Benchmark Study on Numerical Codes for the Prediction of Damage Ship Stability in Waves

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ABSTRACT

Results of an ongoing international benchmark study on the performance of computer codes for the assessment of the stability of the damaged ships in waves are summarized in this paper. Benchmark codes are reviewed on a comparative way with respect to the specified numerical tests in order to conclude on the present state of their performance as well as to assess their sensitivity with respect to their dependence on characteristic parameters of the damaged ship simulation models. Beyond the individual performance of the codes the study leads to the conclusion that the general performance level remains unchanged during the last years, with still notable divergences of the numerical estimations for the damaged ship's survivability in waves.

KEYWORDS

Benchmark; time domain; simulation; damage stability; flooding; survivability; capsize

INTRODUCTION

Numerical simulation codes for the prediction of the motion of the damaged ships in waves may be employed for the assessment of the damage ship stability and survivability in waves. In the recent past two related international benchmark studies were conducted in the frame of activities of the 23rd and 24th ITTC *specialists committee on stability in waves* SiW with the aim to review and assess the performance of relevant codes, *Papanikolaou* (2001), *Papanikolaou and Spanos* (2004), respectively. These studies identified several issues that needed further investigation, but ascertained that in general numerical methods could contribute to the pre-assessment of the survivability of the damaged ships and support relevant physical model experimental studies.

The dynamics of the damaged ship in waves, the effects of the floodwater on the ship motion, the values of the assumed semi-empirical coefficients for the flow through the outer shell damage or other openings and the semi-empirical viscous damping coefficients were all sources of uncertainty for the accuracy of the stability predictions achieved by the numerical simulation codes.

In order to refine the impact of these factors on the numerical prediction of ship's damage stability as well as to provide updated information on the capabilities of current simulation codes a new international benchmark study was launched in June 2007. This study is organized within the European research project *SAFEDOR* (2005-2008), is supported by *ITTC Specialist Committee SiW* and coordinated by NTUA.

The benchmark study refers to the simulation of a modern, damaged RoRo/Passenger ferry in waves and the estimation of the survival wave height for a set of selected conditions as well as the exploration of the dependence of the numerical estimations on the basic simulation parameters. The study is planned to be completed in May 2008, however preliminary results and conclusions are already available and presented in this paper. The relevant benchmark activities are sited on the webpage www.naval.ntua.gr/~sdl/sibs.

Participation

There were six (6) independent participants expressing their interest in participating in this benchmark, each employing different and independently developed computer simulation code, as listed in Table 1. The number of participants is assumed sufficient for the purpose of the study especially when considering the participation in the past benchmarks and the limited number of simulation codes worldwide available. The below listed top five organisations had also collaborated in the past benchmarks.

Table 1 Participants to the benchmark study

Institute/organization	Acronym	Country
National Technical University of Athens – Ship Design Laboratory	NTUA-SDL	Greece
The Ship Stability Research Center, Universities of Glasgow and Strathclyde	SSRC	United Kingdom
Marine Research Institute	MARIN	The Netherlands
Instituto Superior Tecnico, Technical University of Lisbon	IST	Portugal
Maritime and Ocean Engineering Research Institute	MOERI[1]	Korea
Germanischer Lloyd Engineering Services - Department of Fluid Dynamics	GL[2]	Germany

Since the study is concerned with the collective (overall) performance of the benchmark codes rather than the performance of individuals and for avoiding any aspect of commercial implications the identity of the participating institutions is kept anonymous and coded by P1 to P6 (with no direct correspondence to the list of Table 1).

[1] Preliminary results submitted by this participant could not be verified at the time of completion of this paper hence they are not included in the presented benchmark

[2] This participant has not completed the numerical results within the time schedule of the benchmark study

BENCHMARK SETUP

The Studied Ship

The investigated vessel is a modern RoRo/Passenger ferry with a bulbous bow and a quite flat stern. The main dimensions of the ferry are given in Table 2 and the body plan is that shown in Figure 1. The ship is of SOLAS 90 stability standard and has been investigated before within the European research project *HARDER* (2000-2003).

Table 2 Main dimension of the RoRo/Passenger ship

Length Lpp	174.80	m
Beam, B	25.00	m
Draft, T	6.40	m
Depth, D	9.10	m

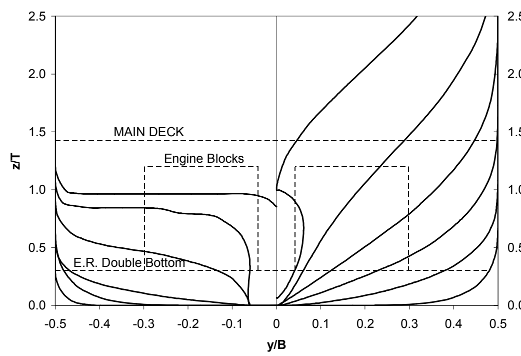


Figure 1 The body plan of the RoRo/Passenger vessel

Two bilge keels of 0.34 m width are fitted on the hull; the astern one has a length of 23.6 m and the forward one 28.0 m.

The Damage Case

The damage case investigated 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. The general arrangement of the damaged compartments is shown in Figure 2.

In the engine room (the aft damaged compartment) two intact blocks are used to model the main engines and lead to engine room permeability equal to 0.70. In the double bottom of the fore compartment the two side tanks are interconnected with a cross duct, while the rest space between them remains intact after the damage.

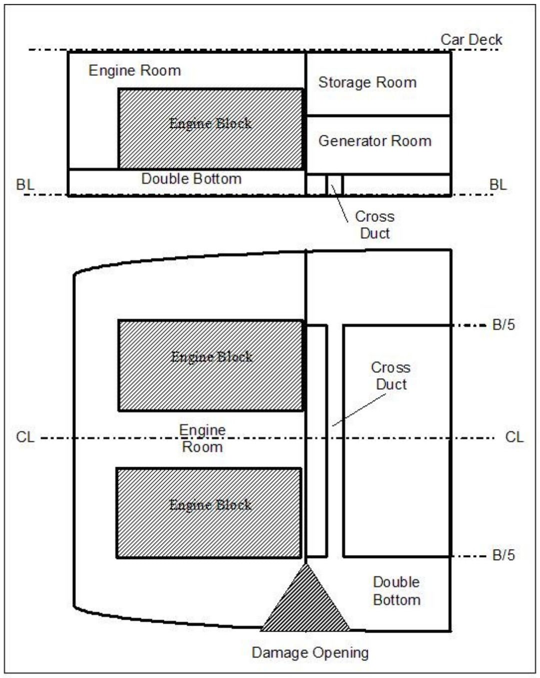


Figure 2 General arrangement of the investigated damage case

Benchmark Tests

The ferry is assumed freely floating on the free surface of the sea, without forward speed, in beam waves coming from the starboard side and is free to drift along the waves' direction.

The benchmark tests consisted of the estimation of the survival boundary $H_{s,surv}$ for a set of five different conditions, and an additional seakeeping test as they are listed in Table 3. All the tests were for the SOLAS damage case described above. Tests 2 to 5 were for the same conditions like Test 1 but having some parameters varied appropriately for a sensitivity investigation. Hence, in Test 2 the KG was reduced by 1.0 m, in Test 3 longer period waves were considered, in Test 4 any assumption on the semi-empirical value of the roll viscous damping that was made for the basic test should be doubled, and in Test 5 the assumed discharge coefficients for the basic test had to be reduced to the half. The last conducted Test 6 is a seakeeping test in which the vessel starts in intact condition and later after 30 min the damage (the same as for the other tests) is assumed to occur.

Table 3 Benchmark Tests (in particulars of Tests 2-5 only the difference to Test 1 is given)

Test	Description	Particulars
1	Basic	*KG* = 12.3 m, JONSWAP, $T_p = 4\sqrt{Hs}$, γ = 3.3, $B44_{v\text{-}basic}$, $C_{discharge\text{-}basic}$
2	Low KG	*KG*=11.3 m
3	Long waves	$T_p = 6\sqrt{Hs}$, γ = 1.0
4	High roll viscous damping	$B44v' = 2 \times B44_{v\text{-}basic}$
5	Reduced discharge coefficients	$C'_{discharge} = 0.5 \times C_{discharge\text{-}basic}$
6	Seakeeping	*KG* = 11.3 m, *Hs* = 3.0 m, *Tp* = 10.4 sec, γ =1.0, $B44_{v\text{-}basic}$, $C_{discharge\text{-}basic}$, Damage onset after 30 min

Comparative Experimental Measurements

The benchmark RoRo/passenger ferry has been systematically tested earlier in the model basin of MARIN, *Vant' Veer* (2001), within the European research project *HARDER (2000-2003).* The test particulars and available experimental measurements defined the basis of the data for the present benchmark.

Free roll decay measurements for the two studied *KG* values and a set of damage stability measurements (survive-capsize) in waves were the experimental data of the study which were made available beforehand to all participants to enable equal initial conditions.

Comparability of Simulation Results

The submitted simulation results were considered comparable when they were complying with the basic benchmark specification and corresponding to the basic hydrostatics of the intact ship. The intact ship displacement and the initial stability, as shown in Figure 3, proved to be very well calculated by all participants. However, for larger heeling angles the differentiation between codes is apparent even for the intact ship hydrostatics. Such differences are considered inherent to the simulation methods and they are not considered affecting their direct comparability.

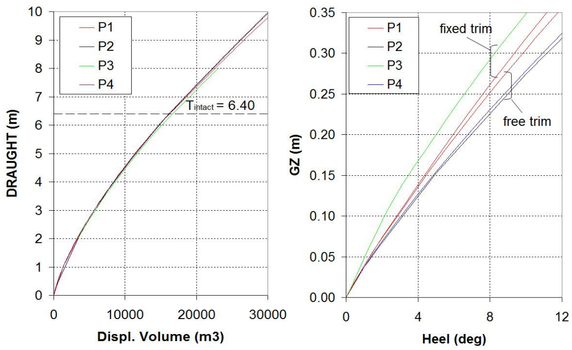


Figure 3 Hydrostatics of the intact RoRo/Passenger ferry

At the beginning of the simulations P1 and P4 have assumed the damaged ship as fully flooded in calm water, whereas P2 and P3 started without any floodwater inside the damaged ship and they have simulated also the transient flooding of the compartments below main deck. Since the transient flooding is limited within the first couple of minutes while capsize events occur much later when simulating close to the survive boundary, see Figure 4, the estimations on survivability are considered not affected by this and they remain comparable.

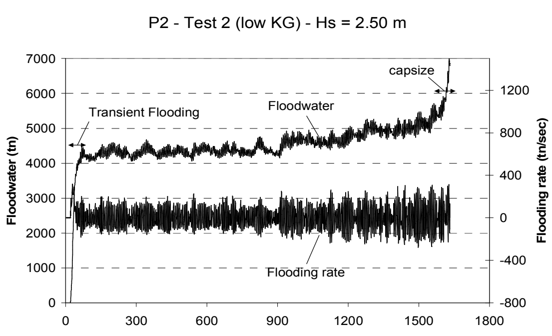


Figure 4 Simulated floodwater history of a capsize event by P2

Another worth noting issue is the assumed by participants motion in the lateral plane. Two of them P1 and P3 did not allow the ship to drift along the waves, while the other two P2 and P4 assumed the ship totally freely floating, as shown in Figure 5. This differentiation with respect to the allowance of drift was assumed not violating the comparability of the results as such assumptions may be considered inherent to the simulation procedure and attributed to the benchmark codes.

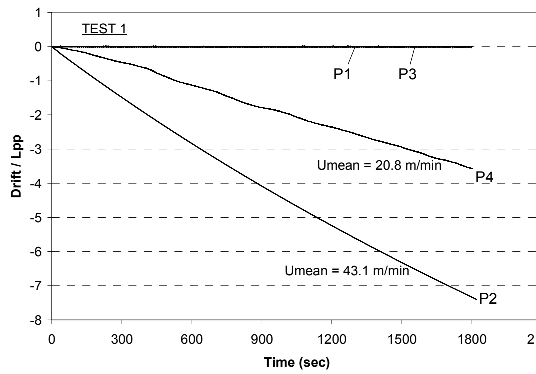


Figure 5 Wave induced drift for survive runs of Test 1

Survive Boundary

In the benchmark study each simulation should run for 30 min in ship full scale. Stability is assessed for each run, where the loss of stability is detected according to specifications set by *ITTC* (2005) for physical model tests in tank. The ship is considered to have lost stability, when a) the max roll angle exceeds 30 degrees at any time, or b) the average roll angle over a period of 3 minutes in full scale exceeds 20 degrees.

Considering also the probabilistic character of the survive wave height, every estimated boundary is complemented with the probability of surviving that boundary. This probability is determined by the participants as it depends on the approach employed for the estimation of this boundary. In any case it should be high enough, greater than about 0.95, in order to rationally define a boundary.

NUMERICAL SIMULATION METHODS

The computer codes employed in the present benchmark are implementations of developed mathematical/numerical models for the motion of the damaged ship in waves. The models follow a basic common formulation whereas they differ in specific issues. They are independently developed which implies that the codes dispose different performance and efficiency. Each participant has tested one code as following (in parenthesis relevant code names): NTUA (*CAPSIM*), SSRC (*PROTEUS*), MARIN (*FREDYN*), IST (*IST software*).

The basic modelling comprises in all cases an appropriate approach to the seakeeping problem of the intact ship in the time domain. Then, the motion of the ship in the time domain is coupled with an appropriate model for the flooding of the ship through the outer shell damage(s) as well as the effects of the floodwater on the ship motion. This basic formulation may be further expanded to include couplings with additional sub-models, e.g. with the progressive flooding to compartments adjacent to the damaged ones.

The ship is assumed as a rigid body and may undergo large amplitude motion in six degrees of freedom. Non-linear effects are in general fully accounted for the ship hydrostatics and the undisturbed wave excitation; other non-linear effects accounted for are those related to the viscous roll damping, the flooding process and the floodwater effects on ship motion.

The ship hydrodynamics, namely the ship to wave interaction forces, are approached in the context of the potential theory. In benchmarked methods, a quasi 2D strip theory is employed for the ship hydrodynamics, except for the NTUA method which employs a 3D panel method for this purpose. Viscous effects, which are significant for a realistic roll motion simulation, are separately treated in a semi-empirical way. All methods use equivalent linearized or higher order models for the total viscous damping on the basis of empirically evaluated coefficients from relevant experimental data. A finer approach may be also applied by decomposing the total roll damping into various components, like friction, eddy, bilge keels and other appendages damping, as proposed by *Ikeda* (1978).

The flooding process is uniformly approached by the use of hydraulic models. The basic Bernoulli equation modified by semi-empirical coefficients is employed for the modelling of the water ingress/egress through damage openings. The same approach is also applied for the progressive flooding, namely the flow between ship compartments through open doors and ducts and other internal openings.

For the modelling of the floodwater motion and its interaction with the ship there are different levels of approach. IST applies shallow water waves modelling for the water motion in rectangular tanks, NTUA and SSRC assume the internal floodwater moving without waves on the free surface of floodwater and apply the lump mass concept and MARIN assumes the free surface of the floodwater remaining horizontal during the simulation.

Background information on the theoretical modelling and numerical methods can be found in *Spanos and Papanikolaou* (2001), *Spanos* (2002) for CAPSIM, *Letizia* (1997) and *Jasionowski* (2001) for PROTEUS, *Santos* (2003) for IST, and *De Kat and Paulling* (2001), *Van't Veer and De Kat* (2000) for FREDYN.

NUMERICAL RESULTS

Survive boundary approach

The survive boundary $H_{s,surv}$ for the defined damage ship conditions is the wave height below which the ship always survives, practically with a very high probability. To estimate $H_{s,surv}$ for some probability level then a long series of simulations are necessary to properly approach this boundary. Regarding this, each benchmark participant applied a different approach to conclude on the boundary estimation.

P1 has systematically approached the survival boundary from the ship behaviour in higher waves. Starting simulations with a high wave height every time a non-survive run was encountered then $H_{s,surv}$ was bounded below that height. When ten (10) successive survive runs were encountered for some height then that height was assumed as the survive boundary.

The other benchmark participants started their simulation procedure with an initial estimation of the range of the wave heights, within which the boundary could be found and then searched over that range with a wave height step of 0.25 m. P2 have carried out forty (40) runs for each individual wave height, P3 five (5) and P4 twenty (20).

The total (for the five tests) number of simulations finally carried out until the $H_{s,surv}$ was estimated is shown in Figure 6. The obtained results by P2 are considered of higher statistical confidence and they in fact better converge. However, this approach is of higher effort in terms of simulation trials.

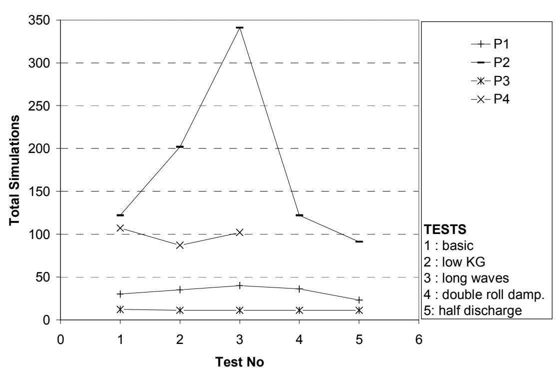


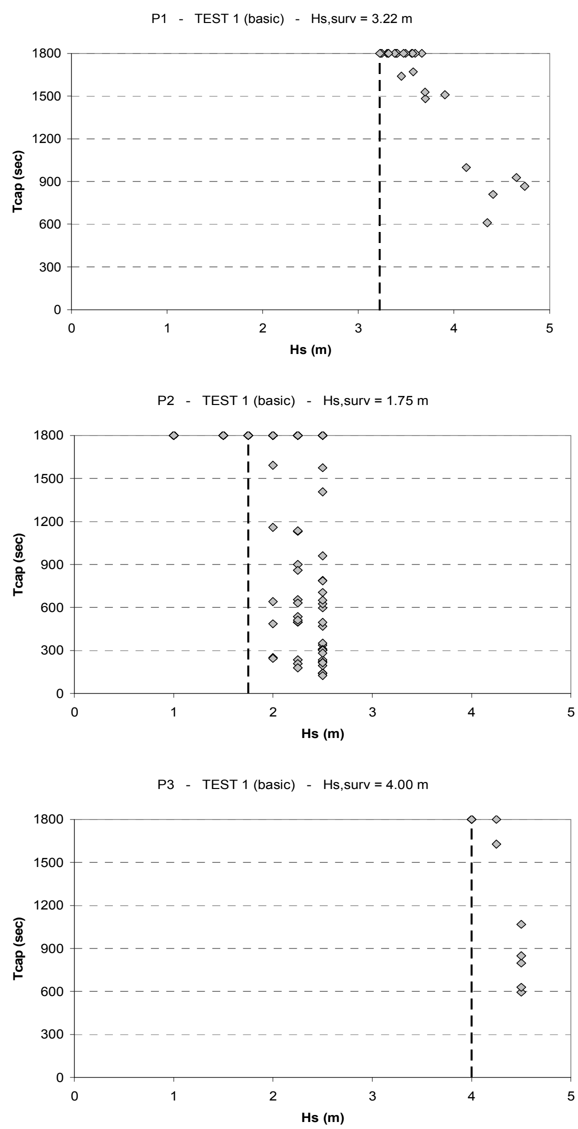
Figure 6 Number of simulations carried out for each test

Survive boundary estimations

The four diagrams of Figure 7 present the simulation results for the basic Test 1. These are the time recorded until the ship is considered lost and is called the time to capsize T_{cap} as all lost events are associated with a ship capsizal. The survive boundaries as recognized by each participant are shown with the dashed lines. T_{cap} is varying over the significant wave height H_s. To facilitated the benchmark analysis the survive simulations are also registered as events at the time 1800 sec (30 min) although these are not capsize events.

The events for benchmark partner P1 are bounded by the survive boundary as a consequence of the employed approach to the $H_{s,surv}$. The results for P2 show that most of the runs for wave heights higher than 2.0 m were not necessary as they do not contribute to a faster or more accurate identification of the survive boundary, identified at 1.75m. The low number of runs for P3 indicates that some weak convergence of the estimated $H_{s,surv}$ should be correlated. For P4 the survive boundary is estimated at 3.0 m on the basis of one (1) lost out of twenty (20) runs, hence a correlated probability of 95%.

Obviously the estimated boundaries depend on the approach applied and they could vary some 0.25 m.



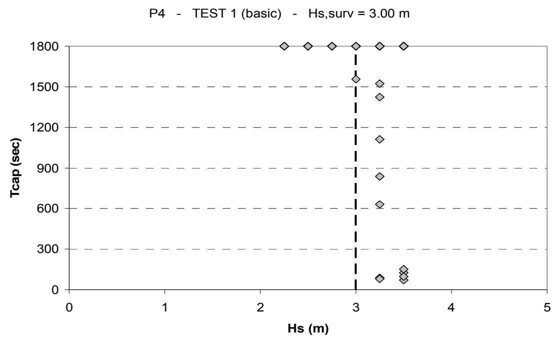


Figure 7 Simulation events for Test 1

The estimated survive boundaries for the basic Test 1 are summarized in Table 4. Based both on the mean and experimental values the estimations attained by P1 and P4 seem rather successful. The other two estimations deviate significantly, P2 with an underestimation and P3 with an overestimation. Such deviations of about 1.0 m from the actual values are surprising for codes considered mature and with relatively good performance in past benchmarks. The benchmark partners need to review these results and to study possible reasons for the observed deviations. In this respect, the preliminary nature of the submitted results should be observed.

Table 4 Survive boundary in (m) for the basic Test 1

Participant	$H_{s,surv}$	Mean	Differ. from mean	Exp.
P1	3.23	3.00	+0.23	≤ 3.00
P2	1.75		-1.25	
P3	4.00		+1.00	
P4	3.00		+0.00	

While P1 and P4 seem to deliver convergent results, the detailed background analysis showed that codes simulate the test phenomena in a substantially different way; thus, it is remarkable how this difference appears subsidiary in the estimation of the survival boundary.

For P1 the simulated roll motion is larger than it is estimated by the other participants and it seems that the ship eventually capsizes due to intensive rolling of the flooded ship. The ship dynamics and the floodwater effects seem to dominate the roll instability while for the other participants, including the tank tests, the ship clearly capsizes in a quasi-static way. Figure 8 samples a capsize event as simulated by P1 where the roll gradually increases due to the gradual increase of the floodwater on the car deck.

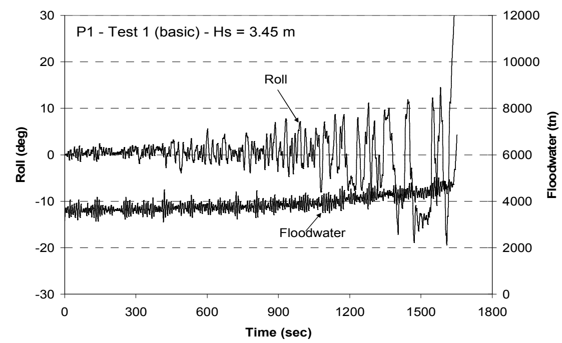


Figure 8 Sample for non-survive run in Test 1 by P1

For P4 the capsize events occur in a random and sudden way, which is also quite different to the other participants. As exampled in Figure 9 the otherwise stable damaged ship will eventually experience a sudden heel and will capsize due to a similar sudden increase of floodwater. Such behaviour seems to be related to some numerical instability rather than capturing a real change of ship's stability.

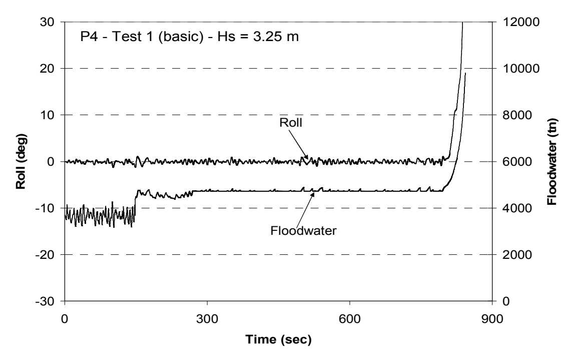


Figure 9 Sample for non-survive run in Test 1 by P4

Sensitivity analysis

The sensitivity of the survivability with respect to the basic simulation parameters has been investigated with the Tests 2 to 5. As pointed out in the section outlining the numerical methods, the simulation results are affected by the semi-empirical parameters of viscous roll damping and the discharge coefficients, while the ship dynamics and hydrodynamics are affected by the ship loading condition and the wave periods respectively. Hence, with the Tests 2 and 3 the sensitivity to the damaged ship dynamics is examined by decreasing KG (equivalently increasing the GM) and the wave periods respectively. With the Test 4 the dependence on the roll damping and with the Test 5 the dependence on the assumed flooding process is also tested.

Figure 10 summarizes the change of the estimated survive boundary $H_{s,surv}$ for these four (4) tests with reference to the basic Test 1. These results demonstrate that the less sensitive code is that of P1, while the other three (P2, P3 and P4) notably respond to the applied variations. It is noted that P4 has not delivered results for Tests 4 and 5.

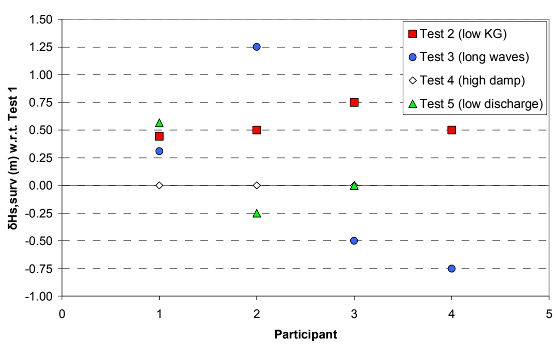


Figure 10 Sensitivity of survive boundary for each code

KG and wave periods

When KG is reduced by 1.0 m (Test 2) the codes have predicted an equal increase of survivability approximately by 0.50 m, while differences up to 0.25 m (like that of P3) are assumed tolerable as discussed above in the section regarding the survive boundary approach. While the codes seem to converge for Test 2, they deliver much divergent results when employed for simulations in longer waves (Test 3). Two of them (P1 and P2) predicted an increase of survivability and the other two (P3 and P4) a remarkable reduction. It is noted that both Tests 2 and 3 define conditions closer to the roll resonance, as in Test 2 the natural roll period is shifted roughly by 3.5 sec towards the wave periods (of Test 1) and in Test 3 the wave periods are shifted roughly by 5.0 sec towards the roll natural period (of Test 1).

Roll viscous damping

The results for Test 4 (higher roll viscous damping) have not revealed any sensitivity by the employed simulation codes. It seems like the initial viscous roll damping as assumed for Test 1 should have been rather small that could not affect significantly the survivability when it was doubled, hence a practically zero change for all the participants was observed. However, from the past benchmark studies it has been observed that simulation codes were strong dependent on the viscous roll damping and specifically on the information gained from experimental data that has not verified with the current test. These results should be further analyzed and clarify the recorded behaviour.

Discharge coefficients

The effect of the assumed discharge coefficient on the simulated survivability (Test 5) was complicated too. The three participants have identified three different trends. P1 predicts an increase of survivability by 0.5 m when the employed discharge coefficients were decreased to half. This change seems consistent to a slow down of the flooding process and a subsequent delay to the development of instable conditions. To the contrary, P2 predicts a worsening of the survivability, whereas P3 seems insensitive to this parameter.

Seakeeping of the damaged ship

Additionally to the survivability assessment the seakeeping behaviour of the damaged ship in waves is a fundamental problem addressed by the benchmarked codes. Test 6 was dedicated to the prediction of the impact on the roll motion of the basic ship damage, the one tested also in the previous tests. The experimental measurements for some conditions indicate a significant damping of the roll motion when the ship is damaged and flooded, with the damaged ship roll reducing to approximately 1/3 of the intact roll. Since the decrease is large a single test is assumed enough in order to qualitatively evaluate the simulation codes with respect to the prediction of this behaviour. Hence, the single Test 6 is defined in long waves (Hs=3.0 m, Tp=10.4 sec, γ=1.0) and KG=11.3 m where the intact ship is damaged at some time (after 30 min). The ship survives this case and the flooding is limited only to the compartments below the main deck. Figure 11 examples the simulation of P3 where after the damage event at 1800 sec the ship is flooded with 3500 tn and rolls around a mean angle of 1.5 deg towards the damage opening.

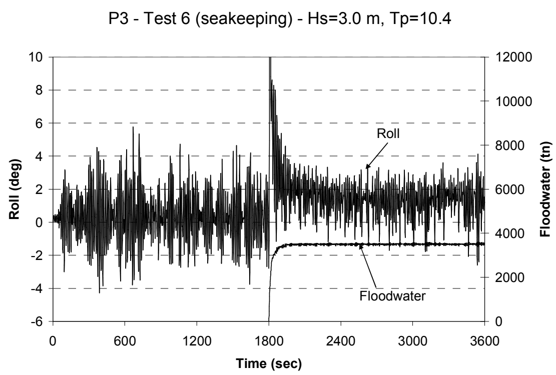


Figure 11 Roll and floodwater series for Test 6 by P3

The change of the roll motion is measured by the comparison of the *rms* value between intact and damage condition as shown in Table 5. The results demonstrate that all the codes underestimate the roll damping of the damaged ship with P3 predicting the most considerable decrease of the roll motion. This code applies to a more detailed model for the floodwater motion.

Table 5 Roll motion in irregular waves, as in Test 6

Participant	*Intact Roll rms (deg)*	Damage Roll rms (deg)	rms ratio (damage/intact)
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

CONCLUSIONS

The capabilities of presently available simulation codes for the assessment of the damaged ship survivability in waves are considered identified with the present benchmark, complementing past and related benchmark studies.

A limited number of independently developed codes are available nowadays worldwide dealing with this very complicate problem of high practical interest.

The overall performance of the benchmarked codes appears divergent. Estimations for the survive boundary could deviate up to 1.0 m, which is quite large, while the codes have partly predicted opposite trends with respect to the variations of the basic parameters of the problem.

Even for the codes that appear accurately predicting the survival boundary it was found that they are characterized by a substantially different performance in the background.

The numerical estimations on survivability of the damaged ship were found to be sensitive with respect to the periods of the incident waves, while less sensitive with respect to the assumptions for the discharge coefficients and ship loading condition. No conclusions could be derived for the effect of the viscous roll damping, while the present results seem to contradict conclusions from earlier benchmark studies, suggesting an increased importance for the values of the semi-empirical roll damping coefficients.

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