A New Technique for the Experimental Investigation of Intact Stability and the Validation of Numerical Simulations

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Abstract

The experimental investigation of extreme wave / structure interaction scenarios puts high demands on both model test procedure and wave generation technique. Until now experimental and numerical investigations of intact stability still have some gaps. Thus, there is a great need for improving procedures to analyse ship
safety in rough seas.

In this paper the latest experimental results of ”SinSee”, a German research project which includes five partners, are presented and, as an application, compared to corresponding numerical simulations in defined dangerous wave sequences. The recently developed innovative and completely computer controlled test procedure is combined with the deterministic wave group technique. Thereby the parameters of the model seaways are systematically varied in order to investigate the ship model response with regard to metacentric height, ship speed, and relative course angle in arbitrary deterministic wave groups such as rogue wave sequences embedded in severe seas.

As a further development of the former model test procedure global forces acting in the midship section of the models are measured within the “SinSee“ capsizing model test campaigns. Besides long-term full scale measurements will be available from an instrumented vessel, which also includes the determination of structural wave induced loads.

Different approaches for modelling non-linear wave propagation are applied in the research project. This allows the exact correlation of wave excitation, ship motions and forces in the moving reference frame.

For the systematic investigation of resonance phenomena, numerical simulations are carried out prior the experiments. This gives a set of parameters and wave sequences leading to large rolling or capsizing. The entire rolling/ capsizing scenario is realised in the model basin, and the experimental results are directly compared to the numerical simulations.

Keywords

100% computer controlled dynamic stability tests, reproducible model tests, intact stability, experimental techniques, wave generation, deterministic wave groups, capsizing tests, numerical simulation of roll motions, validation, responses to extreme waves, full scale measurement.

Introduction

Available means to investigate the seakeeping performance of designs are numerical simulations and/or model tests. Both, model tests and motion simulations are often used post-accidental, in order to investigate the causes. Standard seakeeping tests (tank or numerical) are available for several phenomena (slamming, green water, capsizing, etc.) but are only occasionally used – mainly for rather unusual designs, or in cases where seakeeping characteristics are more vital than for standard vessels. Numerical assessments are faster and less expensive than model experiments, but are not standardised with respect to scope and minimum quality. So far usually only model test are accepted by authorities.

In the framework of the German research project ”SinSee” which is funded by the German Federal Ministry of Education, Research, and Technology (BMBF) five partners are co-operating on the evaluation of safety in severe seas. Thereby fields like numerical analysis and simulation, validation by means of model test investigations, full scale measurements and evaluation of capsizing risks are covered.

Results with respect to the evaluation of the safety of several ship types and sizes against intact capsizes were already presented in the past. This paper summarises the ongoing developments in model testing and numerical motion simulations, especially focussing on the interaction between these two procedures to investigate the ship's performance. Furthermore these findings are associated with long-term full scale measurements which were conducted aboard a tested vessel.

Concept of Fully Computer Controlled Model Test Technique

Analysing the process of large rolling and capsizing has to consider the following wave characteristics:

- extreme wave height and wave steepness,
- wave groupiness, and
- propagation velocity and direction.

Unfavourable phase relations of wave components as well as detrimental wave/ structure interactions lead to dangerous situations such as:

- loss of stability at the wave crest,
- resonant excitation, esp. parametric rolling, and
- broaching due to a loss of course stability.

Analysis of these complex, non-linear mechanisms puts high demands on the capsizing test set-up and procedure:

- exact correlation of cause (wave excitation) and reaction (ship motion),
- reproducibility, high accuracy at measurement and control units, and
- deterministic course of test events.

These demands are realised by a sophisticated test procedure at HSVA. Figure 1 shows the principle test configuration for computer controlled seakeeping tests. Three main system components are coordinated:

- wave maker,
- towing carriage (including the horizontal carriage), and
- ship model.

In head seas, the ship is positioned at the side wall of the tank's end, opposite to the wave maker position. In seas from astern, the ship model has to wait close to the wave maker until a defined sequence of the wave train has passed.

The ship's course is controlled by the master computer by telemetry which commands a Z-manoeuvre at constant course angle and model velocity. These test parameters as well as the model sea parameters are varied according to the metacentric height, GM, of the model, the expected rolling mode and occurrence of resonance. Ship motions in six degrees of freedom are registered precisely by computer controlled guidance of both, the towing and the horizontal carriage: During the entire test run, the ship model stays in the field of vision of the optical system line cameras. Additionally, the wave train is measured at several fixed positions of the wave tank.

When the model reaches the critical safety limit at the wave maker or the absorbers at the opposite side of the tank, the ship and the carriage stop automatically. Thus, the test is realized by a deterministic course of test events which allows a reproducible correlation of wave excitation and ship motion (Brink et al. (2002)).

Wave Generation and Processing

The experimental investigation of extreme structure behaviour such as large rolling and capsizing calls for an appropriate approach for generating the harsh wave environment.

The wave generation process can be divided into the following steps (compare figure 2):

- definition of the target wave train,
- transformation of the target wave train to the position of the wave maker,
- calculation of wave maker control signals, and

- performance of model test.

Definition of the target wave train

As a first step, a target wave sequence is chosen as time series at a target position in time and space — i. e. the position where the ship encounters the wave train at a given time. At this location, the target wave train is either reproduced from an existing wave registration or specifically designed. For the design different methods are available. One procedure is to define target parameters like a typical ”Three Sisters” wave sequence H_s-$2H_s$-H_s in terms of the significant wave height H_s (Wolfram et al. (2000)). An optimization routine is applied to get a target wave train satisfying the selected parameter set, see Clauss and Steinhagen (2000). A target wave is also defined as output of numerical simulations of a rolling or capsizing scenario (as in figure 2).

Transformation of the target wave to the wave maker

The second step in wave generation is the transformation of the given target wave train to the location of the wave maker. Since most extreme responses are caused by rather steep wave sequences the transformation has to consider non-linear wave propagation. Whereas many of the existing non-linear wave models can be derived accurately from mathematical formulations or widely accepted wave theories, they are sometimes too complex for day-to-day use in model testing. On the other hand, simplified methods tend to be imprecise if the wave becomes steeper. Thus, a combined modified non-linear wave theory based on classical wave theories and empirical insights into non-linear wave propagation is applied (Clauss et al. (2004a)) as it works fast and gives accurate results. This approach uses linear wave theory as a backbone for non-linear wave description and is developed at each time step. It can be applied both to ”forward” (downstream) and ”backward” (upstream) prediction of wave trains. The ”forward” prediction at arbitrary positions of the model tank includes the representation of wave trains in the moving reference frame of a cruising vessel. The ”backward” calculation is used for the transformation of given target wave trains to the location of the wave maker. This is an unique feature of the modified non-linear approach which can also be adapted easily for new requirements as the implementation of different wave theories is possible.

Calculation of control signals

Knowing the wave train at the wave board it is easy to calculate the appropriate control signal(s) using the different characteristic transfer functions of the wave maker (Clauss and Hennig (2003)) which allows to generate the desired wavetrain for the model test at the target location. The resulting wave train is generated and measured at the selected positions in the tank. The ship model arrives at the target position by the corresponding target time (measured from the beginning of wave generation). This is achieved by the fully automated test procedure described above.

Deterministic wave trains

Applying the non-linear approach all kinds of waves can be tailored for each individual test and generated in the model tank (Clauss et al. (2004b)):

- wave packets,
- extreme waves such as ”Three Sisters”,
- storm seas,
- random seas with embedded high wave sequences,
- regular waves with embedded high wave groups, and
- realization of natural wave scenarios.

We call these wave trains ”deterministic wave trains”.

Calculation of wave trains in the moving reference frame of cruising ships

For the deterministic analysis of motions and forces of ships the wave excitation denotes the beginning of a complex cause-reaction chain. This requires knowledge of the wave evolution in time and space to correlate wave excitation to the structural response. Especially when the ship is sailing at non-constant speed it is not a state of the art task to determine the wave excitation with regard to a moving reference point as wave probes can be installed at defined positions, but usually not at the position of the model (due to relative motions and disturbances). With the presented technique wave scenarios can be analyzed from the point of view of a sailing ship. The linear calculation scheme for transformation of the measured wave train to a reference position of the model (both stationary and moving reference frame) can be extended to non-linear wave propagation by introducing the appropriate wave numbers and amplitudes from non-linear wave theory (Clauss et al. (2004a)). The wave train has to be calculated at the position of the model reference point $x(t_i)$ at each time step in order to get the non-linear moving reference frame wave train. An example of such a wave train is given in figure 2.

Numerical Simulation

Several numerical motion simulation programs exist worldwide ranging from rather simplified linearised tools to sophisticated non-linear tools. All simulation methods use underlying assumptions in their mathematical model, in order to reduce the computing time. Still some of the highly non-linear methods have longer computing times than simulated time, which strongly reduces their practical applicability for safety assessments. For practical applications (i.e. safety assessments, design evaluations, etc.) often specialized tools are in use. All numerical simulation programs require a thorough validation of their results and have restrictions regarding their applicability depending on the underlying assumptions and models. Unfortunately no common criteria and methods for quality and accuracy control exist. In “SinSee“ three goals are targeted with respect to numerical simulations:

- Dedicated model tests are carried out in order to produce reliable and suitable data for the validation of numerical methods. For the validation purpose as such different approaches are used to identify different weaknesses (i.e. in the wave or force model respectively).
- Existing numerical tools are being further developed based on the findings. These models are developed to support the ship design process, therefore it is necessary that the numerical tools are fast and robust at sufficient reliability.
- Methodologies are being developed to assess the safety of ships with respect to intact stability.

With regard to the validation of numerical tools – the main basis for the validation are scaled model tests. Within “SinSee“ computer controlled model test techniques are used and further developed to allow for more detailed studies of dangerous phenomena in model testing on one hand, and the generation of synchronized data of waves and ship motions for validation purposes on the other (Kuehnlein et al. (2003)). Model tests are quite intense with respect to time and costs, thus the test conditions should be well chosen. With respect to dangerous roll angles two conditions are of major interest:

- The performance of the vessel in resonance conditions (not necessarily extreme).
- The performance of the vessel in extreme conditions.

Based on the tests from the Roll-S project (former German Research Project), quite some experience is available for the modelling of extreme conditions, e.g. extreme wave groups embedded in regular or random seaways. When assessing resonance phenomena the testing condition need to be tuned to the individual ship characteristics. For the latest test series numerical simulations were successfully used to pre-select interesting conditions. This new approach will be further developed. Based on these findings further developments are also planned to re-model conditions measured in full scale in numerical or tank environments. These links between numerical simulations, model tests and full scale measurements are vital for the further development of safer ships and as basis for future decision support systems.

Linking Numerical and Experimental Models

Model tests are rather expensive and time consuming. Thus, especially when testing in irregular seas, the test conditions should be well chosen. Within “SinSee“ numerical investigations were used to identify interesting conditions with respect to resonance phenomena for the latest series of tests. Numerous simulations in following and head seas were run and evaluated. Some of the most interesting or typical examples with respect to parametric excitation as well as pure loss of stability were chosen as test cases. Corresponding model seaways were generated and the test conditions (especially with respect to timing between waves and vessel) designed (figure 2). This set-up is regarded as rather promising in order to investigate dangerous resonance problems in rough but not necessarily extreme conditions. Further tests were run in extreme conditions to extent the test conditions and identify possible gaps in the numerical pre-investigation.

Vice versa - when focussing on validation – regular waves are frequently used for validation purposes, mainly because the comparison is relatively straight forward, especially if the ship’s response reaches a steady state (as far as amplitude and phase shift are concerned). In irregular waves a comparison is more complicated. Traditionally statistical quantities are compared, but this of course does not deliver a detailed analysis of possible weaknesses in the numerical tool. Based on the new test set-up where the wave elevation is known at all positions of the tank and at all times during the test it is now possible to extent the validation of tools to more details. At the same time the already mentioned pre-calculation of tests is possible, and might also prove to be a very trust enhancing set-up, as here the motions are predicted before the actual test run.
Figures 3 and 4 show preliminary qualitative comparisons of a capsize in a wave group.

Results of Seakeeping Model Tests and Long-Term Full Scale Measurements

With the help of the completely computer controlled seakeeping model tests, the motion behaviour of different ship designs in response to the actual wave pattern encountered is determined. Besides global bending moments and forces are recorded. The results are given in form of time histories at defined positions.
Exemplary results of single test runs with the model of a twin-screw Ro-Ro vessel running in stern seas are presented in Figure 5. In the upper part of the diagram the roll motions of the vessel are shown while the characteristics of global bending moments (acting about the vessels transversal and vertical axis) is given in the lower part. This example reveals the influence of the extreme roll motions, which finally lead to a capsize, on the global hydrodynamic loads which act on the vessel.
Similar investigations have been conduced by means of long-term full scale measurements aboard the same ship design. Thereby the motion behaviour of the vessel as well as local structural stresses were measured. A short sequence of the full scale measurements are represented in Figure 6. Again, the ship’s roll motions are shown in the upper part of the diagram. Thereby a single large motion response is identifiable which is in the range of 10° roll angle. In the lower part of the same diagram the measured signals of four strain gauges are shown. The analysis of these measurements will allow a precise assessment of the structural stresses acting on the vessel in heavy seas.

Conclusions and Perspectives

In “SinSee” developments focus on ship safety in severe seas. This paper summarises some of the developments in numerical analysis and validation, improved model testing techniques, full scale measurements and the modelling of seaways. Joint efforts of this type are important, as it is necessary to provide links/connections between the real world, the model world, and simulation to investigate ship safety, understand phenomena and support ship design and operation. Next steps in the project will target the precise correlation of time and place of ship and waves between model tests and numerical simulations, thus more detailed quantitative comparisons are possible. The principles for modelling wave propagation outlined here can be applied to transform wave registrations from space to time domain. Thus, the data from the full scale measurement campaign will be thoroughly analysed and interesting situations will be chosen for a future re-modelling in the test tank and in simulations.

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Appendix A

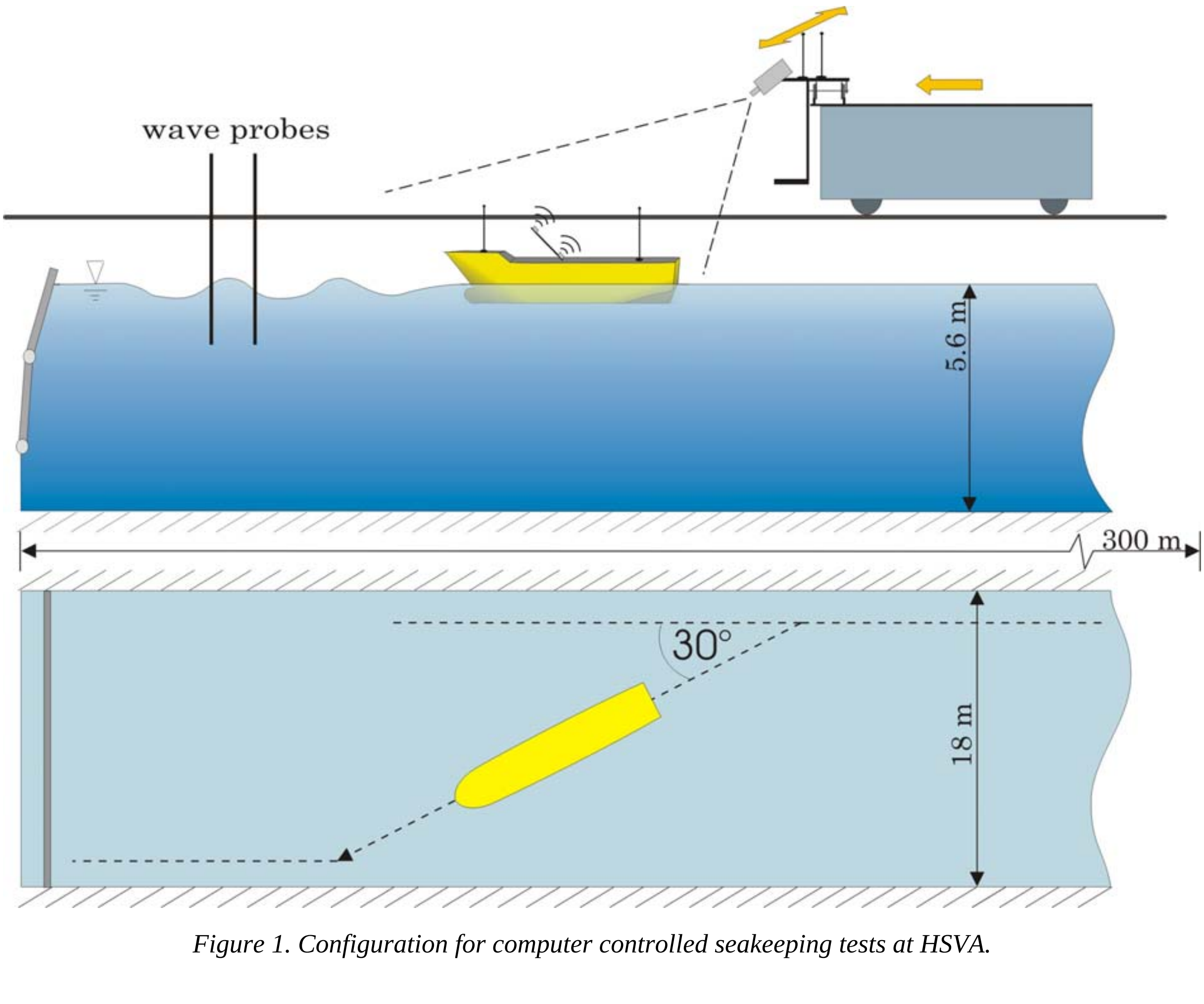

Figure 1. Configuration for computer controlled seakeeping tests at HSVA.

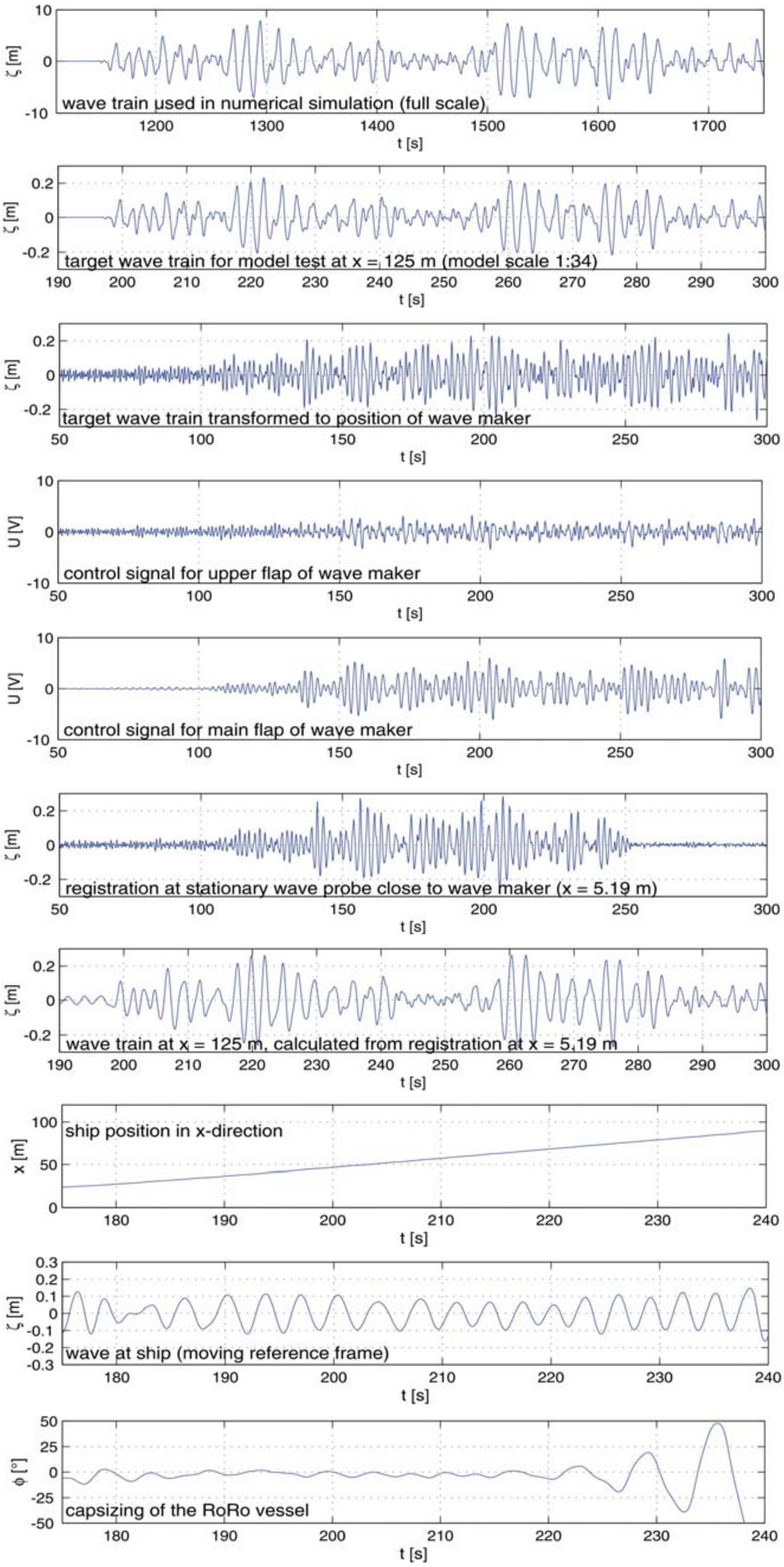

Figure 2. Experimental realization of dangerous wave sequences from numerical capsize simulations: Starting with the target wave train the wave at the position of the wave maker is calculated using a modified non-linear wave theory to get the corresponding control signals. From registration at a stationary wave probe close to the wave maker the stationary wave train at x=125 m is given by the modified theory (compare target wave) and transformed to the position of the ship model (scale 1:34) to obtain the moving reference frame wave train which can be compared to the roll motion of the RoRo ship which subsequently capsizes. See also figures 3 and 4.

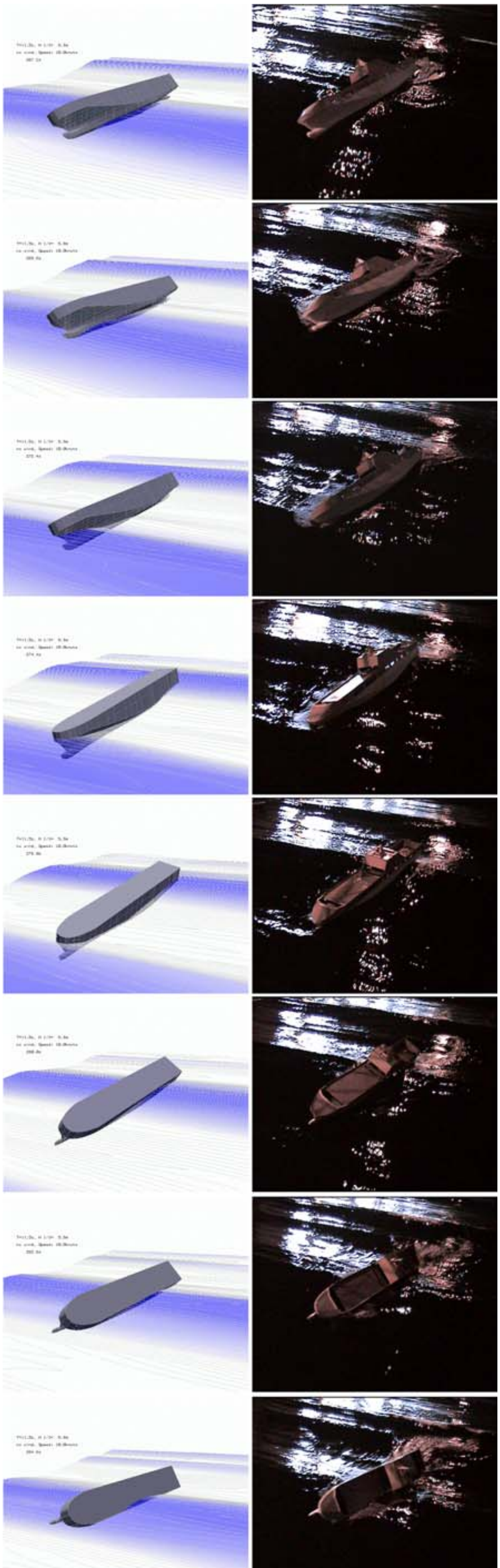

Figure 4. The following pictures show another preliminary qualitative comparison of a capsize in a wave group:

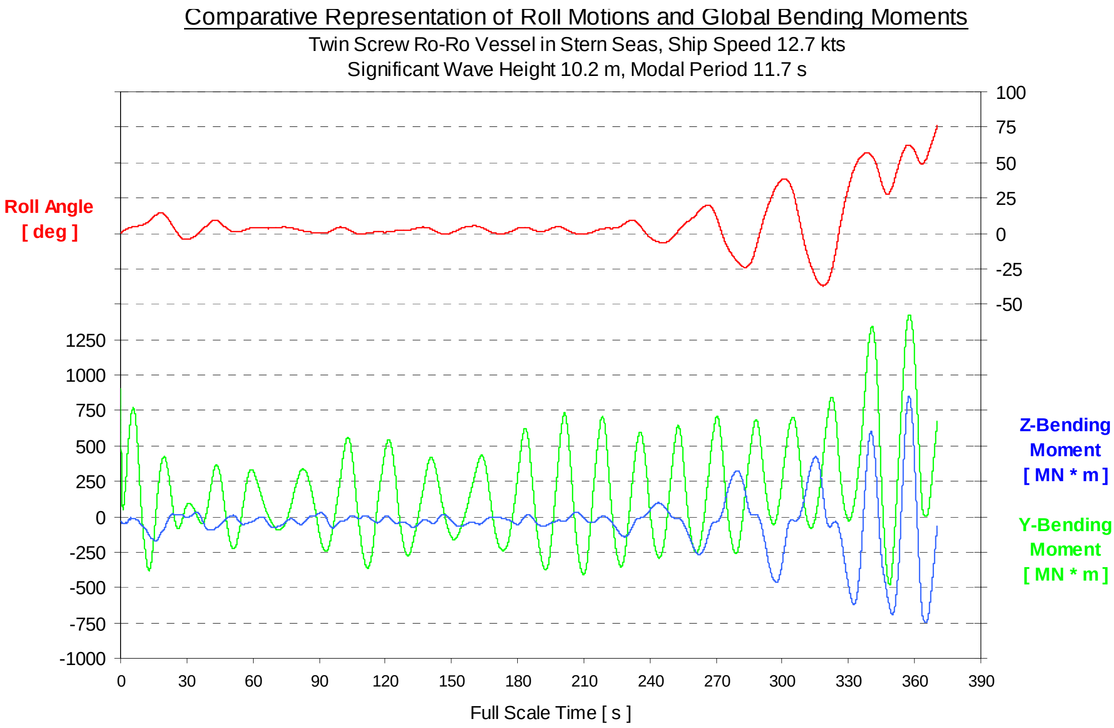

Figure 5. Time histories of roll motions and global bending moments measured during seakeeping tests.

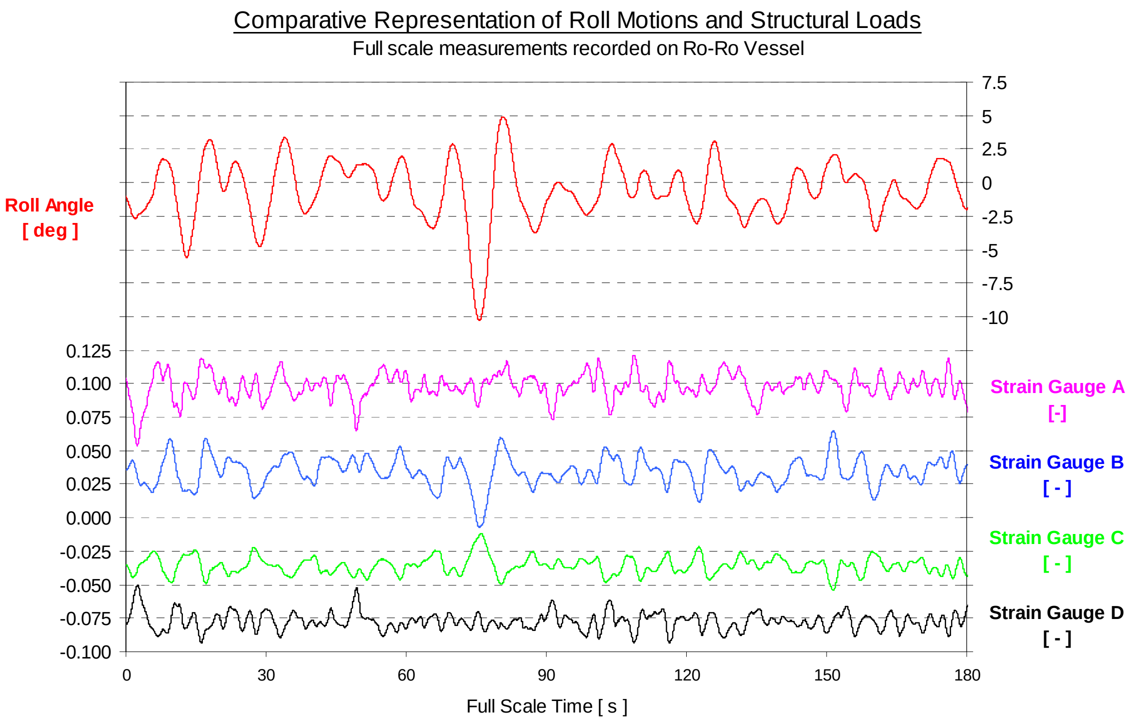

Figure 6. Time histories of roll motions and local stresses recorded during long-term full scale measurements.