding software international benchmarks, namely: ITTC benchmark (model tests performed by the University of Helsinki on a barge) and SAFEDOR benchmark (model tests performed on the Ropax ship “PRR02” in the EU HARDER project).

This paper presents comparisons of the obtained results with the numerical results and/or available experimental data published for these benchmarks.

## NUMERICAL METHOD

SHIPSURV Pretti-flooding software is a time domain simulation code for the prediction of the behaviour of a damaged ship experiencing progressive flooding. The program consists of a time domain 6 DOF seakeeping code. The actual waterline is evaluated at each time step. Hydrostatic and wave pressures are integrated over the actual wetted surface. Diffraction forces are obtained by solving the potential flow problem. Radiation forces are calculated using the Cummins equations. Additional forces from water ingress and progressive water flooding through the ship are included using a hydraulic flooding water model, based on the Bernoulli equation, with discharge and head loss coefficients defined respectively in openings and in ducts. The free surface in flooded compartments is assumed to remain horizontal at any time. Air compression effects can be modelled. Thus, a complete calculation is performed in three successive steps: hydrodynamic coefficient frequency domain calculation, floodable compartments tank tables calculation and time domain seakeeping and progressive flooding calculation.

## ITTC BENCHMARK

### *Benchmark description*

Following an invitation from the 48th session of the IMO/SLF sub-committee, the ITTC Stability in Waves committee organised a benchmark test of time domain flooding simulation tools (see *ITTC (2007)*). The benchmark consisted in modelling the time domain behaviour of a box shaped barge in six different flooding scenarios in calm water, which had been previously modelled experimentally by the Technical University of Helsinki (see *Ruponen (2006)).*

The study performed in SHIPSURV consisted in reproducing these six scenarios and in comparing the time domain behaviour with experimental measurements.

### *Barge model tests description*

The barge considered as the basis for the study was a box shaped barge with a chamfer in the bilge as shown in Fig.1. The model scale was 1:10 with a corresponding model length of 4 m and an initial transverse metacentric height of 0.11 m. The barge was arranged with eight floodable tanks (see Fig.2) located slightly forward from the midsection to reach various trim angles in flooded condition. All these compartments were opened to the atmosphere with the exception of the two ones located in the double bottom (DB1 & DB2) which were airtight.

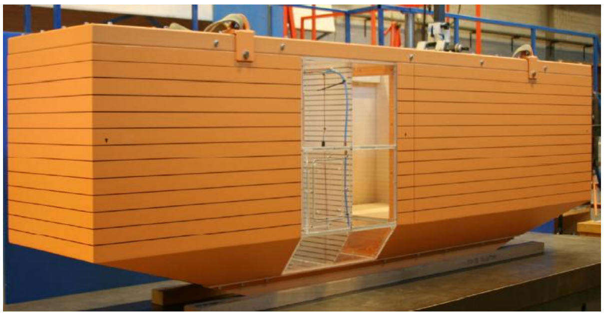

Fig. 1: Damage case arrangement

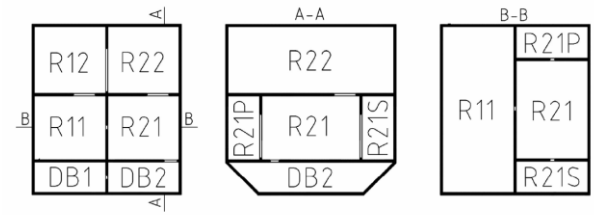


Fig. 2: Floodable compartments arrangement

The compartments were fitted with water level sensors. The double bottom compartments were also instrumented to allow air pocket pressure measurement. In addition the model heel, trim angles and draught were recorded.

The six flooding scenarios are described in Table 1. They correspond to combinations of damage location (bottom DB2 or DB1, side), size (small/large), opening between R12 and R22 (modelling a watertight door opening), allowing to obtain cross flooding and vertical flooding configurations.

**Table 1: Barge test cases:**

| Name: | Damage case: | R12-R22 opening: | Special: |
|---|---|---|---|
| Test 1 | Bottom DB2 small | Closed | Fixed floating pos. |
| Test 2 | Bottom DB2 small | Closed | |
| Test 3 | Bottom DB2 small | Open | |
| Test 4 | Bottom DB2 large | Closed | |
| Test 5 | Bottom DB1 large | Closed | |
| Test 6 | Side R21S large | Closed | DB1 and DB2 not floodable |

### *Numerical modelling*

The barge has been modelled at full scale. Like for model tests, upper compartments R12 and R22 were fully vented and side compartments R21S and R21P were vented by pipes connected to the atmosphere. Discharge coefficients of openings and head loss coefficients of pipes identified by *Ruponen (2006)* have been used for simulations. A roll decay test was also available in *Ruponen (2006)*. However, the corresponding experimental roll damping ratio (1.9%) was smaller than the calculated potential roll damping ratio (6.2%). Consequently, no viscous roll damping has been added in simulations. Finally, simulations have been carried out with three free degrees-of-freedom (heave, roll and pitch), except for Test 1 performed with no free degree-of-freedom (fixed barge).

### *Results*

For modelling reasons, comparisons have been performed at full scale, by extrapolating model test results using Froude scaling. This does not allow to fully correctly scale air compression effects. In addition, calculated free surface levels in flooded compartments had to be post-processed to obtain water heights as delivered by *Ruponen (2006)* and defined as the free surface height above the keel line amidships.

Test 3 (bottom damage), whose comparison with experimental results is representative of those obtained also for Tests 2, 4 and 5, and Test 6 (side damage) are presented hereafter.

### *Test 3 (bottom damage)*

Test 3 is a bottom (DB2) damage case. The corresponding flooding sequence is illustrated on Fig.3.

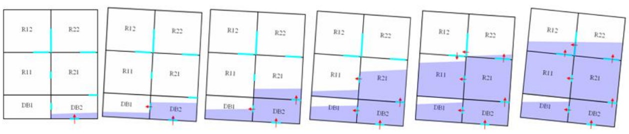

Fig. 3: Test 3 flooding sequence

A good agreement is obtained between predicted and measured trim and heave time histories, as shown on Fig.4.

Fig.5 shows that predicted water height in DB1 is very close to the experimental one. The predicted maximum height corresponds to the fully filled condition, which is not the case for the measurement. R21 water height predictions are also very close to experimental ones, with again a maximum consistent with a fully filled compartment. For DB2, the same maximum values are reached at the equilibrium. However, the calculated height rises earlier and quicker than the measured one. According to the modelling, the water height in DB1 should increase as soon as the free surface in DB2 reaches the opening between these compartments and water starts flooding DB1.

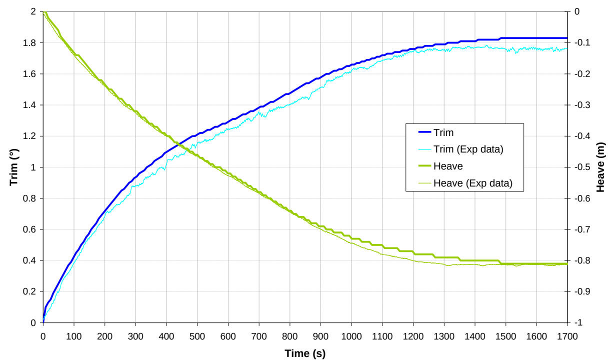


Fig. 4: Test 3 predicted vs exp. trim and heave

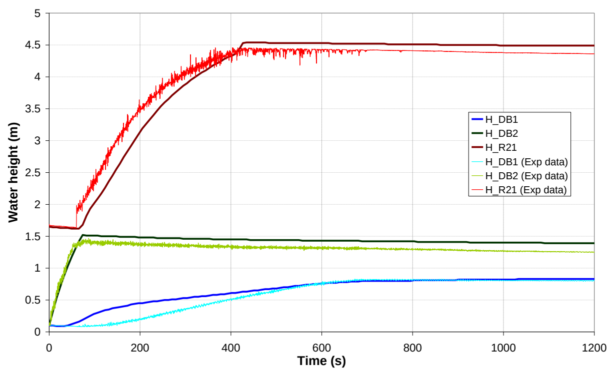


Fig. 5: Test 3 predicted vs exp. water height (DB1,DB2,R21)

This is observed on the predicted DB1 water height, but not on the measured one. This phenomenon has been encountered for all tests with damage in DB2, but not on Test 5 with a damage in DB1, which could suggest a relation with the water height measurement in DB1 and/or the modelling of the start of flooding of DB1 trough the side opening.

In other compartments R11, R21 and R22, fairly good agreement is obtained between predicted and measured water heights (see Fig.6).

Finally, similar trends are obtained on pressures on the top of the two double bottom compartments (see Fig.7). The predicted pressure difference between the two compartments at equilibrium (5480 Pa) is consistent with the predicted difference of water heights inside these compartments (0.55 m), whereas the difference in measured pressures (650 Pa) is not consistent with the difference in measured water heights (0.42 m).

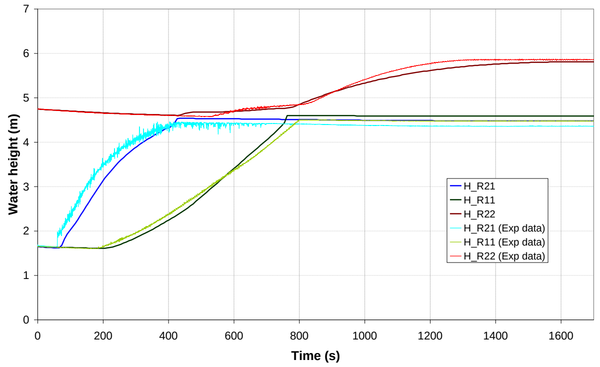


Fig. 6: Test 3 predicted vs exp water height (R11,R21,R22)

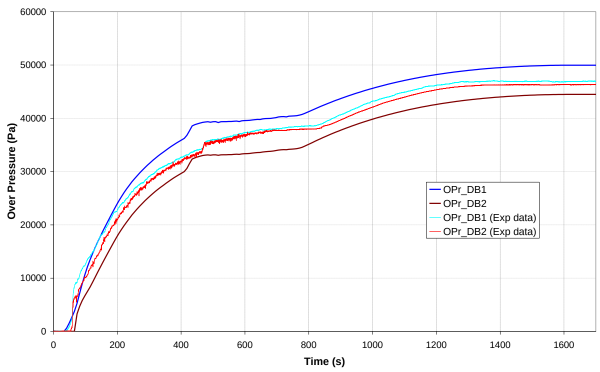


Fig. 7: Test 3 predicted vs exp. tank top pressure (DB1, DB2)

### *Test 6 (side damage)*

Test 6 is a side (R21S) damage case, leading to an unsymmetrical flooding yielding roll motion in addition to heave and pitch.

Good agreement between predicted and measured draught and trim angle at equilibrium has been obtained, with discrepancies of 4.5% and 2.7% respectively. A larger difference is observed on roll motion with a predicted peak roll angle almost five times the measured one (see Fig.8). In addition, the measured roll motion exhibits an unexpected and unpredicted oscillatory behaviour, with a period (5.7 s) lower than the roll natural period of the barge (between 5.9 and 6.3 s).

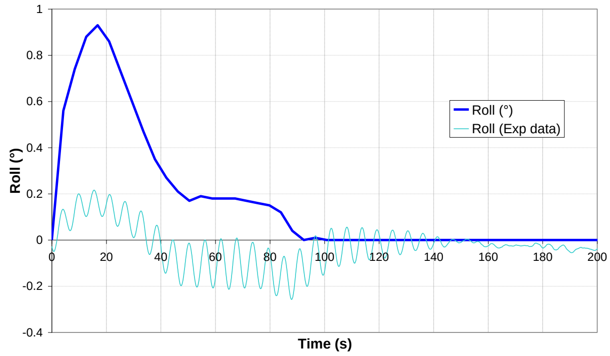


Fig. 8: Test 6 predicted vs exp. roll motion

Significant differences have also been obtained on the water heights in compartments R21S, R21 and R21P (see Fig.9). Predicted water heights in R21S and R21P are respectively larger and lower than the measured one, which is consistent with the larger predicted roll motion towards the damage.

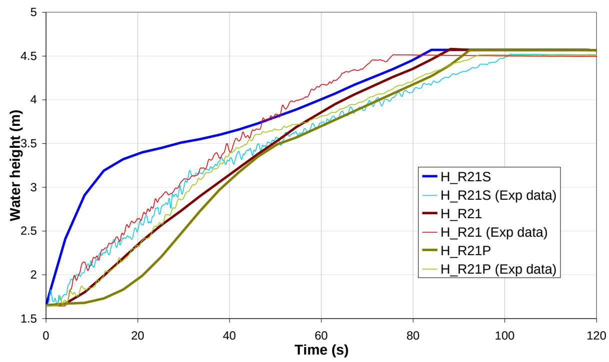


Fig. 9: Test 6 predicted vs exp. water height (R21S,R21,R21P)

Better agreements have been obtained in other compartments, as shown on Fig. 10.

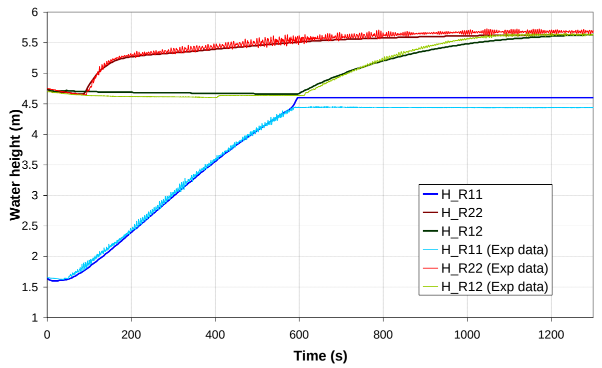


Fig. 10: Test 6 predicted vs exp. water height (R11,R12,R22)

## SAFEDOR BENCHMARK

### *Benchmark description*

The EU project SAFEDOR organised an international benchmark study on numerical codes for the prediction of the motions and flooding of damaged ships in waves. The study, which is described by *Spanos & Papanikolaou (2008)*, consisted in comparing the performance of four software codes to simulate the response of a damaged ROPAX on beam irregular waves, for five specified numerical cases and one specified additional case for which model experimental data were available. For the five numerical cases, the study consisted in comparing the prediction of the so-called survival boundary $Hs_{surv}$, defined as P(capsize|Hs ≤ $Hs_{surv}$) ≤ 5% made by each code. For the sixth case ("Seakeeping test"), the predicted ratios of roll motion *rms* value in intact condition to roll motion *rms* value in damage condition have been compared to the experimental one.

The study performed in SHIPSURV consisted in comparing, for three out of the first five test cases, the survival boundary obtained by Pretti-flooding with the ones obtained in SAFEDOR with the four codes, and, for the sixth case, in comparing the ratio of roll motions in intact/damage conditions predicted by Pretti-flooding, with the experimental ones.

### *Test cases description*

Tests are performed on the PRR02 ROPAX ferry which has been investigated before within the European research project HARDER (2000-2003). It is designed according to SOLAS 90 stability standard, with main particulars as given in Table 2:

**Table 2: PRR02 main particulars:**

| | |
|---|---|
| Length, Lpp (m) | 174.80 |
| Beam, B (m) | 25.0 |
| Draft, T (m) | 6.40 |
| Depth, D (m) | 9.10 |
| KG (m) / ixx (m) basic / GMt<br>KG (m) / ixx (m) reduced / GMt | 12.33 / 10.5 / 2.1<br>11.33 / 10.1 / 3.1 |

The ship is equipped with bilge keels. The damage case refers to the damage of two adjacent compartments located amidships and corresponds to the worst SOLAS 90 damage case. The length of the damage opening is 8.25 m (3%L+3.00 m), with a triangular penetration and unlimited vertical extent causing damage to the vehicles space on the main deck too. This arrangement leads to seven floodable compartments (see Fig.11).

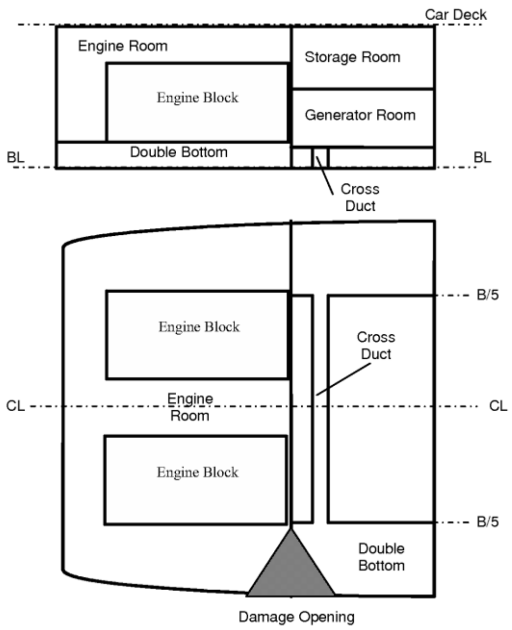


Fig. 11: Damage case arrangement

Tests are performed on irregular beam waves. Table 3 below describes the four cases that have been used in SHIPSURV.

**Table 3: SAFEDOR benchmark test conditions used in SHIPSURV:**

| Test | Reference | Description / difference |
|---|---|---|

| | | **wrt Test 1** |
|---|---|---|
| 1 | Basic | KG=12.3m, Jonswap, $Tp = 4\sqrt{Hs}$ , γ=3.3, $B44_{v\text{-}basic}$, $C_{discharge\text{-}basic}$ |
| 4 | High roll viscous damping | $B44v' = 2 \times B44_{v\text{-}basic}$ |
| 5 | Reduced $C_D$ | $C'_{discharge} = 0.5xC_{discharge\text{-}basic}$ |
| 6 | Seakeeping | KG=11.3m, $H_S$=3m, Tp=10.4s, γ=1, damage 30min after simulation starts |

***Numerical modelling***

In Pretti-flooding, openings are geometrically described by four corners, and characterised by a discharge coefficient. The V-shaped damage opening was thus modelled by a series of horizontal triangular elements and vertical rectangular elements, as described on Fig.12.

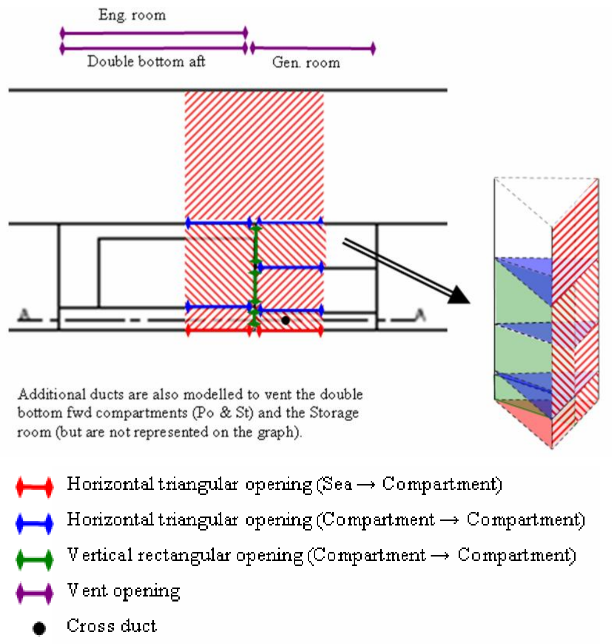


Fig. 12: Modelling of damage opening & compartments venting

A discharge coefficient value of 0.6 has been used for all these elements. For the duct connecting the two double bottom compartments, a head loss coefficient of 1.78 has been used.

All compartments have been vented to remove air compression effects.

A linear plus quadratic formulation has been used for modelling the ship roll damping. The corresponding terms have been identified, for both KG conditions, from the roll decay test presented in *Spanos & Papanikolaou (2008).*

A spring and dashpot have been added in the transverse horizontal direction in order to leave the model free from swaying, while removing the drift due to wave forces. The added stiffness and damping have been adjusted to obtain a sway natural period of 120 s with a 10% damping ratio.

Before running flooding simulations on irregular waves, preliminary checks have been performed on the calculated GZ curve and natural roll frequency in intact condition. The calculated GZ curve lies within the ones calculated by the four SAFEDOR benchmark codes (see Fig.13).

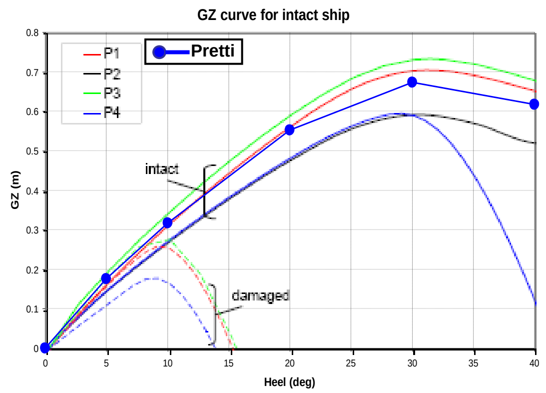


Fig. 13: GZ curves for intact ship calculated by Pretti and other SAFEDOR codes

**Table 4: Comparison between calculated and experimental roll natural frequencies:**

| | Roll natural frequency | | |
|---|---|---|---|
| KG (m) | Calculated (rad/s) | Experimental (rad/s) | Difference (%) |
| 12.33 | 0.395 | 0.388 | 1.8 |
| 11.33 | 0.492 | 0.491 | 0.2 |

In addition, differences lower than 2% have been obtained between the calculated and the experimental roll natural frequencies (see Table 4).

***Results of irregular wave tests***

Simulations have been performed by considering, as in SAFEDOR benchmark, that the ship capsizes if the roll angle exceeds

30 deg, or if the average roll angle over a period of 30 minutes exceeds 20 deg.

Five significant wave heights have been tested for tests 1, 4 and 5. Hs values have been determined iteratively by starting, for each test, with the lower and higher $Hs_{,surv}$ obtained in SAFEDOR, and then, according to the results obtained with Pretti-flooding, by dichotomy in order to bound $Hs_{,surv}$ until five wave heights have been tested. For each Hs, ten 30 minutes duration simulations have been performed: five runs by opening the damage at the start of the simulation and five runs with a damage opened 2000 s after the start of the simulation. New wave spectrum random phases have been generated for each simulation.

The capsizing probabilities obtained for the three test cases are presented on Fig.14.

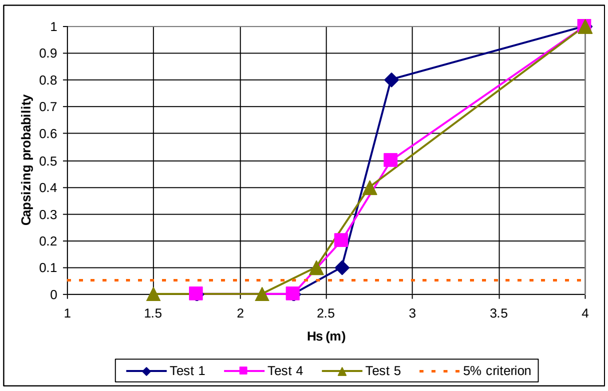


Fig. 14: Capsizing probabilities obtained with Pretti-flooding

The corresponding 5% probabilities derived from Fig.14 are compared to the ones obtained in the SAFEDOR benchmark on Fig.15.

Pretti-flooding predictions are in the lower range of the SAFEDOR codes ones. In addition, the effect of doubling the viscous damping or dividing by two the discharge coefficients does not seem significant.

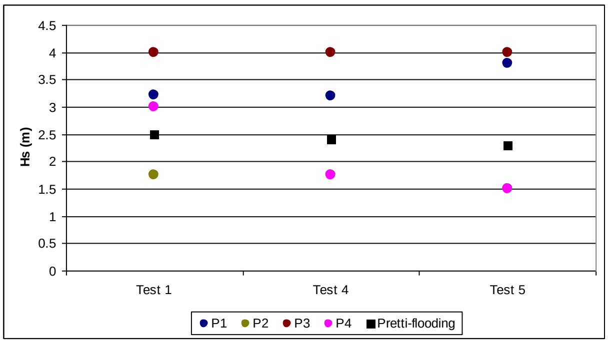


Fig. 15: Predicted 5% capsizing probabilities

The capsizing mechanism predicted by Pretti-flooding is very similar for tests 1, 4 and 5. The amount of flooded water oscillates around an average value which is reached quickly after the damage is opened. Capsizing is then observed when a larger wave train floods the main deck.

Test 6 corresponds to a simulation on long waves. The damage is opened after 30 minutes simulation in intact condition, and is continued for additional 30 minutes. The experiments report a 1/3 reduction of the roll *rms* value in damaged condition, with time trace of Fig.16:

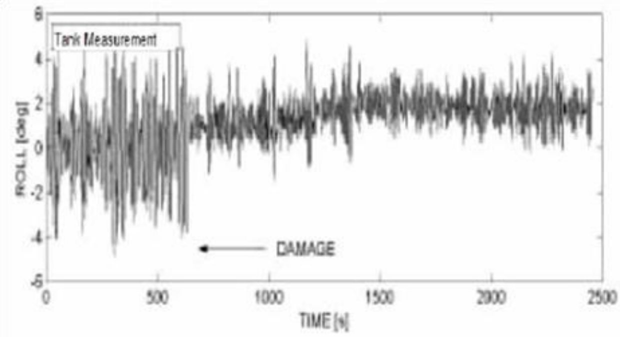


Fig. 16: Test 6: experimental roll motion before/after damage

A similar roll response is predicted by Pretti-flooding as shown on Fig.17:

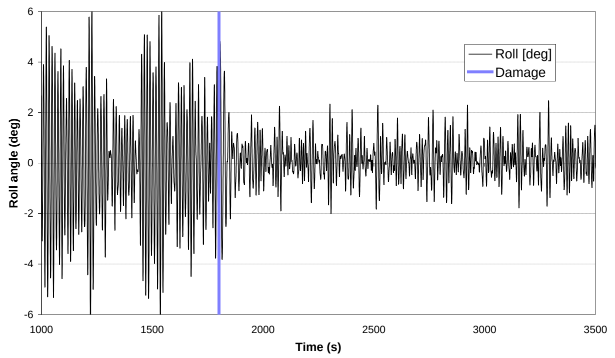


Fig. 17: Test 6: predicted roll motion before/after damage

Pretti-flooding seems to provide a satisfactory prediction of the damaged ship roll damping, with a ratio of roll *rms* values after/before damage of 0.35, which is closer to the experimental observations than the predictions of the SAFEDOR benchmark code (see Table 5).

**Table 5: Test 6 – predicted roll rms values by SAFEDOR benchmark codes and Pretti-flooding:**

| Code | Roll rms intact (deg) | Roll rms damaged (deg) | Roll rms ratio |
|---|---|---|---|

| | | | |
|---|---|---|---|
| P1 | 2.61 | 1.91 | 0.73 |
| P2 | 2.72 | 2.37 | 0.87 |
| P3 | 1.58 | 1.02 | 0.64 |
| P4 | 1.84 | 1.80 | 0.98 |
| Model tests | - | - | ~0.33 |
| Pretti-flooding | 2.28 | 0.80 | 0.35 |

## CONCLUSION

The ITTC benchmark test cases provide relatively simple validation scenarios on calm water and with limited ship dynamics.

Good agreement has been generally obtained between Pretti-flooding predictions and model test measurements. In all cases, the results predicted by Pretti-flooding seem consistent with the assumptions on which the flooding model is based. However, some deviations in results suggest that more validation in configurations of air compression coupled with air evacuation trough openings as well as configurations of unsymmetrical flooding should be carried out.

The SAFEDOR benchmark test cases complement the above validation cases by adding the influence of irregular waves, in situations of larger ship dynamics.

The survival wave height boundary obtained for the three first test cases selected in SHIPSURV were well in the range of the values predicted by the four codes tested in the SAFEDOR benchmark.

Larger discrepancies have been obtained on predicted roll motions for the fourth “seakeeping” test, with, however, a reduction of rms roll angle between intact and damage situation closer to the available experimental data than the reductions predicted by the four codes of the SAFEDOR benchmark. It should be noted that the mechanics of capsizing, which, according to experiments, correspond to a gradual increase of floodwater, is not observed in the simulations performed with Pretti-flooding; as a matter of fact, the quantity of floodwater always reached quickly an almost constant volume, and capsizing seemed to occur after a large wave train flooding the car deck was encountered.

Further validation work, which will also include internal loads prediction, will be performed in 2011, using new model tests that will be specifically carried out in this purpose within SHIPSURV.

## ACKNOWLEDGEMENT

This work has been carried out within the SHIPSURV project of the Cooperative Research Ships (www.crships.org).

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