24th ITTC Benchmark Study on Numerical Prediction of Damage Ship Stability in Waves Preliminary Analysis of Results

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Abstract

The 24th ITTC Specialists Committee on Stability in Waves is conducting an international benchmark study where numerical methods for the calculation of ship motion in damaged condition are compared reviewed on the basis of specified tests in order to assess the present state of the art in this field. While the study is still in progress, some preliminary results are presented in this paper providing an initial insight into the status of various methods and computing codes and a collective assessment of their performance. The preliminary analysis has shown that current methods are very close to satisfactory capture the fundamental physical performance of damaged ships in specified conditions.

1. Introduction

In December 2001 a first international benchmark study on numerical methods for the prediction of capsize of damaged ships in sea waves was launched, coordinated by the 23rd ITTC Specialist Committee on the Prediction of Extreme Motions & Capsizing [1], [2]. There were five (5) independent participants in this study each employing different and independently developed computer simulation code. The five participants were: *Marine Research Institute* (MARIN), *Ship Design Laboratory of National Technical University of Athens* (NTUA-SDL), *Osaka University, Flensburger Schiffbau Gesellschaft* (FSG) and *The Ship Stability Research Center of Universities of Glasgow and Strathclyde* (SSRC). This benchmark study is believed to have represented at the time of its conduct the state of the art in the field.

The study ascertained that at the current state of knowledge theoretical numerical prediction methods could greatly contribute to a pre-assessment of the survivability of damaged ships in waves. However, considering the relatively low number of the benchmark participants and the complicated nature of the set benchmark study problem it was suggested to extend and refine the study in the future with the aim to attract more benchmark study participants and to resolve to the extent feasible several open questions identified in the study.

The 24th ITTC Specialists Committee on Stability in Waves has initiated the extension of the benchmark study in early 2004 and the study is expected to be completed at the end of year 2004. The basic objective of this work is to update the state of the art in the field of numerical methods for the prediction of motion and capsize of damaged ships in waves. There were five institutes expressing their interest for participation in the present study, listed in Table 1.

The benchmark study consists of two phases, [3]. At the first one, the numerical methods are tested with respect to the simulation of ship's motion in calm water for a selected set of transient motion and flooding conditions. In the second phase, test cases for damaged ship's behavior in irregular waves are considered.

The first benchmark phase, testing in calm water, consists of four major tests series. The first one deals with the behavior of a Ro-Ro/passenger ferry in free roll decay motion in the intact condition whereas at the second test series the same ferry is investigated in damage condition. The third series deals with the behavior of a tanker in free roll motion having one tank partially flooded with constant amount of water inside. And the last series deals with the behavior of a second Ro-Ro/passenger ferry in transient flooding condition.

Following the completion of the first three of the above test series, the preliminary study results are presented in this paper with the aim to widely present the progress of the study to the participants of the International Stability workshop and enable an early assessment of the study by the ITTC Specialists Committee.

Institute	Acronym	Country
National Technical University of Athens, Ship Design Laboratory	NTUA-SDL	Greece
Ship Stability Research Center, Universities of Glasgow and Strathclyde	SSRC	United Kingdom
Marine Research Institute	MARIN	The Netherlands
Instituto Superior Tecnico	IST	Portugal
Korea Research Institute of Ships and Ocean Engineering	KRISO[1]	Korea

Table 1 Benchmark Study Participants

2. Study Setup

Considering the complicated character of the numerical methods addressing the motion of damaged ships in waves and the prediction of ship's stability in extreme conditions the present study has been set up to provide comparative information for the basic aspects of the methods and to enable their assessment individually as well as a whole.

The selected tests are derived by consideration of the fundamental phenomena taking place in the motion of the damaged ship and the corresponding modeling applied by numerical methods. The basic factors recognized for such a physical system, expressed as forces, are the inertia, the restoring, the damping and the wave induced forces. The flooding process through a damage opening and the floodwater effects on the ship motions are the two extra terms that characterize the problem. The various numerical methods apply to these two terms a specific modeling to be assessed in the framework of the benchmark study.

The two phases that the present benchmark testing is divided are called phases A and B. In the phase A, the wave induced forces have been excluded and the ship models are tested in calm water, whereas in the phase B, the models are going to be investigated in the presence of waves too. The phase A consists of four (4) test series, namely Test A, B, C and D. These tests are all referring to the free roll motion of ship models in calm water and they are defined as follows:

Test A – Free roll motion of an *intact* passenger/Ro-Ro model, coded as PRR01, with two different KG values.

Test B – Free roll motion of the passenger/Ro-Ro model PRR01 in *damaged* condition and the same two KG values as Test A. The specified damage opening is continuously open during the test and at the start of the test the damaged compartment is already fully flooded. The flooding process and floodwater dynamics are present in this test.

Test C – Free roll motion of a tanker model, coded as TNK, in *partially flooded* conditions. The model has one rectangular compartment amidships partially flooded with constant amount of water inside, which corresponds to a compartment breadth to water fill depth ratios equal to 31.8, 7.9 and 2.0. In this test there is no damage opening and subsequent flooding process. The test focuses on the floodwater dynamics and effects on ship motion.

Test D – Free roll motion of a second Passenger/Ro-Ro ferry, coded as PRR02, in *transient* flooding. The intact model starts from equilibrium position. Then a specific damage opening is released and the water ingress is initiated. After that the model freely oscillates under the effects of transient flooding. In this test the flooding process is of prime interest.

The passenger/Ro-Ro ferry PRR01 investigated in the Tests A and B is a model also investigated in the previous benchmark study [2]. This model has been also tested in systematic model experiments within the EU funded research project *Nereus*, [3], and the experimental data were made available to this study. The main dimensions of the ferry are given in Table 2, and the body plan is depicted in Figure 1. In damage condition the ship has two adjacent compartments flooded amidships and the damage opening is according to SOLAS 90 specification (3% L + 3.00 m), which extends unlimited vertically upwards making the cargo space also damaged.

[1] At the time of completion of this paper the numerical results of this institute were still pending

The tanker model TNK, investigated in Test C, is equipped with a rectangular tank amidships, representing a flooded compartment. The main dimensions of the model and the inside tank are given in the Table 3 and the body plan in Figure 2.

The TNK model has been tested in free roll motion having the compartment partially filled with constant water, and the corresponding experimental data used were those published in [5].

In all test cases, the study is focusing on the simulation of roll motion. However the motion in other degrees of freedom is also recorded and analyzed in the study.

It is noted that the experimental data corresponding to each benchmark test were available beforehand to all study participants to enable equal benchmarking conditions for all participants.

In the following the identity of the participating institutions is coded by P1 to P4 (there is no direct correspondence to the list of participants in Table 1).

Length Lpp (m)	170.00
Beam, B (m)	27.80
Draft, T (m)	6.25
Displacement (tons)	17269
Car deck (m)	9.00
Model scale	1:40

Table 2 Main dimensions of Passenger/Ro-Ro PRR01

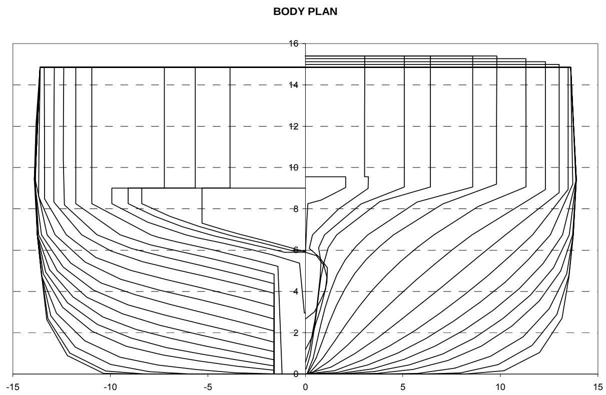

Figure 1 Body plan of the Passenger/Ro-Ro ferry model PRR01

Length Lpp (m)	310.20
Beam, B (m)	47.20
Draft, T (m)	16.00
Displacement (tons)	202600
Depth, D (m)	26.07
Model scale	1:82.5
Length of compartment, Lc (m)	82.50
Width of compartment, Bc (m)	31.76
Compartment’s height above baseline	5.20

Table 3 Main dimensions of tanker model TNK

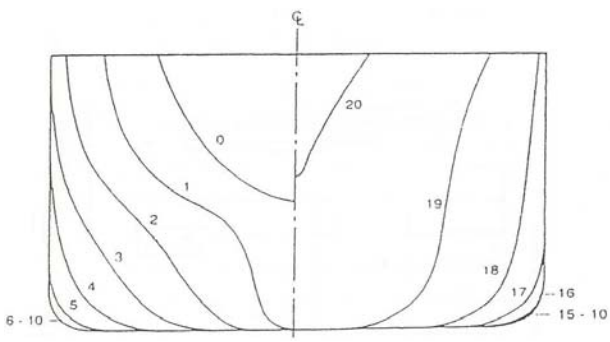

Figure 2 Body plan of the tanker model TNK

3. Numerical Methods

The mathematical models for the motion of the damaged ship in waves, employed within the present benchmark study, are presented in a unified way. In particular, the methods are decomposed into their fundamental properties and their specific modeling applied to each part of the study.

All simulation methods are characterized by the particular modeling and treatment they apply to the equations of motion, namely the inertia, the restoring and the damping terms, as well as the ship to wave interaction, the modeling of the floodwater effects on the ship motion and the flooding process itself.

All participating methods are non-linear time domain simulation methods considering the ship as a rigid body inertia system and accounting for non-linearities of large amplitude motion and floodwater effects. The six degrees of freedom are considered for the ship motion, by exception of method P4 where surge and yaw are omitted. The restoring forces are related to the hydrostatic term of water forces, and are calculated by direct integration of hydrostatic pressure over the instantaneous wetted surface.

The ship hydrodynamics, namely the ship to wave interaction forces, are approached by potential theory, applying either strip theory or 3D panel methods. In particular, method P3 employs a 3D panel method, whereas all the others quasi 2D strip theory approaches.

The radiation forces are calculated in the frequency domain and are transferred to the time domain by use of retardation functions. The diffraction forces in the time domain are taken by superposition of wave harmonic components calculated in frequency domain.

The part of wave excitation corresponding to the undisturbed wave Froude-Krylov forces is calculated by direct integration of the wave dynamic pressure over the instantaneous wetted surface.

Viscous effects, which are particularly significant for the roll motion simulation, are treated in a semi-empirical way. All methods use of linear or higher order models for the total viscous damping on the basis of empirically evaluated coefficients form relevant experimental data. A finer approach is also applied by decomposing the total damping into various components, like friction, eddy, bilge keels and other appendages damping, according to [6], [7].

The flooding process is uniformly approached by the use of hydraulic models. Pending the possible implementation of advanced CFD methods, the basic Bernoulli equation modified by semi-empirical coefficients proved to be satisfactory for the modeling of the water ingress/egress through a damage opening. The same approach is also applied to the progressive flooding, namely the flow between ship compartments through open doors and ducts and other internal openings.

The floodwater motion and its interaction with the ship is approached by omitting internal wave effects and assuming the internal free surface always plane. The instantaneous orientation of the free surface is part of the numerical solution. This approach is applied by participants P1 and P3. The floodwater modeling can be further simplified by assuming the internal free surface of water always horizontal, an approach that is adopted by participants P2 and P4. Participant P4 also applies a shallow water modeling to the internal water motion in case of the rectangular tank in Test C.

Numerical Method	P1	P2	P3	P4
ship's degrees of freedom	6	6	6	4
hydrostatic forces by direct integration	x	x	x	x
strip theory	x	x		x
3D panel method			x	
incident wave forces by direct integration	x	x	x	x
semi-empirical roll viscous	x		x	x
roll viscous analysis in components		x		
floodwater with horizontal free surface		x		x
floodwater with moving free surface	x		x	
Internal motion by shallow water equations				x
flooding by simple hydraulic model	x	x	x	x

Table 4 The basic attributes of the applied numerical methods in benchmark study

Further background information on the numerical methods can be found in [8], [9], [10], [11].

The next Table 4 summarizes the basic attributes of the numerical methods as they have been applied in the present benchmark study.

4. Numerical Results

The numerical results submitted in the present benchmark procedure were time series of ship motion responses for each test case considered. The results are directly comparable to each other as well as to corresponding experimental data enabling a first qualitative assessment of the performance of the methods. The analysis focuses on the roll response as this motion is of prime interest in view of ship's stability. The ship's natural period and the damping rate can be deduced from the submitted results. These two quantities can be considered representative for the modeling of ship's restoring to mass and hydrodynamic inertia relationship and the damping phenomena correspondingly.

TESTS A & B

The first two test series, Test A and B, carried out in the benchmark study regard the free roll motion of the passenger/Ro-Ro ferry PRR01 in intact and damaged conditions. Two different KG values were investigated for each test. The roll response in case of the lower KG value (Test A1 in intact and B1 in damaged) is presented in the diagrams of Figure 3. Each diagram presents in comparison the roll motion in the intact against the damaged condition. The top diagram corresponds to the experimental results as they have been obtained in the model tank tests whereas the others correspond to the numerical results of each participant.

As observed in the experimental results an increase of roll damping as well as of the natural period occur when the ship is damaged. The numerical methods satisfactorily predict the change in period whereas the increase of damping is only met by the P3 results. It is also remarkable the substantial underestimation of the overall damping estimated by method P2. It is noted, however, that the P2 method is based on theoretical damping estimations without consideration of the experimental data.

TEST C

The results of the third Test C, namely the free roll motion of the tanker TNK having one compartment partially filled, are presented Figure 4. For each diagram four curves are plotted, each one corresponding to a different level of water fill depth into the rectangular compartment, namely 0.0, 1.0, 4.0 and 16.0 m of depth in full scale, which correspond to compartment fill depth ratios equal to infinite, 31.8, 7.8 and 2.0.

As observed, the ship model changes under the effect of the internal water motion significantly its behavior. The most significant effect on ship's roll motion is observed for the intermediate fill depth of 4.0 m, whereas the damping seems to be higher for the lower water depth. Comparing the numerical results to each other, this motion pattern is apparently closer simulated by methods P3 and P4. It is also remarkable that although these two methods apply different modeling to the internal water to ship interaction they demonstrate quite similar results.

COMMON ANALYSIS OF TESTS A, B & C

Continuing the analysis of obtained numerical results, the natural roll period is deduced and compared for each test and method. In Figure 5 the natural period for the passenger/Ro-Ro ferry PRR01 deduced from Tests A and B, namely for the intact and damage condition as well as the lower and higher KG values, is presented. This diagram shows the sensitivity of each method with respect to the change of the intact to damage condition as well as the shift of the center of gravity. The increase of periods in case of damage is clear for both KG values, whereas as a sequel the periods also increase for higher KG (or lower GM), as could be expected.

Regarding the sensitivity of results with respect to the presence of damage there is a satisfactory behavior of the methods, with exception of the P2 method, which appears to be strongly affected by the change of hull's integrity. Furthermore, the method P2 fails to follow the change of the natural period due to the shift of the center of gravity, whereas the perfect correlation of results for intact cases appears for method P1 is a matter of calibration of the method with respect to the experimental data for both these tests.

Figure 6 summarizes the corresponding results of the natural period for the Test C. In this figure it can be observed that the period remains unaffected for the lower fill depth compared to the intact case without internal water. The period substantially increases with the increase of water fill depth, whereas at a further increase of water fill depth the period decreases to lower values. This complicated behavior is well captured by the two methods P3 and P4. In particular, it is noted that increasing the fill depth from 1.0 m to 4.0m the period significantly increases by 17.0% according to the experimental results.

The next diagrams of Figure 7 and Figure 8 present the logarithmic decrement of the decayed roll motion for the Test A1 and B1 respectively, defined as the $\log(A_o / A_i)$ where A_i is the i-th roll amplitude and A_o the initial.

These two diagrams in comparison clearly show, in a measurable way, the increase of damping in case of damage as previously discussed. The substantial underestimation of damping resulting in method P2 is notable in Figure7, whereas the fine correlation of experimental and numerical results of method P3 can be observed in Figure 8.

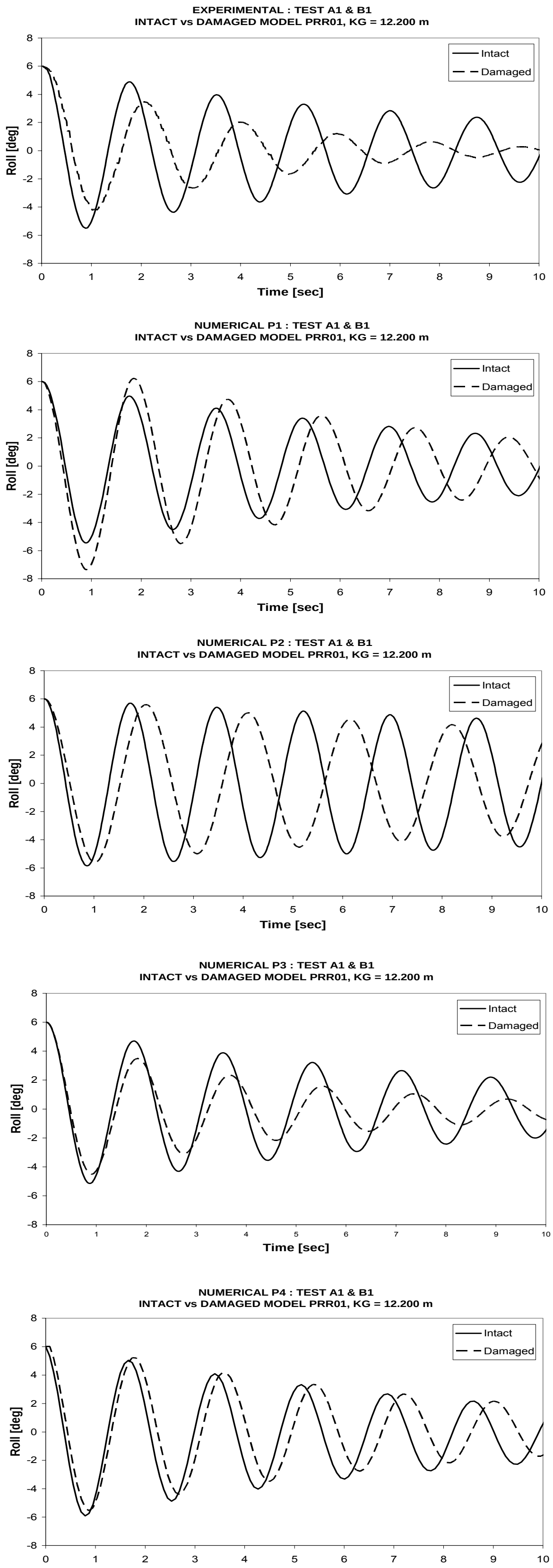

Figure 3 Roll motion of Tests A1 and B1

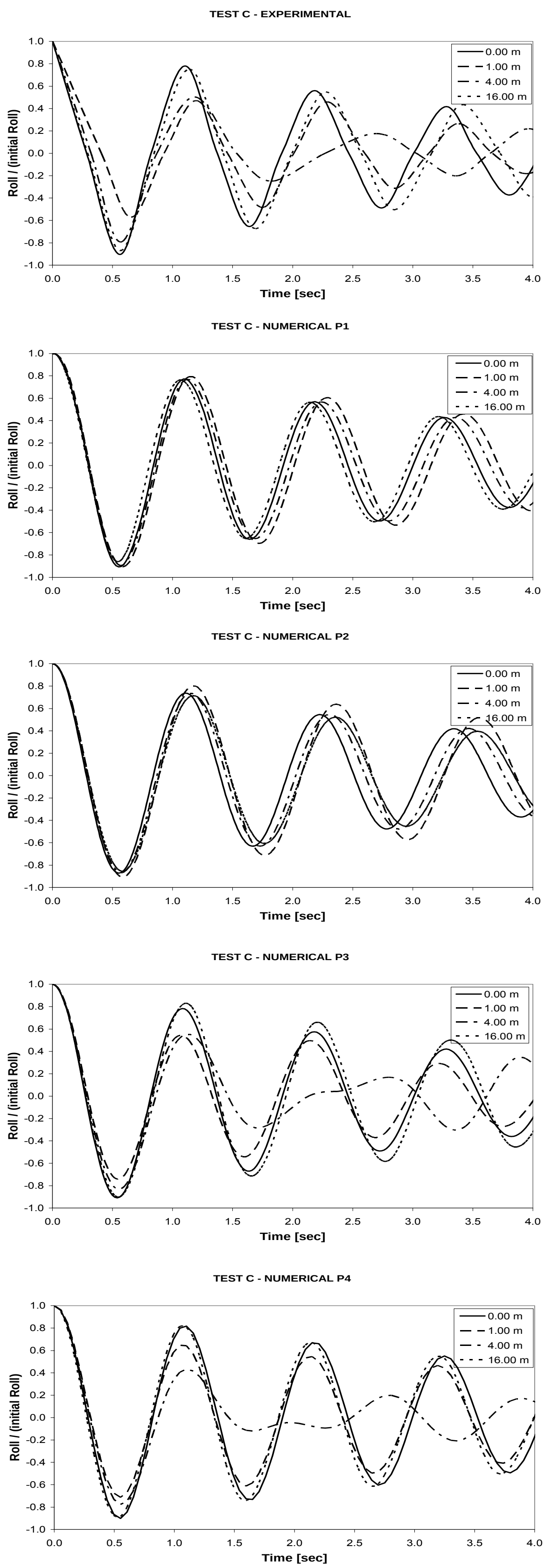

Figure 4 Roll motion of Test C

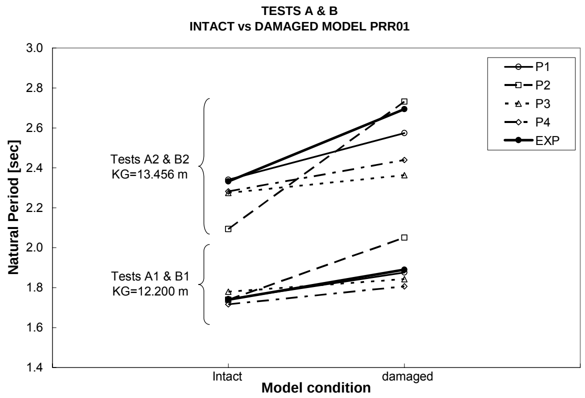

Figure 5 Natural periods of Tests A and B

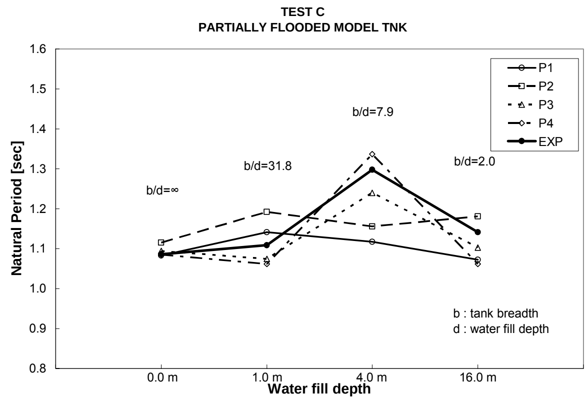

Figure 6 Natural periods of Test C

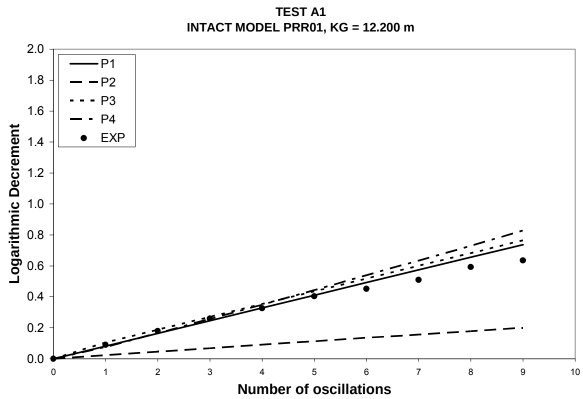

Figure 7 Logarithmic decrement of Test A1 (intact)

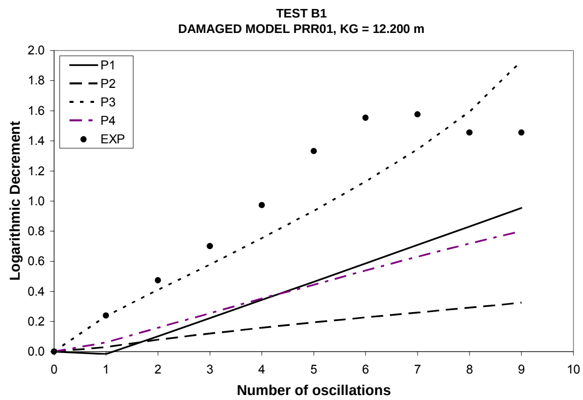

Figure 8 Logarithmic decrement of Test B1 (damaged)

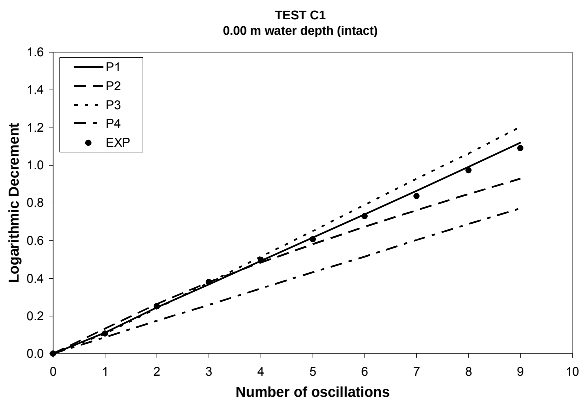

Figure 9 Logarithmic decrement in Test C1 (0.00 m)

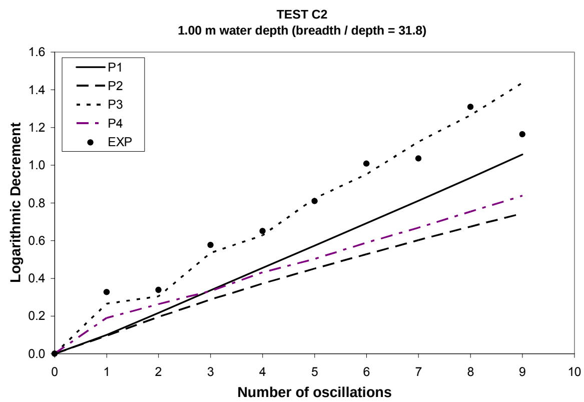

Figure 10 Logarithmic decrement in Test C2 (1.00 m)

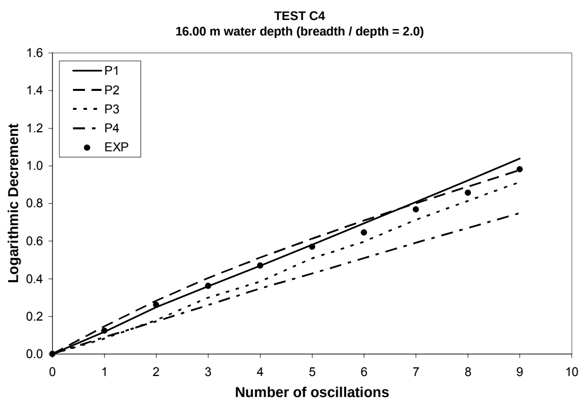

Figure 11 Logarithmic decrement in Test C4 (16.00 m)

Figure 9 to Figure 11 present the logarithmic decrement of Test C. Figure 9 shows a fine correlation between the numerical and the experimental results in case of absence of inside water. This can be explained by the use in the process of numerical simulation information derived by experimental data. In the presence of internal water the increase of damping is apparent in Figure 10, which is well captured by method P3. This change is obviously a pure effect of the internal water motion on ship's motion. For the case of higher water fill depth, shown Figure 11, the results become even better correlated to the experimental ones as the influence of the internal water motion seems to be more confined.

5. Conclusions

The reviewed preliminary results of the first phase of the 24th ITTC damage stability benchmark study provide a first insight into the present status of the numerical methods for the simulation of the motions of damaged ships.

The efficiency of the reviewed methods regarding the modeling of the inertia and restoring forces has been ascertained. The estimation of the viscous roll damping, when satisfactory experimental data for the determination of employed semi-empirical coefficients are available, seems to be well addressed. Observed deviations between the numerical methods are found to be mainly due to different approaches to the effects of the floodwater on ship motions. It is found that two (2) out the four (4) benchmarked methods can well capture these effects.

In the final stage of this part of the benchmark study it remains to assess the results of the transient flooding test where the modeling of the flooding process and the progressive flooding will be addressed. Finally, the results of the second phase of the study will enable the critical review of the methods with respect to conditions in the presence of waves, which were excluded in the present phase.

6. Acknowledgements

The authors would like to acknowledge the contribution to this benchmark study of the *Danish Maritime Institute* (DMI) providing the experimental data of Tests A and B and thank all benchmark study participants, namely IST-Lisbon, MARIN-Wageningen and SSRC-Glasgow, for their contributions for the conduct of the present study.

7. References

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