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CONTENTS

List of symbols and abbreviations

CFD	computational fluid dynamics
CL	centerline
DOF	degree-of-freedom
ITTC	International Towing Tank Conference
RANS	Reynolds-Averaged Navier-Stokes
SWE	shallow water equations
TTC	time-to-capsize
TTF	time-to-flood
VOF	volume of fluid

1 EXECUTIVE SUMMARY

1.1 Problem definition

Over the past two decades several simulation tools have been developed for time-domain analyses of flooding and motions of damaged ships, both in calm water and in waves. Methods based on hydraulics (Bernoulli's equation) are most common due to computational efficiency. However, recently also CFD (Computational Fluid Dynamics) methods have been applied for a more detailed assessment of the flooding process.

Several Benchmark studies were organized by the International Towing Tank Conference (ITTC), and in addition, many individual validation studies have been published. However, there has not been a wide benchmark study for validation and analyses of the available simulation tools since 2007. The aim of this FLARE Benchmark study is to fill this gap.

Some partners in the FLARE consortium have developed their own flooding simulation codes, but it was recognized that these do not cover the whole range of different approaches for codes that have been implemented. Therefore, participants outside the FLARE consortium were also invited to this Benchmark, in order to get a good overview of the characteristics and capabilities of as many simulation codes as possible. All invited participants have published new innovative approaches to flooding simulation during the recent years.

1.2 Technical approach and work plan

Flooding of a damaged passenger ship is a complex process, especially if it happens in waves. Therefore, the benchmark was divided into three separate parts, each concentrating on specific phenomena:

- Part A: flooding fundamentals, with captive models and simplified geometries
- Part B: transient and progressive flooding of a cruise ship
- Part C: transient and gradual flooding of a ropax ship

All participants received details about the studied geometries and test cases. In addition, some key measurement results (graphs) and some videos from the tests were shared beforehand, in order to ensure fair and equal conditions to all participants.

Water levels at sensor locations were the key quantities for comparison in Part A. For Parts B and C, the focus was more on the motions of the flooded ship, especially the development of the roll angle.

Three informal online workshops were organized between the benchmark participants who had provided simulation results. These discussions on the results enabled a better insight into the codes used by the external participants, which was essential for preparing this report, and thus complements the knowhow within the FLARE consortium.

1.3 Results

In total, 11 organizations provided results to some parts of the benchmark. Participants from the FLARE consortium were:

- Brookes Bell (BROO)
- DNV
- HSVA
- MARIN
- University of Strathclyde, Maritime Safety Research Center (MSRC)
- NAPA

And external participants:

- China Ship Scientific Research Center (CSSRC), China
- Korea Research Institute of Ships & Ocean Engineering (KRISO), Republic of Korea
- University of Applied Science Kiel (UAK), Germany
- University of Naples “Federico II” (UNINA), Italy
- University of Trieste (UNITS), Italy

The flooding fundamentals (Part A) confirmed that most of the codes can correctly calculate the basic flooding mechanisms, including up and down flooding, and that only one code had significant problems with these cases. Somewhat surprisingly, there was a quite notable deviation in the results for the deck flooding case (Part A4) between the Bernoulli-based simulation codes, indicating possible accumulation of numerical error in the solution of the governing equations.

For the cruise ship flooding cases (Part B), the maximum transient roll angle was predicted rather well by most of the codes, although there was a quite notable variation in the subsequent decrease of the roll until the stable heel angle was reached. In irregular beam seas with a significant wave hight of 4.0 m, the same damage scenario resulted in capsizing. All participants could properly capture the capsize, but the variation in the time-to-capsize (TTC) was significant. In general, the simulated TTC was shorter than the observed for all three model test experiments. The benchmark scenarios for cruise ship flooding were extended to include an additional scenario (case B3), with a notable up-flooding and progressive flooding, since simple up-flooding cases were already found to be problematic in Part A1. Unfortunately, experimental data is not yet available for this particular case, but comparisons of the simulated water levels indicate similar results as in Part A1.

The final part of the benchmark considered a damaged ropax vessel, with a 2-compartment breach extending vertically up to the vehicle deck. For transient flooding in calm water, all codes could properly capture capsize and survival cases with different initial conditions.

1.4 Conclusions and recommendation

The simulation codes have developed significantly since the previous benchmark studies, organized within ITTC (International Towing Tank Conference). Most notably, with 11 organizations now participating to the FLARE benchmark, this study is much more extensive than the previous ones. This indicates a wider interest to the topic in the field, which can also be seen in that new simulation codes have been introduced.

In general, the fundamental flooding mechanisms were well captured by most of the participating codes. Also the final outcome of a flooding process, either capsize or survival, was well predicted, for both the cruise and ropax cases, but with a significant variation in the time-to-capsize. Moreover, the flooding process, especially concerning the momentum of floodwater, should be considered more carefully, and there is room for further development of the codes.

The CFD (Computational Fluid Dynamics) tools can provide valuable insight into the details of the flooding progression. However, these analyses are still computationally demanding, and thus not suitable for survivability studies, especially concerning large number of damages and complex arrangement of flooded compartments.

In order to make final conclusions on benchmark for the cruise ship model, additional model tests for the flooding scenario B3, involving also up-flooding, were considered essential. Consequently, MARIN has already planned and scheduled these tests. This new experimental data and more comprehensive analysis of the benchmark results can be included in a planned journal article, dedicated to the cruise ship flooding cases.

The following topics are considered important for future research and development of the simulation codes:

- Progressive flooding through multiple compartments, especially up-flooding, which is characteristic for grounding scenarios
- Effects of floodwater momentum on flooding progression and filling of the flooded compartments
- Drifting of the ship during flooding in beam seas
- Hydrodynamics of a flooded ship, especially roll damping
- Computational performance, which is essential when the simulation codes are used as first principle tools for survivability assessments of large passenger ships with large number of compartments

The FLARE benchmark has been a valuable study on the current capabilities and challenges of time-domain simulation of flooding progression and motions of damaged passenger ships. The results can be used to further develop the tools, and to select suitable methods for use in the other work packages of the FLARE project.

1.5 Recommendations for FLARE project

One of the objectives of this benchmark study was to provide guidance for the use of simulation tools for analyses of flooding and damaged ship motions within the FLARE framework in other work packages. Considering only the simulation tools that are available within the FLARE consortium, the following conclusions can be drawn:

- **CFD tools**: Suitable for providing detailed information for development and testing of simplified but more efficient tools. Due to the required extensive pre-processing and long computation times, CFD tools are practically unsuitable for survivability assessments with large numbers of damage scenarios.
- **PROTEUS**: It can be stated that in its current state, the more ship motions are governed by the external actions of waves, and when internal vertical water progression is not governing, the better the results are. In case the damaged ship motions are mainly

driven by internal water motions, e.g. for grounding damages, then the code is not capturing well the physical phenomena due to modelling simplifications. Also, transient flooding details for the ropax were not captured, although capsize cases were properly identified. Acceptable results can be expected for collision damages in calm water and in waves if there is no significant down-flooding and all up-flooding routes are modelled as vertical trunks.

- **NAPA**: Proper calculation of progressive flooding, but the simplified approach, with only dynamic roll motion, limits the applicability to moderate sea states. Capsize conditions for both the cruise and the ropax ships in waves were correctly captured, but the time-to-capsize tends to be too short.
- **HSVA-Rolls**: Suitable for simulation of at least damaged ropax vessels. The applied model with the shallow water equations seems to work for flooding of the vehicle deck and large open compartments. Suitability for complex progressive flooding cases with up/down-flooding typical to cruise ships has however not been tested.
  - **XMF** by MARIN: Recently, MARIN started the implementation of a new flooding module in XMF time domain simulation environment. This library replaces the FREDYN flooding module that exists for over 25 years now, but which has certain drawbacks in application. The development includes a new solver strategy. Promising results are obtained, but the benchmark results in waves show that the progressive flooding in waves and in particular the air-entrapment functionality needs further robustness. It is expected that by the end of the FLARE project the solver is well validated and applicable for complex flooding simulations in any prescribed environment.

2 INTRODUCTION

Time-domain simulation of flooding progression and motions of damaged ships is already a useful tool for studying the survivability in different scenarios. These first principle tools play an essential role in the FLARE project. Proper validation of such tools against experimental data is therefore necessary. Various simulation codes have been developed over the years, based on different approaches and implementations. Although individual validation results have been published, a large benchmark with many participants is needed to obtain insight into the capabilities and limitations of the different methods available today.

Between 2001 and 2007 several international benchmark studies on damage stability of ships were carried out, mainly organized within the International Towing Tank Conference (ITTC), Papanikolaou and Spanos (2001, 2005, 2008), van Walree and Papanikolaou (2007). The results were partly promising, but also notable problems were identified.

During the past decade, new simulation methods have been introduced, such as, Dankowski (2013), Lee (2015), Acanfora and Cirillo (2016, 2017) and Braidotti and Mauro (2019, 2020). Furthermore, also application of CFD methods have been studied, e.g. Bu and Gu (2019, 2020) and Ruth et al. (2019). In many cases, also validation results have been presented, mainly using the previous ITTC benchmark material.

Most notably, flooding simulation is more frequently being used in survivability analyses for new passenger ships. Therefore, it is essential to carry out an open benchmark study on validation and analysis of the suitability and efficiency of the available time-domain simulation tools for flooding and motions of damaged ships.

Previous benchmark studies, including main results and observations, are first recalled in chapter 3. An overview of the FLARE benchmark study and participants is given in chapter 4. Details of the benchmark cases and results are presented in the conference and journal papers, in chapters 5, 6 and 7.

3 PREVIOUS BENCHMARK STUDIES

3.1 ITTC Benchmark on the Capsizing of a Damaged Ro-Ro/Pass. Ship in Waves (2001)

The first international benchmark study on damage stability and simulation of capsizing of a damaged ship was carried out within the International Towing Tank Conference (ITTC) in 2001. The studied ship is the passenger/ro-ro vessel PRR01 and the case is a two-compartment damage, involving also the main vehicle deck. The results of the benchmark are described in detail in the public report by Papanikolaou and Spanos (2001) and ITTC (2002).

There were five participants in this benchmark:

- NTUA (National Technical University of Athens, Greece)
- SSRC (University of Strathclyde, UK)
- University of Osaka, Japan
- MARIN, The Netherlands
- Flensburger Schiffbau Gesellschaft, Germany

The damage and calculated righting lever curves in this damaged condition are reproduced in Figure 3.1. It is obvioua that there are very notable differences in the hydrostatics of the damaged ship in calm water.

The benchmark focused on the steady state after flooding. In addition to roll decay tests in calm water, also regular and irregular waves were studied. The simulation of roll decay for an intact ship was reasonably successfully calculated by all participants. However, the simulation of roll decay in the damaged condition was less successful. Also, for the calculation of the roll response amplitude operator (RAO) the results of the participants partly differed significantly.

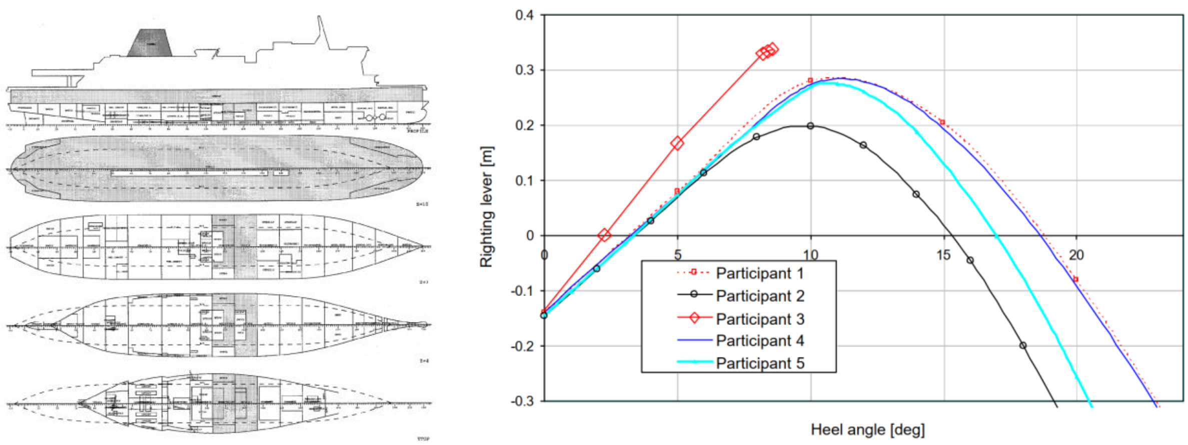


Figure 3.1 Studied damage case and comparison of righting lever curves for a damaged ship, adopted from Papanikolaou and Spanos (2001)

For the results in irregular waves, Papanikolaou and Spanos (2001) note that:

> *"A visual comparison/analysis of the numerically predicted and experimentally measured time series shows a rather unsatisfactory level of agreement between the different participants and the experiments. Indeed, none of the numerical time series match satisfactorily at least in qualitative terms the experimental values where in particular the character of the experimentally measured roll response indicates a quite distinct independence of the response components induced by the wave excitation and low-frequency response due to floodwater accumulation."*

Furthermore, Papanikolaou and Spanos (2001), conclude that:

> *"it appears necessary that a more comprehensive study should be carried out in the future to investigate the relation between the employed damping models by the benchmark study participants"*

3.2 ITTC Benchmark on Numerical Prediction of Damage Ship Stability in Waves (2005)

Based on the recommendations from the first ITTC benchmark study on capsizing of a damaged ro-ro passenger ship in waves, a more comprehensive benchmark on numerical prediction of damage ship stability in waves was organized. Details are presented in the final report in Papanikolaou and Spanos (2005) and ITTC (2005).

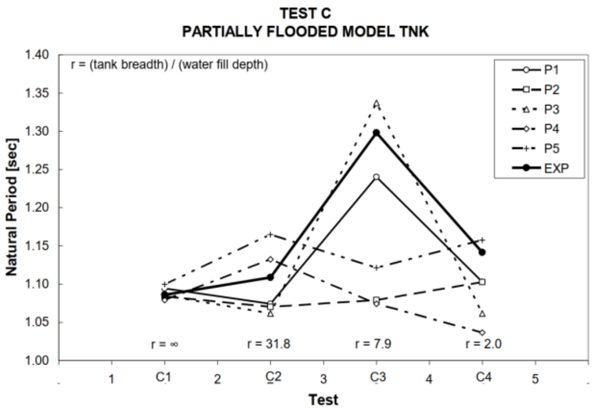
There were five participants in the benchmark, partly different ones than in the previous benchmark:

- NTUA (National Technical University of Athens, Greece)
- Korea Research Institute of Ships and Ocean Engineering, KRISO
- Instituto Superior Tecnico, University of Lisbon, Portugal
- MARIN, The Netherlands
- SSRC (University of Strathclyde, UK)

The study consisted of four separate tasks, using test data from three different model tests:

- Task A: free roll motion of an intact passenger/ro-ro model PRR01
- Task B: free roll motion of PRR01 in damaged condition (same damage case as in the previous benchmark)
- Task C: free roll motion of a tanker model TNK with a large partially filled tank, no connection to the sea, presented in de Kat (2000)
- Task D: transient flooding in calm water with the passenger/ro-ro PRR02, van't Veer (2001), with flooding of an engine room compartment, including also a cross-flooding duct

Some examples of the results are shown in Figure 3.2.



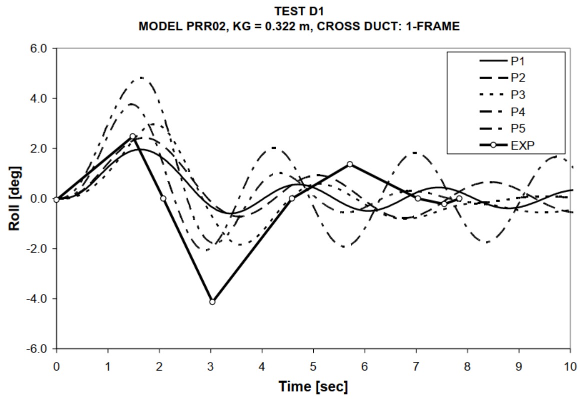


Figure 3.2 Examples of benchmark results: natural roll period for tanker with partially filled large tank (left) and comparison of roll motion in the transient flooding case with PRR02 (right), figures adopted from Papanikolaou and Spanos (2005); note that experimental data contains only a small set of points, not the full time history for PRR02 (right).

The observed deviations between the numerical methods in the damage condition were considered to result from the different approaches to the effects of floodwater on ship motions. The numerical methods assuming a horizontal waterplane in flooded compartments could not capture the floodwater dynamics properly, whereas methods considering moving water surfaces demonstrated satisfactory sensitivity with respect to the floodwater effects. Papanikolaou and Spanos (2005) also concluded that:

> *"Special focus should be given on the semi-empirical weir coefficient as well as the implementation of the flooding model."*

3.3 ITTC Benchmark on Time-to-Flood – Phase 1 (2007)

The next benchmark study within the ITTC focused on the calculation of progressive flooding in the compartments of the damaged ship. A box-shaped barge, with a nominal scale of 1:10, was used in this study. Details of the model and the tests have been presented in Ruponen et al. (2007). All cases were tested in calm water, and also air compression in the flooded compartments were measured.

There were five participants in this benchmark, partly different ones than in the previous benchmark:

- Helsinki University of Technology, Finland (with code NAPA)
- NTUA (National Technical University of Athens, Greece)
- MARIN, The Netherlands
- Safety at Sea, UK (with code PROTEUS)
- Maritime and Ocean Engineering Research Institute (MOERI), Republic of Korea

The results of the benchmark were presented by van Walree and Papanikolaou (2007), with anonymous codes. The model test data included experimentally evaluated discharge coefficients for all openings in the model. However, it appeared that some of the participating codes used fixed discharge coefficient (0.6). However, the analysis of the results clearly indicates that this alone does not explain the notable differences in the predicted water levels. Some examples are shown in Figure 3.3 and Figure 3.4. Most notably, van Walree and Papanikolaou (2007) summarise that:

> *"the steady state condition of all tests is reasonably well predicted by the codes. The prediction of the flooding rates and transient phenomena is less satisfactory."*

Furthermore, they note the need to continue the benchmark with more complex internal geometries in calm water, and for seaway conditions.

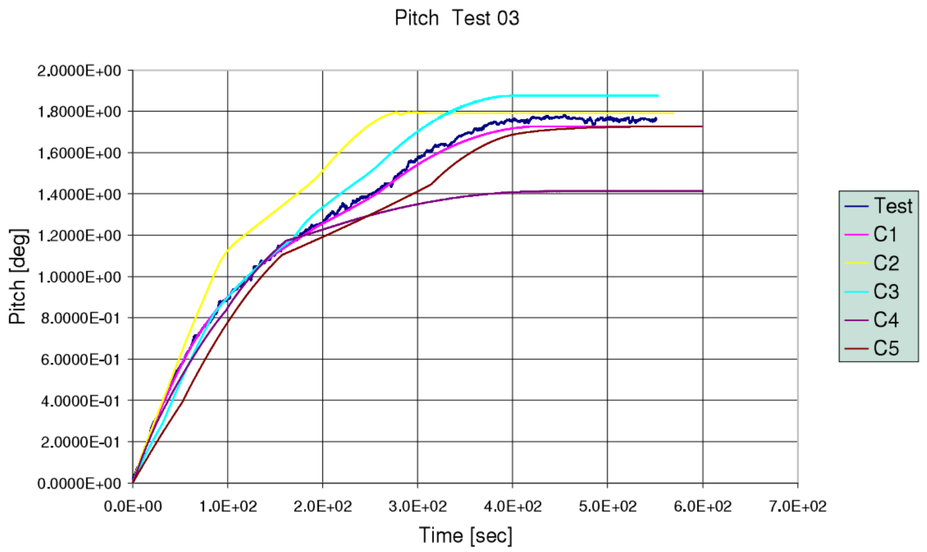


Figure 3.3 Example of experimental and numerical results for pitch/trim angle, adopted from van Walree and Papanikolaou (2007)

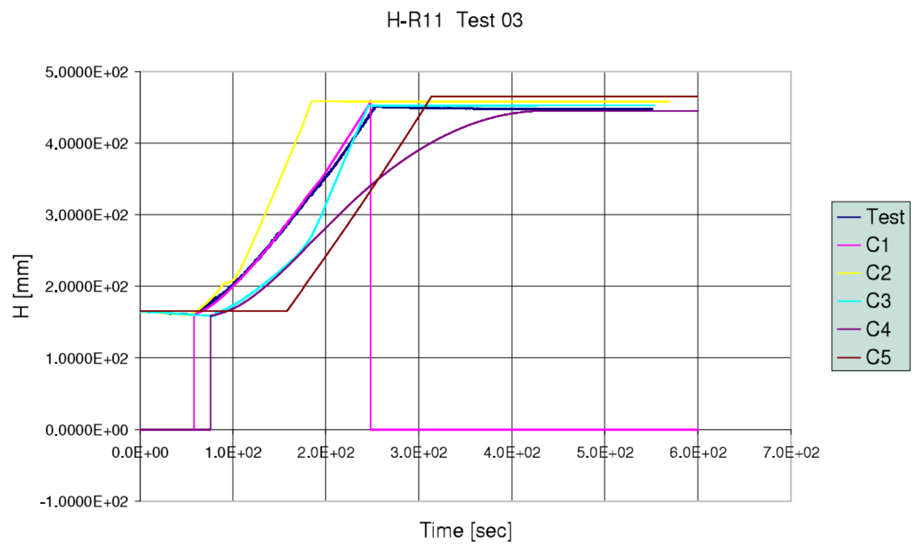


Figure 3.4 Example of experimental and numerical results for water level height in a flooded room, adopted from van Walree and Papanikolaou (2007)

3.4 ITTC Benchmark on Time-to-Flood – Phase 2 (2008)

The ITTC benchmark study on time-to-flood continued with a second phase with a large passenger ship design. However, this study was not a proper benchmark since no experimental data was available. Moreover, only two organizations MARIN and SSRC (University of Strathclyde) participated. The results are reported by van Walree and Carette (2008).

The two participating codes produced quite different results. An example is shown in Figure 3.5. Proper conclusions could not be drawn since experimental data was not available. However, the observed differences in the results clearly indicate the need for further validation and benchmark studies.

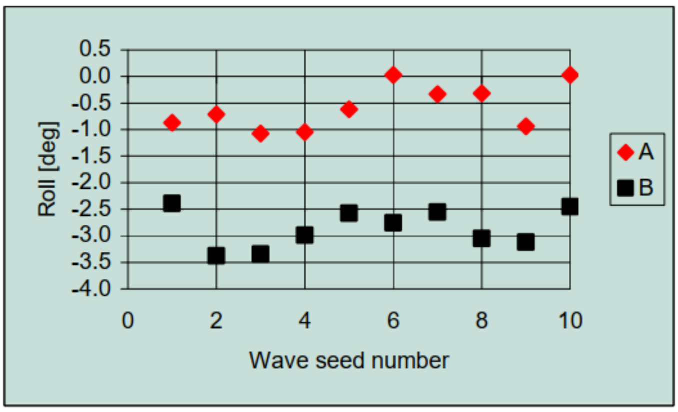


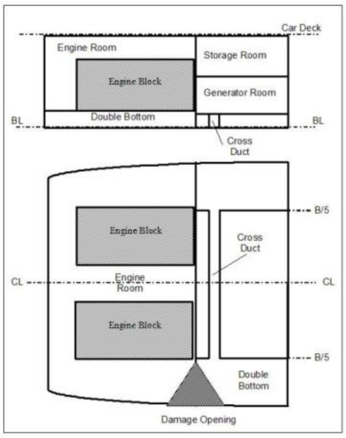
Figure 3.5 Example of mean heel angles with the two codes A and B in damage case D2 with significant wave height of 4 m, adopted van Walree and Carette (2008)

3.5 SAFEDOR Benchmark (2008)

An additional benchmark study was carried out within the EU FP6 project SAFEDOOR. A summary was presented by Papanikolaou and Spanos (2008). Initially, there were 6 participants, but results were presented only for 4 participants:

- NTUA (National Technical University of Athens, Greece)
- SSRC (University of Strathclyde, UK)
- MARIN (The Netherlands)
- IST (Technical University of Lisbon, Portugal)

The test case is the passenger/ro-ro ferry PRR02 from the project HARDER. The model test results have been reported by van't Veer (2001). The case is the same as Task D in the second ITTC benchmark study in 2005. The damage case and some example results are presented in Figure 3.6. The results from the codes were reported anonymously in the study.



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

Figure 3.6 Investigated damage case in the SAFEDOR benchmark and the results for the survival boundary significant wave height

The main analysis focuses on the survival boundary, i.e. a significant wave height below which no capsize occurred during simulations. However, Papanikolaou and Spanos (2008) point out an interesting observation:

> *"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"*

This indicates that comparison of a survival boundary is not a sufficient quantity for benchmarking. Instead, the details of the simulated flooding process and damaged ship motions need to be compared.

3.6 Summary of recommendations

Although several model tests have been done with various different ship models, there is not enough publicly available model test data for proper benchmarking of numerical methods. Most of the previous benchmarks have used old model tests data for two passenger/ro-ro ferries (PRR01 and PRR02) from the EU funded research projects HARDER and NEREUS. In addition, Helsinki University of Technology (currently Aalto University) in Finland, has published details and test results for progressive flooding of a box-shaped barge. These tests have been used for validation of several numerical methods during the past decade.

Even more concerning from a code validation point of view, is that there is no publicly available data for real ship geometries with extensive flooding, presenting typical characteristics of transient and progressive flooding, both in calm water and in waves.

The results of the previous benchmark studies show a notable deviation in the results, both for the dynamic roll motion of a flooded ship in waves and for progression of floodwater in relatively simple internal layout of compartments. Consequently, new benchmark studies need to also include the flooding fundamentals, such as up and down flooding and progressive flooding in a complex arrangement with a fixed floating position in calm water.

It has been over a decade since the last benchmark study, and old simulation codes have been improved and new ones have been introduced. In addition to this, the computing capacity has increased a lot, enabling detailed calculations also for large ships and larger number of damage scenarios. Therefore, one of the objectives of the Horizon 2020 project FLARE is to get an insight into the currently available simulation tools for flooding and damage stability of ships, both within the consortium and globally. Based on the previous benchmark results, it is essential to arrange an extensive study, with focus on:

- Flooding mechanisms, including breach and internal openings
- Effects of (regular) wave on flooding with a fixed floating position
- Inertia and roll damping characteristics of a flooded ship
- Flooding and damaged ship motions both in calm water and in waves, including capsize cases during both transient flooding, and progressive flooding stages
- Effects of water on the vehicle deck for a damaged ro-ro passenger vessel

4 FLARE BENCHMARK OVERVIEW

4.1 Objectives and Structure

Previous benchmarks have focused on flooding and motions of damaged ships, both in calm water and in waves. Ypma and Turner (2019) point out the importance of the coupling between flooding and ship motions in validation of flooding simulation codes. Consequently, the main objective of this new benchmark study is to obtain insight into both:

1) accuracy and performance of available tools in modelling typical flooding characteristics, especially for passenger ships, and
2) coupling of the flooding process and damaged ship dynamics in both calm water and in waves.

In addition, to flooding tests in both calm water and in waves, also fundamental flooding mechanisms in a controlled environment need to be included. Therefore, the benchmark study consists of three separate parts, each with different test cases:

- Benchmark Part A: Flooding fundamentals
    - up-flooding
    - down-flooding
    - extensive flooding on a deck of a cruise ship
- Benchmark Part B: Cruise ship flooding
    - transient flooding in calm water
    - transient and progressive flooding in waves
    - progressive flooding in calm water
- Benchmark Part C: Ropax ship flooding
    - transient flooding in calm water
    - transient flooding in waves
    - gradual flooding and capsize in waves

The participants had the opportunity to choose which parts of the benchmark they wanted to contribute to, based on the assumptions and limitations of the applied codes. In order to enable a more detailed analysis of the results, Part A was recommended for everyone.

4.2 Schedule

In addition to the FLARE project partners, also other experts outside the consortium were invited to this benchmark study. An early invitation was sent to selected flooding and damage stability experts in December 2019, and the structure of the benchmark was released in May 2020. Details about the benchmark cases, including geometry, were later shared to the confirmed participants. The timeline of the benchmark is presented in Table 4.1. Model tests were carried out at MARIN and HSVA during the spring and summer 2020. The COVID-19 situation, and consequent remote working, unfortunately had an adverse effect on the original schedule. In addition, some further model tests were required, and therefore the deadline of the benchmark had to be extended.

Table 4.1 Benchmark timeline

12/2019	Early invitation to potential external participants
05/2020	Invitations, benchmark structure released with details on Part A
07/2020	Part A details and videos distributed & geometry of Part B released
10/2020	Initial results on Part A received and updated material on Parts B & C distributed
19.11.2020	Online workshop between participants on preliminary results of Part A
12/2020	Comparison of hydrostatics, test cases for Part C distributed
1/2021	Preliminary results for Part C and clarifications to the geometry in Part B
26.3.2021	Online workshop on preliminary results of Part C (ropax)
13.4.2021	Online workshop on preliminary results of Parts B (cruise ship)
6/2021	STAB&S conference paper on results from Part A
3/2022	Journal paper on results from Part C (Ropax)
11/2022	Journal paper on results from Part B (cruise ship)

4.3 Material

Model tests for the fundamental flooding cases and cruise ship were conducted by MARIN and tests with the ropax vessel by HSVA. The experiments formed the FLARE WP4.2 and the relevant experimental results[1] were shared beforehand to all confirmed participants, in order to enable fair and equal benchmarking conditions to all. In general, the following data was provided:

- 3D geometry (Rhino 3dm and/or Autodesk dwg files)
- Hull form geometry in IGES format (Parts B & C)
- 2D drawings in dxf/dwg format
- Locations of level sensors, coordinate convention, etc.
- Overview of measurements, containing measured water levels (Part A) and roll angle (Parts B & C) in graphical format
- Videos on tests for Parts A and B

Hydrostatic and volumetric data were collected and checked beforehand, in order to find out possible modelling errors before conducting the calculations. The benchmark instructions were frequently updated.

[1] Graphs of measured data and videos

4.4 Participants

In total 11 organizations contributed to this benchmark study. Most of the codes are in-house tools, developed at a university or a research institute, with NAPA and the CFD software being the exceptions. The participants for each of the benchmark parts and tests are summarized in Table 4.2.

Table 4.2 Summary of benchmark participants

Organization	Code	Type	A1	A2	A3	B1	B2	B3	C1	C2	C3
BROO	PROTEUS	in-house	✓	✓	✓	–	–	–	✓	✓	✓
CSSRC	wDamstab	in-house	✓	✓	✓	✓	✓	✓	–	–	–
CSSRC	StarCCM+	commercial	–	✓	✓	–	–	–	–	–	–
DNV	OpenFOAM	commercial	–	✓	✓	–	–	✓	–	–	–
HSVA	HSVA-ROLLS	in-house	–	–	✓	–	–	–	✓	✓	✓
KRISO	SMTP	in-house	✓	✓	✓	✓	✓	✓	✓	✓	✓
MARIN	XMF	in-house	✓	✓	✓	✓	✓	✓	✓	✓	✓
MARIN	ComFLOW	in-house	✓	✓	✓	–	–	–	–	–	–
MSRC	PROTEUS	in-house	✓	✓	✓	✓	✓	✓	✓	✓	✓
NAPA	NAPA	commercial	✓	✓	✓	✓	✓	✓	✓	✓	–
UAK	E4 flooding	in-house	✓	✓	✓	✓	–	✓	✓	–	–
UNITS	LDAE	in-house	✓	✓	✓	✓	–	✓	–	–	–
UNINA	FloodW	in-house	✓	✓	–	–	–	–	✓	✓	–

5 PART A: FLOODING FUNDAMENTALS

Ruponen, P., van Basten Batemburg, R., Bandringa, H., Bu, S., Dankowski, H., Lee, G. J., ... & van't Veer, R. (2021, June). Benchmark study on simulation of flooding progression. In 1st International Conference on the Stability and Safety of Ships and Ocean Vehicles.

Benchmark Study on Simulation of Flooding Progression

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ABSTRACT

Several time-domain flooding simulation codes have been developed and improved over the past decade, after the previous international benchmark study in 2007. Consequently, within the ongoing EU Horizon 2020 project FLARE, a new benchmark study was organized. The first part of this study focuses on different fundamental flooding mechanisms, characteristic for progressive flooding in damaged passenger ships, including up- and down-flooding, as well as extensive horizontal flooding along a typical deck layout. Numerical results are carefully compared against measured water levels at different locations. Similarities and differences between the codes and applied modelling practices are discussed, and the reasons for observed deviations are analysed.

Keywords: *progressive flooding; simulation; benchmark; validation; damage stability*

1. INTRODUCTION

Development of time-domain simulation methods for flooding and motions of damaged ships has enabled advanced survivability assessments, especially for passenger ships. Over the past two decades, several codes have been developed. Mostly, these methods are based on hydraulic models, with flooding progression calculated by using Bernoulli's equation. Recently also computational fluid dynamics (CFD) tools have been applied, as presented e.g. by Ruth et al. (2019) and Bu and Gu (2019, 2020).

Earlier international benchmark studies have been organized within the International Towing Tank Conference (ITTC). The first two concentrated on flooded ship motions in waves, Papanikolaou and Spanos (2001, 2005), while the third one, van Walree and Papanikolaou (2007), focused on progressive flooding with experimental data on model tests with a box-shaped barge, Ruponen et al. (2007), concluding that prediction of the flooding rates and transient phenomena is not yet satisfactory in general. Since then, the same box-model case has also been used for validation of several new simulation methods, including CFD tools.

Based on the recommendations of the previous benchmarks and the fact that several new codes have been introduced, a new open benchmark, with extensive set of different flooding cases, was considered essential. The FLARE benchmark consists of three separate parts. In this paper, the results of the first part are presented, focusing of various typical flooding mechanisms. The latter parts will deal with cruise and ropax ships, focusing on transient and progressive flooding in both calm water and in waves, and the findings will be presented later.

2. BENCHMARK STRUCTURE

2.1 Test Cases

The coupling between the flooding process and damaged ship motions is extremely complex, especially when the damage occurs in waves. Figure 1 illustrates the couplings between the flooding and damaged ship motions in waves. The whole FLARE benchmark is divided into separate parts, eventually, covering the whole process, including flooding of a floating ship both in calm water and in irregular waves.

Recently, Ypma and Turner (2019) have presented an approach to validation of flooding simulation considering also captive model tests, and a somewhat similar methodology has been adopted, with the first part of the benchmark focusing on the accuracy and performance of the simulation tools for various typical flooding mechanisms. Simplified geometries and flooding scenarios are used in captive model tests, so that the floating position of the model is fixed. The follow-up studies, with focus on transient and progressive flooding in both calm water and in waves, will be published later, once all results have been analysed.

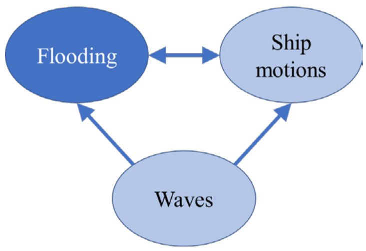

Figure 1 Couplings between flooding, ship motions and waves, the present study focuses on flooding

In the first part of the benchmark study three different flooding scenarios are investigated:

- Up-flooding in a box model with two compartments
- Down-flooding in the same box model with different openings
- Extensive progressive flooding on a typical deck layout of a cruise ship

2.2 Participants

In total 11 organizations provided numerical results for the benchmark study, as summarized in Table 1. Some participants used more than one code. In addition to the FLARE consortium, also external participants were invited, based on recent publications on the topic. Most of the codes are based on hydraulic models using Bernoulli’s equation. CSSRC, DNV and MARIN used CFD tools, based on volume of fluid (VOF) method, and HSVA applied shallow water equations (SWE) for flooding along the deck, combined with Bernoulli-based calculation of flow through the internal openings. A short description of each code, with key references, is presented in Table 2.

Table 1. Overview of the benchmark study participants

Participant			Code	up flooding	down flooding	deck flooding
BROO	Brooks Bell	UK	PROTEUS	✓	✓	✓
CSSRC	China Ship Scientific Research Center	China	Star-CCM+	–	✓	✓
			wDamstab	✓	✓	✓
DNV	DNV	Norway	OpenFOAM	–	✓	✓
HSVA	Hamburgische Schiffbau-Versuchsanstalt GmbH	Germany	HSVA-Rolls	–	–	✓
KRISO	Korea Research Institute of Ships & Ocean Engineering	Rep. of Korea	SMTP	✓	✓	✓
MARIN	Maritime Research Institute Netherlands	Netherlands	XMF	✓	✓	✓
			ComFLOW	✓	✓	✓
MSRC	Maritime Safety Research Center	UK	PROTEUS	✓	✓	✓
NAPA	NAPA	Finland	NAPA	✓	✓	✓
UAK	University of Applied Science Kiel	Germany	E4 flooding	✓	✓	✓
UNINA	University of Naples Federico II	Italy	FloodW	✓	✓	–
UNITS	University of Trieste	Italy	LDAE	✓	✓	✓

Table 2. Summary of the simulation code features

BROO & MSRC	In-house code **PROTEUS** owned by Safety at Sea Ltd, a subsidiary of BROO. Originally developed at University of Strathclyde (MSRC). Flooding rates are calculated applying Bernoulli's equation with a hard-coded discharge coefficient of 0.6. Floodwater motions are modelled as a pendulum (Free-Mass in Potential Surface). Resolution of a multi-body multi-degrees of freedom system, with 6-DOF for ship motion and 3-DOF per each flooded compartment. Regular and irregular waves. Froude-Krylov and restoring forces integrated up to the instantaneous wave elevation. Radiation and diffraction are derived from 2D strip theory. Hydrodynamic coefficients vary with the attitude of the ship during the flooding process (heave, heel and trim). Details presented in Jasionowski (2001).
CSSRC CFD	Commercial CFD software **Star-CCM+** is used, with volume of fluid (VOF) approach for floodwater. Six degrees of freedom ship motions can be considered. Both regular and irregular waves can be considered by instantaneous integral of pressure along the wet surface. Details of the method are presented in Bu and Gu (2019, 2020). For decks and bulkheads, also "slip" boundary condition was applied since plexiglass surfaces of the models are smooth. Simulations were done also with the normal "no-slip" condition.
CSSRC Meth1	In-house code **wDamstab**. Bernoulli for flooding rates with horizontal surface for floodwater. Four degrees of freedom (Sway-heave-roll-pitch) can be considered. Ship motion is calculated based on the potential flow theory (STF). regular waves, Froude-Krylov and hydrostatic forces can be calculated based on the integration of pressure along instantaneous wet surface.
DNV	**OpenFOAM** CFD toolbox is used. The air and water flows are resolved by a finite volumes formulation to solve the Reynolds-Averaged Navier-Stokes (RANS) equations. For details about using CFD in flooding analyses, see Ruth et al. (2019).
HSVA	In-house version code the Rolls code, **HSVA-Rolls**. The ship roll motion and surge are solved with ordinary differential equations using nonlinear hydrostatics in waves (NAPA based) + linear strip theory for wave excitation and for RAOs (response amplitude operators) of other four Degrees of Freedom (DOF); altogether 2 non-linear DOF + 4 linear DOF solved in time domain. Flooding rates are calculated with Bernoulli, using empirical discharge coefficients. Floodwater is treated either with a pendulum model, or with shallow-water-equations (SWE).
KRISO	In-house code **SMTP**. Flooding rates calculated with Bernoulli, using empirical discharge coefficients. Floodwater has either horizontal surface or pendulum model appropriate at each compartment. The program provides several kinds of types for compartments and openings, and their numbers are unlimited. Ship motions are calculated by 6-DOF non-linear equations in time-domain, the hydrodynamic forces are calculated by strip method. Details presented in Lee (2015).
MARIN	The Extensible Modeling Framework (XMF) is a software toolkit on which all MARIN's fast-time and real-time simulation software is based applying Newtonian dynamics, of which Fredyn and ANySim are known examples. XMF is recently extended with a flooding module library (XHL) based on Bernoulli's equation with empirical discharge coefficients, using generic 3D defined floodable objects. A graph-solver technique is utilized to capture the complexity of entrapped air in compartments and for hydrostatic pressure-corrections from fully flooded compartments.

MARIN CFD	The CFD code **ComFLOW** is a Cartesian (cut cell) grid-based Volume of Fluid (VOF) CFD solver, using a staggered finite-volume discretization of the Navier-Stokes equations. Geometrically reconstruction of the free surface interface. Automatic grid refinement by means of surface and object tracking criterion and explicitly integrating the free surface in time using a variable time step. Details are given by Veldman et al. (2014) and Bandringa et al. (2020).
NAPA	Commercial software **NAPA** is used. The flow rates calculated from Bernoulli's equation, with user-defined discharge coefficient for each opening. Horizontal free surface assumed in all flooded rooms. Pressure-correction algorithm applied to solve the governing equations (continuity and Bernoulli). Ship motions are either fully quasi-static (heel, trim & draft) or with dynamic roll motion. Effect of waves (regular or irregular) on flooding can be considered. Details are presented in Ruponen (2007, 2014).
UAK	In-house code **E4 Flooding Method**, with flooding calculated by using Bernoulli's equation with horizontal surface and flooding path modelled as directed graphs. Ship motions either 3-DOF quasi-static or 6-DOF dynamic, with support for regular waves and other effects e.g. interaction with cargo and seabed, Dankowski and Dilger (2013), conditional openings and leakage, Dankowski et al. (2014) and cargo shift. Details of the simulation method are presented in Dankowski (2013) and Dankowski and Krüger (2015).
UNINA	In-house tool **FloodW**, coded in Matlab-Simulink. Flooding rates are calculated based on Bernoulli's equation with empirical discharge coefficients. Floodwater is treated as a non-horizontal flat surface, in agreement with the pendulum model. Regular and irregular wave effects are modelled, accounting for all pertinent nonlinearities. Details are presented in Acanfora and Cirillo (2016, 2017) and Acanfora et al. (2019).
UNITS	In-house code **LDAE**. The flooding process is modelled using a DAE system based on the Bernoulli equation, which is linearized and solved analytically. A flat horizontal free surface is assumed for the sea and waterplanes inside flooded rooms. An adaptive integration time step, based on floodwater level derivatives, is adopted. The model does not include dynamic ship motions. Only quasi-steady change of heel, trim and sinkage is considered. Details in Braidotti and Mauro (2019, 2020).

2.3 Benchmark Methodology

Details on the geometry of the models and some videos on the tests were provided in advance to all participants. In addition, some measurement results on the water levels were shared in graphical format, to ensure fair and equal conditions between the participants.

2.4 Discharge Coefficients

Most of the participating codes use a hydraulic model, based on Bernoulli's theorem, for calculation of the flow rates through the openings. This approach is computationally efficient, when compared to the CFD tools, but it requires semi-empirical discharge coefficients for modelling the flow losses in the openings. For full-scale simulations, the "industry standard" value of 0.6 has proven to be reasonably accurate, Ruponen et al. (2010). Although the generally applied value 0.6 is valid for most cases, it is not realistic e.g. for cross-flooding ducts and pipes.

Since frictional losses are proportional to the Reynolds number, somewhat larger discharge coefficient is characteristic for model-scale openings, Idel'chik (1960). This has also been observed in the previous experimental studies, e.g. Katayama and Ikeda (2005) and Ruponen et al. (2007). Consequently, all participants using Bernoulli's theorem, were recommended to use discharge coefficients given in Table 3. The values were obtained from analysis of dedicated tests carried out at MARIN for different openings.

Most codes include a possibility for manual definition of discharge coefficients for each opening. However, PROTEUS, used by both BROO and MSRC, has a hard-coded discharge coefficient 0.6. In view of a proper benchmark comparison, it was necessary to compensate this by adjusting other opening characteristics, in order to achieve the same effect on flooding progression. The alignment was required BROO modelled the effect by considering the openings as leaking doors with a large leakage area ratio, while MSRC modified the opening areas.

Table 3 Recommended discharge coefficients based on model tests

Case	Opening	Cd
Up & Down	80 mm × 80 mm	0.65
Up	80 mm × 40 mm	0.65
Down	40 mm × 40 mm	0.70
Deck	Narrow (width < 30 mm)	0.73
Deck	Wide (width ≥ 30 mm)	0.70
Deck	Breach	0.65

3. UP-FLOODING

Calculation of flooding progression through a compartment that is filled-up with water is known to be challenging for simulation codes since the effective hydrostatic pressure is higher than the top of the filled-up compartment. Therefore, the first benchmark case focuses on up-flooding with extremely simple geometry.

The box-shaped model has two sub-compartments that are separated by a deck with a 40 mm × 80 mm hole in the middle. There is a breach hole of size 80 mm × 80 mm in the side of the lower compartment. Draft is constant 400 mm. A sketch of the test case is presented in Figure 2.

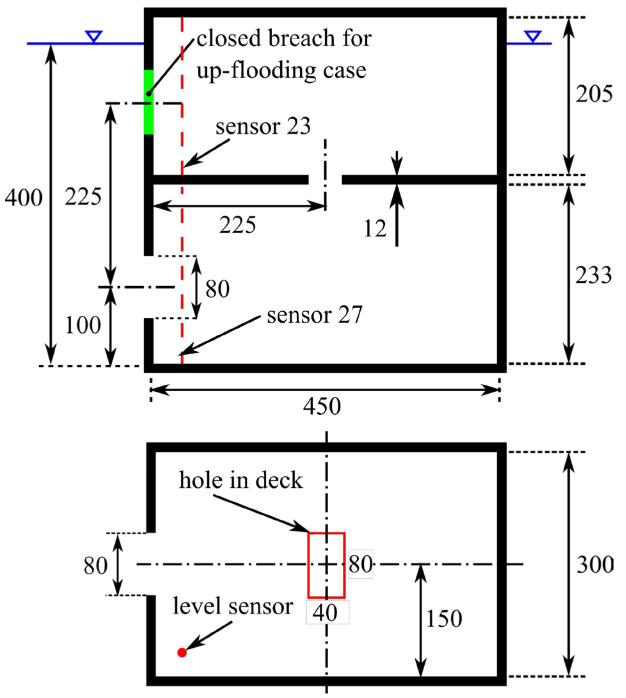

Figure 2 Box model arrangement and dimensions for the up-flooding case

The lower compartment is vented through a pipe and the upper compartment has an open top and is thus vented as well. A snapshot from ComFLOW simulation by MARIN, visualizing also the ventilation arrangement, is shown in Figure 3 below.

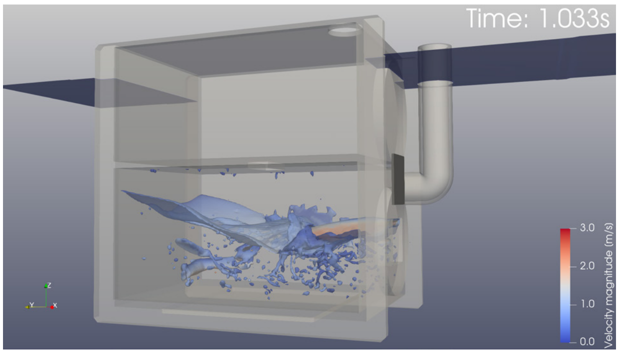

Figure 3 Snapshot of ComFLOW simulation of up-flooding by MARIN

Most codes can predict the flooding progression rather well, and hence each code is compared separately against the measured water levels in Figure 4. In general, the rising of the water level in the lower compartment during the first 3.5 s is slightly underestimated. For the upper compartment, the simulation results match well with measurement. Only the code PROTEUS, used by both BROO and MSRC, predicts much slower up-flooding through the fully flooded lower compartment. Based on analysis by MSRC, this is a problem in core level implementation, and can currently be overcome only by artificial changes to geometry to avoid up-flooding through a completely filled-up room.

Eventually, only MARIN provided CFD results for this case, showing very good correlation with the measurements. CFD captures the fluctuations in the water levels, but the general development is the same as with Bernoulli-based codes.

4. DOWN-FLOODING

Like up-flooding, also down-flooding is a fundamental flooding process that is very typical, especially in case of extensive progressive flooding in passenger ships. Therefore, the second part of the benchmark focuses on simulation of this simple flooding mechanism.

The compartment geometry is the same as in the up-flooding case, Figure 2, but the breach opening (size 80 mm × 80 mm) is now located in the upper compartment and the hole in the deck is smaller, 40 mm × 40 mm.

Most codes can accurately predict the increase of the water level in the upper compartment. In general, the down-flooding rate is slightly under-estimated, Figure 5. The small increase in the water level in the upper compartment when the lower compartment is filled-up is also captured.

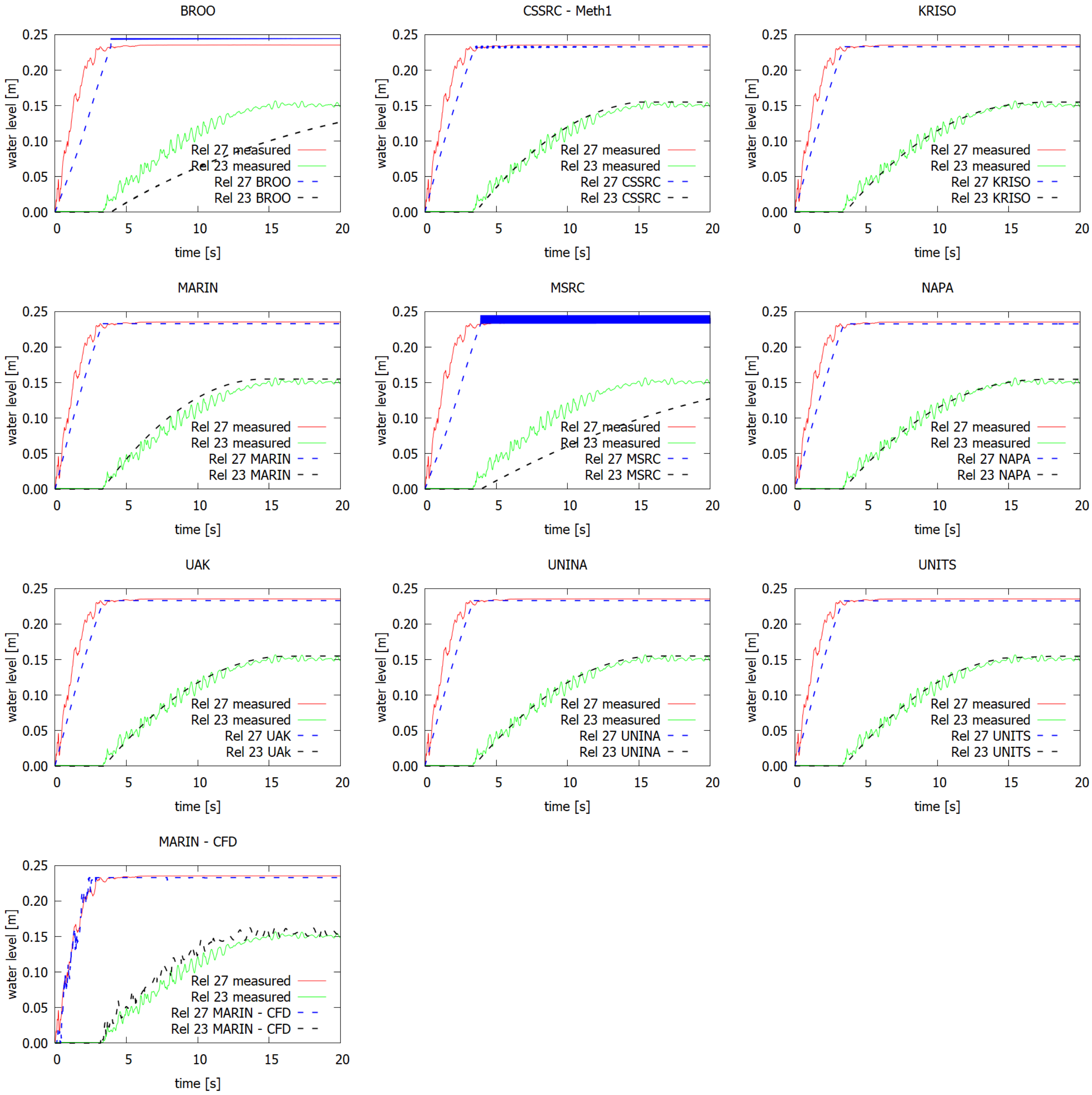

Figure 4 Comparison of water levels in the up-flooding case at Rel 27 in the lower compartment and Rel 23 in the upper compartment

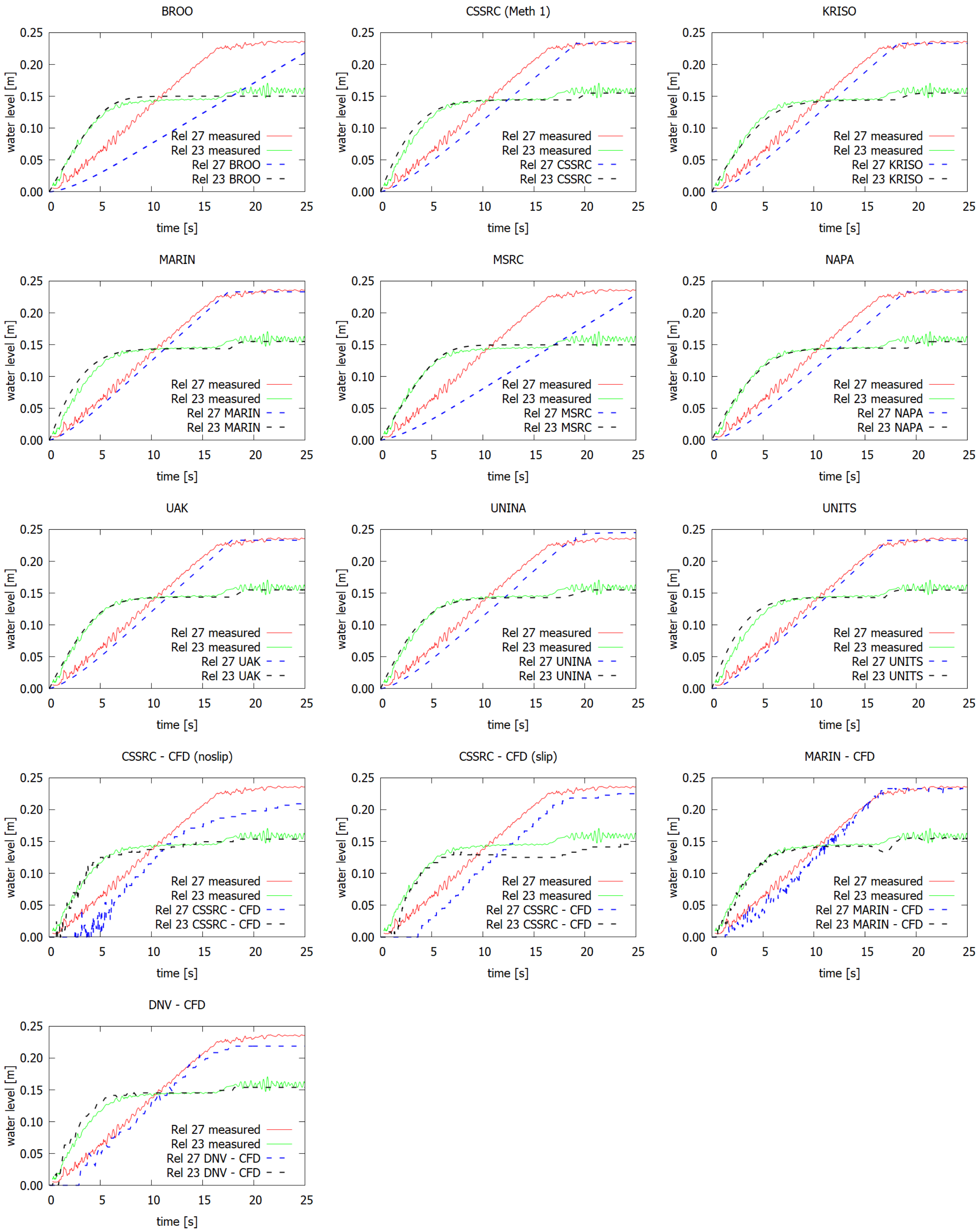

Figure 5 Comparison of water levels in the down-flooding case

All simulation codes with a hydraulic Bernoulli-based flooding model provide good results, except PROTEUS, used by BROO and MSRC. This code can predict the flooding of the upper compartment, but the down-flooding rate is seriously underestimated. Similar problems are not encountered with the other Bernoulli-based simulation codes. According to the code analysis by MSRC, this results from a hard-coded ramp function for down-flooding openings that unrealistically reduces the flow rate.

With CFD methods "no-slip", i.e. wall condition is normally used for decks and bulkheads. Since in the physical model the plexiglass surfaces are much smoother than the steel structures in full-scale ship, CSSRC decided to study separately also "slip" condition, i.e. a perfectly smooth surface, considering only the normal pressure without tangential force. The "no-slip" condition results in better match with the measurements, indicating the frictional effects on the surfaces are notable. Furthermore, CSSRC applied Realizable $k-\varepsilon$ two-layer turbulence model. DNV and MARIN considered laminar flow, which seems to provide more realistic results, at least in model scale. The beginning of the down-flooding is visualized in Figure 6 from the OpenFOAM simulation by DNV.

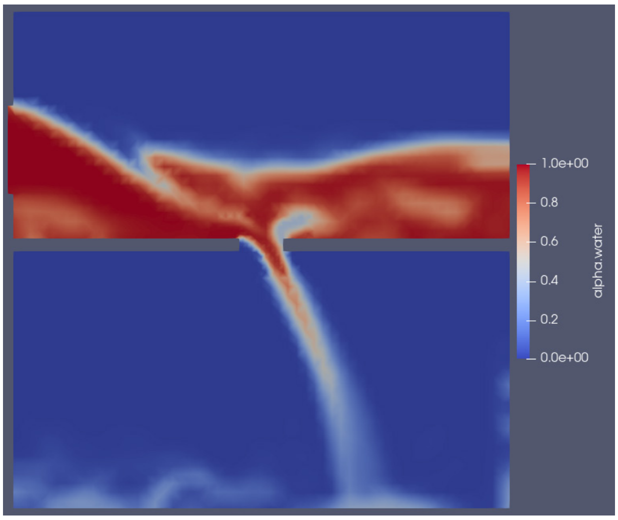

Figure 6 Visualization of the beginning of the down-flooding at 2.0 s in simulation by DNV

5. DECK FLOODING

The third case considers extensive progressive flooding along a typical deck layout of a cruise ship, including a long central service corridor, Figure 7. The scale of the model is 1:60, and the draft of the model is constant 0.03 m above deck level (in model scale). The breach on the side of one compartment is opened instantly, causing the flooding of the deck. For Bernoulli-based codes, a common modelling practice for the corridor was adopted, by dividing the long corridor into five adjacent rooms with division at the locations of the partial bulkheads. A discharge coefficient 1.0, i.e. no flow losses, was applied for these artificial openings.

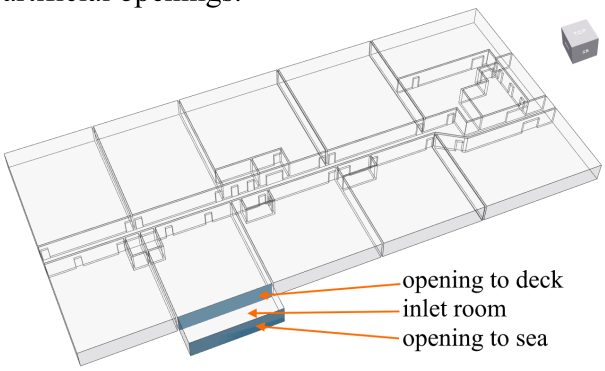

Figure 7 Arrangement for deck flooding case

HSVA applied Bernoulli's equation for real physical openings only, and the deck was divided into a grid of 38 × 78 cells for solution of the shallow water equations. CSSRC used a grid of 1 080 000 cells with realizable $k-\varepsilon$ two-layer turbulence model. Moreover, both slip and no-slip boundary conditions for the decks and bulkheads were applied separately. DNV used a grid of 165 000 cells with laminar flow model, while the MARIN CFD simulation was based on a local refined grid, solving between 505 186 and 1 196 604 cells

Simulation results are compared to measured water levels at various locations on the deck, Figure 8. Results are presented in Figures 9 – 13. Excluding the CFD codes, the participants performed calculations in full scale, but all results are presented in model scale for consistency.

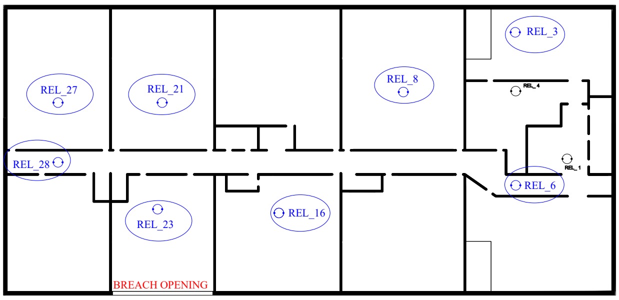

Figure 8 Locations of selected water level sensors

The breached room is flooded rapidly, with a clear decaying wave, sensor REL 23, that is captured only by the CFD and SWE codes, Figure 9. Floodwater progresses rapidly along the long corridor. Consequently, flooding to the rooms along the corridor, e.g. at REL 16 in Figure 10, is initially slow, but after about 45 s water level starts to increase more rapidly. The CFD tools by CSSRC, DNV and MARIN, as well as the SWE simulation by HSVA, capture this phenomenon rather well. This behaviour is even more pronounced at sensor REL 8, Figure 11, where the flooding of the room from the corridor is notably delayed. This is properly predicted only by the CFD codes and by the hydraulic model of KRISO.

In general, the Bernoulli-based codes predict much faster flooding of these compartments. Despite of the unified modelling principles, the scatter of the results is very wide. The code by KRISO provides very good results, likely due to the newly implemented “corridor room model” that considers the momentum of the flow along the long corridor. The details of this new feature have not yet been published by KRISO.

Water elevation at the aft end of the corridor, sensor REL 28, is predicted rather well by the simulation codes, Figure 12. However, the fluctuations in the beginning of flooding are captured only by the CFD and SWE methods.

The sensor REL 3 is furthest away from the breach in the forward part of the deck. The trend is well captured by all codes, but the variation in the results is notable, Figure 13.

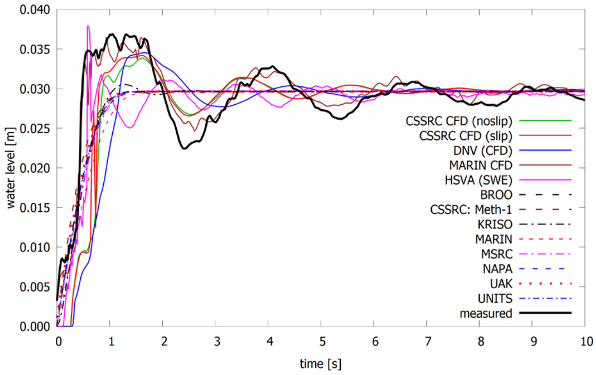

Figure 9 Water level in the breached room at sensor REL 23

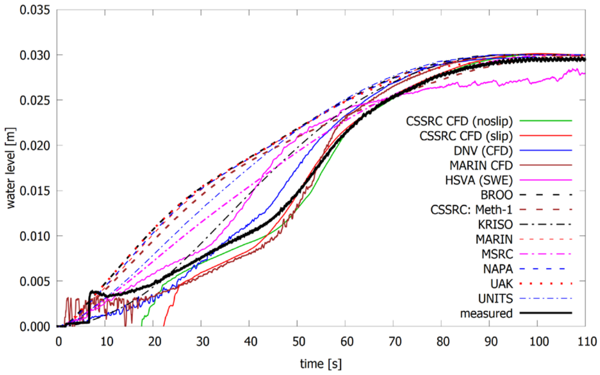

Figure 10 Water level at REL 16 in a room at the middle of the corridor

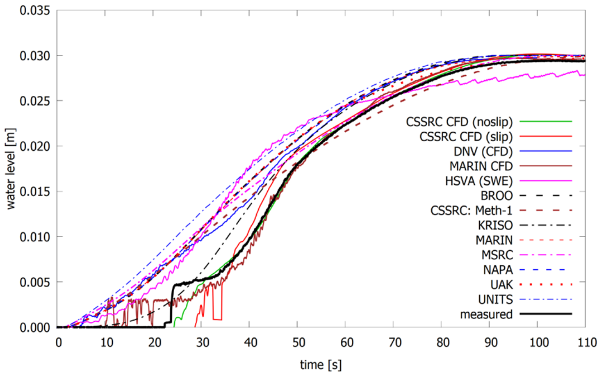

Figure 11 Water level at REL 8, in a room along the corridor

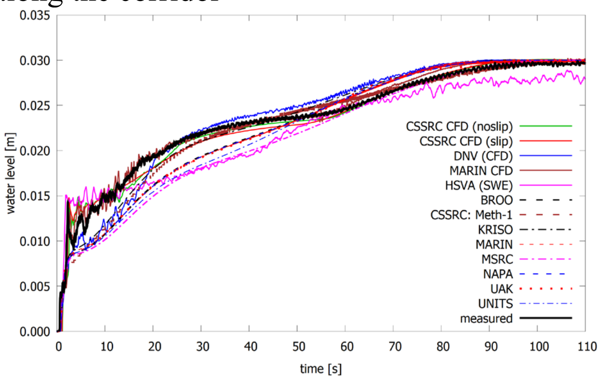

Figure 12 Water level at REL 28 located in the aft end of the corridor

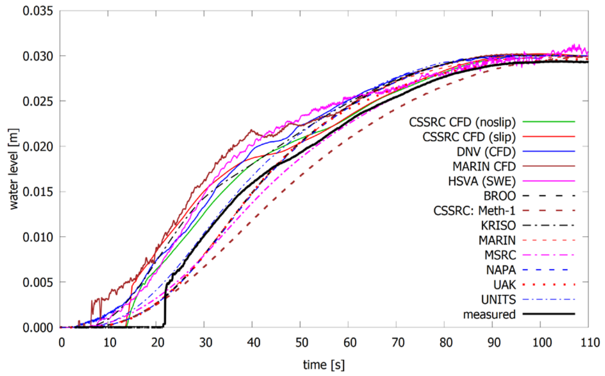

Figure 13 Water level at sensor REL 3, furthest distance to the breach

The scale of the model was small (1:60) and surface tension effects caused notable step in the level sensor data, Figures 10, 11 and 13. This behaviour was captured in the CFD simulations. The flooding progression in visualized in Figure 14, using CFD results by CSSRC with the no-slip boundary condition. The effect of the long corridor on flooding of the rooms is clearly visible.

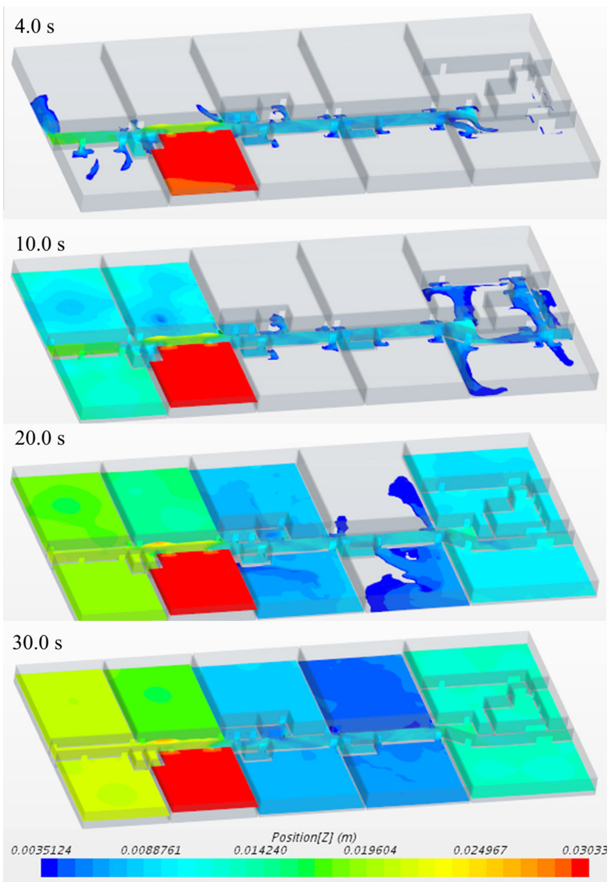

Figure 14 Visualizatoin of deck flooding from CFD simulation by CSSRC (no-slip)

With the CFD codes the computation time for the deck flooding case was about 100-1000 times slower than real time (in full-scale), whereas the Bernoulli and SWE methods were all faster than real time, albeit with quite notable range as the most efficient code is about 50 times faster than the slowest Bernoulli-based code. Applied code level implementation, such as time discretization and integration methods for volumes, can have a notable effect on the performance.

6. DISCUSSION

Most codes with a hydraulic model correctly predicted the flooding progression for the simple up and down-flooding cases in close agreement to model tests. Use of CFD tools provided more additional information on the details, especially during the initial flooding process, but for rather simple cases the CFD tools hardly provide a better prediction of the water level height development when compared to the Bernoulli-based methods (CSSRC-Meth1, KRISO, MARIN, NAPA, UAK, UNINA, UNITS). Only the code PROTEUS, used by both BROO and MSRC, predicted severely underestimated flooding rates for both up- and down-flooding. Based on investigations by MSRC, this resulted from built-in ramps for flooding rates and problems with fully filled-up compartments, so the problem is in the code implementation, not in the Bernoulli-based methodology for flooding progression, and not initiated by the prescribed discharge coefficient.

The deck flooding case is characterized by progressive flooding along the long service corridor. In the experiments, the rooms adjacent to both ends of the corridor were flooded much faster than the rooms in the middle. This phenomenon was properly captured by the CFD codes and the SWE method used by HSVA. In addition, the newly developed extension of the SMTP simulation code by KRISO, considering the momentum of the flow in a long compartment, provided very promising results.

In general, the variation on the results in the deck flooding case with simulation codes based on hydraulic model was much larger than expected, especially when considering that the corridor was divided into smaller rooms at same locations and that the same discharge coefficients were applied. This indicates differences in the numerical methods for time integration.

7. CONCLUSIONS

The benchmark cases have provided valuable information on the performance and characteristics of different time-domain flooding simulation codes. Obvious errors in implementation were found for one code. The deck flooding case demonstrated that transient flooding progression along a long corridor can be captured, not only with CFD tools, but also with SWE model of HSVA and with Bernoulli based methods, when the momentum of the flow is considered, as in the simulation by KRISO.

Due to the large variation in the simulation results for the deck flooding case, a new set of experiments on progressive flooding of several compartments with fixed floating position could be valuable. In the present study, some scale effects were noticed, and therefore, in future model tests a large scale should be used.

This benchmark study with the simplified test cases paves way for more extensive benchmarking of the same codes for simulation of flooding and motions of damaged ships in calm water and in waves, which will be studied and reported in the latter part of the FLARE benchmark.

8. ACKNOWLEDGMENTS

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6 PART B: CRUISE SHIP FLOODING

Pekka Ruponen, Rinnert van Basten Batenburg, Riaan van't Veer, Luca Braidotti, Shuxia Bu, Hendrik Dankowski, Gyeong Joong Lee, Francesco Mauro, Eivind Ruth, Markus Tompuri,

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International benchmark study on numerical simulation of flooding and motions of a damaged cruise ship

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ABSTRACT

Large cruise ships can carry 10 000 persons onboard, and consequently, survivability of the ship in the event of a flooding accident is essential. Many designers are already conducting advanced damage stability analyses beyond the regulatory requirements. With increased computing capacity, survivability analyses, by using time-domain simulation tools, are already commonly applied in the design of new cruise ships. Consequently, it is essential that such tools are properly validated, in terms of ship response and detailed flooding behavior, to assess the capability and applicability of the tools. For this purpose, an international benchmark study on simulation of flooding and motions of damaged cruise ships was conducted within the EU Horizon 2020 project FLARE, using experimental data from new dedicated model tests as a reference. The test cases include transient and progressive flooding, both in calm water and in irregular beam seas. The results indicate that capsize is properly captured by simulation codes, but there are notable differences in the flooding progression and capsize mechanisms, especially when flooding takes place in high waves.

1. Introduction

Flooding of a damaged ship is a very complex process, and consequently, accurate numerical modelling of the relevant fluid structure interactions is challenging. During the past two decades, there has been significant development in numerical tools for simulation of the flooding process and motions of damaged ships. An overview of these advancements was presented by Papanikolaou (2007). The subsequent progress is discussed e.g. in the review papers by Bačkalov et al. (2016) and Manderbacka et al. (2019). Such simulations have been used for various studies on damage survivability of passenger ships, as presented in e.g. van't Veer et al. (2004), Spanos and Papanikolaou (2014), Vassalos (2016), Ruponen et al. (2019), Atzampos et al. (2019), Braidotti et al. (2021) and Mauro et al. (2022). With increasing importance of survivability studies in the design of passenger ships, a thorough validation and benchmarking of the simulation methods is considered essential.

The applied simulation tools are usually based on hydraulic model with Bernoulli's theorem. However, recently the use of computational fluid dynamics (CFD) tools for simulation of the flooding process has expanded from the simple scenarios, Gao et al. (2010) and cross-flooding analyses, Ruponen et al. (2012), to extensive simulations of flooding and motions of a damaged ship in waves, Caldas et al. (2018) and Ruth et al. (2019). Consequently, comparison of different types of simulation tools is also relevant.

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Over the years, flooding and damage stability of ships have been studied experimentally with scale models. Especially, after the rapid capsize and sinking of the passenger/ro-ro (ropax) vessel Estonia in 1994, so-called Stockholm Agreement model tests were performed, both for existing ships and new designs, Schindler (2000). Later also more complex arrangements of flooded compartments have been studied. Ikeda et al. (2003) conducted flooding tests with a small model (1:185) of a large cruise ship, and later with a larger scale (1:50) section of the same ship, Ikeda et al. (2011), focusing on the effects of the internal layout of the flooded compartments. Within the SAFENVSHIP (2002–2006) project, transient and progressive flooding of a large cruise ship were studied experimentally, and the main results were reported by Italy (2004a, 2004b) at IMO SLF47 meeting. In addition, Cho et al. (2009) have presented flooding tests for a cruise ship model with simplified compartment arrangement. However, experimental data on cruise ship flooding was not available for validation of benchmarking purposes.

Progressive flooding has also been studied experimentally with simplified hull geometries, Ruponen et al. (2007) and Lorkowski et al. (2014). The former being used also in a benchmark study by ITTC (International Towing Tank Conference), and widely as a validation material for various numerical codes. In addition, navy vessels with complex internal arrangement in the flooded compartments have been studied in model scale by Macfarlane et al. (2010) and in full ship scale by Ruponen et al. (2010).

During the past two decades, several benchmark studies on damaged ship stability and motions in waves have been organized, mainly within the ITTC. In the first study, Papanikolaou and Spanos (2001), the roll motion and the limiting significant wave height were studied for a passenger/ro-ro ferry with one damage case, involving also the main vehicle deck. The focus was solely on the seakeeping characteristics of a flooded ship in waves. The next ITTC benchmark, described by Papanikolaou and Spanos (2005), was more extensive, including also transient flooding process of a ro-ro/passenger ship in calm water, based on experimental results from the EU FP5 project HARDER (2000–2003), reported by van't Veer (2001).

The third ITTC benchmark study focused on progressive flooding in a large-scale (about 1:10) box-shaped barge model, Ruponen et al. (2007). The results are reported by van Walree and Papanikolaou (2007). Motions of the barge were fully quasi-static, and discharge coefficients for all openings were shared in advance, but still the results showed large variation in the progressive flooding.

A further benchmark study on transient flooding and capsize of a ro-ro/passenger ship in waves, with model test results from van't Veer (2001), was carried out within the EU FP6 project SAFEDOR (2005–2009) and summarized by Papanikolaou and Spanos (2008). The significant wave height at the survival boundary was estimated quite well by two out of the four participants. However, it was also concluded that the detailed background analysis showed that codes simulated the test phenomena in a substantially different way.

The recommendations of the previous benchmark studies clearly indicate a need for further studies, focusing on the different phenomena and fluid structure interactions involved in the flooding process of ships with complex internal arrangement. Moreover, new flooding simulation tools have been developed, further emphasizing the need for a new international benchmark study.

Although several experiments have been done with various ship models, there is not enough publicly available test data for proper benchmarking of numerical methods. Consequently, dedicated model tests were conducted within the EU Horizon 2020 project, FLARE (2018–2022), focusing on progressive flooding in a typical large cruise ship with complex arrangement of flooded compartments, both in calm water and in beam seas.

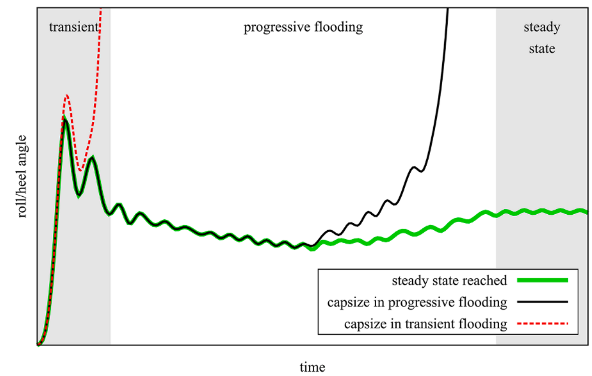

Fig. 1. Schematic visualization of the different stages of flooding process.

2. Objectives

The flooding process can be divided into three separate stages with distinctive characteristics. The transient flooding stage involves rapid inflow to the damaged compartments, typically resulting in a large roll angle, or even rapid capsize. This stage may be followed by progressive flooding to undamaged compartments through various internal openings. This stage can last for a very long time for ships with dense non-watertight internal subdivision. The progressive flooding can be so extensive that the ship capsizes. If the ship does not sink or capsize during this stage, a final steady state is reached. These different flooding stages are visualized in Fig. 1.

The previous benchmark studies have mainly focused on the stability and motions of a damaged ship in the steady state condition after flooding. In addition, both transient flooding and progressive flooding stages have been studied in simplified scenarios. Furthermore, the previous part of the FLARE benchmark study focused on flooding and capsizing of a ropax ship, without any internal non-watertight subdivision in the flooded compartments, as presented in Ruponen et al. (2022). Since the capsize mechanisms can be notably different for ropax and cruise ships, another benchmark study was considered necessary, since flooding scenarios with actual capsize either during the transient or progressive flooding stage had not yet been studied experimentally for a ship model with complex arrangement of flooded compartments. Within the EU Horizon 2020 project FLARE, such model tests were conducted at MARIN, and the results are used as a reference data for a new international benchmark study.

3. Benchmark setup

3.1. Methodology

The flooding process is strongly coupled with the motions of the damaged ship. Flooding process affects damaged ship motions, and vice versa. In addition, the presence of waves has an impact on both the flooding process and the ship motions, as visualized in Fig. 2. Previously, Ypma and Turner (2019) have presented a new approach for validation of flooding simulation, considering both captive and freely floating model tests. In the FLARE benchmark study, the flooding part was first studied with captive model tests in calm water, Ruponen et al. (2021). Transient and gradual flooding of a damaged ropax vessel, with two open damaged compartments and large vehicle deck were studied separately, Ruponen et al. (2022). For a ship with dense internal subdivision in the watertight compartments the flooding and capsize mechanisms are known to be different from ropax vessels, and therefore, in this follow-up study with a model of a typical large cruise ship, flooding in calm water and in irregular beam seas are investigated.

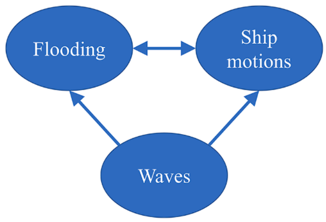

Fig. 2. Visualization of the couplings between waves, flooding and ship motions.

3.2. *Cruise ship model*[1]

An unbuilt large cruise ship design (about 95 900 GT) was provided by Chantiers de l'Atlantique. Tests were carried out at MARIN with a model built in scale 1:60, Fig. 3. A model of the studied ship was constructed in scale 1:60. The bow and stern are filled with Styrofoam, and the floodable compartments are made from transparent PVC. The sections were stiffened by two carbon fiber box beams on top of the model.

The main dimensions are listed in Table 1 and the hull form is shown in Fig. 4. The hull of the model extends vertically over 8 decks, and floodable rooms are located on 6 lower decks, as shown in Fig. 5. In total, the model contains 60 floodable rooms bounded by bulkheads and decks. The rooms are connected by 82 internal openings in the bulkheads and 11 openings in the decks. The actual geometry of the model was distributed, and each participant modelled the arrangement based on their own practices and expertise. Thickness of the plexiglass decks and bulkheads is 4 mm (in model scale), and it was recommended to model actual compartment limits accurately and apply a permeability of 1.0 for each room, instead of simply adjusting the permeability to account for the volume occupied by the decks and bulkheads. The bulkhead deck arrangement (Deck 4 in Fig. 5) is the same that was studied in the deck flooding in captive model test for the first part of the FLARE benchmark study, Ruponen et al. (2021).

The deepest subdivision draft of 8.20 m was selected for the test condition. According to current SOLAS Ch. II-1 requirements the smallest allowed metacentric height (GM) at this draft is 3.50 m. Based on initial simulation and model test results, notably smaller GM was needed to achieve also capsize cases in a sea state with a significant wave height of 4.0 m. Consequently, a GM value of 2.36 m was selected for the benchmark cases.

The studied large 3-compartment damage scenario was selected by MSRC, based on initial simulations for the original ship design and subdivision with PROTEUS software, using standard discharge coefficient 0.6 and assuming thin decks and bulkheads. Further simplifications were done in the construction of the model, and consequently, the actual damage scenario differs from the one used in the initial simulations.

The breach is on the starboard side, forward from amidships. Vertically the breach extends over 6 decks from the baseline. The flooding case is asymmetric, and the modelled geometry is a simplification of the original design, provided by Chantiers d'Atlantique.

3.3. *Scope and structure*

The benchmark study focuses on both flooding progression and motions of a damaged cruise ship, and contains three separate test cases:

(1) Transient flooding in calm water.
(2) Transient and progressive flooding in irregular beam seas.
(3) Up-flooding in calm water with smaller breach size.

[1] Detailed geometry and drawings of the model are available on request from the corresponding author

The benchmark was open to participants outside the FLARE consortium, and various organizations with recently published studies on flooding simulation were invited beforehand. Eventually eight organizations provided numerical results to the benchmark study. A summary of the participation in the benchmark study is presented in Table 2. The relevant experimental data (time histories of key quantities, such as roll angle, and videos of the tests) were shared beforehand to all participants in order to enable fair and equal benchmarking conditions.

In general, the codes can be categorized based on the treatment of floodwater:

- simplified model with the free surfaces in flooded rooms modelled as horizontal planes,
- inclined plane, based on an apparent gravity (lumped mass) or a simplified dynamic resonance model,
- Volume of Fluid (VOF) type of Computational Fluid Dynamics (CFD) model with compartments discretized into a mesh of computational cells.

The category of each code is also listed in Table 2.

The applied codes are mainly in-house software, developed and maintained at a university or a research institution. The exceptions are NAPA and Star-CCM+ (used by DNV), which are commercially available. Furthermore, the code PROTEUS, used by MSRC, is currently managed by Safety at Sea Ltd.

3.4. *Overview of the numerical simulation methods*

3.4.1. *CSSRC*

In-house code **wDamstab**. Bernoulli's equation is used for calculation of flooding rates through openings and horizontal flat plane is assumed for floodwater surfaces. Four degrees of freedom (sway, heave, roll and pitch) are considered. Ship motion is calculated based on the potential flow theory, namely Salvesen–Tuck–Faltinsen (STF) strip theory. Froude-Krylov and hydrostatic forces are calculated based on the integration of pressure over the instantaneous wet surface. More details are given in Bu et al. (2018), (2020), in Chinese.

3.4.2. *DNV*

CFD results for the Case 3 with **Star-CCM+** software. A mesh of about 3 million cells, using an overset mesh approach with a time step of 0.002 s was used. Model scale was used, and the results have been converted to full scale for comparison with the other codes. Also the ventilation pipes were modelled and calculations included the air flows. The model was free in all 6 degrees of freedom. The simulation was conducted with laminar flow and without prism layers to reduce computation time. Laminar flow was considered a reasonable assumption since the simulation was performed in model scale. Including prism layers would have improved the modeling of the water-wall friction, but this was believed to be of minor importance compared to the flooding dynamics.

3.4.3. *KRISO*

In-house code **SMTP** was used with flooding rates calculated by Bernoulli's equation and empirical discharge coefficients. The floodwater in compartments can be modeled either with a horizontal free surface or with a dynamic model in which the equation of motion of the mass center is solved using the tank resonance mode of the standing wave for the instantaneous water depth, and the resulting inclined free surface is used for the calculation of the pressure at openings. The compartments are treated independently, so the model can be selected appropriately to represent the property of each compartment. Ship motions are calculated by 6-DOF non-linear equations in time-domain, in which the Froude-Krylov and restoring forces are calculated for instantaneous wetted surface, and the hydrodynamic forces are

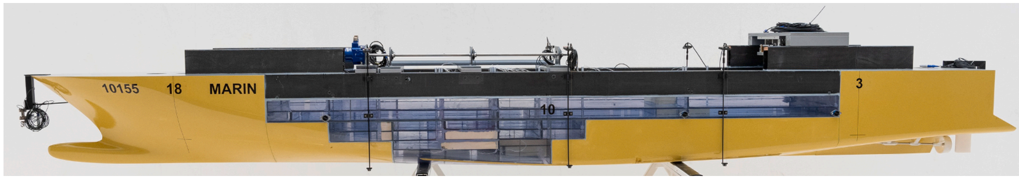

Fig. 3. Model of the cruise ship, courtesy of MARIN.

Table 1
Main dimensions of the studied cruise ship and the applied initial intact condition in model tests.

	Full scale	Model scale
Length over all	About 300 m	About 5.0 m
Length between perpendiculars	270.00 m	4.5 m
Breadth	35.20 m	0.587 m
Draught (in tests)	8.20 m	0.137 m
Trim (in tests)	0.00 m	0.000 m
Height of bulkhead deck form base line	11.00 m	0.183 m
Gross tonnage	95 900	-
Metacentric height (in tests)	2.36 m	0.0393 m
Radius of inertia for roll	13.904 m	0.2317 m

calculated by the traditional strip method. The floodwater affects the ship motion as internal forces, not as external forces. In other words, it changes the mass and its center of gravity resulting in changes of the inertial and gravity forces. Details are presented in Lee (2015a), (2015b). For this study, the dynamic resonance model was selected for the compartments with a connection to the sea. The air flows were calculated for all compartments and the air pipes were modeled as in model test pictures.

3.4.4. MARIN

The Extensible Modelling Framework (**XMF**) is a software toolkit on which all MARIN's fast-time and real-time simulation software is based applying Newtonian dynamics, of which Fredyn and ANySim are known examples. XMF is recently extended with a flooding module library (XHL) based on Bernoulli's equation with empirical discharge coefficients, using generic 3D defined floodable objects. A graph-solver technique is utilized to capture the complexity of entrapped air in compartments and for hydrostatic pressure-corrections from fully flooded compartments. To account for the flow inertia effects in the progression of flood water through the ship, the XMF framework is recently extended with a new inertia-based flow solver, denoted as the unified internal flow (UIF) module. The theory and first results of this solver are presented in van't Veer et al. (2021). The ship hydrodynamics were calculated by program SEACAL using zero-speed Green functions. The complete underwater part of the hull was represented by 14544 flat quadrilateral panels in the potential flow calculations. During the simulations the complete 3D ship hull is used. Retardation functions were constructed for the upright hull at initial draft and used to represent the hull radiation forces in time domain. The diffraction loads are calculated through the pre-computed RAO functions. The incident wave pressures are integrated on the actual submerged hull volume under the incident wave profile. In each flooded compartment the water surface is a flat plane with a normal vector pointing perpendicular to the resulting effective gravity angle(s) composed from all 6-DOF rigid body accelerations. To obtain this, the local gravity angle is calculated in each last known center of mass in each compartment. The center of mass is calculated based on the 3D object geometry, water surface orientation and actual volume of water in the compartment. The horizontal mooring system was modeled, and full ventilation was assumed in all simulations.

3.4.5. MSRC

In-house code **PROTEUS** owned by Safety at Sea Ltd., and originally developed at University of Strathclyde (MSRC). Flooding rates are calculated applying Bernoulli's equation with a hard-coded discharge coefficient of 0.6. The code has a feature for Free-Mass-In-Potential-Surface (FMPS), Papanikolaou et al. (2000), where the whole mass of water in the compartment is treated as a single point mass. However, in this benchmark study, the current default setting, where the FMPS model is omitted, was used. Consequently, the calculation assumes that the water level inside a compartment is always parallel to the

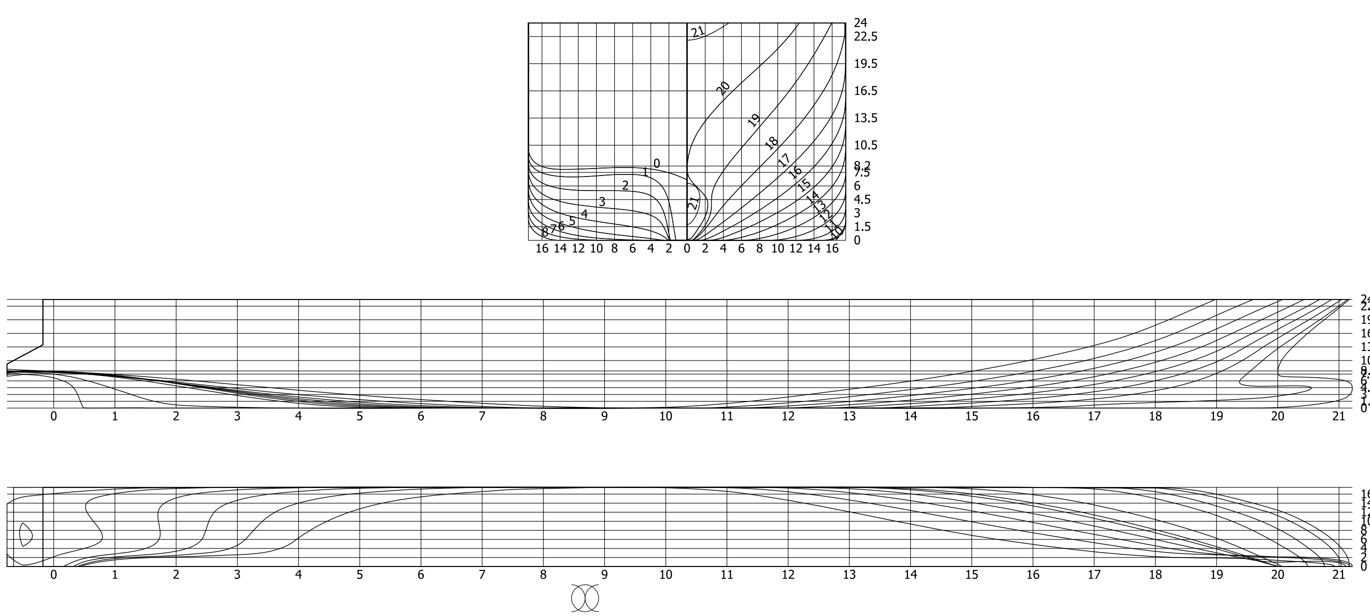

Fig. 4. Lines drawing of the bare hull of the studied cruise ship.

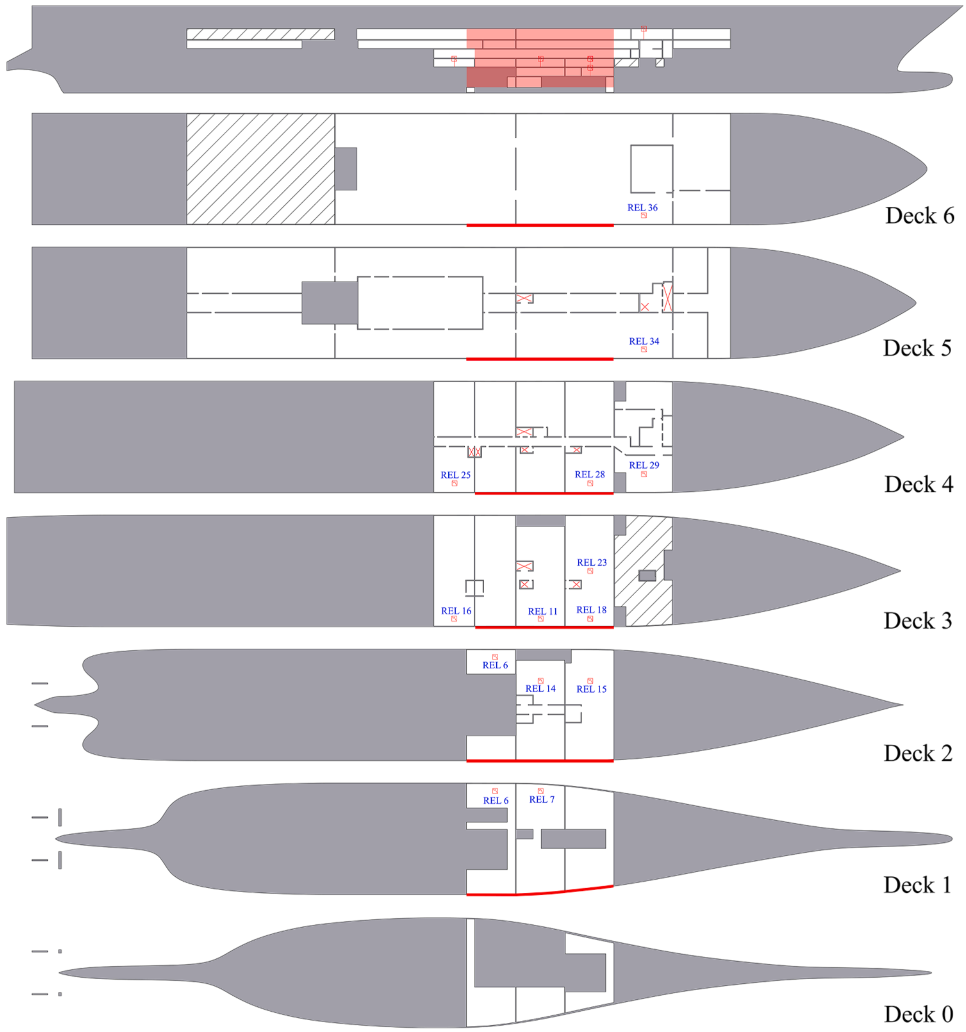

Fig. 5. Arrangement of the ship model; the hatched rooms were filled with foam and thus not floodable, and the red squares mark the selected water level sensors, red × symbols denote holes in the deck and thick red lines mark the large breach.

Table 2
Summary of the participation in the benchmark study (symbol ✓ denotes participation in the case).

ID	Participant	Code	Treatment of floodwater surface	Case 1: large breach in calm water	Case 2: large breach in waves	Case 3: small breach in calm water
CSSRC	China Ship Scientific Research Center (CHI)	wDamstab	Horizontal plane	✓	✓	✓
DNV	DNV (NOR)	Star-CCM+	VOF	–	–	✓
KRISO	Korea Research Institute of Ships & Ocean Engineering (ROK)	SMTP	Inclined plane	✓	✓	✓
MARIN	Maritime Research Institute Netherlands (NED)	XMF	Inclined plane	✓	✓	✓
MSRC	Maritime Safety Research Center (UK)	PROTEUS	Horizontal plane	✓	✓	✓
NAPA	NAPA (FIN)	NAPA	Horizontal plane	✓	✓	✓
UAK	University of Applied Science Kiel (GER)	E4 Flooding	Horizontal plane	✓	–	✓
UNITS	University of Trieste (ITA)	LDAE	Horizontal plane	✓	–	✓

undisturbed sea water level. Froude-Krylov and restoring forces are integrated up to the instantaneous wave elevation both for regular and irregular waves. Radiation and diffraction are derived from 2D strip theory. Hydrodynamic coefficients vary with the attitude of the ship during the flooding process (heave, heel and trim). Details are presented in Jasionowski (2001). In the test cases, motions were evaluated by solving a 4 DOF system of equation (yaw and surge not modelled) assuming the vessel is allowed to drift freely. Hydrodynamic forces for the actual attitude of the vessel are obtained through interpolation on a precalculated set of forces obtained by 2D strip theory calculations. Drift forces are modelled according to empirical formulations, as presented in Letizia (1996).

3.4.6. NAPA

The commercial software **NAPA** is used. The flow rates are calculated from Bernoulli's equation, with user-defined discharge coefficients for each opening. Horizontal flat free surface is assumed in all flooded rooms. Pressure-correction algorithm is applied to solve the governing equations (continuity and Bernoulli). In the presented simulations, dynamic roll motion was calculated, while draft and pitch were considered quasi-static. The effect of waves on flooding rates was considered. Details are presented in Ruponen (2007), (2014).

3.4.7. UAK

In-house code **E4 Flooding** with flooding calculated by using Bernoulli's equation with horizontal surface and flooding path modelled as directed graphs. In the studied cases, 6-DOF dynamic ship motions were calculated. Linear roll damping was assumed. The code supports simulation either in calm water or in regular waves, and thus results for the Case 2 were not provided. Details are presented in Dankowski (2013) and Dankowski and Krüger (2015).

3.4.8. UNITS

In-house code **LDAE**, developed for fast onboard simulation of progressive flooding, was used. The flooding process is modelled using a DAE (Differential Algebraic Equations) system, based on the Bernoulli equation, which is linearized and solved analytically. A flat horizontal free surface is assumed for the sea and waterplanes inside flooded rooms, while the floating position of the ship is updated at each integration step accounting for floodwater weight. An adaptive integration time step, based on floodwater level derivatives, is adopted. The model does not include dynamic ship motions. Only quasi-steady change of heel, trim and sinkage is considered. A detailed description of the method can be found in Braidotti and Mauro (2019, 2020) and Braidotti et al. (2022).

3.5. Numerical modelling of the compartments

In order to capture the transient asymmetry of flooding with hydraulic simulation models, most participants divided some larger rooms with open connections, following the principle introduced by Santos et al. (2002). The double bottom compartments are wide, and without such numerical subdivision the Bernoulli-based codes are unable to model the transient asymmetric flooding of these compartments, Santos et al. (2002). Each participants modelled the compartments based on their experience and requirements of the applied software. Modelled rooms and connections for the double bottom compartments are visualized in Fig. 6. UAK did not divide the rooms in order to avoid rapid capsize in the transient flooding case. For CFD simulation, the compartments were discretized into computational cells, based on the expertise of the participant, and convergence studies to ensure that the applied grid was fine enough for the purpose.

4. Model tests

4.1. Test arrangement

A magnetic cover sheet closed the breach before the test, Fig. 7. At the start of the flooding (zero time), the coversheet was pulled upwards with a winch. The speed was about 2.5 m/s in model scale. Therefore, the breach was opened very rapidly, in less than 4 s in full scale, and an instant opening time for the breach was applied in the numerical simulations. For practical reasons a nominal capsize limit of 40° was used in the tests. All results are presented in full scale, with roll angle positive to the breach side (starboard) and pitch (trim) angle towards bow is positive. Measurements included 6 DOF motion of the model, as well as water levels in several locations in the flooded compartments.

The floodable compartments were vented with large air pipes on the leeward (intact) side, as visualized in Fig. 8. In this respect, the effects of air compression were considered small, and consequently full ventilation was assumed by most participants. Air pressures inside the model were not measured, so this assumption cannot be confirmed. However,

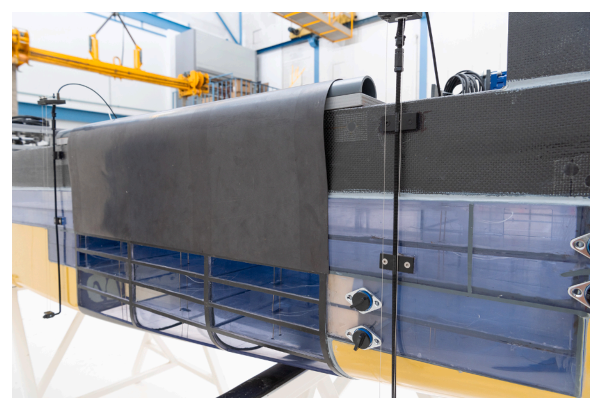

Fig. 7. Breach opening and the magnetic cover (photo courtesy of MARIN).

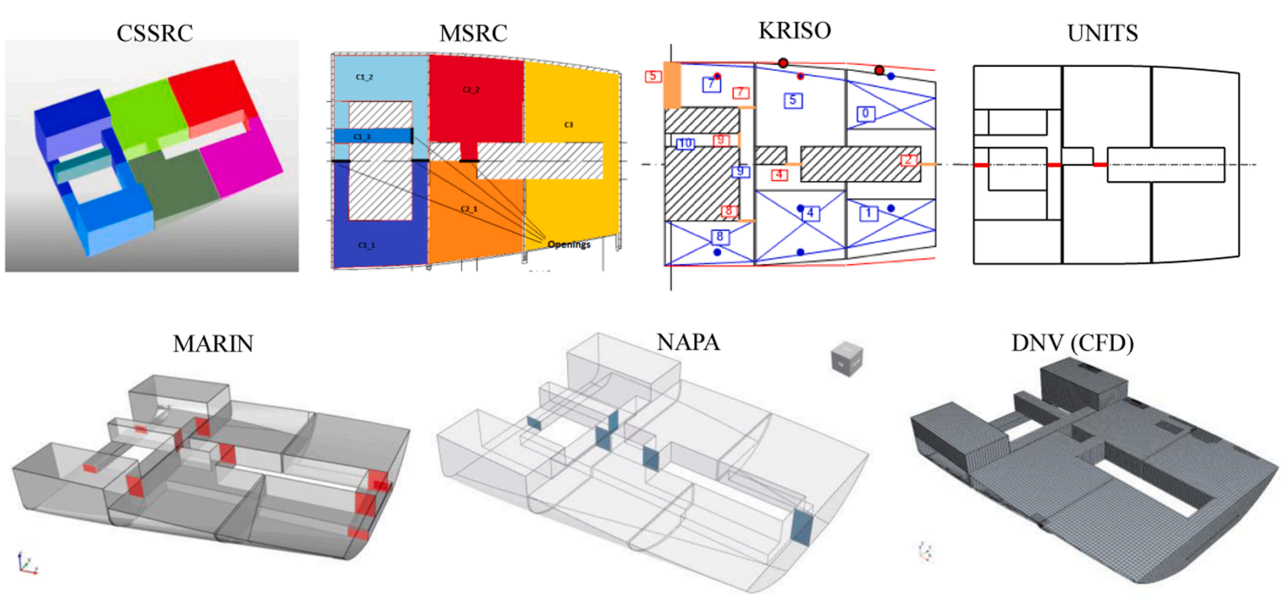

Fig. 6. Modelling of the flooded compartments in the double bottom; for Bernoulli based simulation codes also the openings connecting the parts of the large void spaces are shown.

in the CFD simulations by DNV in model scale, also the air pipes were modelled and formation of small air pockets in some compartments were observed. Also these results indicate that full ventilation is a reasonable assumption in this case.

4.2. Discharge coefficients

Many simulation codes use a hydraulic model, based on Bernoulli's theorem, for calculation of the flow rates through the openings. This approach is efficient, when compared to CFD tools, but it requires semi-empirical discharge coefficients to model the flow losses in the openings. For full scale simulations, the so-called industry standard value $C_d = 0.6$ has proven to be reasonably accurate, see e.g. Ruponen et al. (2010). Since frictional losses are proportional to the Reynolds number, somewhat larger discharge coefficient is characteristic for model-scale openings, Idel'chik (1960). This has also been observed in some recent experimental studies, e.g. Katayama and Ikeda (2005) and Ruponen et al. (2007). Consequently, all participants using Bernoulli's theorem, were recommended to use discharge coefficients given in Table 3. The values were obtained from dedicated experiments carried out at MARIN. The software PROTEUS, used by MSRC, has hard coded discharge coefficient 0.6, and therefore, it was necessary to compensate this by adjusting the opening areas in order to achieve the same effect.

4.3. Hydrostatics

The hull form and arrangement of the floodable compartments were shared to participants in the form of drawings, 3D geometry files and tables. Most participants applied the provided 3D hull form and only KRISO used lofting table data. In order to ensure that the geometry was modelled sufficiently accurately, the volumes of the buoyant hull (up to 20.4 m above the baseline) and displacement (V_{hull} and V_{disp}), as well as the center of the buoyant hull (X_{hull}, Y_{hull}, Z_{hull}) and the center of displacement at intact draft (X_{disp}, Y_{disp}, Z_{disp}) were compared. In addition, the total volume and center of the floodable compartments (V_{rooms}, X_{rooms}, Y_{rooms} and Z_{rooms}) were checked. Results are listed in Table 4, showing good consistency.

The intact metacentric height GM = 2.36 m was obtained from an inclining test of the model, assuming a straight righting lever curve between upright and the achieved inclination of 2.44°. Due to the hull form, the waterplane area changes significantly even at small heel angles. Consequently, the intact stability is sensitive to how accurately the hull geometry is described in the various simulation tools. For the benchmark study the GM was given, and it was up to the participants to define the associated vertical center of gravity (KG) for their simulations. The applied values are listed in Table 5, showing an average KG of 17.51 m, with a standard deviation of 0.089 m and a difference of 0.278 m between the largest and smallest values. Some participants finetuned the KG value to obtain the same final flooding angle as in the model tests, under the assumption that the floodwater distribution in the simulations was equal to that in the model tests.

The discretization and integration methods in the numerical codes are possible sources for inaccuracies, especially related to calculation of the waterplane area surface inertia moment. Moreover, some small variation was also observed in the vertical center of displacement, which is directly affecting the initial stability. Consequently, the static righting

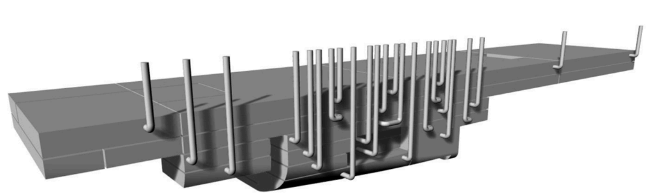

Fig. 8. Rendering of the 3D model of the compartments and ventilation pipes (courtesy of MARIN).

Table 3
Recommended discharge coefficients for the openings.

Opening	C_d	Explanation
Narrow openings (width < 30 mm)	0.73	Based on test at MARIN with opening size 17 mm × 34 mm
Wide openings (width ≥ 30 mm)	0.70	Based on test at MARIN with opening size 47 mm × 34 mm
Breach openings	0.65	Based on test result for 80 mm × 80 mm opening

lever (GZ) curve of the intact ship, especially at small heel angles, is considered as a more reliable check for correct modelling of the initial condition before flooding. The GZ curves, and corresponding trim angles, with different codes are presented in Fig. 9. At small heel angles the differences are minimal, but most notably the maximum righting lever values are quite different, and this is expected to have some effect on the simulation results at roll angles larger than 20°.

4.4. Roll decay

The model included simplified propeller and shaft arrangement, as well as rudders and bilge keels. Participants were provided with detailed geometry of the appendages. Furthermore, a roll decay test was performed by MARIN for an intact model, including all appendages. The measured history of roll angle was provided to all participants to help in modelling roll damping characteristics since the focus of the benchmark was on the flooding model performance. The effect of roll damping is notable during the transient flooding stage, but it is not expected to play a major effect in the progressive flooding stage. A comparison of simulated roll decay tests and measurement is shown in Fig. 10. The damping of the roll motion is rather well captured by all codes, but there are still some notable differences. Also the roll period is slightly longer in the simulation by MSRC. The code SMTP, used by KRISO, does not use roll damping input, and instead damping due to wave making is calculated by potential theory and skin friction and eddy making damping are calculated by empirical formulae, including also the appendages.

5. Transient flooding in calm water (Case 1)

In the first benchmark case, transient flooding in calm water is studied. The large breach is opened rapidly, causing a large transient roll angle towards the damage. This is rapidly equalized by cross-flooding on the lower decks in the damaged compartments, and the ship reaches a steady equilibrium since flooding is limited to the breached compartments and the partial bulkheads on the Deck 4 prevent progressive flooding.

The key quantities for comparison are the maximum roll angle and the time-to-flood (TTF). The measured and simulated development of roll and pitch angles are presented in Fig. 11. The maximum measured transient roll angle is 30.7°, and it was reached at about 17.4 s (full scale) after the breach was initiated. After about 90 s, a steady heel angle of 6.7° is achieved.

There is some variation in the maximum simulated transient roll angle, but in general this is slightly underestimated. The smaller second peak in roll motion is qualitatively captured by KRISO and MARIN, i.e. the codes where the water levels in the compartments are considered as inclined planes (Table 2). Also MSRC simulation results in similar roll characteristics, related to transient flooding, although the second peak is very small.

There is also some variation in the final steady state heel angle between the simulation codes, however, the maximum difference to the measured value is only about 0.5°. Both CSSRC and MSRC predict the final steady heel angle very accurately, Fig. 12. UNITS underestimates the final heel, while the other codes overestimate it. However, in general the differences are less than 1°. Small differences in the applied KG (see

Table 4
Comparison of hydrostatics and modelling of compartments (values in full scale).

ID	Buoyant hull (up to 20.4 m from BL)				Displacement at 8.2 m draft				Floodable compartments			
	V_{hull} m^3	X_{hull} m	Y_{hull} m	Z_{hull} m	V_{disp} m^3	X_{disp} m	Y_{disp} m	Z_{disp} m	V_{rooms} m^3	X_{rooms} m	Y_{rooms} m	Z_{rooms} m
CSSRC	161555	126.111	0.000	11.287	51218	127.926	0.000	4.612	47947	149.695	-0.167	13.451
KRISO	161831	126.379	0.000	11.267	51356	127.920	0.000	4.591	48059	149.726	-0.169	13.434
MARIN	164300	124.346	0.000	11.337	51476	127.943	0.000	4.591	47689	149.675	-0.126	13.511
MSRC	162007	126.226	0.000	11.263	51548	127.801	0.000	4.591	48110	149.800	-0.172	13.418
NAPA	162174	126.088	0.000	11.262	51632	127.601	0.000	4.589	48005	149.641	-0.172	13.437
UAK	162063	126.197	0.000	11.262	51608	127.668	0.000	4.591	48005	149.733	-0.177	13.431
UNITS	162003	126.166	0.000	11.272	51477	127.813	0.000	4.596	47993	149.703	-0.171	13.443

Table 5
Applied values of vertical center of gravity KG.

ID	KG (m)
CSSRC	17.580
DNV	17.646
KRISO	17.500
MARIN	17.470
MSRC	17.500
NAPA	17.450
UAK	17.368
UNITS	17.590

Table 5) and possible inaccuracies in the modelling of the flooded compartments and buoyant hull are identified as potential explanations for the observed differences in the final heel angle.

All codes result in slightly larger pitch angle than measured, with UNITS having the best match. The maximum difference is about 0.15°, which is a rather small angle, but still has an effect on the draft values at bow and stern. Interestingly, all codes predict a notable transient pitch angle in the beginning of flooding, whereas the measured pitch angle increases steadily.

Comparisons of water levels in the flooded compartments are presented in Fig. 13 at locations of four sensors. The sensor REL 6 is located in the intact side of a large U-shaped room. The extensive transient roll motion causes a smaller initial peak in the water level, and then the water level decreases back to zero until it starts to steadily increase due to cross-flooding after about 30 s. In general, this initial peak in water level is slightly over-estimated in simulations, and MSRC and UAK predict much larger peak and fail to capture the drying up of the sensor. KRISO estimates the peak well, but it occurs slightly faster than measured, which matches well with the simulation of the transient roll. UNITS simulation, with quasi-static ship motions, underestimates the water level peak and fails to capture the drying of the sensor.

Also measurement of cross-flooding on Deck 2 at sensor REL 14 contains a short initial water level peak that is not captured by any of the simulation codes, although CSSRC captures the start time of flooding at this sensor. The secondary flooding starts much earlier in simulations than in the experiment, which agrees with the roll response results. The secondary flooding between 30 and 60 s is well predicted by MARIN, NAPA and UAK. Both MSRC and UNITS estimate notably slower time for the whole sensor to be immersed, while KRISO predicts much too fast full immersion of the sensor. It should be noted that the sensor did not cover the whole deck height due to the sealings of the wires on the top, and this has been accounted in the plotted graphs of simulated water levels.

For sensor REL 28 on Deck 4, the codes predict correctly that the whole sensor is temporarily immersed during the transient roll motion. However, KRISO, MARIN, MSRC, NAPA and UAK simulations end with notably larger final water level than measured. Also the sensor REL 34 on Deck 6 is briefly completely immersed, and this is captured by KRISO, MARIN, MSRC and NAPA, although both MSRC and NAPA predict much longer period of immersion. MARIN has a proper timing and duration, but with fluctuations in the water level that were not recorded in the model tests.

As a summary, the following observations were made from the Case 1 results:

- CSSRC predicts the qualitative behavior of the ship well, but the smaller second peak of roll motion is not captured. Water levels are estimated well, although the code predicts lower maximum water level at REL 34.
- KRISO simulation captures the shape of the roll motion graph, including the second peak. However, the maximum transient roll angle is under-estimated, and the period of the transient roll motion is too short. Water level trends are captured, and the differences to the experimental results are likely due to the faster equalization of transient roll.
- MARIN simulation captures the maximum transient roll angle very well, and also the second peak is predicted. The roll decay seems to be slightly under-estimated. Water levels in the compartments are well predicted.

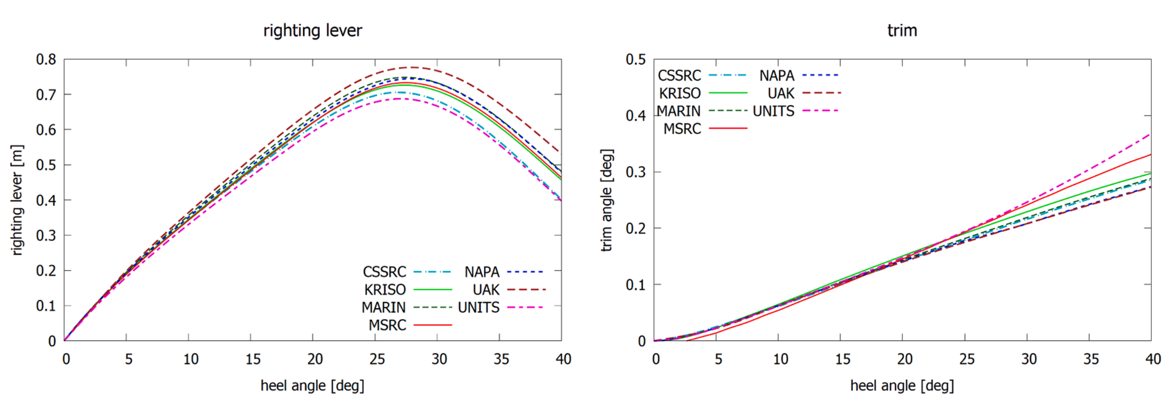

Fig. 9. Comparison of righting lever curves and related trim angles for the intact ship.

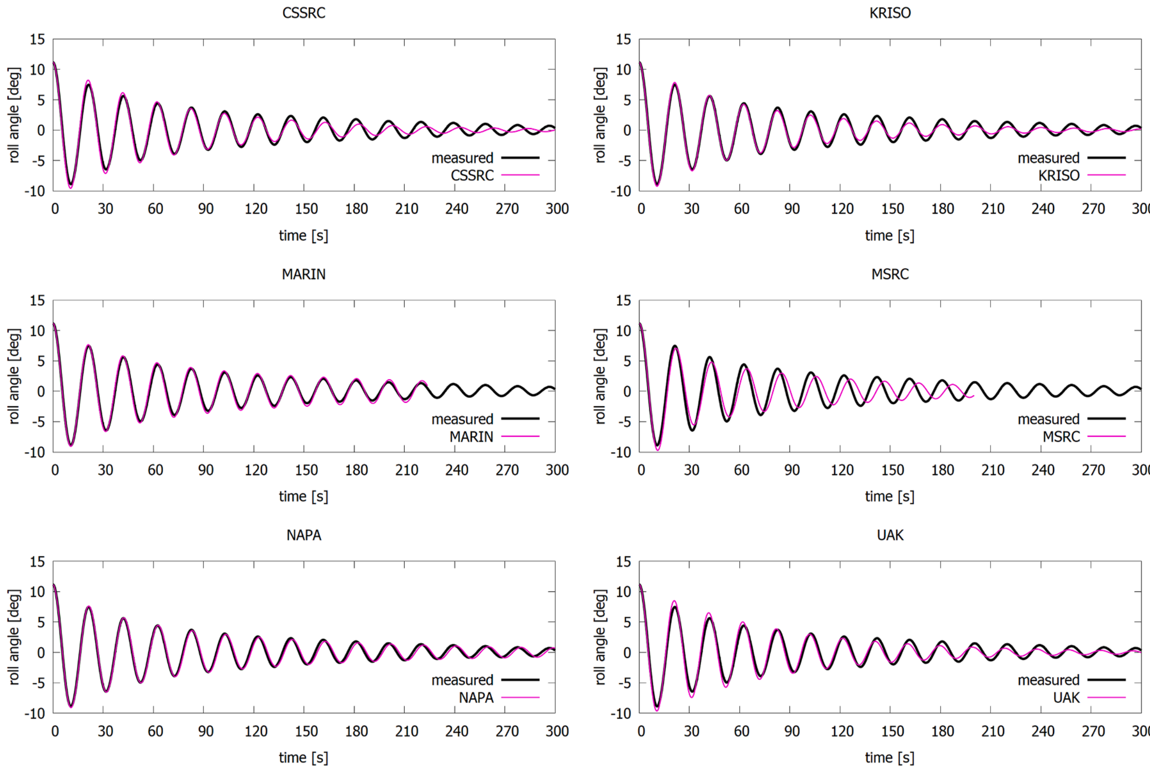

Fig. 10. Measured and simulated roll decay test for an intact ship.

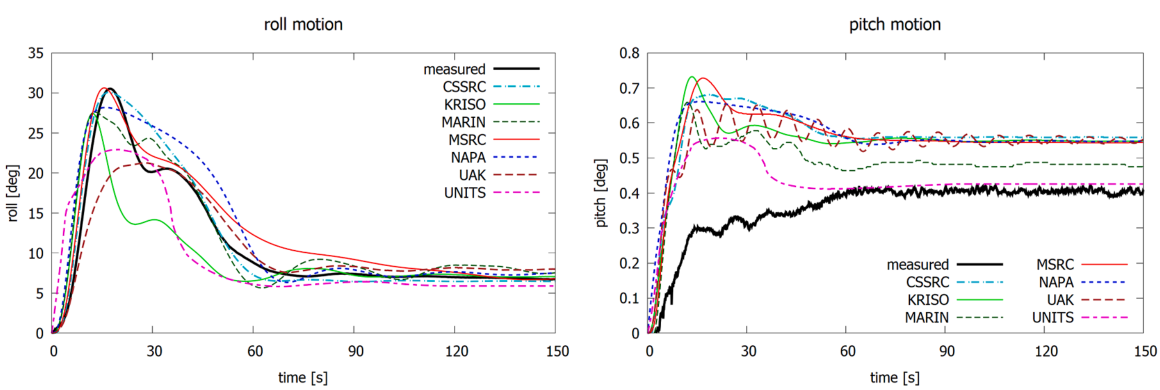

Fig. 11. Roll and pitch angles in the transient flooding benchmark Case 1.

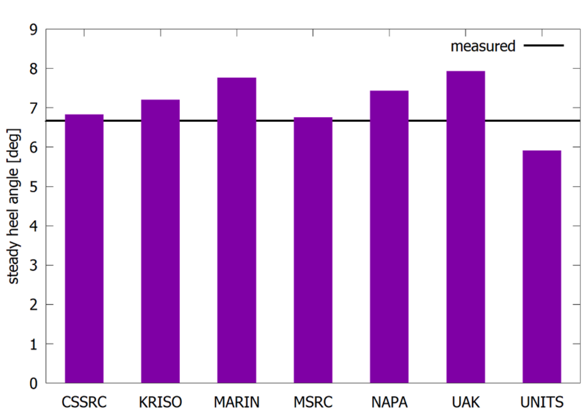

Fig. 12. Comparison of final steady heel angle in the Case 1

- MSRC captures the development of roll angle very well. However, the foremost breached compartment with cross-flooding had to be modelled as a single flooded room in order to avoid capsize in this case. In addition, there are notable differences in the water levels, especially in the cross-flooded compartment at REL 6.
- NAPA simulation is based on a simplified 1-DOF dynamic roll motion, yet the maximum transient roll angle is only slightly underestimated. However, the second peak is not captured, and the equalizing cross-flooding seems to be slightly slower than in the experiment. The water levels match rather well with the measurements.
- UAK simulation underestimates the transient roll angle, but after about 30 s the results match well with measurements, both for the roll angle and the water levels in the flooded compartments.
- UNITS simulation uses fully quasi-static ship motions, and therefore the transient roll angle is much smaller than measured, which also results in smaller water levels on the height decks, e.g. at REL 34. Otherwise, the flooding progression is captured well. Also UNITS

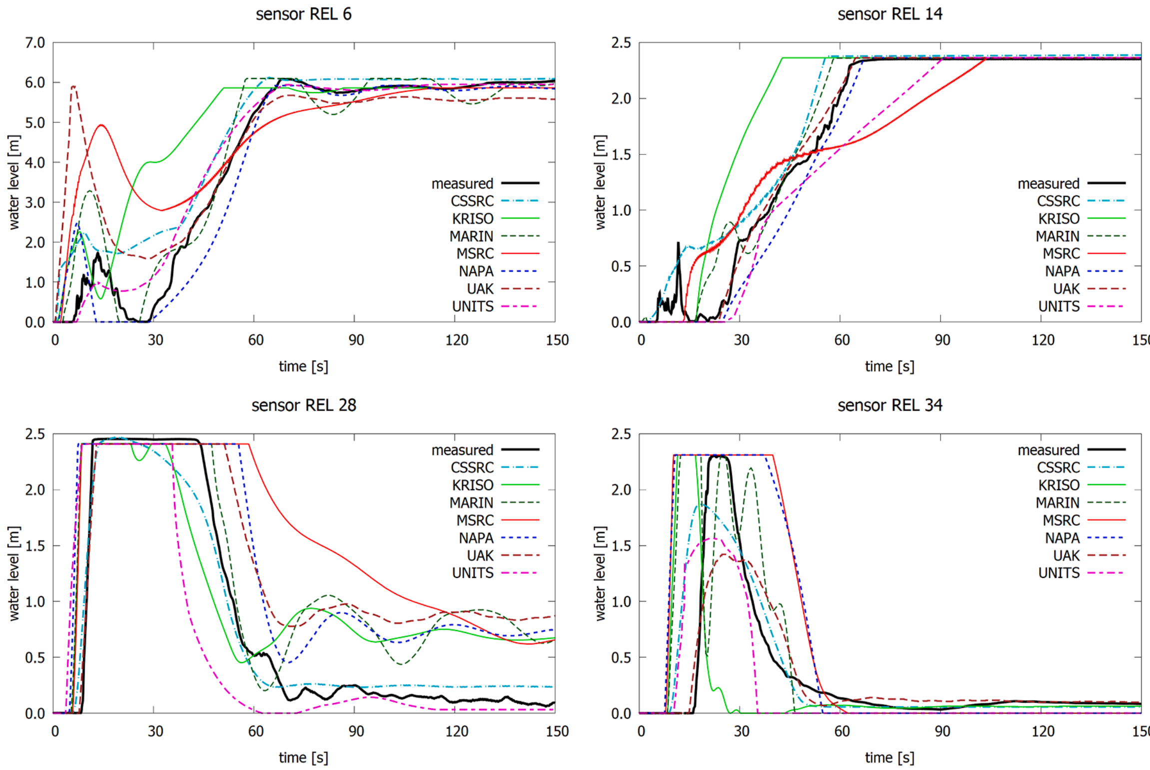

Fig. 13. Comparison of water levels in the flooded compartments in the test Case 1; sensor locations are shown in Fig. 5.

modelled the foremost breached compartment as a single room without cross-flooding.

6. Gradual progressive flooding in waves (Case 2)

6.1. Comparison of results with measured wave train

In the second benchmark test case the model is softly moored in irregular beam seas with the damage facing the waves, Fig. 14. JONSWAP wave spectrum ($\gamma = 7$ due to wavemaker limitation at high frequency and scale of the model) with significant wave height of 4.0 m and peak period of 8.0 s. The breach and intact conditions are the same as in the Case 1.

The maximum transient roll angle is about 30°, which is almost the same as in calm water in Case 1. Flooding is rapidly equalized, and roll angle reduces to less than 10°. Waves pump water to the bulkhead deck level (Deck 4), causing progressive flooding through the service corridor, and subsequent down-flooding to the undamaged compartment on Deck 3, as visualized in Fig. 15. This results in slow increase in the roll angle. There is further progressive flooding with larger roll angles when also Decks 5 and 6 are flooded through the breach opening, eventually causing a capsize at about 30 min (full scale).

The measured undisturbed wave history was provided as input to all participants. However, for KRISO the best matching simulation result out of 20 random realizations of the given sea state was used for comparison since the code does not support wave history input. The results for the roll angle are presented in Fig. 16.

CSSRC, MARIN and NAPA capture the transient roll motion rather well, while in the MSRC simulation the maximum transient roll is captured, but the decrease of transient roll is notably prolonged. KRISO underestimates the transient roll angle, but this could also be explained by the fact that a different wave realization was used.

KRISO and MSRC predict the time-to-capsize (TTC) rather accurately, although in the case of KRISO, the measured wave train was not used. MSRC also captures the temporary increase in the roll angle at around 15 min. In the simulation by KRISO the roll motion during progressive flooding is pronounced, compared to both measurement signal and other simulations. With CSSRC, MARIN and NAPA the TTC is notably shorter. NAPA simulation is based on a simple dynamic roll motion model, yet the transient roll motion is captured well, but flooding of the upper decks seems to be too fast, likely due to the applied quasi-static handling of heave motion, and consequently TTC is too short.

Time histories for water levels at four sensors are shown in Fig. 17.

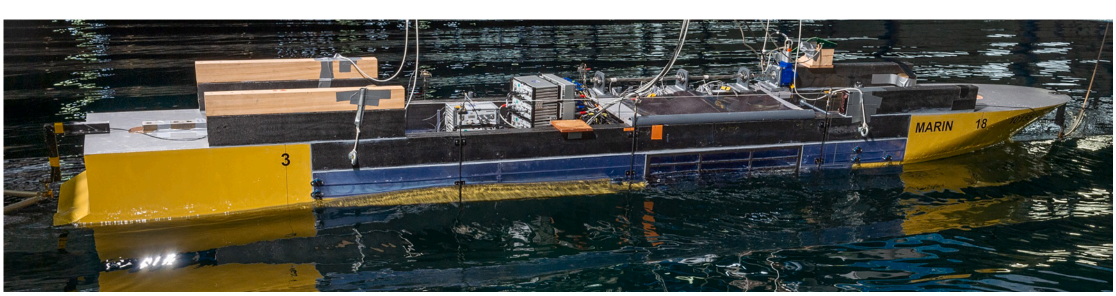

Fig. 14. Cruise ship model in irregular beam seas (courtesy of MARIN).

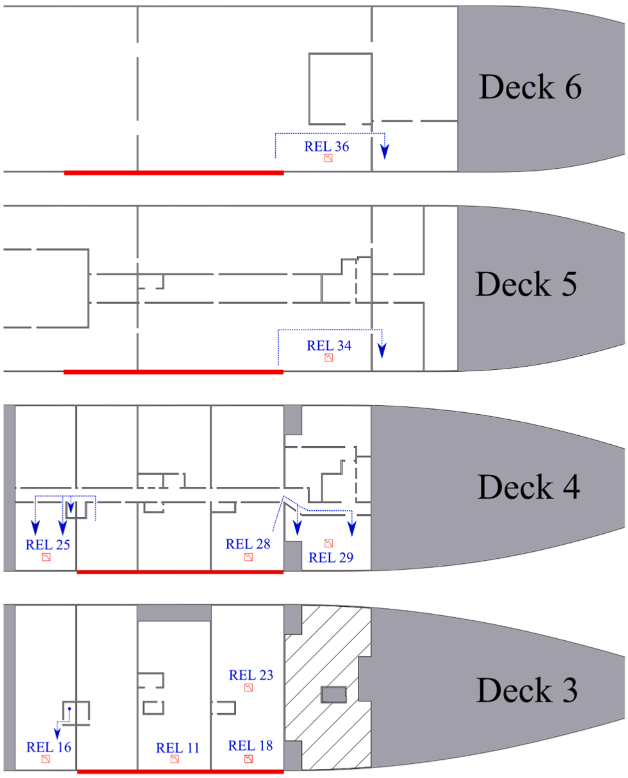

Fig. 15. Visualization of progressive flooding routes for the Case 2; in the aftmost compartment there is down-flooding from Deck 4 to Deck 3.

Although both MSRC and KRISO captured the TTC rather well, there are significant differences in the water levels. MSRC predicts well the water level peaks at REL 36 on Deck 6 that is temporarily flooded by high waves. However, MSRC predicts that the sensor REL 16 is fully immersed when the ship capsizes, whereas in the experiment the water level was significantly smaller. In the KRISO simulation the levels rise notable faster than measured, both at REL 16 and at REL 25. This indicates that although the capsize is properly captured, the actual flooding mechanism that leads to capsize is notably different.

6.2. Time-to-capsize

For a more comprehensive comparison between the different codes, all participants provided simulation results for 20 random realizations of the studied sea state. Results for the roll motion are shown in Fig. 18, together with measurements from three model tests using different wave trains. In two experiments the TTC is nearly identical, about 30 min in full scale, while in the third case the model capsized in about 20 min (in full scale).

In one of the CSSRC simulations the ship did not capsize within 40 min, while the other codes predict a capsize rate of 1.0. However, there is notable variation in TTC, as shown in Fig. 19. It is also noteworthy that all codes, except MARIN and NAPA, predict some rapid capsizes during transient flooding stage. MSRC predicts 50% likelihood for capsize within the first 10 min, whereas with other codes the clear majority of capsizes take place after the transient flooding stage. The number of experimental tests was limited to only 3, and therefore, a definite conclusion on the TTC cannot be drawn.

6.3. Drifting

In the experiments the model was kept positioned by a soft spring mooring system. The mooring lines were connected at the bow and stern of the vessel. The angle of the mooring lines was 45 degrees with the centerline. Line stiffness was reported by MARIN to be 241 kN/m and the pretension 6516 kN. The natural period of the mooring was about 5-times higher than the roll natural period, so that the soft mooring system does not affect the first order vessel motions. The mooring system prevents the model to drift away in the irregular wave. The second order drift loads will result in a slow oscillatory sway motions with respect to a mean sway offset due to the mean drift loads. The vessel position in the basin can only be predicted well if the mooring system and the second order drift loads are included in the numerical simulation set-up. Usually this is not the case since many codes neglect one or both affects (mooring loads and drift loads). The actual position of the ship in the wave spectrum realization will determine the relative wave velocity and the wave elevation at the damage opening and thus the ingress and egress of water.

A comparison of the drift is presented in Fig. 20. There is significant difference between KRISO and MSRC, both assuming free drift motion. Similar large variations in the simulated drift of the flooding ship in waves were found in the SAFEDOR benchmark study, Papanikolaou and Spanos (2008). Only MARIN modelled the mooring system, but the resulting sway motion in waves is notably smaller than measured. The fact that the MARIN simulation shows a lower amplitude of low frequent sway motions points to an under prediction of the sway draft load for the listed ship. This might be due to the fact that the drift loads from the upright ship are used since the potential seakeeping calculations were done for the intact loading condition only. In NAPA simulation the ship has a fixed transverse position.

It should be noted that most flooding simulation codes are intended for simulation of ship motions in full scale, and thus a feature to include the mooring line effects is normally not included. Even so, completely restraining the sway motion does not fully represent the model test

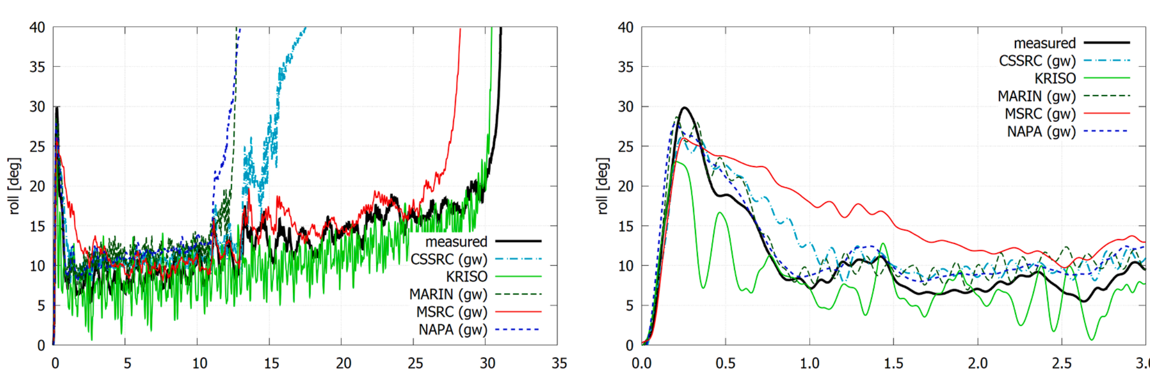

Fig. 16. Roll angle in the Case 2: codes marked with (gw) used the given wave train input, while for others the random realization of the given sea state with the best match has been selected; the graph on the right-hand side shows the details of transient roll motion.

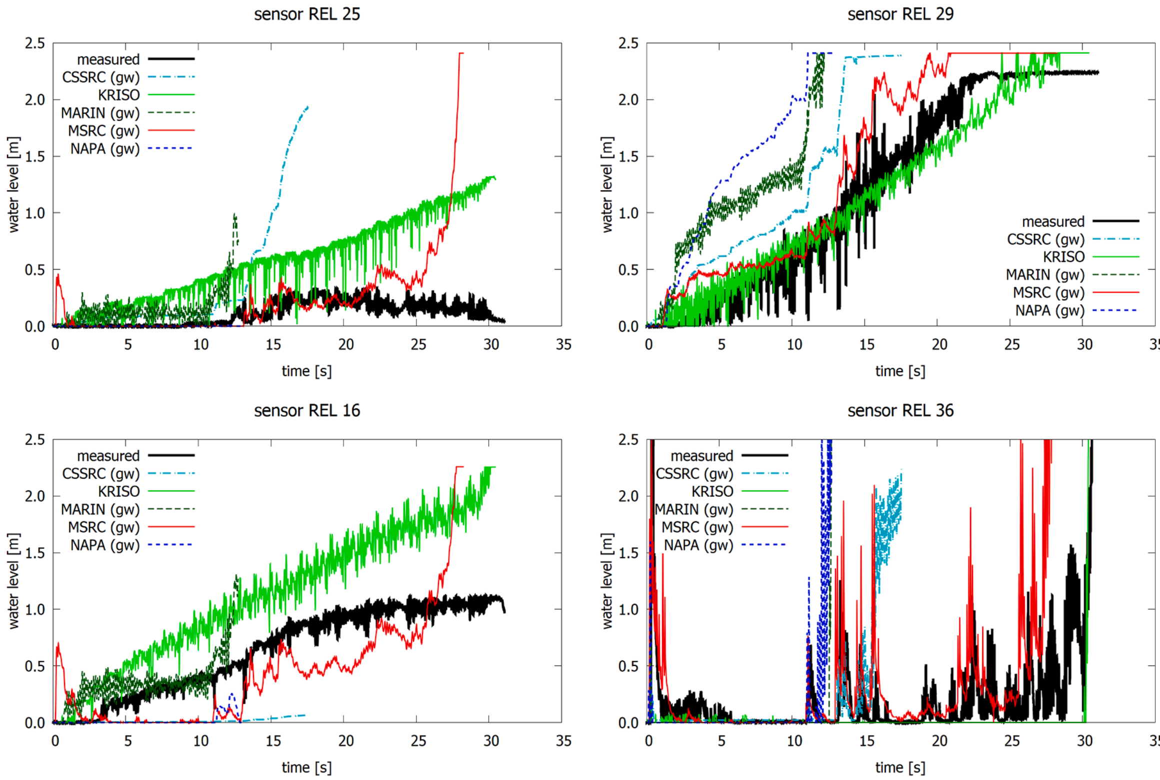

Fig. 17. Comparison of water levels in the flooded compartments in the test Case 2 (sensor locations are shown in Fig. 15); the curves are plotted up to the time when ship capsized (roll reached 40°).

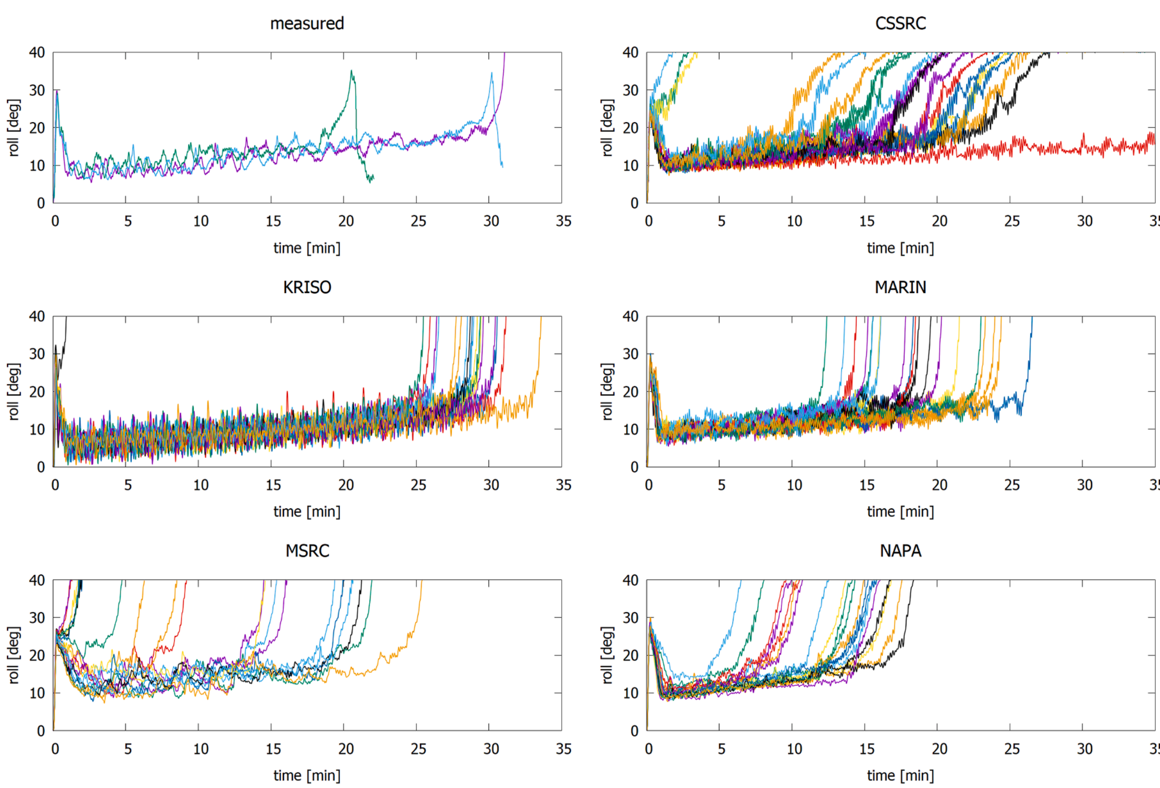

Fig. 18. Simulated development of roll angle in 20 realizations of the sea states and measured results in 3 realizations for Case 2.

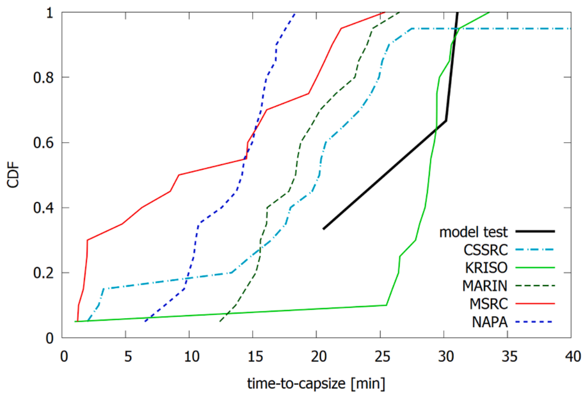

Fig. 19. Cumulative density functions (CDF) for time-to-capsize in the benchmark Case 2.

condition either.

7. Up-flooding in calm water (Case 3)

The third studied damage case is characterized by up-flooding through staircases. The same three compartments are damaged, but in this case the breach is vertically limited to the lowest two decks, as shown in Fig. 21. The routes of progressive flooding are visualized in Fig. 22. The model tests with the smaller breach size were conducted separately, after some participants had already conducted the calculations. Therefore, simulation results are presented for the original target intact GM of 2.36 m, whereas experimental results are shown separately for initial GM of 2.41 m and 2.29 m. The model test results show that the studied damage scenario is not very sensitive to the initial stability before flooding.

Results for the roll angle are shown in Fig. 23. CFD simulation by DNV slightly overestimates the maximum transient roll angle. Also the roll period is slightly longer than measured. It is believed that these differences are mainly caused by the slightly higher vertical center of gravity than with the other codes, as presented in Table 5. CSSRC, MARIN and MSRC predict this well, whereas KRISO and NAPA simulations slightly underestimate the peak. In the case of UAK, the maximum transient roll angle is notable smaller than measured, most likely since the large compartments in the bottom were not divided into parts. However, in general the subsequent roll motion is captured well by UAK. The fully quasi-static approach for ship motions by UNITS results in significantly smaller maximum roll angle and cannot capture the subsequent oscillations, but the final steady equilibrium angle is properly captured.

The final steady equilibrium is well predicted by CSSRC, MSRC and UNITS, whereas the other codes slightly overestimate it, Fig. 24. Likely reasons are small inaccuracies in the modelling of the flooded compartments and the slightly different KG values.

Like in Case 1, there is some variation in the final pitch angle, as shown in Fig. 25. However, the absolute differences are less than 0.1°. In general, the pitch angle is slightly overestimated, and only UNITS notably underestimates the final steady state pitch angle. It is worth noting that MARIN and UNITS simulations result in smaller final pitch angle than the other codes also for the Case 1, as shown in Fig. 11.

Comparisons of water levels at different sensors in the flooded rooms in Case 3 are shown in Fig. 26. The locations of the sensors are indicated in Fig. 22. The sensors REL 6 and REL 14 capture cross-flooding in the damaged compartments. In general, the development of water level is well predicted, although there is quite notable variation between the codes. Cross-flooding to the intact side (sensor REL 6) starts notably faster with the Bernoulli-based simulation codes than measured. But the CFD simulation by DNV captures this accurately, as well as the MARIN code that models flow inertia effects.

The sensors REL 11 and REL 18 capture the up-flooding to Deck 3 through the staircases. In the simulations, including also CFD, the up-flooding increases more rapidly compared to the measured water levels. The only exception is CSSRC, where the simulated water level at REL 18 matches well with the measurements. In UNITS simulation the

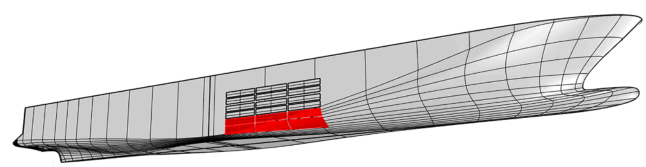

Fig. 21. Breach openings (red) for the up-flooding in the Case 3.

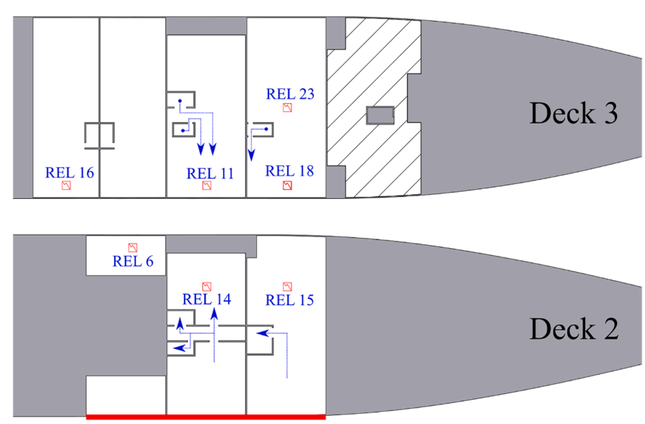

Fig. 22. Up-flooding routes from Deck 2 to Deck 3 in the Case 3.

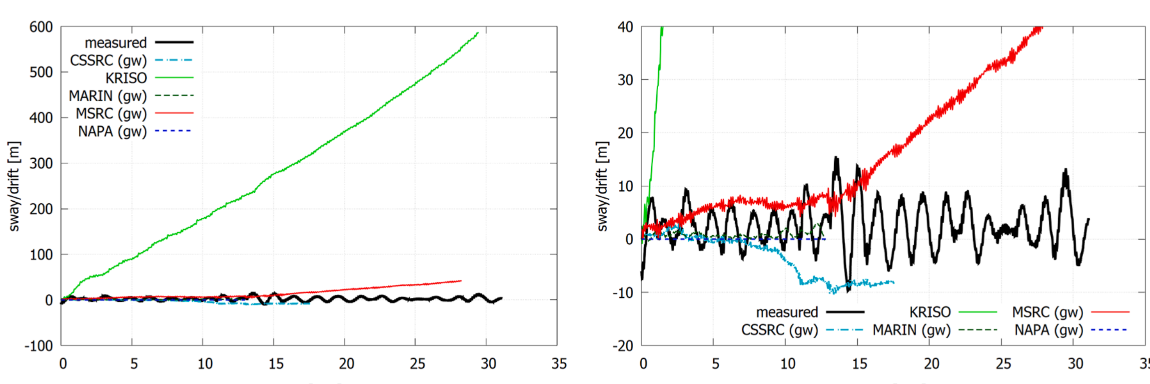

Fig. 20. Simulated drifting (i.e. sway motion) in the Case 2, the graph on the right shows the zoom to smaller values

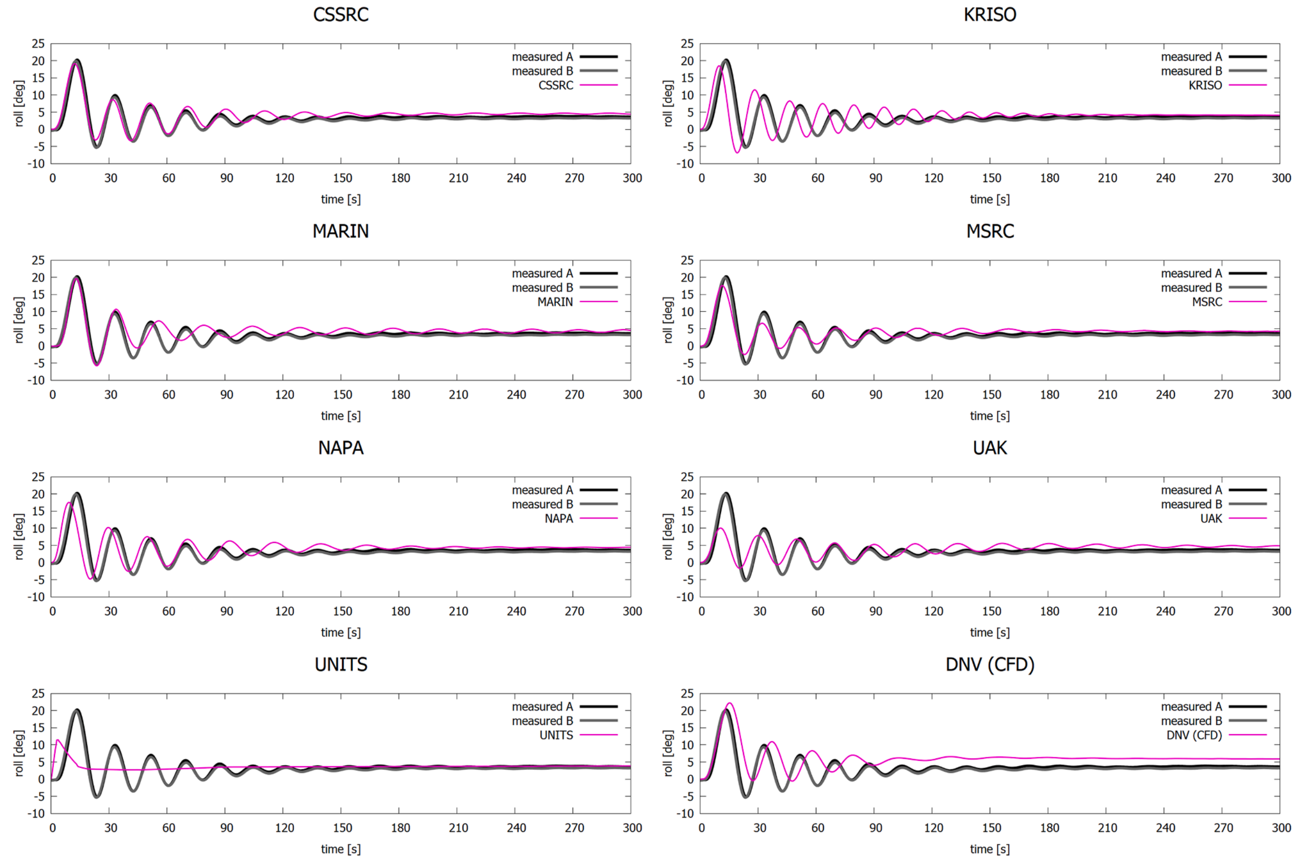

Fig. 23. Roll motion with different codes in the Case 3.

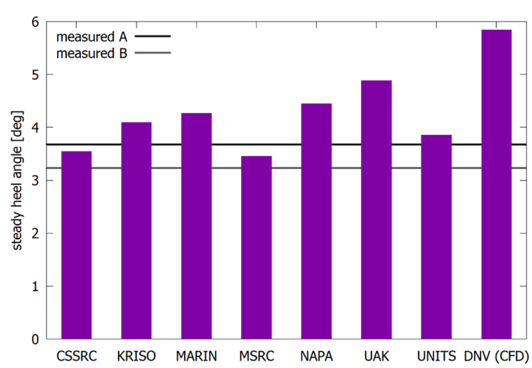

Fig. 24. Comparison of final steady heel angle with different codes in the Case 3

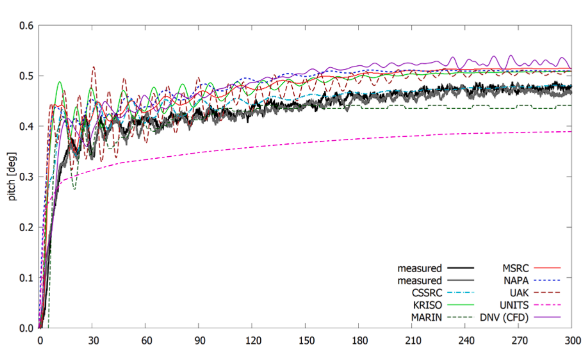

Fig. 25. Comparison of pitch motion with different codes in the Case 3.

water level at REL 11 is slower than measured, but at REL 18 somewhat faster. At both sensors the flow rate seems to slow down towards the equilibrium, a phenomenon that is also visible in the measurements. The CFD results with laminar flow model by DNV are in line with the Bernoulli-based methods. The up-flooding takes place through small vertical trunks (staircases and lifts), so the frictional flow losses on the trunk surfaces may be one explanation. Furthermore, the oscillations due to roll motion in the water levels at REL 11 and REL 18 are notably larger in the simulations than in the measurements.

The flooding condition at the maximum transient roll angle and at final condition are visualized in Fig. 27 from the CFD simulation results by DNV. At equilibrium, there is a small air pocket in the damaged side of the large U-shaped void in the aftmost compartment. Note that the air entrapment seen at the maximum transient roll in the complex aft compartment has disappeared in the final stage. These results indicate that air compression may have had some effect on the flooding progression in this damage case, but possible effects can be considered small.

8. Discussion

Flooding of a cruise ship with complex internal layout of the damaged compartments is a very complex process. This is challenging both in numerical simulation and in experimental tests in model scale. Unique tests were conducted in the EU Horizon 2020 project FLARE, that enabled an extensive benchmark study involving both transient and progressive flooding.

Compared to the latest ITTC benchmark study, van Walree and Papanikolaou (2007), some notable improvements are noted, both in the number of participants and in the quality of simulation results. Considering the results for progressive flooding in captive model tests in the first part of the FLARE benchmark, Ruponen et al. (2021), it is noted

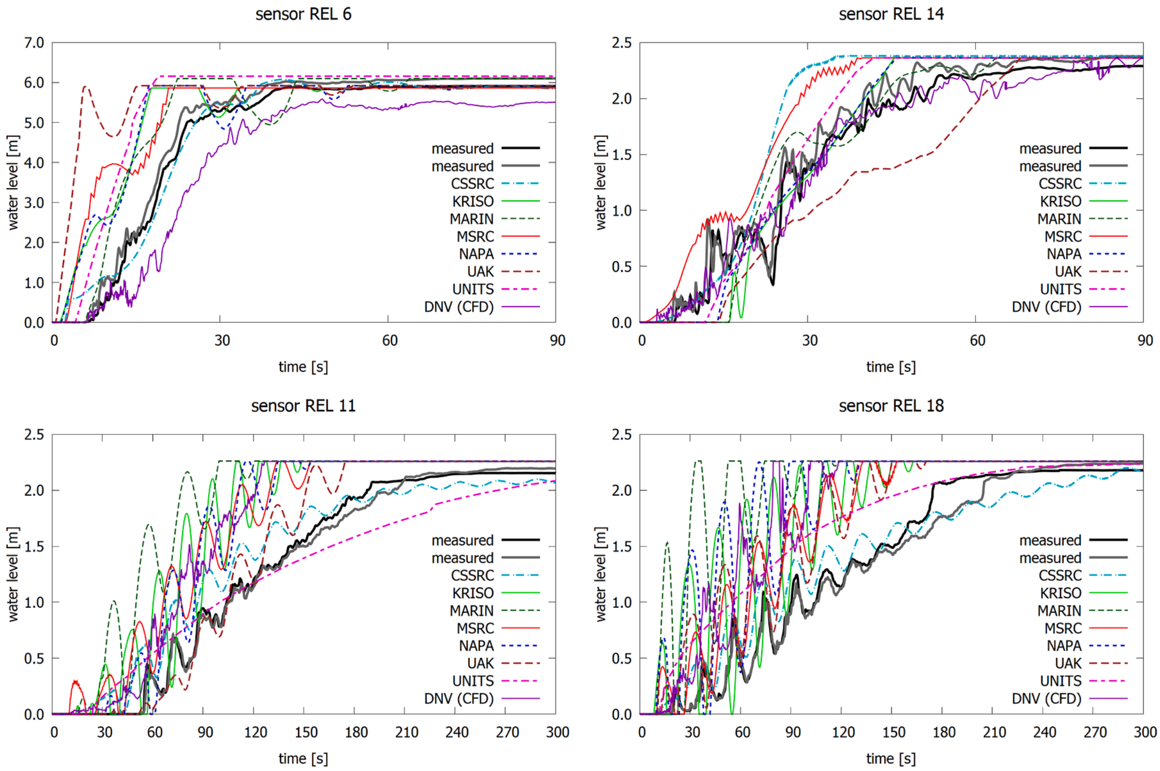

Fig. 26. Comparison of water levels in the flooded compartments in the test case 3 (sensor locations are shown in Fig. 22).

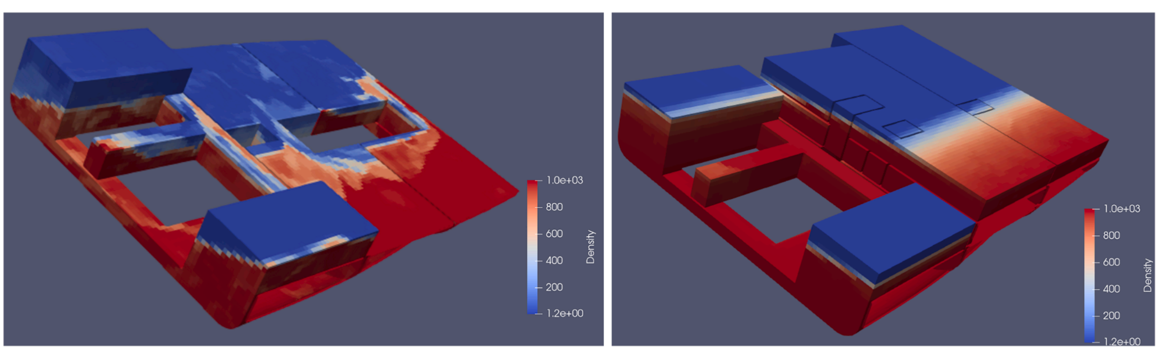

Fig. 27. Visualization of flooding progression inside the model in Case 3 from CFD results by DNV: maximum transient roll angle (left) and at final condition (right).

that all codes can capture the flooding progression rather realistically, but there is still notable deviation in the results. With a complex arrangement of flooded rooms of a cruise ship model, the differences are much larger, but the magnitude of transient roll angle can be captured well by most of the codes. Also the capsize in beam seas was properly predicted, but significant deviation was observed both in the time-to-capsize and in the distribution of floodwater at the time of capsize.

The main challenge with CFD tools is the required simulation time, making it currently unsuited for statistical evaluations with large numbers of simulations. The simulation codes that are based on a hydraulic model and Bernoulli's theorem are efficient, and the computations are typically notably faster than the simulated time. For CFD codes, the computation time is extensive, and in the Case 3, the computational time with CFD was almost 10 000 times longer than simulated time, even though model scale was used with assumption of laminar flow. Also the setup for the simulations is more laborious than with the simple and well-established Bernoulli-based codes. Although in general CFD can capture the internal flooding more realistically, instead of assuming that the water surfaces in the flooded rooms are either horizontal or inclined planes, in the present benchmark Case 3 the overall results are very similar with the other codes that are computationally much more efficient. Further studies on the benefits of CFD codes for detailed studies on flooding progression in complex arrangement of compartments should still be conducted, also considering turbulent flows and possible scale effects.

Although the hull form of the studied cruise ship design is very typical for modern large cruise ships, it was found out that it is not very suitable for benchmarking since the hydrostatic parameters are very sensitive to the modelling accuracy, especially at the selected intact draft. In future studies, a more conventional hull form should be adopted, along with somewhat simpler arrangement of the floodable compartments. Measured righting lever values for several heel angles should be given as input instead of specifying only the initial metacentric height. In addition, the effects of the mooring lines should be studied. Experiments with a freely drifting mode could be used, as instructed in ITTC (2017), which is a more realistic condition for a damaged ship in waves. On the other hand, then the drift loads should be modelled in the codes in order to get to the same timing of the model in waves. Also a smaller ship could be used, allowing a larger scale that would reduce the possible scale effects in the results.

9. Conclusions

Time-domain simulation of flooding and damaged ship motion is becoming a viable tool for survivability assessment for design of safer passenger ships. Consequently, validation and benchmarking of the applied simulation codes is essential. For this purpose, dedicated model tests have been conducted in the project FLARE, enabling an extensive benchmark study. The vast amount of internal wave probes in the model to measure the water levels throughout the flooded compartments was an essential part in the study.

The results show that time-domain simulation tools can capture the maximum transient roll angle for a passenger ship with an extensive breach and dense internal subdivision in the damaged compartments. On the other hand, notable differences were observed in the distribution of water inside the compartments during the flooding process. In calm water the differences were smaller, but in beam seas also the capsize mechanism was considered to be different between the codes. This indicates that further research and development of the simulation codes are still needed, especially regarding the effects of waves on the flooding process. On the other hand, the qualitative results of the benchmark study are rather promising, and the status of the flooding simulation tools have considerably improved compared to the last ITTC benchmark study, where a rather simple progressive flooding scenario in calm water was not properly captured by most of the codes. Based on the new results, the Bernoulli-based simulation codes, with proper modelling of roll dynamics and irregular waves, are considered suitable for survivability assessments of ships with dense internal non-watertight subdivision, such as cruise ships, with a focus on the probability of capsizing instead of the details of progressive flooding and accurate time-to-flood.

CRediT authorship contribution statement

Pekka Ruponen: Conceptualization, Methodology, Writing – original draft, Visualization, Writing – review & editing. **Rinnert van Basten Batenburg:** Conceptualization, Data curation, Investigation, Writing – review & editing. **Riaan van't Veer:** Conceptualization, Investigation, Writing – review & editing. **Luca Braidotti:** Investigation, Writing – review & editing. **Shuxia Bu:** Investigation, Writing – review & editing. **Hendrik Dankowski:** Investigation, Writing – review & editing. **Gyeong Joong Lee:** Investigation, Writing – review & editing. **Francesco Mauro:** Investigation, Writing – review & editing. **Eivind Ruth:** Investigation, Writing – review & editing. **Markus Tompuri:** Investigation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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7 PART C: ROPAX FLOODING

Pekka Ruponen, Petri Valanto, Maria Acanfora, Hendrik Dankowski, Gyeong Joong Lee, Francesco Mauro, Alistair Murphy, Gennaro Rosano, Riaan van't Veer,

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Results of an international benchmark study on numerical simulation of flooding and motions of a damaged ropax ship

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ABSTRACT

Survivability of damaged ships, especially ro-ro/passenger (ropax) vessels, is of paramount interest. Nowadays, time-domain simulation of flooding and motions of damaged ships are more frequently performed to obtain a more realistic overview of the actual survivability in case of a flooding accident. An international benchmark study on simulation of flooding and motions of damaged ropax vessels was conducted within the EU Horizon 2020 project FLARE, using new dedicated model tests as a reference. The test cases include transient flooding in both calm water and in irregular beam seas, as well as gradual flooding and capsizing in beam seas. The studied damage case is a two-compartment collision damage, and the studied intact metacentric height values were lower than the statutory requirements to achieve also capsize cases. Numerical results were carefully compared against measurement data from the model tests. In transient flooding cases the capsize conditions were generally detected well by most codes. However, much variation was observed in the internal flooding and capsize mechanisms. For gradual flooding in beam seas, the results for capsize rate and time-to-capsize were characterized by significant variability among the codes. Results indicate that more research is needed to further improve the time-domain flooding simulation methods to correctly capture both transient flooding phenomena and motions of damaged ship in high waves.

1. Introduction

Ro-ro ships are known to be vulnerable if the large open vehicle deck is flooded, and already the early experimental research on damage stability in waves by Middleton and Numata (1970) studied capsizing of a damaged ship in waves with large, flooded compartments. Later (Bird and Browne, 1974) focused on a ro-ro/passenger (nowadays known as ropax) ship model. The tragic accidents of the *Herald of Free Enterprise* in 1987 and the *Estonia* in 1994 further motivated model tests on accumulation of water on deck, such as Pucill and Velschou (1990), Dand (1991), Damsgaard and Schindler (1996), Molyneux et al. (1997) and Chang and Blume (1998). Thereafter, the so-called Stockholm Agreement model tests have been conducted especially for many existing ropax vessels, Schindler (2000), and also numerical simulation methods for the water on deck problem were developed, e.g. Chang (1999) and Vassalos (2000). During the past two decades, there has been extensive development in numerical tools for simulation of the flooding process and motions of damaged ships. An overview of these advancements was presented by Papanikolaou (2007), and subsequent progress is discussed in the review papers by Bačkalov et al. (2016) and Manderbacka et al. (2019).

Transient asymmetric flooding of damaged compartments was initially introduced in Spouge (1986) as an explanation for the rapid capsize of the ferry *European Gateway* in 1982. The first model tests on

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Table 1
Main dimensions of the studied ropax vessel.

	Full scale	Model scale
Length over all	About 162 m	About 5.8 m
Length between perpendiculars	146.72 m	5.24 m
Breadth	28.0 m	1.00 m
Draught	6.1 m	0.218 m
Height of ro-ro deck from baseline	9.2 m	0.329 m
Height of tank top from baseline	1.5 m	0.054 m
Gross tonnage	28 500	-

transient flooding were conducted with a simplified geometry, Vredeveldt and Journée (1991), and later also for ropax vessels, e.g. by Journée et al. (1997) and de Kat et al. (2000). A comprehensive review of the characteristics and entailed factors of transient and progressive flooding stages of damaged ro-ro vessels is given in Khaddaj-Mallat et al. (2011), emphasizing flooding of the large open main vehicle deck and possible transient flooding effects. More recently, studies on transient flooding with simplified model geometries, by Lorkowski et al. (2014) and Manderbacka et al. (2015), have focused on the dynamics of the floodwater in the compartments during the transient stage. In addition, the effects of the breach opening position and the internal arrangement of the flooded compartments in the steady state after transient flooding have recently been studied with model tests, Acanfora and De Luca (2016, 2017).

The previous benchmark studies on flooding and motions of damaged ships have been organized by the International Towing Tank Conference (ITTC), and reported by Papanikolaou and Spanos (2001, 2005) and van Walree and Papanikolaou (2007). The first two included also motions of damaged ropax vessels, while the third one focused on progressive flooding in a box-shaped model, Ruponen et al. (2007). An additional benchmark study with transient flooding of a ropax vessel was conducted within the EU FP6 project SAFEDOR, as reported by Papanikolaou and Spanos (2008). The analysis focused on the critical significant wave height for surviving the studied two-compartment damage case. In addition, several validation studies on individual codes with dedicated model tests, Lee et al. (2007), Hashimoto et al. (2017), Ypma and Turner (2019), or even full-scale flooding tests, Ruponen et al. (2010), have been published.

Considering the increased importance of time-domain flooding simulations and the newly developed codes since the previous studies, a new and extensive benchmark study was conducted within the EU Horizon 2020 project FLARE. The first part focused on fundamental flooding mechanisms with captive models, Ruponen et al. (2021), concluding that most participants were able to properly simulate simple up- and down-flooding cases. In the case of extensive progressive flooding on a deck with complex arrangement, there was quite large variation in the simulation results, but the relevant phenomena were properly captured. It was also noted that CFD codes can produce realistic results on the details of the flooding progression. However, only codes based on either Bernoulli's equation or shallow water equations were sufficiently fast for use in practical assessment of flooding and survivability of damaged ships.

The benchmark study continues with flooding of a ropax vessel both in calm water and in irregular waves, using measurements from new dedicated model tests at HSVA. The main purpose is to study the capability of currently available simulation tools to assess survivability of damaged ropax vessels, considering both transient and gradual flooding.

2. Benchmark study

2.1. Ropax ship model

An unbuilt ropax design (about 28 500 GT) provided by Meyer Turku was used. Tests were carried out at HSVA with a model in scale 1:28. Main parameters of the ship are listed in Table 1 both in full scale and in model scale. The lines drawing of the bare hull is shown in Fig. 1. All dimensions and results are presented in full scale.

At the studied draft of 6.1 m the minimum GM value according to the current SOLAS Ch. II-1 requirements is 3.2 m. This ensures a good survivability level, and therefore, much smaller GM values have been used in the model tests to achieve also capsize cases for proper benchmarking and validation of the numerical simulation codes.

The arrangement of the floodable compartments is shown in Fig. 2. There are no internal connections between the compartments. A two-compartment collision damage is studied, as described in detail in section 4. There is a casing on the port side of the centerline on the vehicle deck, having an impact on the accumulation of water on the deck in waves. All damaged compartments were ventilated through ventilation pipes in the compartment corners. Consequently, full ventilation is

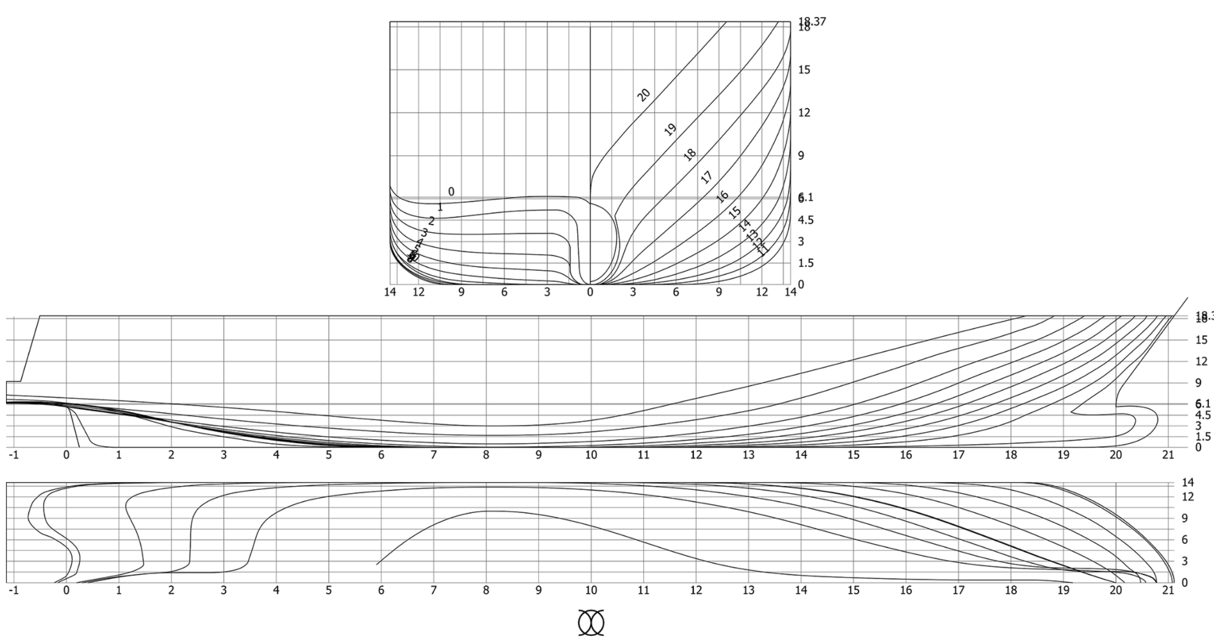

Fig. 1. Bare hull lines drawing of the studied ropax.

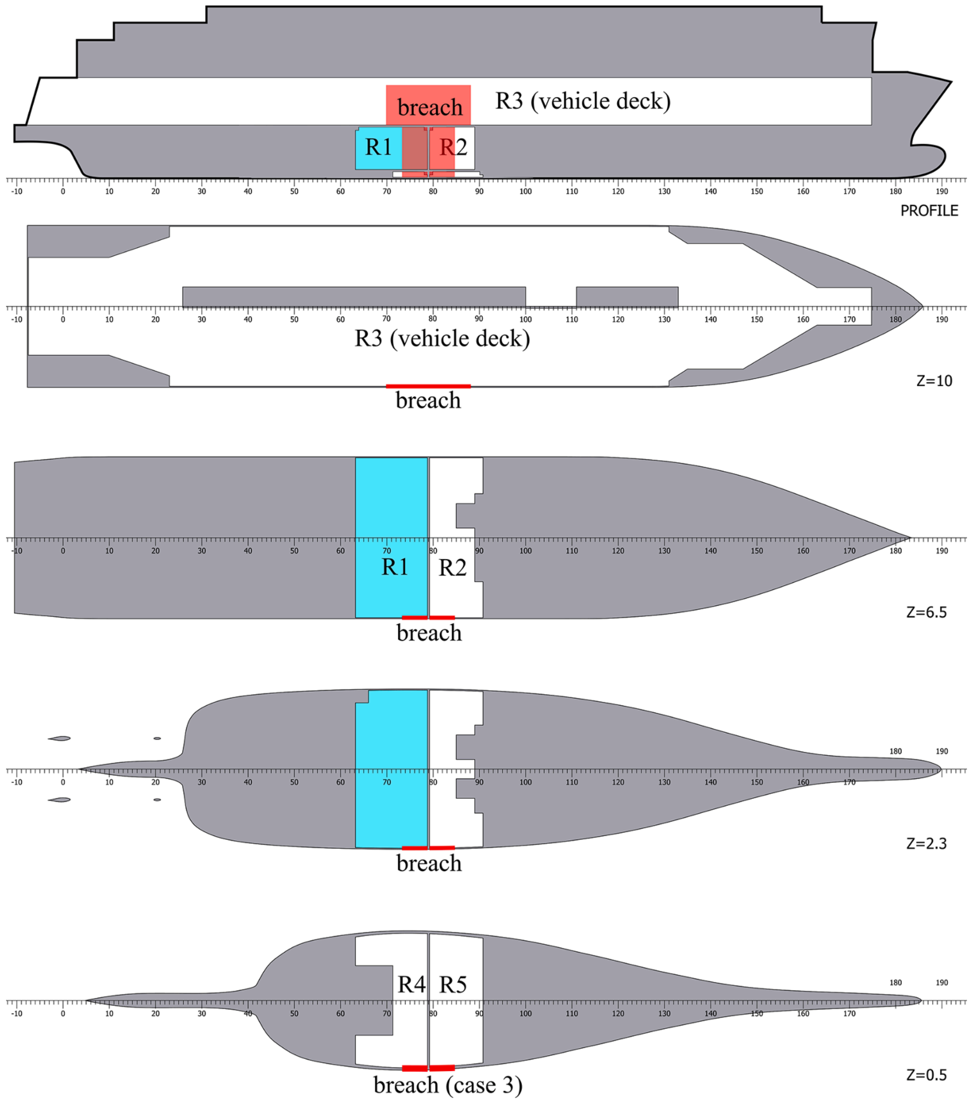

Fig. 2. Breach and floodable compartments of the ropax model; R1 is called "blue compartment", frame spacing is 0.8 m.

Table 2
Summary of the participation in the benchmark study: the symbol ✓ indicates participation in the case.

ID	Participant	Code	Treatment of floodwater surface	Case 1: transient flooding in calm water	Case 2: transient flooding in waves	Case 3: gradual flooding in waves
BROO	Brooks Bell (UK)	PROTEUS	horizontal plane	✓	✓	–
HSVA	Hamburgische Schiffbau-Versuchsanstalt GmbH (GER)	HSVA-Rolls	Shallow water eqs.	✓	✓	✓
KRISO	Korea Research Institute of Ships & Ocean Engineering (ROK)	SMTP	inclined plane	✓	✓	✓
MARIN	Maritime Research Institute Netherlands (NED)	XMF	inclined plane	✓	✓	✓
MSRC	Maritime Safety Research Center (UK)	PROTEUS	horizontal plane	✓	✓	✓
NAPA	NAPA (FIN)	NAPA	horizontal plane	✓	✓	–
UAK	University of Applied Science Kiel (GER)	E4 Flooding	horizontal plane	✓	–	–
UNINA	University of Naples Federico II (ITA)	FloodW	inclined plane	✓	✓	–

assumed in the simulations. Due to the large scale (1:28) of the model, the openings are quite large, and therefore, the industry standard discharge coefficient 0.6 was recommended for all openings. All participants were provided a detailed 3D model of the hull geometry and internal compartments. The thickness of the decks and bulkheads, as well as some support structures, were also taken into account.

2.2. Test cases

The flooding process of a damaged ropax ship can involve various phenomena, that are investigated separately in the benchmark study:

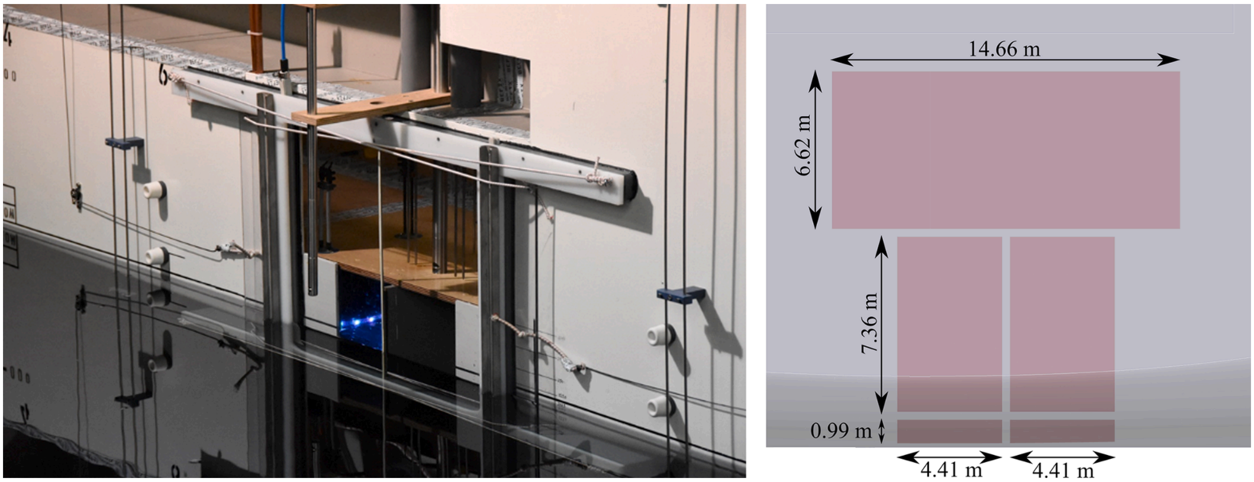

Fig. 3. Breach opening mechanism for the transient flooding tests (photo courtesy of HSVA) and full-scale dimensions of the breach.

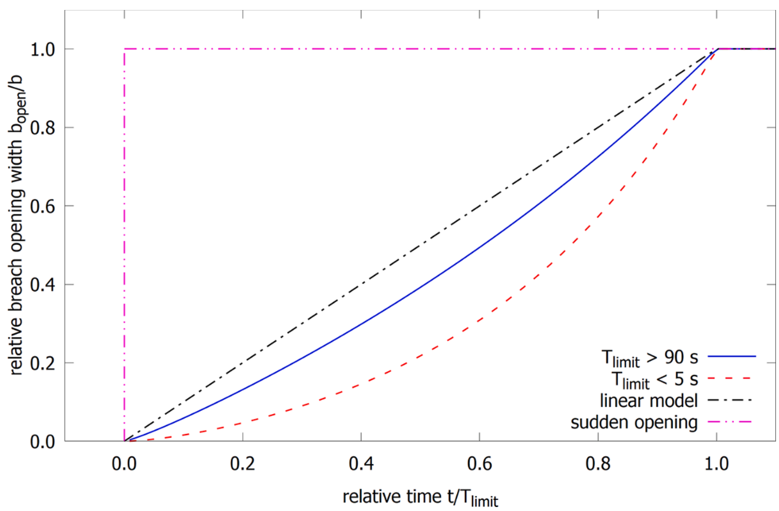

Fig. 4. Relative breach opening width as a function of time for the lower compartments.

Table 3
Natural roll period and logarithmic decrement parameters from the roll decay tests with an intact model for the initial conditions used in the benchmark study; values in full-scale; note that values in brackets were derived by interpolation.

GM (m)	Cases	Roll period (s)	*p* (-)	*q* (1/°)
1.338	1b, 1c	25.91	0.3658	0.02010
1.425	2a, 2b, 3a	(24.67)	(0.3612)	(0.02090)
1.505	1a	23.59	0.3565	0.02160
3.250	3b	15.84	0.1424	0.03545

1. Transient flooding in calm water with two different initial metacentric height (GM) values (Cases 1a and 1b) and a third one (Case 1c) with slower opening time for the breach
2. Transient flooding in waves with two small variations in the initial steady heel angle (Cases 2a and 2b)
3. Gradual flooding of the vehicle deck in waves in two different sea states (Cases 3a and 3b)

All participants were provided with a detailed geometry of the ship and description of the benchmark cases. In addition, time histories of the measured roll motion for the transient flooding cases were shared in

Table 4
Comparison of hydrostatic and compartment data (full-scale).

Code ID	**Buoyant hull up to T = 17.4 m**				**Volume of displacemet at T = 6.1 m**				**Floodable compartments**				**deck**
	V_{hull} m^3	X_{hull} m	Y_{hull} m	Z_{hull} m	V_{disp} m^3	X_{disp} m	Y_{disp} m	Z_{disp} m	V_{rooms} m^3	X_{rooms} m	Y_{rooms} m	Z_{rooms} m	**area** m^2
BROO	61675	66.746	0.000	9.655	16186	67.851	0.000	3.456	29629	63.233	-0.135	12.012	3089.6
KRISO	61646	66.709	0.000	9.669	16084	67.963	0.000	3.458	29899	62.660	-0.131	12.031	3101.0
MARIN	61606	66.833	0.000	9.665	16118	68.019	0.000	3.457	29627	63.233	-0.135	12.013	3090.3
MSRC	61677	66.768	0.000	9.661	16163	67.817	0.000	3.458	29651	63.245	-0.129	12.003	3081.7
NAPA	61702	66.771	0.000	9.657	16189	67.838	0.000	3.455	29625	63.231	-0.135	12.013	3089.7
UAK	61667	66.790	0.000	9.660	16162	67.909	0.000	3.456	29871	63.445	-0.148	11.958	3093.6
UNINA	61683	66.790	0.000	9.660	16170	67.910	0.000	3.460	29627	63.233	-0.135	12.013	3090.3

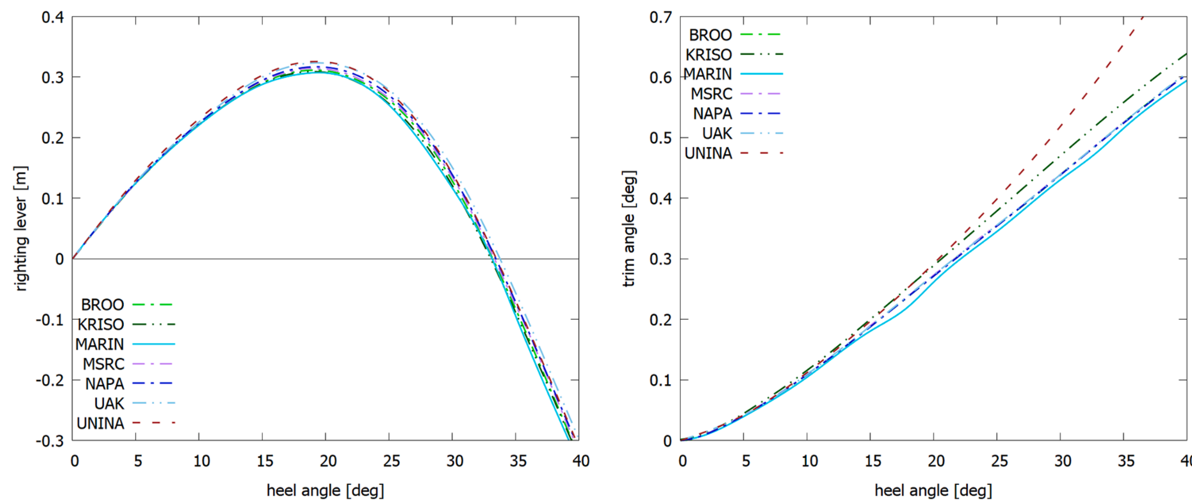

Fig. 5. Comparison of the righting lever curve (left) and trim angle (right) for an intact ship (GM = 1.505 m) with different codes, bow trim is positive.

Table 5
Test cases and initial conditions for transient flooding in calm water (values in full-scale, bow trim and heel towards damage are positive).

Case	Description	GM (m)	Initial heel (°)	Initial trim (°)	Opening time T_{limit}, lower breach (s)	Opening time T_{limit}, upper breach (s)
1a	Stable final equilibrium	1.505	-0.78	0.30	2.96	3.81
1b	Capsize case	1.338	-0.52	0.30	1.80	2.54
1c	Slower opening time	1.338	-1.01	0.33	94.61	136.73

graphical format, to ensure fair and equal conditions for all participants.

2.3. Summary of participation

In addition to the FLARE partners, also other organizations with recent publications on flooding simulations were invited to the benchmark study. In total eight organizations participated, using seven different simulation codes. A summary of the participants is presented in Table 2, including the method used for treatment of floodwater. The codes are mainly in-house software, developed at universities and research institutions. NAPA is a commercially available tool and PROTEUS, used by BROO and MSRC, is managed by Safety at Sea Ltd.

2.4. Applied simulation codes

All participants calculated the flow rates in the openings with a hydraulic model, based on Bernoulli's equation. The methods for treatment of floodwater vary between the codes, as presented in Table 2. In general, these can be divided into three separate groups:

- Shallow Water Equations (SWE) with a discretized free surface,
- inclined plane, based on an apparent gravity (lumped mass) or a simplified dynamic resonance model,
- simplified model with the free surface modelled as a horizontal plane.

In addition, different approaches for considering the hydrodynamic forces were applied. A detailed description of each code, including applied methods, modelling, and references, is presented below.

BROO & MSRC

In-house code **PROTEUS** owned by Safety at Sea Ltd. Originally developed at University of Strathclyde (MSRC). Flooding rates are

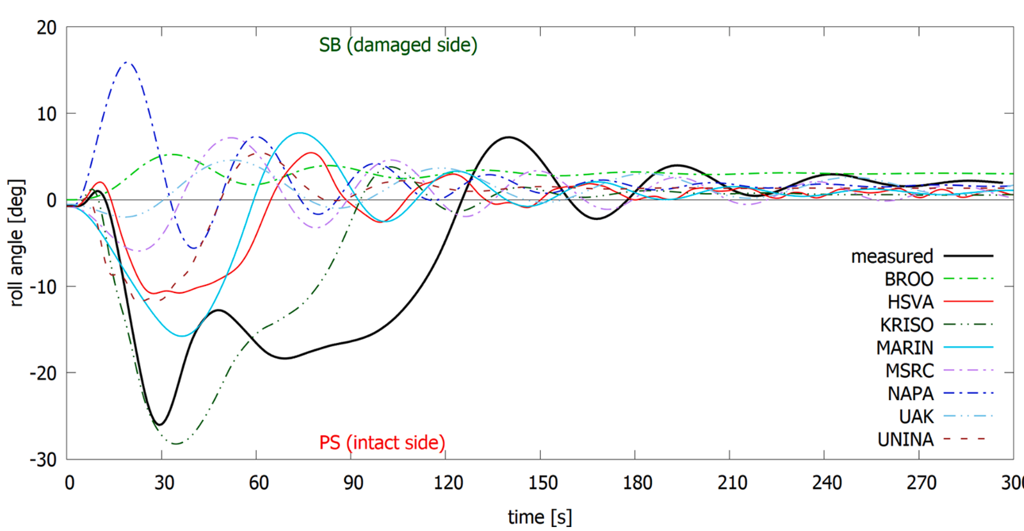

Fig. 6. Comparison of roll angle for transient flooding Case 1a with stable final equilibrium.

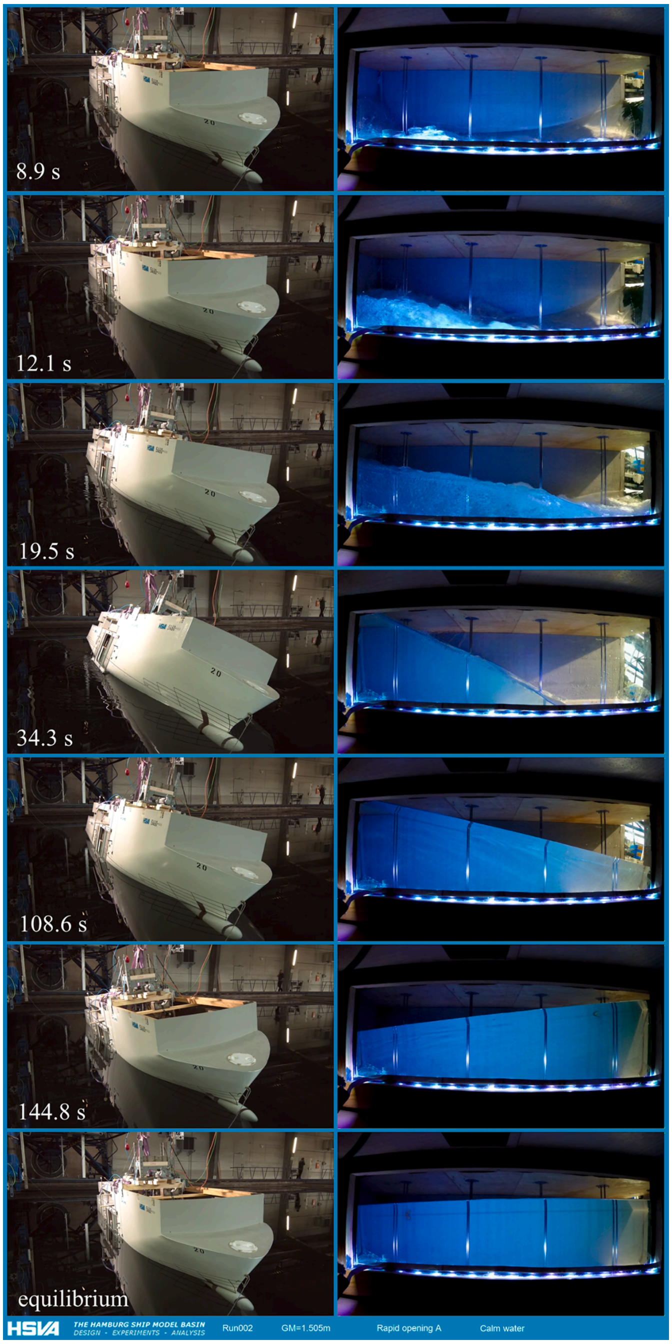

Fig. 7. Video captures showing the floating position and flooding of the "blue compartment" R1 in transient flooding in calm water, Case 1a, time stamps are in full scale; the compartment views show also the water level sensors.

calculated applying Bernoulli's equation with a hard-coded discharge coefficient of 0.6. The code has a feature for Free-Mass-In-Potential-Surface (FMPS), Papanikolaou et al. (2000), where the whole mass of water in the compartment is treated as a single point mass. However, in this benchmark study, both MSRC and BROO used the current default setting, where the FMPS model is omitted, and the calculation assumes that the water level inside a compartment is always parallel to the undisturbed sea water level. Froude-Krylov and restoring forces are integrated up to the instantaneous wave elevation both for regular and irregular waves. Radiation and diffraction are derived from 2D strip theory. Hydrodynamic coefficients vary with the attitude of the ship during the flooding process (heave, heel and trim). Details are presented in Jasionowski (2001). In the test cases, motions were evaluated by solving a 4 DOF system of equation (yaw and surge not modelled) assuming the vessel is allowed to drift freely. Hydrodynamic forces for the actual attitude of the vessel are obtained through interpolation on a precalculated set of forces obtained by 2D strip theory calculations. Drift forces are modelled according to empirical formulations. Compartments below the vehicle are considered as single rooms, while the vehicle deck has been divided at the centerline. Due to code limitations instant opening of the breaches was assumed in PROTEUS simulations, and consequently, BROO and MSRC did not provide results for the Case 1c.

HSVA

In-house version of the Rolls code, the **HSVA-Rolls** is used. Floodwater in internal compartments and decks can be modelled either with Shallow Water Equations (SWE) or with a pendulum model. For all cases in this study SWEs were used in all flooded spaces. Flow rates through the breaches are based on Bernoulli's equation. For the ship heave, pitch, sway and yaw motions the method uses response amplitude operators (RAO) determined in the frequency domain with a linear strip method. The roll and surge motions are determined with time-integration using non-linear equations of motion coupled with the other four degrees of freedom (DOF), with hydrodynamic contributions based on linear strip theory and nonlinear hydrostatics in waves (based on NAPA calculations). Additional roll moments to this equation are provided by the flood water motions in the internal compartments. The vehicle deck R3 was discretized with a 160 × 30 SWE grid resulting in altogether 3650 elements. In the transient Cases 1a to 1c rectangular 24 × 42 and 20 × 56 grids were used for the damaged R1 ('blue') and R2 compartments, respectively, whereas in the more gradual flooding Cases 2a to 3b in waves grid sizes of 12 × 28 and 10 × 28 for the R1 ('blue') and R2 compartments were used. In these cases the grid spacing was roughly 1.0 m for both longitudinal and transverse directions, whereas in the transient flooding cases finer grids in the two damaged compartments were found more appropriate.

KRISO

In-house code **SMTP** was used with flooding rates by Bernoulli equation and empirical discharge coefficients. The floodwater in compartments can be modeled either with a horizontal free surface or with a dynamic model in which the equation of motion of the mass center is solved using the tank resonance mode of the standing wave for the instantaneous water depth, and the resulting inclined free surface is used for the calculation of the pressure at openings. The compartments are treated independently, so the model can be selected appropriately to represent the property of each compartment. Ship motions are calculated by 6-DOF non-linear equations in time-domain, in which the Froude-Krylov and restoring forces are calculated for instantaneous wetted surface, and the hydrodynamic forces are calculated by the traditional strip method. The floodwater affects the ship motion as internal forces not as external forces, in other words, it changes the mass and its center of gravity resulting in changes of the inertial and gravity forces. Details are presented in Lee (2015a, 2015b). For this study, the large vehicle deck was divided into several compartments, and the dynamic resonance model of floodwater was selected for all compartments.

MARIN

The Extensible Modelling Framework (**XMF**) is a software toolkit on which all MARIN's fast-time and real-time simulation software is based applying Newtonian dynamics, of which Fredyn and ANySim are known examples. XMF is recently extended with a flooding module library (XHL) based on Bernoulli's equation with empirical discharge coefficients, using generic 3D defined floodable objects. A graph-solver technique is utilized to capture the complexity of entrapped air in compartments and for hydrostatic pressure-corrections from fully flooded compartments. To account for the flow inertia effects in the progression of flood water through the ship, the XMF framework is recently extended with a new inertia-based flow solver, denoted as the unified internal flow (UIF) module. The theory and first results of this solver are presented in van't Veer et al (2021). The presented MARIN results were obtained by using the Bernoulli-based flow equations, while the free

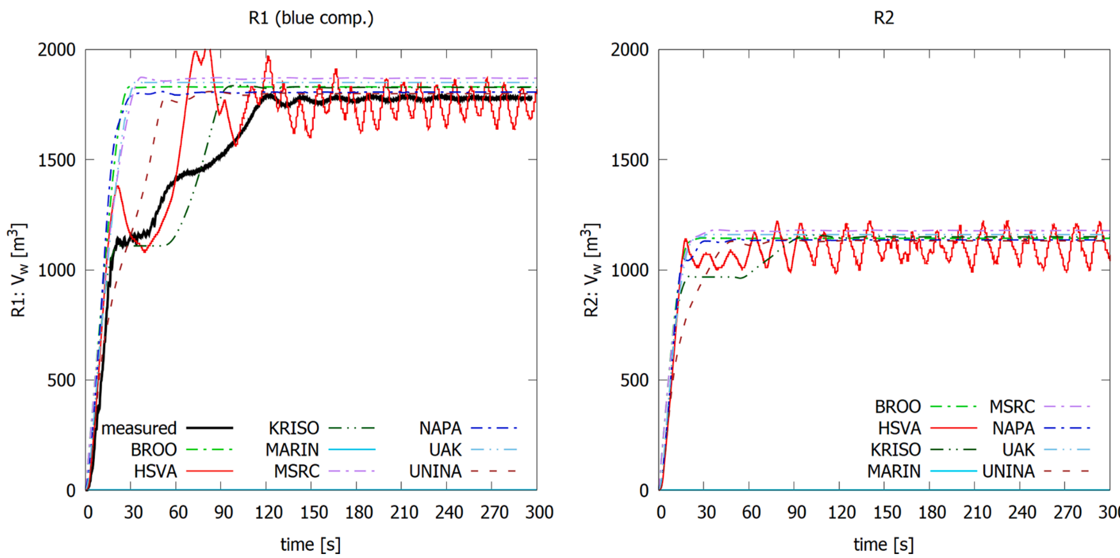

Fig. 8. Comparison of volumes of floodwater in transient flooding Case 1a with stable final equilibrium.

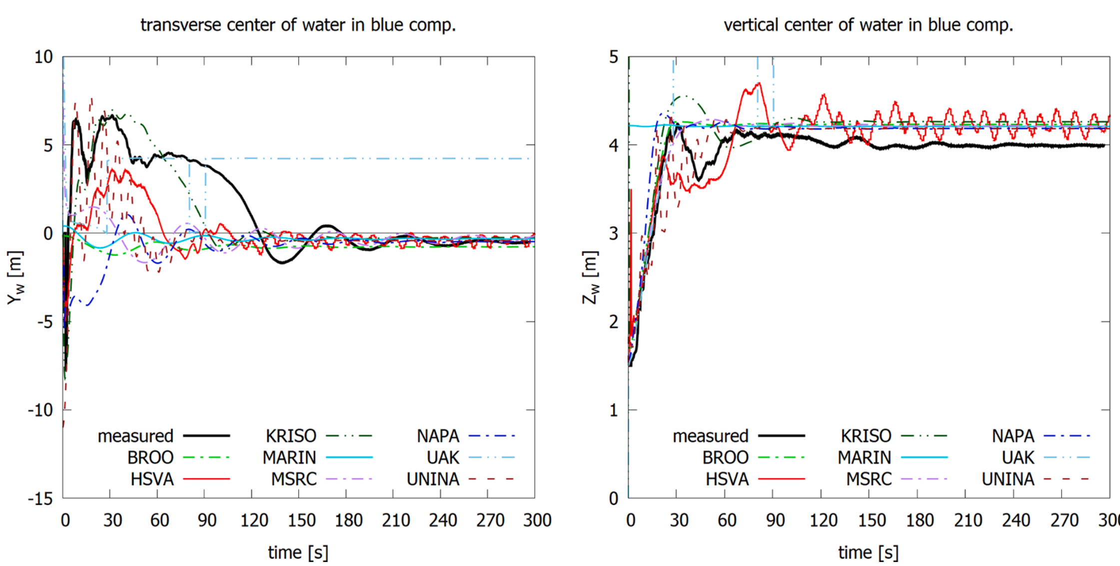

Fig. 9. Comparison of center of floodwater in the blue compartment R1 in transient flooding Case 1a with stable final equilibrium.

surface inclination due to the local effective gravity angle was used in the compartments R1 and R2. In other compartments a horizontal free surface was applied. The 6 DOF time domain solver is based on the convolution integrals, using memory functions obtained from frequency dependent hydrodynamic coefficients. The frequency domain hydrodynamic data was obtained from a linear 3D panel code PRECAL.

NAPA

The commercial software **NAPA** is used. The flow rates are calculated from Bernoulli's equation, with user-defined discharge coefficients for each opening. Horizontal free surface is assumed in all flooded rooms. Pressure-correction algorithm is applied to solve the governing equations (continuity and Bernoulli). Dynamic roll motion is solved with empirical user defined coefficients for intact ship. Draft and trim are treated as quasi-static. Effect of waves are considered only for flooding through the breach openings. Details are presented in Ruponen (2007, 2014). The simulation method is primarily intended for progressive flooding analyses. Since horizontal water levels are assumed, the two damaged compartments below the vehicle deck were divided at the centerline (CL), and the parts connected by a large opening (size equal to the intersection of the room at CL).

UAK

In-house code **E4 Flooding Method**, with flooding calculated by using Bernoulli's equation with horizontal surface and flooding path modelled as directed graphs. Ship motions either 3-DOF quasi-static or 6-DOF dynamic, with support for regular waves and other effects, e.g. interaction with cargo and seabed, Dankowski and Dilger (2013), conditional openings and leakage, Dankowski et al. (2014) and cargo shift. Details of the simulation method are presented in Dankowski (2013) and Dankowski and Krüger (2015).

UNINA

In-house tool **FloodW**, coded in Matlab-Simulink. Flooding rates are calculated based on Bernoulli's equation with empirical discharge coefficients. Floodwater is treated as lumped mass in agreement with the pendulum model. The position of the lumped mass, given the amount of floodwater and the free surface inclinations, depends on the tank geometry. The free surface is treated as a non-horizontal plane because normal to the so-called apparent gravity vector, (accounting for the instantaneous accelerations of the floodwater). Therefore, the free surface can have different inclinations from the ship roll and pitch angles. The code is able to perform 6-DOF simulations of the ship behavior both

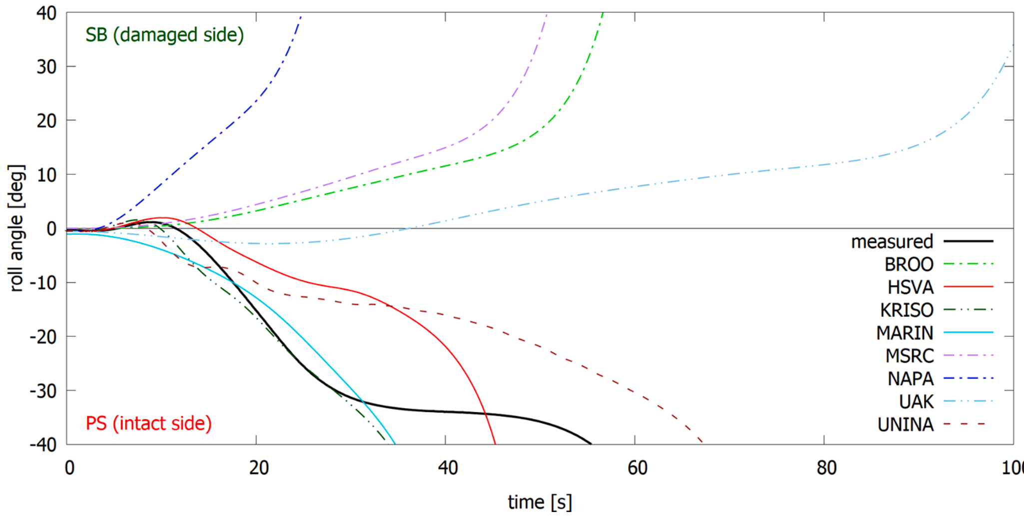

Fig. 10. Comparison of roll angle for transient flooding Case 1b with capsize.

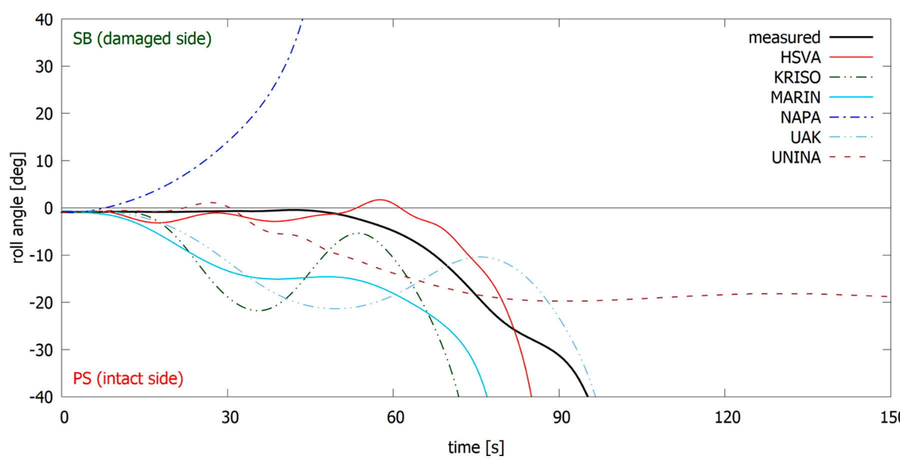

Fig. 11. Roll angle in transient flooding in calm water with slow opening of the breach, Case 1c.

Table 6
Initial conditions for transient flooding in waves (values in full-scale, bow trim and heel towards damage are positive).

Case	Initial heel (°)	Initial trim (°)	Opening time T_{limit}, lower breach (s)	Opening time T_{limit}, upper breach (s)
2a	1.15	0.47	2.08	2.86
2b	-0.39	0.45	2.22	2.96

in intact and damaged conditions. The hull is discretized into panels. Regular and irregular wave effects are modelled, accounting for all relevant nonlinearities, Acanfora and Rizzuto (2019). Details are presented in Acanfora and Cirillo (2016, 2017) and Acanfora et al. (2019).

3. Model tests

3.1. Damage case

The examined damage is a collision breach on the starboard side, extending to two watertight compartments. The breach opening consists of two rectangles, one below the main vehicle deck and one above. Only the side shell is removed from the model, as shown in Fig. 3, and there are no cuts in the decks or bulkheads. In the transient flooding tests (Cases 1 and 2) the breach is initially closed by two sliding doors, and the double bottom rooms (R4 and R5) are intact. In the tests for gradual flooding in waves (Case 3) the whole breach is open and all the compartments below the vehicle deck (R1, R2, R4 and R5) are already flooded, i.e. open to sea, when the test begins.

In the transient flooding tests (Cases 1 and 2), the breach is initially closed by two sliding doors. When the test begins, both doors slide away from the transverse bulkhead (see Fig. 3), and the widths of the breaches to the compartments increase. The breach opening mechanism in the model tests was operated with elastic bands. The sliding doors had some inertia and also the static friction in the system was bound to be higher than the sliding friction. For these reasons, the rate of opening was not completely linear and depends on the opening time T_{limit} of the lower compartments (R1 and R2). Based on detailed analyses at HSVA, the open width of the breach to these compartments in the case of rapid opening, $T_{limit} < 5.0$ s is approximately:

$$b_{open}(t) = b \cdot \left(\frac{t}{T_{limit}}\right)^{1.7+\frac{t}{T_{limit}}} \tag{1}$$

where b is the total width of the breach opening, as presented in Fig. 3. For slow opening process, $T_{limit} > 90.0$ s:

$$b_{open}(t) = b \cdot \left(\frac{t}{T_{limit}}\right)^{1.2+0.3\frac{t}{T_{limit}}} \tag{2}$$

The times are given in full scale. Both functions, along with a linear assumption, are presented in Fig. 4. Due to code limitation, BROO and

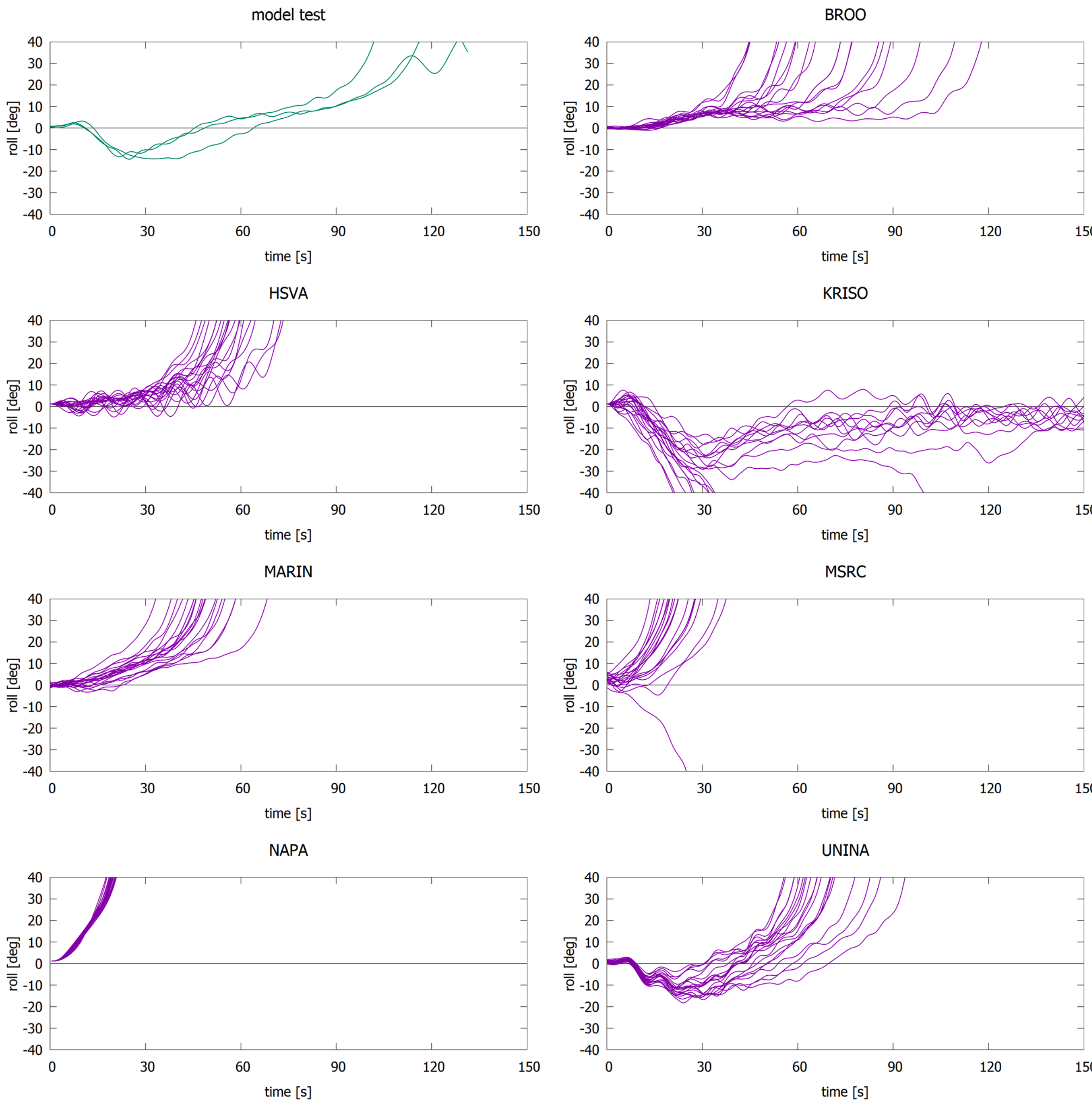

Fig. 12. Development of roll angle in transient flooding with small initial heel towards the damage (Case 2a).

MSRC modelled breaches to be suddenly opened. KRISO, MARIN, NAPA and UAK applied the linear model, whereas HSVA and UNINA used the approximate functions, (1) and (2). The opening time of the breach to the vehicle deck is less important in the studied transient flooding cases since in the benchmark cases it is not submerged until the doors are fully open. For each transient flooding case, the T_{limit} values are given in tables in the following sections.

3.2. Test setup and measurements

All the tests were conducted for a freely drifting model. For the tests in waves, bow and stern lines were occasionally used to correct the model orientation back to beam seas condition. For practical reasons, the roll angle of 36° was used as the nominal limit for capsizing, and the test was interrupted when the roll angle exceeded this limit.

The model was equipped with instruments to measure the 6 Degrees-of-Freedom motions, the relative wave elevations at several positions on and below the main vehicle deck. All data were recorded at a sampling rate of 100 Hz in model scale, which corresponds to 18.9 Hz in full scale.

Four video cameras were used to record the tests, two outside cameras focusing on the ship motions, one recording the water elevation in the compartment R1 below the main vehicle deck, and one showing water ingress to the vehicle deck (room R3).

For transient flooding cases the volume of water and its centroid in the blue compartment R1 were analyzed by HSVA based on the six water level sensors in the compartment. These sensors were located transversally, and therefore, the analysis is based on the assumption of two-dimensional water surface.

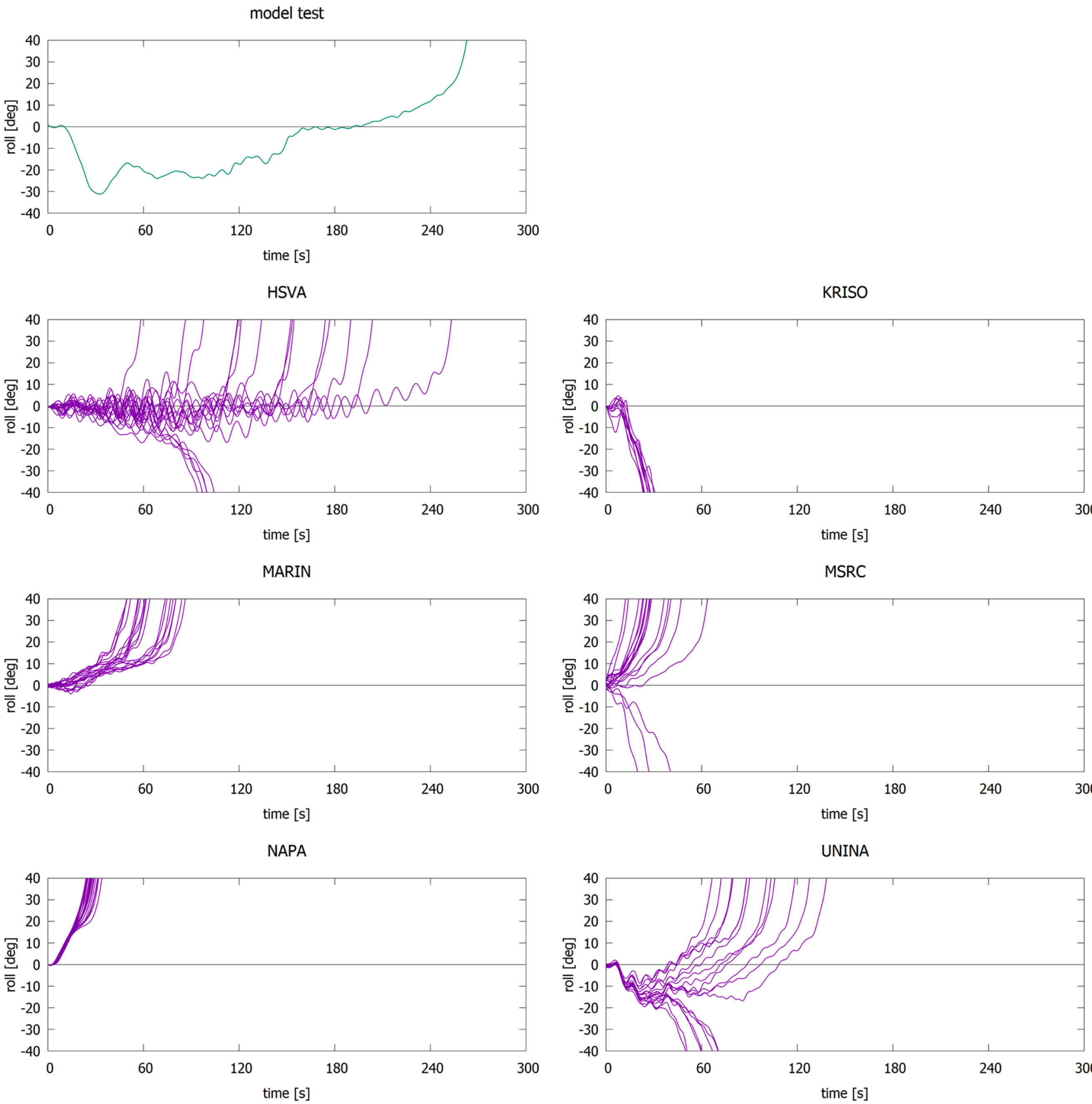

Fig. 13. Development of roll angle in transient flooding with small initial heel away from the damage (Case 2b).

3.3. *Roll damping characteristics*

The model included shaft lines, rudders, and bilge keels. In the tests with transient flooding (Cases 1 and 2), the bilge keels on the starboard side were removed to compensate the additional roll damping of the door supporting frame (see Fig. 3). Roll decay tests were conducted by HSVA for an intact model with the bilge keels and other appendages, and the results presented in Table 3, were provided beforehand to all participants. For roll damping characteristics, the logarithmic decrement:

$$\Lambda = \ln\left(\phi_{a,i} / \phi_{a,i+1}\right) \tag{3}$$

where $\phi_{a,i}$ and $\phi_{a,i+1}$ are roll amplitudes (separated by one roll period), was provided as a linear fit:

$$\Lambda(\phi_a) = p + q\phi_a \tag{4}$$

The coefficients p and q are given in Table 3, along with the measured roll period. For GM = 1.425 m (in Cases 2a, 2b and 3a) interpolated values were used, as indicated in Table 3.

4. Comparison of hydrostatics

In order to ensure that all participants had modelled the hull form and floodable compartments accurately, some basic hydrostatic results were collected and checked beforehand, Table 4. Buoyant hull was considered to extend up to 17.4 m above the baseline. The volumes of the hull and displacement (V_{hull} and V_{disp}), as well as the center of the buoyant hull (X_{hull}, Y_{hull}, Z_{hull}) and the center of displacement at intact draft (X_{disp}, Y_{disp}, Z_{disp}) were compared. In addition, the total volume and center of the floodable compartments (V_{rooms}, X_{rooms}, Y_{rooms} and Z_{rooms}) were checked, as well as the deck area of the vehicle deck (room

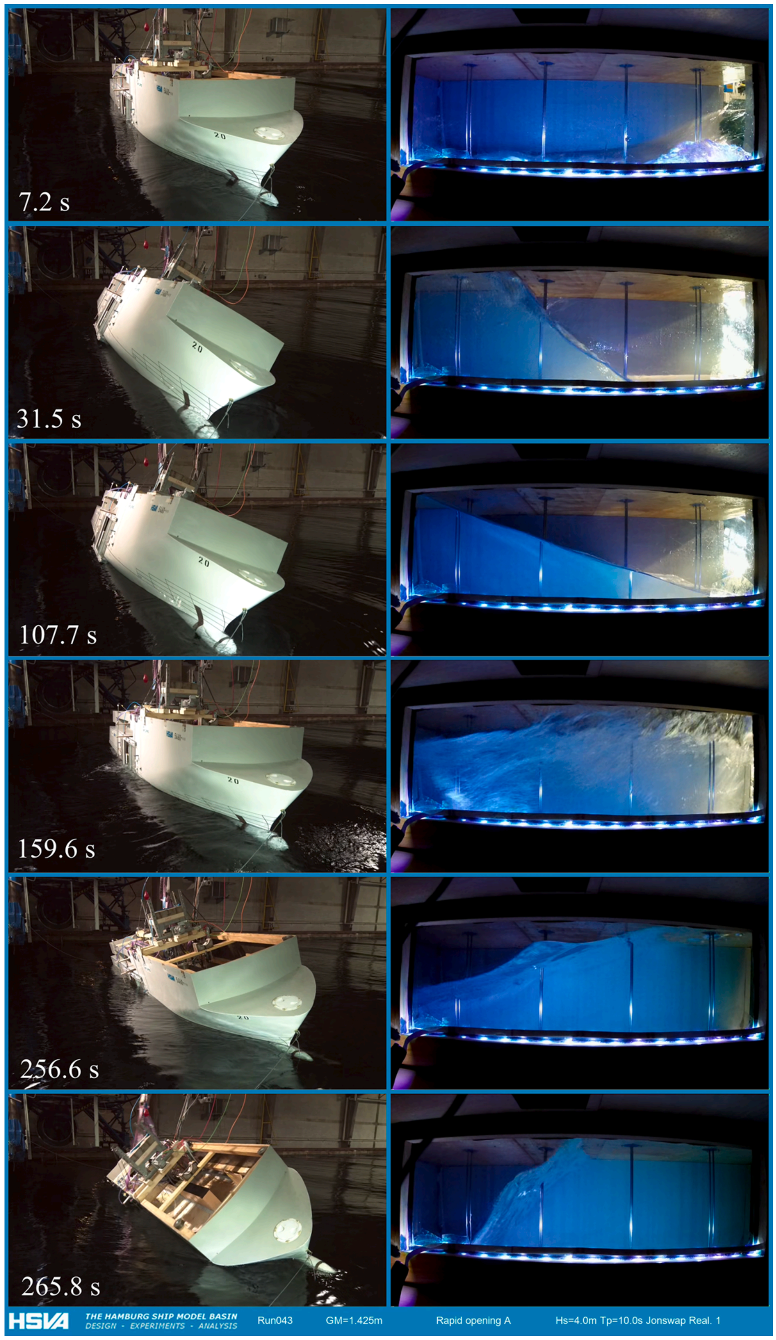

Fig. 14. Video captures showing the floating position and flooding of the "blue compartment" R1 in transient flooding in beam seas, with small initial heel away from the damage Case 2b, time stamps in full scale.

R3). No significant deviations in either volumes or the centroids between the different codes were found. Consequently, the numerical models of the ship are considered similar enough, and thus suitable for benchmarking.

Intact stability characteristics of the ship were compared at an upright condition with initial metacentric height of 1.505 m (in full scale). The righting lever curves and related trim angles, as calculated with different codes, are presented in Fig. 5. Some small variation at large heel angles can be observed, especially regarding the trimming of the ship. On the other hand, some curves are practically overlapping, and thus not clearly visible in Fig. 5. In general, the restoring moments are very similar. Moreover, the hull form is rather conventional, and there are no significant discontinuities in the waterplane area around the studied draft. Therefore, small differences in the modelling of the hull form are not expected to have a notable effect on the hydrostatic quantities. It should be noted that the hydrostatics from HSVA were based on pre-calculated hydrostatics using NAPA Software, and hence they are not included in the comparison.

5. Transient flooding in calm water (Case 1)

With a low metacentric height, the transient flooding can cause a large roll even in calm water, and in a worst case this results in capsize. Moreover, the time frame when the breach is introduced can have notable effects on the transient response, de Kat et al. (2000). Consequently, three separate test cases were included. The initial condition for each case is listed in Table 5, based on measured floating position of the model just before flooding was initiated. It should be noted that all

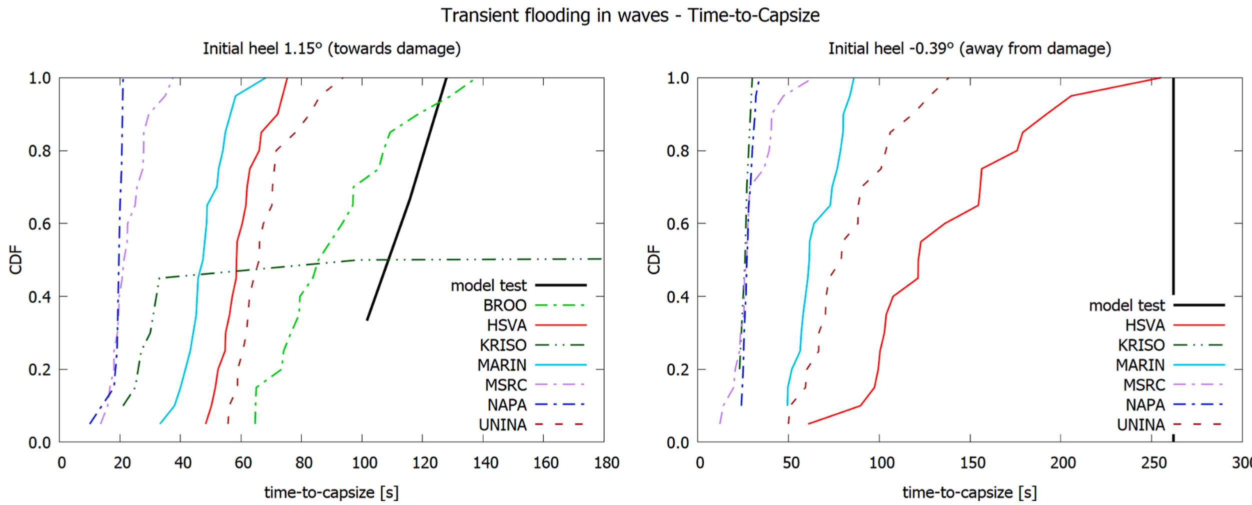

Fig. 15. Cumulative time-to-capsize for transient flooding in waves with different initial heel angles, Case 2a on left and Case 2b on right.

Table 7
Test cases for gradual flooding in waves.

Case	H_s (m)	T_p (s)	Intact draft (m)	Intact GM (m)
3a	3.5	10.0	6.10	1.425
3b	7.5	10.0	6.10	3.250

studied GM values are significantly below the minimum value to pass the SOLAS Ch. II-1 requirements, in order to produce interesting phenomena, including a capsize, for benchmarking purposes. It is also emphasized that the objective was not to investigate the real survivability of the ship design. Furthermore, Table 5 contains the times for opening the doors that cover the breach openings. The effective width of the breach as a function of time can be estimated by using equations (1) and (2). These can also be used for the upper part of the breach to the vehicle deck (room R3), but it is irrelevant since the whole breach was already open when this part of the breach was immersed in all test cases.

5.1. Transient flooding with stable final equilibrium (Case 1a)

In the first test case the ship has a low initial metacentric height GM = 1.505 m (full scale), but it is still sufficient for achieving a stable equilibrium floating position after flooding. Before the test, the model had a small steady initial heel angle -0.78° (away from the damage), and a zero initial roll velocity was applied as initial condition.

Initially the ship rolls towards the damage (positive roll angle) but the actual transient roll is towards the intact side (negative roll angle). After about 120 s (full-scale) the ship has recovered from the transient roll towards the intact side and starts to roll towards the damaged side. Eventually, the roll decays to a small stable heel angle towards the damage, see Fig. 6. Similar transient roll towards the intact side has been previously observed with a box-shaped barge model, Manderbacka et al. (2015).

The large transient roll towards the intact side is explained by the momentum of the in-flooding water, and possibly also with small initial

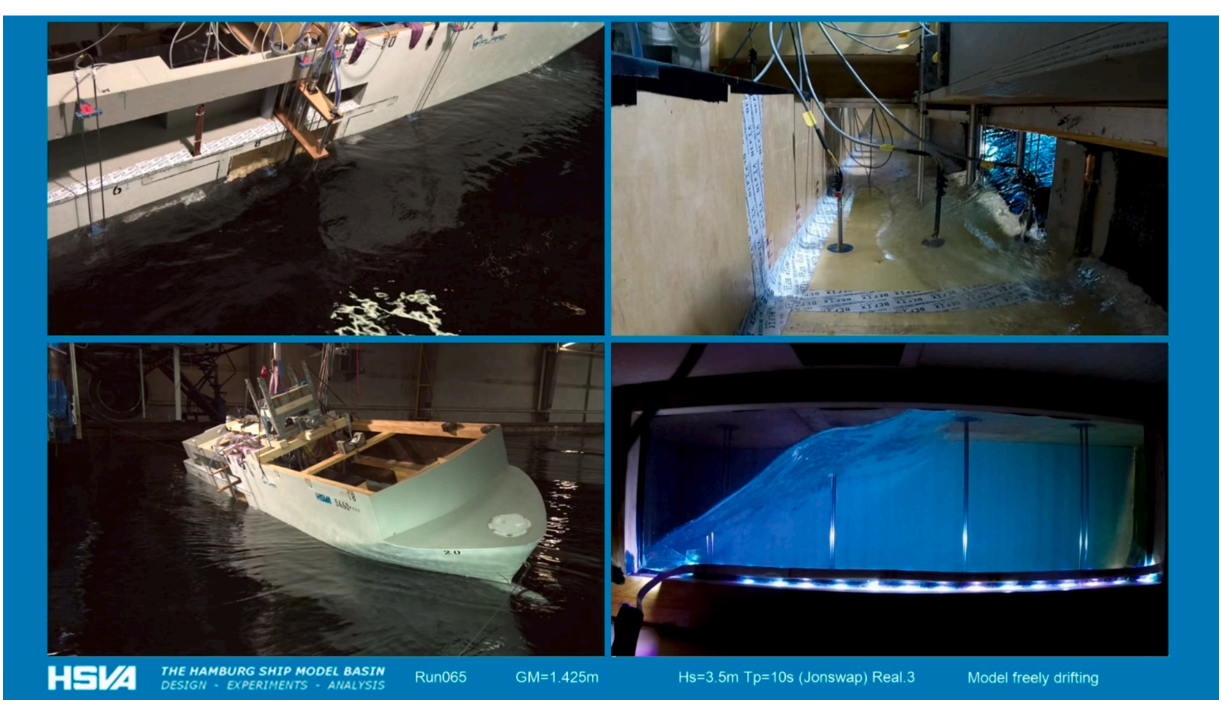

Fig. 16. Video capture on gradual flooding in beam seas (Case 3a) with H_s = 3.5 m when the main vehicle deck is being flooded, resulting in capsize.

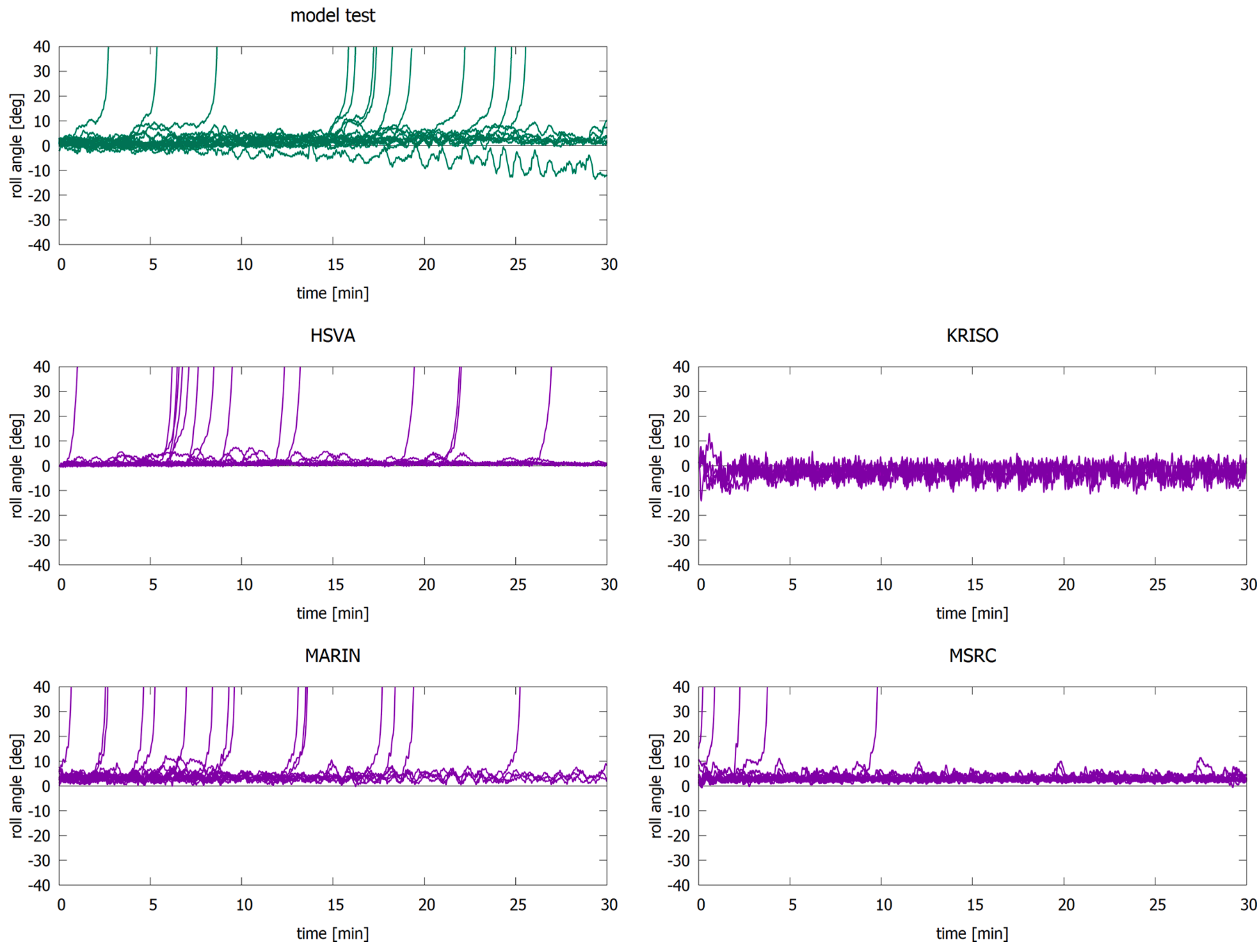

Fig. 17. Measured and simulated roll angle for 20 wave realizations for Case 3a with $H_s = 3.5$ m.

heeling towards that side. Some video captures showing the floodwater in the "blue compartment" R1 and the corresponding floating position of the model are presented in Fig. 7. It can be clearly seen that floodwater initially accumulates on the intact side of the compartment. HSVA has analyzed the time histories for the volume and center of floodwater in R1, based on the signals from six water level sensors in this compartment. Comparisons of the volumes of floodwater in both compartments R1 and R2 are shown in Fig. 8 and for the center of floodwater in R1 in Fig. 9.

The code by KRISO predicts the trend of the development of roll motion very well, only the peak angle is slightly overestimated. Also HSVA, MARIN and UNINA capture the transient heeling towards the intact side, but the magnitude is notably smaller. HSVA, KRISO and UNINA also capture the small initial roll towards the damage before the larger transient roll towards intact side, whereas MARIN predicts roll towards intact side from the beginning of the flooding. MSRC predicts the initial roll direction to intact side correctly, but the peak is about 20° smaller than measured. BROO used the same code but applied zero initial heel, resulting in transient roll towards the damage. Also UAK predicts similar development of roll, but with smaller magnitude than MSRC. Similarly, the quasi-static flooding model in NAPA predicts a transient roll towards the damage.

There is some variation in the final equilibrium heel angle, however, in general, the results are rather consistent, especially when considering the low initial GM of the ship and extensive flooding.

The underestimation of the transient roll towards the intact side results in too fast flooding of the breached compartments, see Fig. 8. Comparison of the transverse center of floodwater in the compartment R1, Fig. 9, explains the observed results in the roll angle with different codes. It is also noted that the HSVA simulation, based on SWE, results in larger oscillations in the volumes of floodwater than the simulations with other codes assuming either horizontal or inclined flat water surface in the compartments.

5.2. Capsize during transient flooding (Case 1b)

In the second transient flooding case, the initial metacentric height was lowered to GM = 1.338 m, which is low enough to cause a capsize in calm water. Before the test, the model had a small stable initial heel angle -0.52° (away from the damage) and trim angle of 0.30° (to bow). The lower part of the breach was opened in 1.80 s (full scale) and the breach of the vehicle deck in 2.54 s. The comparison of measured and simulated roll angles is shown in Fig. 10. Roll motion towards the damage is minimal, and after about 12 s (full scale) the ship starts to roll towards the intact side and capsizes in about 55 s.

HSVA, KRISO and UNINA can correctly capture small initial roll towards the damage and the subsequent roll away from the damage, although there is quite notable difference in the actual time-to-capsize. Also MARIN predicts well the capsize towards the intact side but the small initial roll towards the damage is not captured. BROO and MSRC simulations result in roughly correct time-to-capsize, but the ship capsizes towards the damaged side. Both participants used the same PROTEUS code, and their difference in the TTC is likely caused by the different initial condition since BROO applied zero initial heel and MSRC considered the small initial heel angle. Also NAPA predicts capsize towards the damaged side, with too short TTC. UAK estimates initial roll towards the intact side, but this is slowly equalized, and eventually the ship capsizes towards the damaged side with significantly

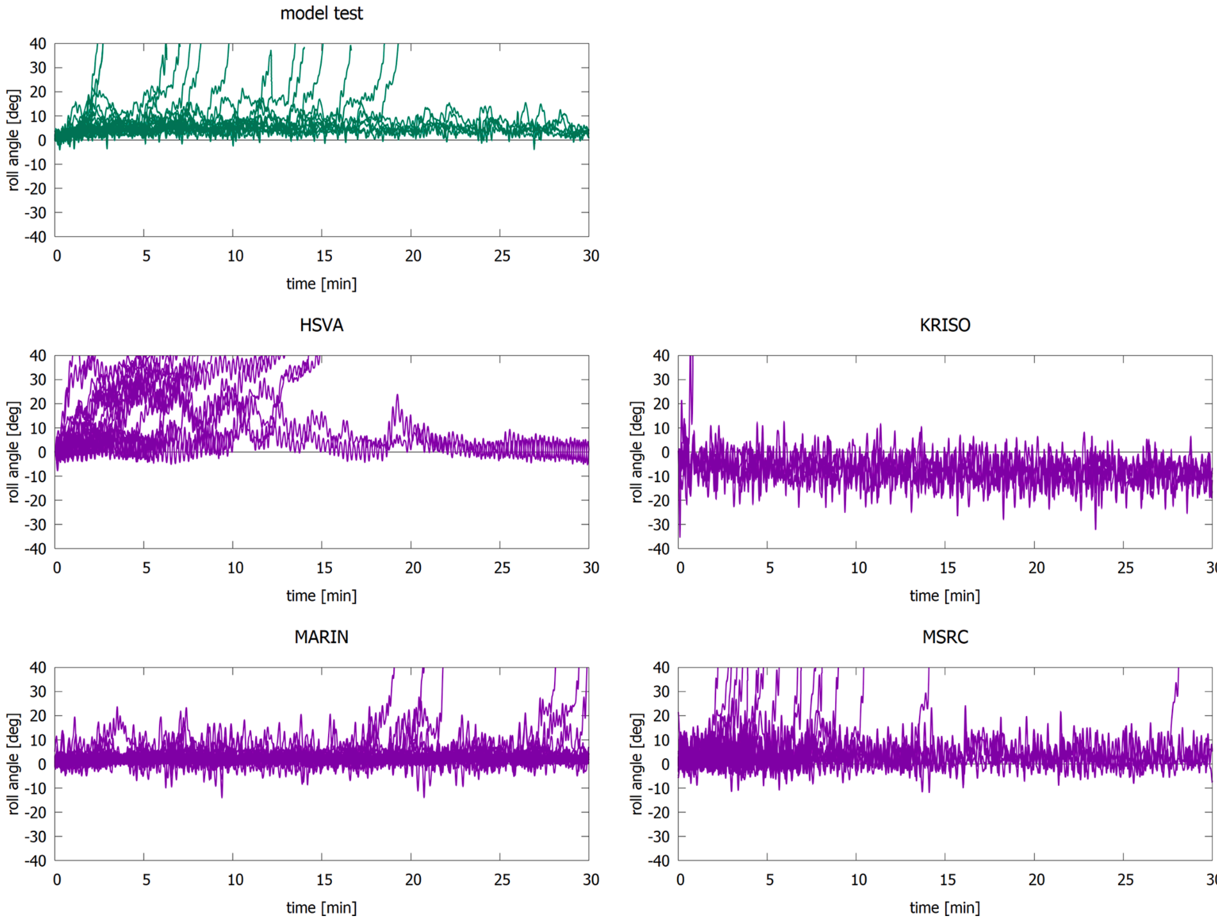

Fig. 18. Measured and simulated roll angle for 20 wave realizations for Case 3b with $H_s = 7.5$ m.

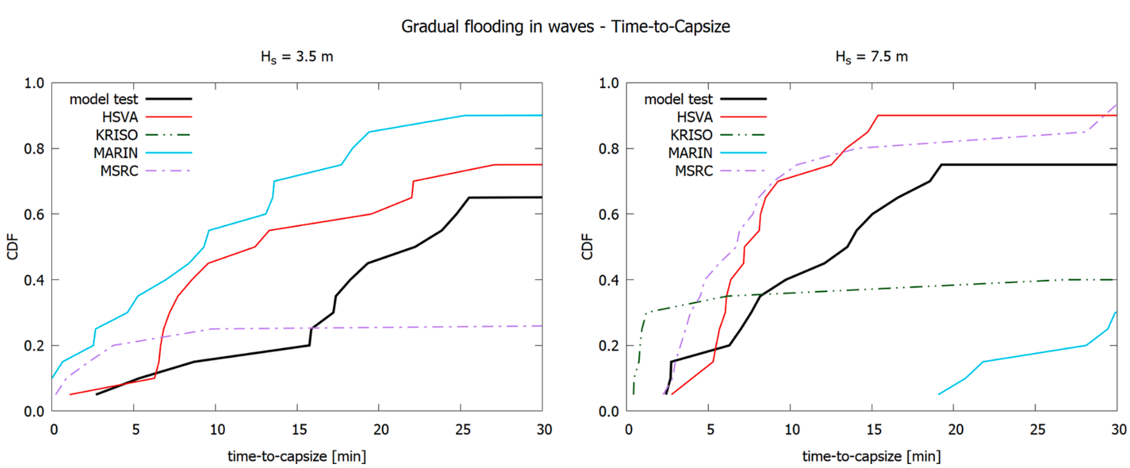

Fig. 19. Cumulative distribution of time-to-capsize (TTC) for Case 3a with $H_s = 3.5$ m (left) and for Case 3b with $H_s = 7.5$ m (right).

Table 8
Capsize rate from 20 repetitions in the same sea state for 30 min (full scale).

Case	H_s	Model tests	HSVA	KRISO	MARIN	MSRC
3a	3.5 m	65 %	75 %	0 %	90 %	25 %
3b	7.5 m	75 %	90 %	40 %	30 %	95 %

slower TTC than in model test.

5.3. *Transient flooding with slow opening time for the breach (Case 1c)*

Usually the studies on transient flooding, both experimental and numerical, rely on the assumption that the breach is opened rapidly. However, for collision damages this is not fully realistic since the striking ship affects the initial flooding process. Previously, de Kat et al. (2000) have observed from model tests that the opening time has a notable effect on the transient roll angle. Yet in most model tests on transient flooding the breach is opened very rapidly, and the standard practice in flooding simulations is to assume that this happens instantly. Consequently, in the third transient flooding test case the breach was opened slowly.

In this test case the stable initial heel angle of the model before the test was -1.01° (away from the damage) and trim angle was 0.33° (to bow). The lower part of the breach was opened in 94.61 s (full-scale) and the upper part in 136.73 s (full-scale). The same initial condition as in the transient capsize Case 1b, with low GM = 1.338 m, was used.

The results for the roll angle are shown in Fig. 11. In the experiment, the roll angle remained minimal for over 40 s (full-scale), whereas in all simulations roll started to increase much faster. The capsize mechanism is in principle the same as with fast opening time of the breach, but the process is now much slower.

HSVA, KRISO, MARIN and UAK correctly capture the capsize towards the intact side, with fairly good estimate on the time-to-capsize. Also UNINA correctly predicts the direction of the roll motion, but instead of a capsize, a steady heel of about -20° is achieved. The quasi-static treatment of floodwater in NAPA results in capsize towards the damage. Only HSVA manages to predict that the roll angle remains rather small for a long period of time, whereas with the other codes roll starts to increase much faster than in the experiment.

6. Transient flooding in waves (Case 2)

The second part of the benchmark study focuses on transient flooding in irregular beam seas. Relatively low initial GM of 1.425 m is applied. JONSWAP wave spectrum (γ = 3.3) with H_s = 4.0 m and T_p = 10.0 s is used, with waves facing the damage. Two variants of the initial condition are studied, as listed in Table 6, with small variation, especially in the initial heel angle. These conditions were determined by HSVA from the heave, roll and pitch signals, averaged over the time range of 10 s (model scale) in calm water before the wave met the model.

Several experiments were conducted for transient flooding in beam seas. In three cases the initial condition before flooding was practically the same (Case 2a). Analysis of experimental data showed large variation for cases with slightly different initial condition, and therefore an additional Case 2b was included in the benchmark study. Participants were asked to provide simulation results for 20 random wave realizations for both studied initial conditions. Eventually, BROO provided results only for zero initial heel angle and KRISO submitted only 10 realizations for the latter condition since the time-to-capsize was very consistent with a smaller number of repetitions. Each participant used their own codes for generating the waves.

Time histories for the roll motion with the two initial conditions are shown in Fig. 12 and Fig. 13. As in the case of transient flooding in calm water, Fig. 6 and Fig. 10, the ship initially rolls towards the damage, which is followed by large transient roll away from the damage. However, in contrary to the calm water case, this transient roll does not result in capsize, due to slightly larger intact GM. The whole breach opening is temporarily emerged from water, but waves cause further flooding, and the ship starts to slowly roll towards the damage, eventually capsizing to this direction. Video captures from the model tests of the Case 2b in Fig. 14 visualize this process.

KRISO predicts capsize towards the intact side, and in the Case 2a the ship survives the large transient flooding stage in several realizations of the studied sea state. With other codes, capsize towards the damage is more common, but also HSVA, MSRC and UNINA predict capsize towards the intact side in some wave realizations in the Case 2b. Cumulative distributions for time-to-capsize are presented in Fig. 15. BROO used zero heel as initial condition, whereas other participants applied the measured initial heel and trim. In the Case 2a, HSVA, MARIN and NAPA simulations always capsize towards the damaged side, but with TTC significantly shorter than in model tests. The difference to the model tests is almost equal to the time the vessel remains heeling towards the intact side in the model tests, which is not seen in these simulations. Based on the single experiment for the Case 2b TTC seems to be longer, but it is still much shorter than in the model tests. In general, the increase of TTC when the ship is initially heeling away from the damage is qualitatively captured well. However, variation in TTC between the codes is significant. For the Case 2a results of BROO are close to the measured TTC distribution, but this is partly explained by the different initial heel angle. Although with only one experiment for the Case 2b, it can be concluded that the codes by HSVA and UNINA seem to provide a qualitatively good estimate of both TTC and the development of roll motion. Moreover, in most realizations of the sea state, UNINA captures well the maximum transient roll angle towards the intact side before the final capsize towards damage, albeit there are some more oscillations in the roll motion than in the measurements. Similar excessive oscillations are visible also in the HSVA and KRISO simulations.

This part of the benchmark study clearly demonstrates that in certain flooding scenarios the time-to-capsize can be very sensitive to the initial condition. A rather marginal difference in the initial steady heel angle between the Cases 2a and 2b results in a large difference in the development of the roll angle, and especially in the eventual time-to-capsize. Although it should be noted that for the Case 2b the experiments were limited to a single test. In general, the details of the flooding and capsizing are not very well captured by the simulation methods, however, the final outcome, i.e. capsizing, is still correctly predicted. It is also noted that in the studied cases the simulations predict shorter TTC than measured, which is conservative.

7. Gradual flooding in waves (Case 3)

The third part of the benchmark study focused on a flooded ship motions in high waves. In the beginning of the tests the whole breach (shown in Fig. 3) is already open and the damaged compartments below the main vehicle deck (R1, R2, R4 and R5) are already flooded, and open to sea. Contrary to the transient flooding cases, also the double bottom compartments, R4 and R5 in Fig. 2, are flooded.

Two different sea states were studied, with JONSWAP wave spectrum with γ = 3.3. The intact condition and the significant wave heights H_s and peak periods T_p are given in Table 7. The model is in beam seas with the breach facing the waves. The model was freely drifting with loose ropes in the bow and stern for correcting the model orientation in the waves when necessary. The tests were repeated 20 times in different realizations of the same sea state. Each participant used their own codes for generating 20 random wave realizations. Maximum time for both experiments and simulations was 30 min (full scale) as in the Stockholm Agreement model tests, EU (2003).

The capsize occurs when a critical amount of water accumulates on the vehicle deck. To a significant extent the center casing reflects the waves and water flows back to the sea through the breach and the floodwater gradually spreads in the longitudinal direction on the starboard side of the vehicle deck. Video capture on the critical flooding of the deck in 3.5 m sea state is shown in Fig. 16.

Measured and simulated time histories for the roll motion in 20 realizations of both studied sea states are presented in Fig. 17 and Fig. 18. Cumulative distributions for the time-to-capsize are shown in Fig. 19. It is noteworthy that in all cases the capsize direction is towards the breach opening. The capsize rates are listed in Table 8.

The simulations by HSVA, with method based on the shallow water equations, seem to capture the capsize rate in waves due to gradual flooding qualitatively correctly in both studied sea states. In general, the HSVA results are slightly conservative with shorter time-to-capsize and larger capsize rate. In the smaller wave height (Case 3a), KRISO predicts zero capsize rate, and in the higher waves (Case 3b) either rapid capsize or survival. Interestingly, MARIN simulations are good in the smaller wave height (Case 3a), with only a small overestimation of the capsize rate, but in high waves (Case 3b) the capsize rate is significantly lower than in the model tests. MSRC predicts too low capsize rate in the smaller wave height (Case 3a), but in the high waves (Case 3b) the time-to-capsize and capsize rate are predicted rather accurately, although the capsize rate is overestimated.

8. Discussion

Damage stability model tests are complex to execute, and they require a lot of expertise. Unique tests were conducted in the EU Horizon 2020 project FLARE, that enabled a detailed benchmark study. In the transient flooding (Cases 1 and 2) the damaged ropax ship rolled towards the intact side, which could not be captured by the simulation codes based on more simplified treatment of floodwater with horizontal waterplanes. It should be noted that this phenomenon is characteristic to flooding of wide undivided compartments with a large breach opening, and this is not specifically limited to ropax vessels. Previously, Manderbacka and Ruponen (2016) have noted that such transient effects are significant when the internal openings are of the same size as the breach opening. Due to the nature of the model test arrangement, the compartments were empty. In real ships, such wide empty compartments are not typical, and the internal non-watertight structures and equipment affect the flooding characteristics. Consequently, some of the phenomena seen in the presented model tests are expected to be less pronounced in full scale flooding.

Also, capsize due to transient flooding in irregular beam seas in the Case 2 was properly captured by most simulation codes, but the capsize mechanism was in many cases very different from the model test result. However, both the shallow water equations (SWE) and advanced pendulum models were found to provide reasonably good results. It was also found out that the time-to-capsize was rather sensitive to a small initial heel angle of the intact ship, both in model tests and simulations.

Transient flooding of wide compartments involves complex phenomena, which in this study could only be captured with advanced pendulum models or with codes based on shallow water equations. However, capsizing could also be properly predicted with some simpler methods with horizontal water levels in compartments. The challenge in modelling transient flooding of large open compartments is the evolution of the distribution of floodwater in time, as this can have a significant impact on the time-dependent heeling moment due to flooding. On the other hand, in transient flooding cases the final outcome, i.e. survival or capsize, was properly predicted by most codes, but the actual capsize mechanism and accurate time-to-capsize were much more difficult to model. Consequently, the general use of such tools for survivability assessment is reasonable, but it is also concluded that more research and validation studies are needed, especially concerning transient flooding. The sensitivity of the results to small variations in the initial condition should also be studied.

In this benchmark study more different simulations codes were used than in the previous ones. Many new codes have been introduced recently, and old ones have been improved. This benchmark study focused more on extreme conditions, including significant transient flooding and extreme sea state for gradual flooding in waves. Consequently, it is difficult to compare the results between different benchmark studies.

It was also observed that the computational performance of different simulation codes varied significantly. Detailed comparison is not possible, mainly because of different computer hardware, but also due to the different methods and their implementation, including the applied programming framework. In general, all simulations were faster than real time, and HSVA, KRISO, NAPA and UAK reported computation times over 10-times faster than simulated time. HSVA and KRISO reached this also for transient flooding in waves.

9. Conclusions

Time-domain simulation of flooding and motions of damaged ships is becoming a common practice for assessment of survivability level during the ship design process, especially for passenger ships. Consequently, it is essential that such simulation codes are thoroughly validated against dedicated model tests. For this purpose, an extensive benchmark study on flooding and motions of a damaged ropax vessel was conducted within the Horizon 2020 project FLARE.

The results for the capsize rate and time-to-capsize in the case of gradual flooding in waves were characterized by a significant variability among the applied simulation codes. With some codes, the capsize rate was seriously underestimated also in a very reasonable sea state with significant wave height of 3.5 m. Consequently, survivability assessments with these tools may provide too optimistic results, and the limitations and deficiencies of the applied codes should always be considered before making any conclusions on the survivability level of a ship design.

The results show that time-domain flooding simulations are a useful tool for both research and practical ship design, although there is still a need for further development. The results of the benchmark study also clearly indicate that more research is still needed to accurately model the damaged ship dynamics in extreme environmental conditions. For example, benchmarking of intact ship motions in irregular beam seas should be conducted to conclude whether the inaccuracies in the capsizing due to gradual flooding in waves are due to hydrodynamics or treatment of floodwater. Furthermore, a repetition of the benchmark study should be considered in the future, when the existing simulation codes have been improved, or new ones have been developed.

CRediT authorship contribution statement

Pekka Ruponen: Conceptualization, Methodology, Writing – original draft, Visualization, Writing – review & editing. **Petri Valanto:** Conceptualization, Investigation, Writing – review & editing. **Maria Acanfora:** Investigation, Writing – review & editing. **Hendrik Dankowski:** Investigation, Writing – review & editing. **Gyeong Joong Lee:** Investigation, Writing – review & editing. **Francesco Mauro:** Investigation, Writing – review & editing. **Alistair Murphy:** Investigation, Writing – review & editing. **Gennaro Rosano:** Investigation, Writing – review & editing. **Riaan van't Veer:** Investigation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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8 SUMMARY AND CONCLUSIONS

Time-domain simulation of flooding and motions of damaged passenger ships is becoming a common practice for assessment of real survivability level in the event of a damage, especially for passenger ships. Within the project FLARE, these simulations have a significant role in the framework developed in WP5. Consequently, it is essential that such simulation codes are thoroughly validated against dedicated model tests. In order to get a wider perspective, also participants outside the FLARE consortium were invited to this benchmark study.

The study was organized in three separate parts, namely A, B and C, focusing on different aspects of the flooding and damaged ship motions. Some participants provided simulation results for all parts, while others concentrated on certain part only.

The first part of the benchmark focused on fundamental flooding mechanisms, with the following main conclusions:

- It was confirmed that most codes can satisfactorily simulate up and down flooding (A1 & A2). For such basic cases, the simple and fast, Bernoulli-based hydraulic simulation methods are in principle as accurate as computationally demanding CFD tools. Only one code had problems in calculation of simple up and down flooding, and it was identified that the problems were due to the implementation of the code, and not because of the applied Bernoulli-based simulation method.
- The deck flooding case (A4) demonstrated that progressive flooding along a long corridor cannot be captured by simple hydraulic models. With CFD codes this is properly modelled, but the computational time is extensive. The advanced approach by KRISO, considering also the momentum of floodwater, seems promising.
- The notable deviations in the simulation results between the Bernoulli-based codes when using same discharge coefficients indicates that different implementations of the time integration for the governing equations results in numerical error, at least for some codes. Naturally, also the applied time step may have an effect on this, but all participants should have ensured that a suitable time step is applied to minimize the numerical error.
- The computational performance of CFD codes is not suitable for practical assessment of survivability of damaged passenger ships. However, the detailed results on the flooding progression can be valuable for development and testing of simplified flooding simulation codes. Notable differences in the performance were also found between the Bernoulli-based simulation codes. When time-domain assessment of survivability is done for a large number of scenarios, the computational performance becomes more important.

The second part on cruise ship flooding provided more insight into the applicability of the simulation codes on flooding of a realistic geometry, considering both transient and progressive flooding stages. The results and observations are summarized in the following:

- An extensive three-compartment damage case was studied both in calm water (case B1) and in irregular beam seas with significant wave height of 4.0 m (case B2). In both cases, there was a large transient roll angle, and in waves the ship eventually capsized due to progressive flooding and accumulation of water on the upper decks due to the waves. The last case (B3) had a smaller breach opening, and the case was characterized by notable up-flooding in the damaged compartments.

- The flooded compartments of the model reflected the general arrangement plan of the FLARE demo ship 3, prepared by Chantiers de l'Atlantique. Consequently, some compartments had very complex geometry, and some inaccuracies and differences between the numerical 3D models are quite likely. In addition, the pram type stern and large discontinuities in the waterplane area likely affected the inclining test, and resulted in uncertainties related to the initial condition for the model tests. For possible future benchmark study, a more simplified geometry of the compartments and a larger scale of the model should be considered. Also a simplified appendage geometry would have made it easier to ensure a consistent modelling of the buoyant hull form.
- Effects of air compression on the flooding and motions of the model could not be completely excluded, and consequently, in possible future model tests for benchmarking, measurement of air pressure in compartments that are rapidly flooded is considered essential.
- The qualitative behaviour of the transient roll motion and the capsize mechanism in beam seas was well captured, but there was a significant variation in the actual flooding progression for the compartments, also in calm water.
- The drifting effect during the flooding process was also identified as one potential explanation for the differences, since direct comparison of experiments with a softly moored model and numerical simulations with a freely drifting ship may not be reasonable.

The last part of the benchmark study consisted of transient flooding of a ropax vessel in calm water and in beam seas, including also a more conventional model test case with gradual flooding and capsizing in high waves.

- The final outcome (capsize or survival) of transient flooding in calm water was well captured by the codes. However, the floodwater inertia, and the resulting capsize towards the intact side could not be correctly modelled by the more simplified simulation methods.
- Also, capsize due to transient flooding in irregular beam seas was properly captured, but the capsize mechanism was in many cases very different from the model test. However, both the shallow water equations (SWE) and advanced pendulum models were found out to provide reasonably good results.
- It is worth noting that the benchmarking condition involves transient flooding of wide and empty compartments below the vehicle deck. This is somewhat unrealistic, since the various equipment and machinery in these compartments on real ships would have had an effect on the floodwater motions.
- The results for the capsize rate and time-to-capsize in the case of gradual flooding in high waves contained a lot of variation in the results.

Before drawing the final conclusions, it is essential to recall the main observations from the most recent ITTC benchmark studies:

- Papanikolaou and Spanos (2005) reported notable deviations between the numerical methods in the damage condition, which were considered to result from the different approaches to the effects of floodwater on ship motions.

- van Walree and Papanikolaou (2007) reported notable variation in the results for progressive flooding of a damaged box-shaped barge with simple internal geometry

Based on the results, the simulation tools have developed significantly since the last ITTC benchmark study, especially regarding fundamental flooding mechanisms, and most of the codes could correctly model both up- and down-flooding. The results for the deck flooding (case A4) were not very consistent, but the flooding progression was still fairly well captured by all codes.

The Benchmark parts B and C included extreme damage scenarios and transient capsizing cases that had not been included in previous studies. In general, the participating codes could properly reproduce the survival and capsize conditions, but especially regarding the transient flooding of large open compartments, the effects of the floodwater momentum can be essential, and many codes did not deal with this properly. Also, significant variation in the time-to-capsize was observed, for both the cruise and ropax ships.

The previous benchmark studies have considered only simulation tools based on Bernoulli's equation, but this time also CFD tools were included. The results show that such advanced methods can rather accurately model the flooding progression, but the computation times are much too long for use in practical work for survivability assessments for ships with complex internal arrangement and involving a large number of damage cases.

The wide participation in the benchmark study, including organizations outside the FLARE project consortium, shows that time-domain simulation tools are now more widely developed and used within the scientific community. The increased interest and wider expertise in dynamics of flooding and damaged ship stability pave way for further improvements.

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11 ANNEXES

11.1 Annex A: Public summary

An extensive benchmark study on time domain simulation of flooding and motions of damaged ships was conducted with the project FLARE. In addition to the FLARE partners, also other organizations with recent publications on this topic were invited to participate. Eventually, a total of 11 organizations contributed to one or several parts of the study.

The benchmark study was organized between June 2020 and April 2021, and the test cases were divided into three separate parts:

- Part A: flooding fundamentals with simplified geometries and fixed floating positions
- Part B: transient and progressive flooding of a cruise ship in calm water and in irregular waves
- Part C: flooding of a ropax ship, considering transient flooding in calm water and in irregular waves, as well as gradual flooding of the vehicle deck in high waves

Most of the codes could correctly predict basic cases of up- and down-flooding. Even the extensive progressive flooding on a deck arrangement was well captured, although only CFD codes could capture the details accurately. Moreover, the variation in the results among the codes using Bernouli's equation, and the same discharge coefficients, was larger than expected.

The motions of a damaged cruise ship in transient flooding were well captured in calm water, although significant deviation between different codes was observed, especially for the water levels in the flooded compartments. Progressive flooding in waves after transient flooding proved to be more problematic, and time-to-capsize was not accurately predicted.

The ropax ship flooding cases were challenging as floodwater momentum caused transient roll motions, and even capsize, towards the intact side. Yet, some codes provided very good results. However, the final outcome of the transient flooding, either survival or capsize, was correctly predicted, but the time-to-capsize varied significantly, especially in waves.

Calculation of flooding progression has significantly improved since the previous benchmark study. However, needs for further development was also identified, and the FLARE benchmark study results are considered an important step on the way for improving the flooding simulation tools of the future.

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