Study of the Dynamics of a Damaged Passenger Ro-Ro Ship

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ABSTRACT

This paper describes a numerical model of the motions of damaged ships in a seaway. The model considers the equations of motion of the ship in the time domain and describes the behaviour of the floodwater inside the ship's compartments using a dynamic method in which the floodwater effects are treated as external forces and moments applied to the ship. The motions of the floodwater in the time domain are obtained by solving the shallow water flow equations. The numerical model is then applied to study the behaviour of a flooded passenger ro-ro ship. A number of damage conditions are studied which include the flooding of double-bottoms and main compartments, with the main deck dry. Results of the numerical simulations are presented for calm waters and beam waves, both in the intact and damage conditions. Comparisons with experimental results are presented and the agreement of the results is discussed, with special attention being given to the problem of the interaction between the ship and the floodwater and the occurrence of two-peaked roll response curves in beam seas for the flooded ship. Finally, the main conclusions of the study are drawn and recommendations for further studies are indicated.

Keywords: *Dynamics, Damage stability, Flooding, Passenger ships, Ro-Ro ships*

1. INTRODUCTION

The safety of passenger ro-ro ships continues to be a major issue in the context of maritime transportation of passengers, as the recent loss of the passenger ro-ro ship *Al Salaam Boccacio 98,* following a fire and subsequent capsize in heavy seas, shows. Furthermore, other recent accidents such as those which occurred with the *Express Samina* (2000), *Joola* (2002), *Super Ferry 14* (2004), *Stena Nautica* (2004) and *Vicenzo Florio* (2004), although with consequences of varying severity, also contribute to a continuing concern with the safety of these ships, which can be traced back to the *European Gateway*, *Herald of Free Enterprise* and *Estonia* accidents.

Each of these accidents have its own causes and peculiarities, but hazards such as collision, grounding and fire, leading to degradation of stability and loss of survivability in the presence of waves, are the most common causes of the accidents. However, for the most recent accidents, it is worth noting that the ships, which were new ships and sailed in European waters, survived the accidents without substantial loss of property or lives. The ships which were older or sailed in non-European waters were lost with severe losses of property and lives. In this respect, factors such as human errors, lack of maintenance, overloading and poor decision making in case of accident came into play as contributing factors.

Theoretical models of damaged ship motions in waves in the time domain certainly have an important role to play in the investigation of these accidents, in the research of the phenomena leading to ro-ro ship capsize or in the improvement of existing rules. These models, as demonstrated by Papanikolaou *et al.* (2000), Santos and Guedes Soares (2000) and Santos *et al.* (2002), allow studying different accident scenarios and a substantial number of non-linear features. This may include the modelling of progressive flooding and/or of the behaviour of the ship in waves, and allows estimating the survivability of the ship.

However, the problem of predicting the behaviour of floodwater accumulated in the compartments below the main vehicle deck or in the main deck of passenger ro-ro ships, if the ship is moving due to the action of regular or irregular waves, is complex. Vassalos and Turan (1994), while studying the motions of damaged ro-ro ships, used a semi-empirical approach to this problem, which continues to be improved and calibrated with experimental results by, for example, Vassalos *et al.* (1997). Recently, Woodburn *et al.* (2002) applied CFD codes to calculate the floodwater dynamics inside a Ro-Ro ship vehicle deck, therefore partly removing the empiricism from the analysis. However, these codes involve solving the Navier-Stokes equations, which is, computationally, very time consuming.

Another problem in this field has been the influence of water on deck on ship motions. This problem was approached by Dillingham (1981) and Pantazopoulos (1988) using the shallow water theory. According to this theory, the water flow can be described by a system of non-linear hyperbolic equations, which can be solved using the method of characteristics, presented by Stoker (1957). However, if there are hydraulic jumps, the ship motions are large or parts of the deck become dry, the method of random choice given by Glimm (1965) and perfected by Chorin (1977) may be used. In this method, the deck is divided in small elements, in which the depth and velocity of the water are assumed constant and the water velocity normal to the deck is zero. Under these conditions, between each two cells, there exists a Riemann problem, or “dam-breaking” problem, which can be solved using the method of characteristics.

This approach is related to CFD methods but offers the advantage of being computationally less demanding while still being capable of yielding descriptions of the water elevation and velocities across the deck. It was applied by Chang and Blume (1998) to evaluate the survivability of damaged ro-ro passenger ships. Santos and Guedes Soares (2003) applied the same approach to simulate the behaviour of a fishing vessel and a tanker with a compartment partially filled with shallow water.

This paper briefly describes the theory of shallow water waves applied to the water on deck problem. This theory, coupled to the ship equations of motion, has been coded in a time domain computer program. The water is considered to be a separate dynamical system and to act on the ship as external force and external moments, a major difference in relation to the works of Spanos and Papanikolaou (2002) and De Kat (1999). This approach is applied in this paper to study the behaviour of a passenger ro-ro ship with floodwater accumulated in two compartments below the main vehicle deck, in order to explain the special features of the motions of the damaged ship in regular beam seas.

2. FORMULATION OF THE COUPLED SHIP MOTION AND WATER ON DECK PROBLEM

2.1 Ship Motion Problem

The ship motions are expressed in the coordinate system shown in Figure 1.

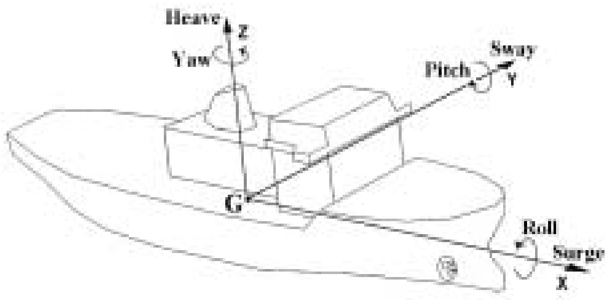

Figure 1 – Coordinate system for ship motions

The equations describing the ship motions are, essentially, similar to those presented by Santos *et al.* (2002):

$$\sum_{j=2}^{6}(M_{ij}+A_{ij})\ddot{X}_j(t)+B_{ij}\dot{X}_j(t)+F_j(t)=F_i^E(t)+F_i^{AC}(t) \qquad (1)$$

for i = 2,…,6, where:

M_{ij} represents the mass matrix,

A_{ij} and B_{ij} represent the radiation coefficients,

F_i represents the hydrostatic forces,

F_i^E represents the wave excitation forces (diffraction forces plus Froude-Krylov forces),

F_i^{AC} represents the accumulated water forces.

The hydrostatic forces are calculated over the instantaneous wetted surface taking into account the ship's motions. These forces are calculated using an hydrostatic pressure integration technique described by Santos and Guedes Soares (2001).

The viscous roll damping is approximated by a linearized coefficient, which is estimated using the results of model experiments.

2.2 Shallow Water Problem

The motion of the water on deck is expressed in the coordinate system shown in Figure 2. The x axis is perpendicular to the ship section shown in that figure.

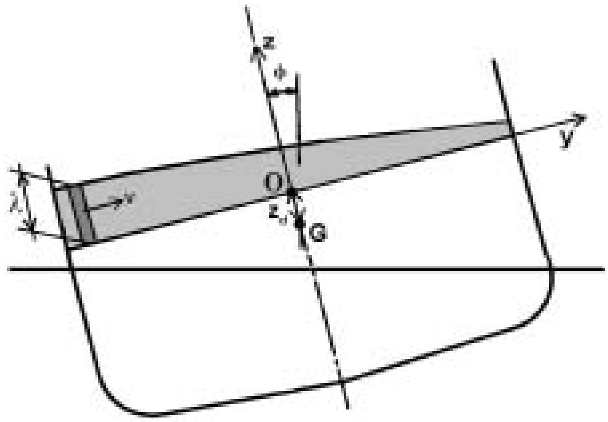

Figure 2 – Coordinate system for water-on-deck

The water motion is governed by a system of non-linear hyperbolic equations. These are derived from the continuity equation:

$$\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \qquad (2)$$

by integrating this equation over the depth while imposing the cinematic, dynamic and bottom boundary conditions.

The equations that describe the motion of the water in a stationary and level deck are:

$$\begin{aligned}&\frac{\partial v}{\partial t}+v\frac{\partial v}{\partial y}=-g\frac{\partial \eta}{\partial x}\\&\frac{\partial[v(\eta+h)]}{\partial y}=-\frac{\partial \eta}{\partial t}\end{aligned} \qquad (3)$$

Extending the same approach to a two dimensional deck, the following equations are obtained:

$$\begin{aligned}&\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-g\frac{\partial \eta}{\partial x}\\&\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-g\frac{\partial \eta}{\partial y}\\&\frac{\partial[u(\eta+h)]}{\partial x}+\frac{\partial[v(\eta+h)]}{\partial y}=-\frac{\partial \eta}{\partial t}\end{aligned} \qquad (4)$$

where $\eta=\eta(x,y,t)$ represents the elevation of the water surface, h is the depth of the water and u and v are the velocity components in the x and y directions.

If the ship is moving, the water equations of motion may be represented by:

$$\begin{aligned}
&\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-a_z\frac{\partial \lambda}{\partial x}+f_1(x)\\
&\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-a_z\frac{\partial \lambda}{\partial y}+f_2(y)\\
&\frac{\partial \lambda}{\partial t}+u\frac{\partial \lambda}{\partial x}+v\frac{\partial \lambda}{\partial y}+\lambda\frac{\partial u}{\partial x}+\lambda\frac{\partial v}{\partial y}=0
\end{aligned} \tag{5}$$

where $f_1(x)$, $f_2(y)$ and a_z represent the accelerations acting on the fluid in the x, y and z direction. Equations for these accelerations may be found in Pantazopoulos (1988). The water equations of motion (5) can then be solved efficiently using the fractional step method proposed by Yanenko (1971) and the method of random choice proposed by Glimm (1965), with further details in Santos and Guedes Soares (2003).

The numerical solution of the equations will produce the field of water heights, λ, and the fluid velocities, u and v. These properties can then be used to calculate the forces and moments caused by the water on the deck and bulwarks, which are given by:

$$F^{AC}=-\iint_S pn\,ds \tag{6}$$

$$M^{AC}=-\iint_S p\vec{r}\times\vec{n}\,ds \tag{7}$$

where:

$$p(x,y,z)=\rho a_z(x,y)\lambda \tag{8}$$

3. COMPARISON OF NUMERICAL AND EXPERIMENTAL RESULTS

3.1 Main Particulars and Body Plan of Selected Ship

Figure 3 shows the body plan of the selected passenger ro-ro ship, known in the literature as PRR1. The hull features a small bulb at the bow and substantial flare in the bow and stern sections.

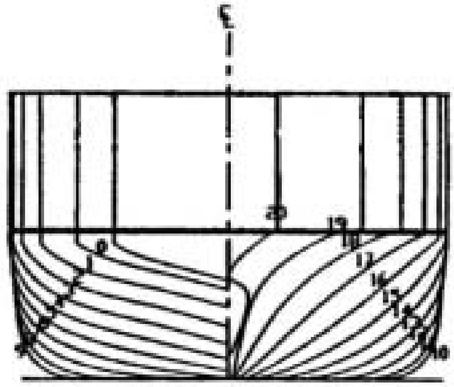

Figure 3 - Body plan of passenger Ro-Ro ship PRR1 (from Papanikolaou (2001))

Table 1 shows the main particulars of the ship, which has been extensively studied in the ITTC benchmark studies, as reported by Papanikolaou (2001) and Papanikolaou and Spanos (2004).

Table 1. Main particulars of passenger Ro-Ro ship PRR1

Displacement, Δ (t)	17268.0
Length between perpendiculars, L_{pp} (m)	170.00
Breadth, B (m)	27.80
Depth to the main deck, D_{md} (m)	9.40
Depth to the upper deck, D_{ud} (m)	17.78
Draught, T (m)	6.25
Trim, d (m)	+0.50
Vertical location of the CG, VCG (m)	12.89
Longitudinal location of the CG, LCG	-2.53
Metacentric height, GM (m)	2.63
Roll radius of gyration, K_{xx}/B	0.378/0.235
Pitch radius of gyration, K_{yy}/L_{pp}	0.25
Yaw radius of gyration, K_{zz}/L_{pp}	0.25
Roll natural period, T_s (s)	13.00
Roll natural frequency, w (rad/s)	0.483

Figure 4 shows the compartments subject to flooding in this study.

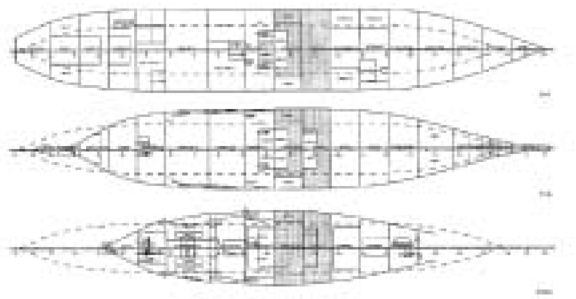

Figure 4 – Damaged compartments of passenger ro-ro ship PRR1 (from Papanikolaou (2001))

3.2 Motions of the Intact Ship

Figure 5 shows the righting lever curve for the intact ship condition when the vertical location of the centre of gravity is 12.89m above the keel. Results obtained by different partners in the ITTC benchmark studies are shown, along with results now obtained (IST). It can be seen that IST results agree perfectly with P2, P3 and P4, while P1 and P5 predict slightly higher righting levers for angles above 15º.

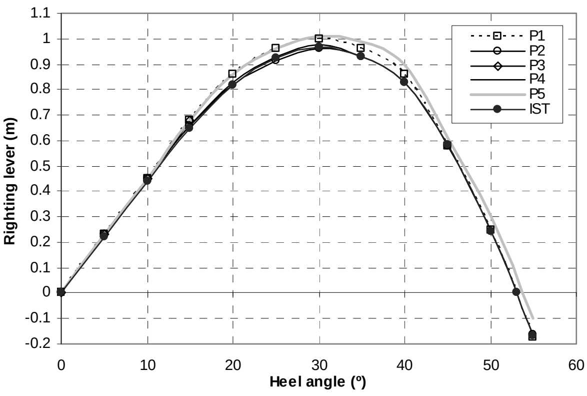

Figure 5 - Righting lever curve for the intact ship condition

Figure 6 shows the roll decay curves obtained experimentally and numerically for the ship in intact condition. It can be seen that the rolls periods are not exactly the same, namely that the one of the numerical results is 12.9s and the one of the numerical results is 12.8s.

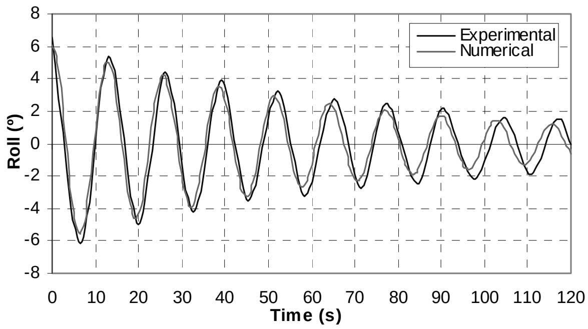

Figure 6 – Roll decay curves of the intact ship

Figure 7 shows the intact ship roll amplitudes obtained numerically within the ITTC benchmark study partners for different beam wave frequencies. Also shown are the roll amplitudes obtained experimentally for the 1.2m and 2.4m wave heights. It may be seen that all partners predict a roll resonance frequency around 0.48rad/s. However, a wide scatter in the roll amplitudes near the roll resonance is present. The results of partners P3 and P1 for the larger frequencies also show very significant differences in relation to the experimental results.

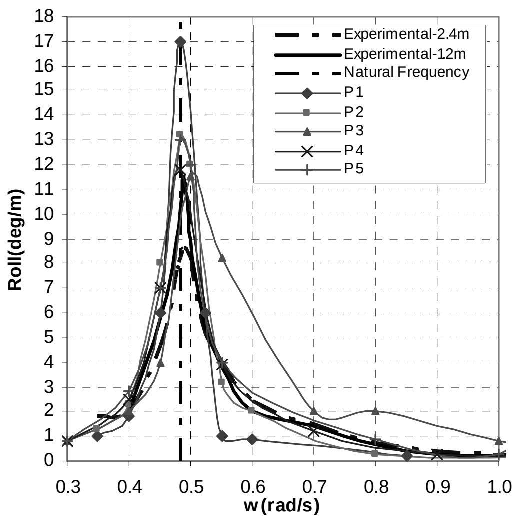

Figure 7 - Roll motion amplitudes of the intact ship obtained within the ITTC Study

Figure 8 shows the results obtained using the current approach in the frequency domain and in the time domain. Also shown are the experimental results. It can be seen that the time and frequency domain results are almost equal, as might be expected. They are also approximately equal to the experimental results for a wave height of 2.4m.

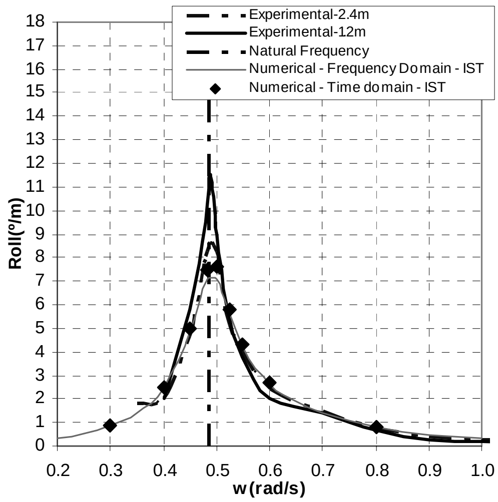

Figure 8 - Roll motion amplitudes of the intact ship

3.3 Motions of the Ship with Flooded Double-Bottoms

Figure 9 shows the righting lever curve for the ship when only the double-bottoms are flooded. The floodwater is taken as an added mass, leading to the centre of gravity being now located 12.45m above the keel. It is possible to see that the righting arms and range of stability increase in relation to those shown in Figure 5.

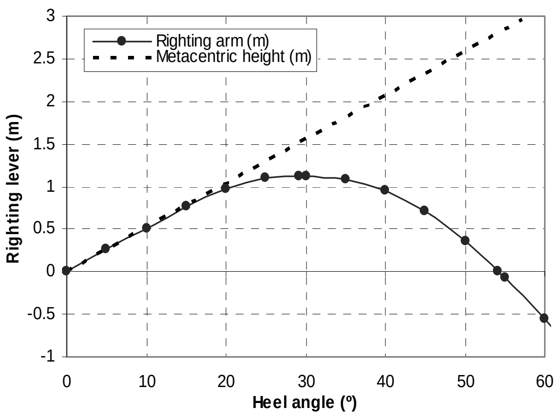

Figure 9 - Righting lever curve for the ship with double-bottoms full of water

Figure 10 shows the roll decay curve obtained numerically. It is worth mentioning that the roll period is approximately 12.4s, corresponding very closely to the roll resonance frequency shown in Figure 11, which is approximately 0.51rad/s.

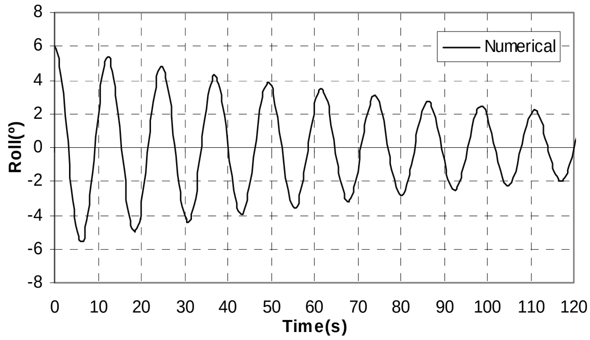

Figure 10 - Roll decay curve of the ship with double-bottoms full of water

Figure 11 shows the roll amplitudes in beam seas for the ship with flooded double-bottoms, in the frequency and time domains. The roll resonance frequency has increased to 0.5rad/s because both the metacentric height and the displacement increased, although the structural mass has also increased. The hydrodynamic forces have also changed because of the increased draught of the ship and different location of the centre of gravity.

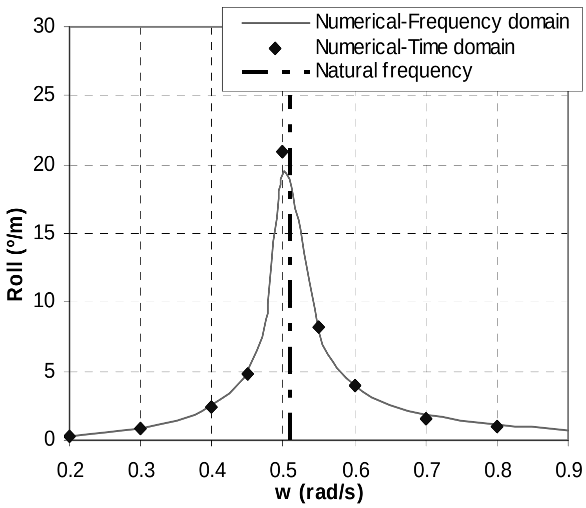

Figure 11 - Roll motion amplitudes of the intact ship with double-bottoms full of water

3.4 Motions of the Damaged Ship

Figure 12 shows the righting lever curve for the damaged ship condition, for the same vertical location of the centre of gravity, 12.89m above the keel. Results obtained by different partners in the ITTC benchmark studies are shown, along with results now obtained (IST). All partners except P3 agree that the heel equilibrium angle is around 3.5º. Regarding the extinction angle, some scattering of results is present, with extinction angles between 15.5º and 19º. The maximum righting levers obtained by the different partners are also different, ranging between 0.2 and 0.28m. The results obtained by IST fall in the middle of the other results and are similar to those of partner P5.

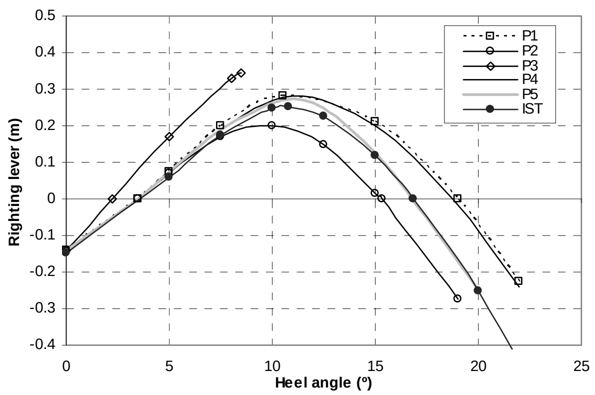

Figure 12 - Righting lever curve for the damaged ship condition

Figure 13 shows the roll decay curves obtained experimentally and numerically. It can also be seen that the experimental results show more damping than the numerical results and that the roll periods are not equal. Figure 13 shows that the period of the experimental results is 15s and the period of the numerical results is 16.75s. These periods match perfectly the experimental and numerical lower resonance frequencies shown in Figure 15.

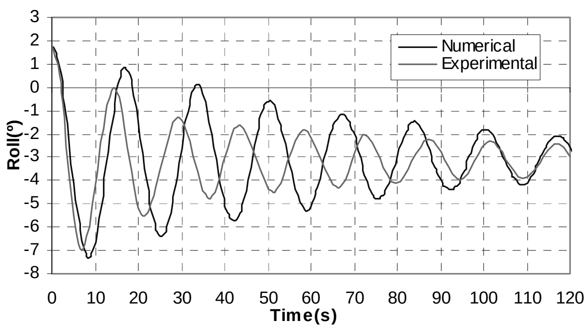

Figure 13 - Roll decay curves of the damaged ship

Figure 14 shows the roll amplitudes in regular beam seas obtained by the different partners of the ITTC benchmark study. The main conclusions is that the different partners are not able to reproduce the experimental results regarding roll resonance frequency, roll amplitude and the presence of a small second peak in the roll spectrum at higher frequencies.

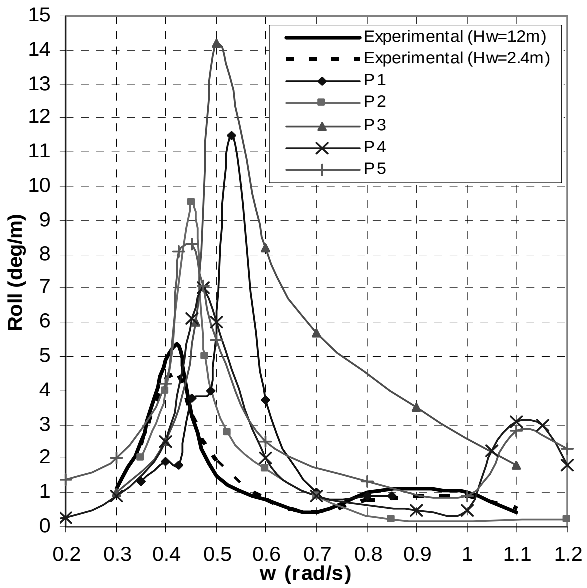

Figure 14 - Roll motion amplitudes of the damaged ship obtained within the ITTC study

Regarding the comparison of the experimental results in Figure 14 with those in Figure 7, it may be seen that the roll natural frequency decreased and the roll amplitudes also decreased up to 0.8rad/s. For higher frequencies, there is a slight increase in roll amplitude.

Figure 15 shows the roll amplitudes obtained using the following approach. The floodwater located inside the double-bottoms is taken as an added mass to the ship, causing an increase in the structural inertia and a decrease in the vertical location of the centre of gravity. No water flows in or out of the double-bottoms, because these are completely full of water. The water in the two compartments above the double-bottom is modelled simply as if compartment number 10 was flooded and compartment number 9 is intact. On the other hand, the tank located inside compartment 10 is ignored. Compartment 10 is then modelled has a tank with a beam of 27.8m, a length of 9.6m and a water depth of 5.5m. The beam/depth ratio is 0.198, therefore marginally below 0.2, the limit of applicability of the shallow water theory. For this tank, the resonance frequency is 0.83rad/s, in the range where the roll response curves show the small peak.

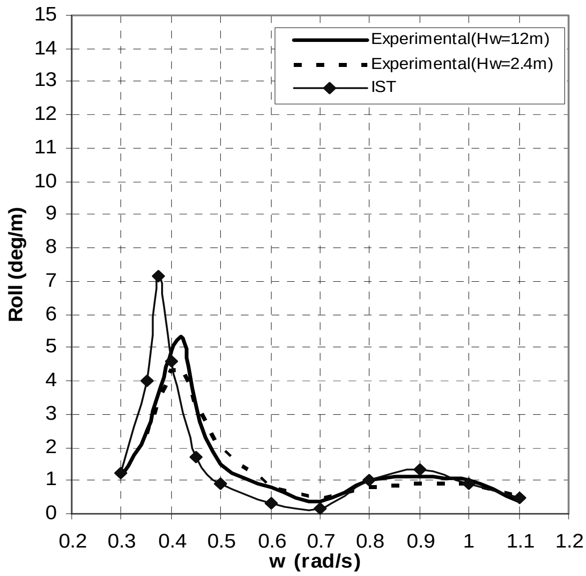

Figure 15 - Roll motion amplitudes of the damaged ship obtained by IST

Figure 15 allows the conclusion that the two peaks in the roll spectrum are captured. The peak in the lower frequency range is slightly overestimated and the resonance frequency is lower than the one shown in the experimental results. This is in accordance with Figure 13. The peak in the upper frequency range is much smaller in magnitude and is well captured both in amplitude and frequency. It is worth pointing out that both the heel angle due to the asymmetrical flooding resulting from the damage condition shown in Figure 4 and the effects of inflow and outflow are neglected.

Figure 16 shows the floodwater surface inside compartment 10. The waves are regular with a 1.2m amplitude and 0.6rad/s frequency. It can be seen that the floodwater surface is quite smooth, with no hydraulic jump.

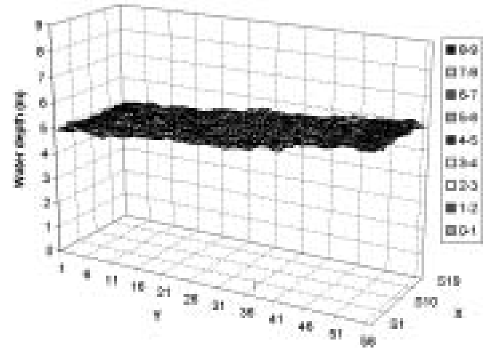

Figure 16 – Floodwater surface inside compartment 10 at T=111s (56×20 cells)

Figure 17 shows the shape of the floodwater surface inside compartment 10 at a specific moment in time. The ship is rolling under the action of 1.2m amplitude waves and with a frequency of 0.9rad/s (period of 7s). A large hydraulic jump travelling in the Y direction can be seen. Figure 18 shows the shape of the floodwater surface inside the same compartment in the same moment and when the wave conditions equal. The floodwater has been modelled using a grid with 84×30 cells. Once again, it can be seen that a large hydraulic jump appears in the middle of the tank, travelling in the Y direction. Its position within the tank is similar to the position in Figure 18 and the amplitude is also similar.

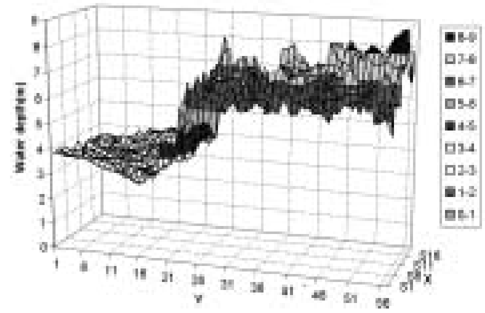

Figure 17 – Floodwater surface inside compartment 10 at T=111s (56×20 cells)

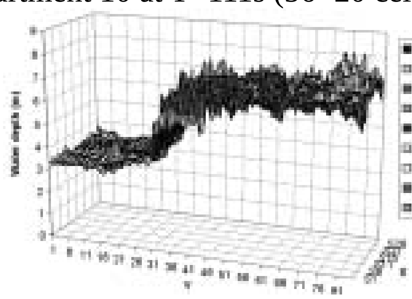

Figure 18 – Floodwater surface inside compartment 10 at T=111s (84×30 cells)

Figures 19 and 20 show the time history of the water depth in the cell immediately adjacent to one side of the ship's hull within compartment 10. The ship is rolling under the action of regular beam waves 1.2m amplitude and 0.9rad/s and 0.375rad/s. It may be seen that the water depth rises suddenly when the hydraulic jump reaches the side of the ship. The period of arrival of the hydraulic jump is approximately 7s, corresponding to the wave frequency of 0.9rad/s. Two runs of the simulation are shown for purposes of comparison, showing a similar behaviour. In Figure 20, it can be seen that the differences between different runs are very small and that no hydraulic jump appears.

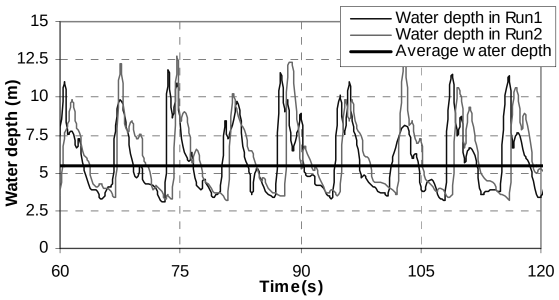

Figure 19 – Time history of water depth on side of compartment 10 (56×20 cells) with wave frequency 0.9rad/s

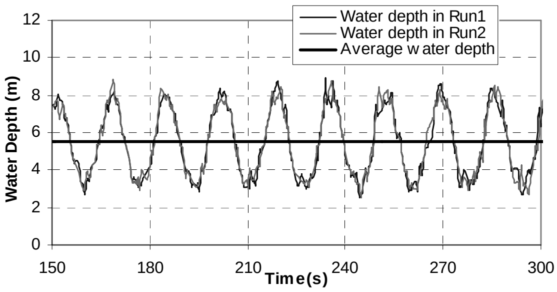

Figure 20 – Time history of water depth on side of compartment 10 (56×20 cells) with wave frequency 0.375rad/s

4. CONCLUSIONS

This paper has presented the application of a time domain theoretical model of damaged ship motions coupled to a shallow water model for the description of the motion of water inside the ship's compartments. It was applied to investigate the effects on roll motion of water inside the compartments below the main vehicle deck of a passenger ro-ro ship.

Good agreement was found between numerical and experimental results for the intact ship roll motion amplitudes for different wave frequencies and between the numerical and experimental results concerning the roll extinction curve.

The behaviour of the ship with flooded double-bottoms was also investigated, considering the water as an added mass to the ship, resulting in an increased displacement, lower centre of gravity and increased inertia. It was found that the roll resonance period increases, but unfortunately there were no experimental results available to compare with.

The numerical results for the roll decay when the compartments above the double-bottom are flooded indicate a smaller damping than that shown in the experimental results and different roll periods.

The numerical results for the roll amplitude response show two peaks of roll response, a feature which is in accordance with the experimental results and constitutes an important result.

The frequency of the lower roll resonance is slightly under predicted and its amplitude is larger than that shown in the experimental results. The roll peak at higher frequency is small and occurs approximately at the frequency of resonance of the water inside the compartments. The numerical method is capable of capturing well this second peak, contributing to an enhanced understanding of damaged ship behaviour.

Finally, this paper also shows that the shallow water theory can provide more realistic descriptions of the moving water surface inside the flooded compartments.

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