THE FLOODING AFTER DAMAGE OF A WARSHIP WITH COMPLEX INTERNAL COMPARTMENTS – EXPERIMENTS ON A FULLY CONSTRAINED MODEL IN CALM WATER AND REGULAR BEAM SEAS

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SUMMARY

In order to provide data to assist in developing and validating a numerical code to simulate the flooding immediately following damage scale model experiments were conducted on a fully constrained model to investigate the progressive flooding through a complex series of internal compartments within a generic destroyer type hull form.

A 3.268 metre long model of a generic destroyer hull form with a simplified, typical internal arrangement was constructed to cover the configuration of greatest interest. A very rapid damage opening scenario was simulated by rupturing a taut membrane covering an opening. The model was instrumented to measure the levels of water and the air pressures in various compartments. In addition, video footage was obtained of the flooding process from both internally and externally of the model.

Previous work presented by Macfarlane *et al*. (2010) showed the results for the unconstrained model. This paper reports on the outcomes from the experimental program where the model was fully constrained in all six degrees of freedom. Firstly, tests were conducted in calm water with damage opening extents ranging from 50% to 100%. When the damage opening was only 50% the rate of rise of water in each of the compartments was only marginally slower than for the 100% damage extent case.

Secondly, the test results in calm water were compared against results from tests in regular beam seas. A ‘set-up’ of water inside each of the compartments on the 2nd Deck was found during the wave tests. The result of this is that the mean equilibrium water level in each compartment in the regular beam sea cases is noticeably higher than the equivalent calm water case, particularly for the two compartments on the port side, away from the damage. Finally, analysis of the data from further calm water and beam sea tests suggests that a similar result also occurs when the model is fixed at various non-zero heel angles.

1. INTRODUCTION

The motions, and consequent safety, of a ship after it has been damaged are highly dependent on the way flood water passes between compartments immediately following the damage event. A lot of work has been done to investigate the behaviour of flood water following damage for simplified internal geometries (for example, de Kat *et al*. 2000; de Kat and Peters 2002; Vassalos *et al*. 2004), however less has been done for the more complex arrangements common to warships.

In order to investigate this behaviour and generate data to assist in ongoing validation of the flooding model used in a non-linear time domain code, FREDYN, developed by MARIN for the Cooperative Research Navies group (CRN), model experiments were conducted using a model of a generic destroyer hull form with an internal arrangement representative of a typical warship. The experiments were conducted in the 35m x 12m basin at the Australian Maritime College (Macfarlane and Renilson, 2010).

Macfarlane *et al*. (2010) and Turner *et al.* (2010) have previously reported on outcomes from this experimental study with a focus on the model being fully unconstrained. The work presented in the current paper concentrates on the experimental results for the model constrained in all six degrees of freedom in both calm water and regular beam seas. FREDYN comprises a ship motion model and a progressive flooding model and the uncertainty in each model can be solved by separating the validation process into several phases, as described by Ypma and Turner (2010). The validation phase of specific interest in the present work requires that the ship model be fully constrained at a prescribed heel, trim and draught which allows for a check of the flooding model without any additional complexities due to the dynamics of the vessel. In addition, the geometry of the numerical model can be verified in this phase.

For consistency, all results given in this paper are at model scale.

2. MODEL DETAILS

A 3.268 metre long model of a generic destroyer was constructed of carbon fibre composite and timber to a scale of 1:45. A removable module containing a simplified arrangement of the internal compartments was constructed out of perspex. The principal particulars of the model are provided in Table 1.

Length overall	3268	mm
Length between perpendiculars	2961	mm
Beam	412	mm
Draught	118	mm
Displacement	68.63	kg
LCG (forward of AP)	1418	mm

Table 1 Model principal particulars

The layout of compartments for each of the three deck levels are shown in Figure 1(a, b and c) and cross sections at locations AA, BB and CC are provided in Figure 2(a, b and c). Detailed information about the model, such as the compartment dimensions and volumes; the names, locations and sizes of each of the hatch openings and doorways between the internal compartments; locations of each sensor; and details of the damage to the hull, bulkheads and decks, are provided in Macfarlane and Renilson (2010) and Macfarlane and Hutchison (2010).

A very rapid damage opening scenario was simulated by rupturing the taut membrane by either sharp blades or hot wires that were operated by a remote switch. The hot wires were used in the later tests as this proved to be a more reliable technique. Rupturing the membrane in this way resulted in the loss of the latex patch within 1/25th second (one video frame), leading to a very rapid damage event. A wave probe was located on the 2nd Deck immediately inboard of the damaged membrane to provide a reliable time datum with the acquired data for when the damage occurred.

3. EXPERIMENTAL SET UP

For all experiments covered in this paper the model was at zero forward speed. The test rig was set up such that the model was fully constrained in all six degrees of freedom (surge, sway, yaw, heave, pitch and roll). In all cases the model was located approximately in the centre of the experiment basin to avoid any interaction with the test basin walls.

Two pairs of draught gauges were fitted to the model to set the required draught. These were checked periodically to ensure that small changes in water level in the basin did not influence the draught of the constrained model (which was not free to heave if the water level changed).

A total of seven wave probes were included to measure the water levels in the following compartments: 0Fwd-S06; 2Aft-S11; 2Centre-S12; 2Centre-S15; 2Fwd-S16; 1Aft-S17 and 1Centre-S23 (the location of these wave probes is indicated by the symbol ‘WP’ in Figure 1). In addition, pressure transducers were fitted into tank 0Fwd-S06 and compartment 2Centre-S12 (indicated by ‘PP’ in Figure 1). All wave probes were regularly calibrated and double-checked by applying a reference datum (known water depth) following the completion of most test runs.

The air pressures within tank 0Fwd-S06 and compartment 2Centre-S12 were measured using Endevco pressure transducers (model number 8510B-2) having a range of 13.8 kPa (2.0 psi) linked to an Endevco Model 136 DC amplifier.

On completion of data acquisition the model was removed from the basin, the water was emptied from all tanks and a new latex membrane fitted prior to setting up for the next run. Once the model was prepared and located, the basin was allowed to return to a calm state before the next run was begun.

The following levels of uncertainty were estimated:

- Model dimensions = breadth and draught ±1.0 mm and for length ±1.5 mm
- Model displacement = ±100 grams
- Water surface elevation = ±2.0 mm

4. RESULTS AND DISCUSSION

4.1 COMPARTMENT WATER LEVELS AND AIR PRESSURES

Figure 3 shows the water elevations at each wave probe within the four selected compartments as functions of time. In all cases these elevations represent the raw wetted lengths of each sensor, with a zero reading corresponding with no water at the base of the wave probe. Note that the damage initiation occurs for all time series plots presented in this paper occurs at time t = 0 seconds.

As can be seen, the water levels at each of the three probes on the 2nd Deck (2Centre-S12, 2Centre-S15 and 2Aft-S11) have all reached equilibrium within about 12s after damage initiation. The probe in compartment 2Centre-S12 very rapidly reaches an equilibrium value, which was expected given that this is the compartment where the damage opening in the hull is located and as such there are no restrictions to impede the incoming flow of water.

The relatively slower rise in water level at the probes in the two port-side compartments, 2Aft-S11 and 2Centre-S15, provide an indication as to the additional time required for the water to pass through the open doorways and neighbouring compartments. The probe in the tank 0Fwd-S06 indicates that it took considerably longer (approximately 38s) for this lower tank to fill with water as the water flowed into this compartment via a smaller hatch opening rather than a larger doorway opening.

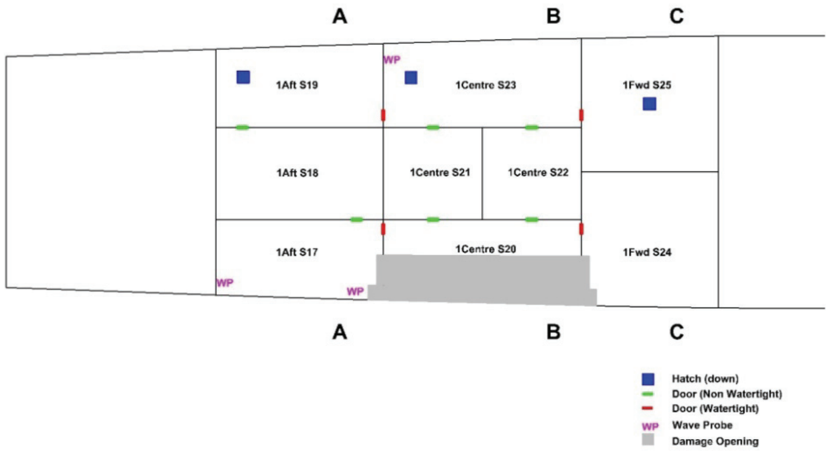

Figure 1a Plan of 1st Deck

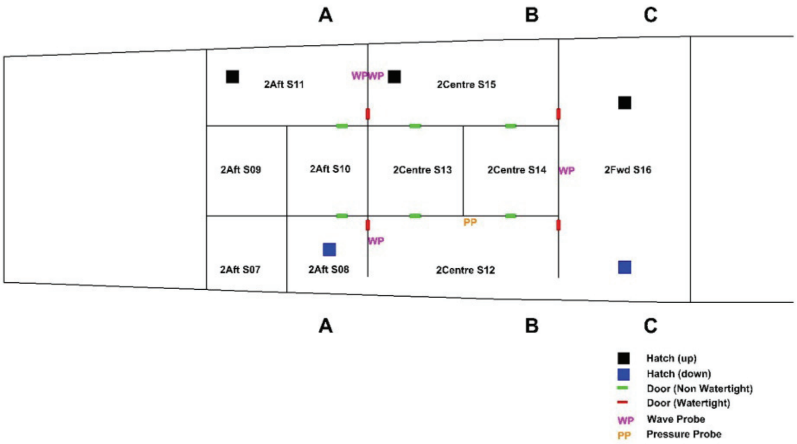

Figure 1b Plan of 2nd Deck

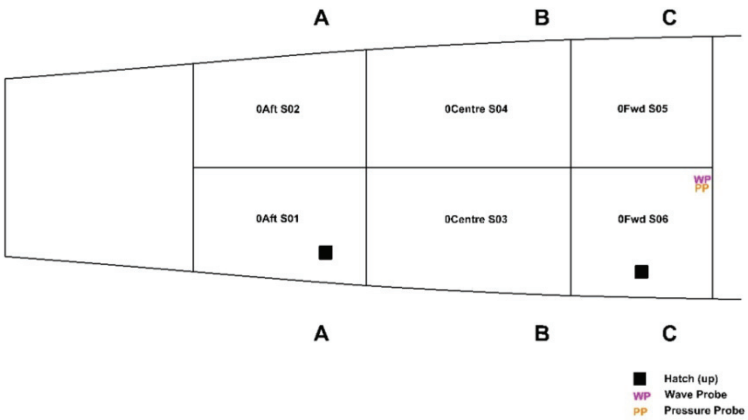

Figure 1c Plan of Tank Deck

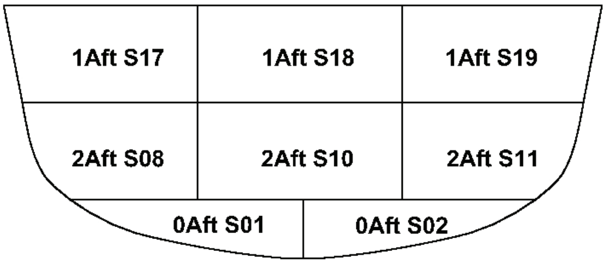

Figure 2a Cross-section AA

Figure 2b Cross-section BB

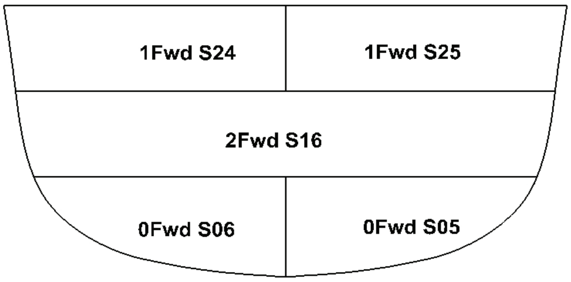

Figure 2c Cross-section CC

The water levels in the lower tank on the starboard side (0Fwd-S06) are plotted as functions of time in Figure 4. As can be seen, there are two distinctly different patterns: one where the water level increases slowly and consistently; and one where the water level increases rapidly to begin with, and then levels out. In each case the tank was full at the end of the run (the slight differences in equilibrium water level are within the expected level of uncertainty).

It was observed that for the cases where the water level increased rapidly, a vortex was formed in the water on the 2nd deck above. This meant that air escaping from this compartment had a direct path to the atmosphere. On the other hand, for the runs where the water level filled more slowly such a vortex did not appear, and consequently the air could only escape from this compartment more slowly as a series of bubbles. This was visible within the footage from the internal video camera. It is unknown as to what triggered this vortex to occur during some runs and not in others.

Note that the area of the damage opening varied between the four runs shown in Figure 4, however it is assumed that this had little effect on the rate at which tank 0Fwd-S06 filled due to its location and because it filled through a down flooding hatch.

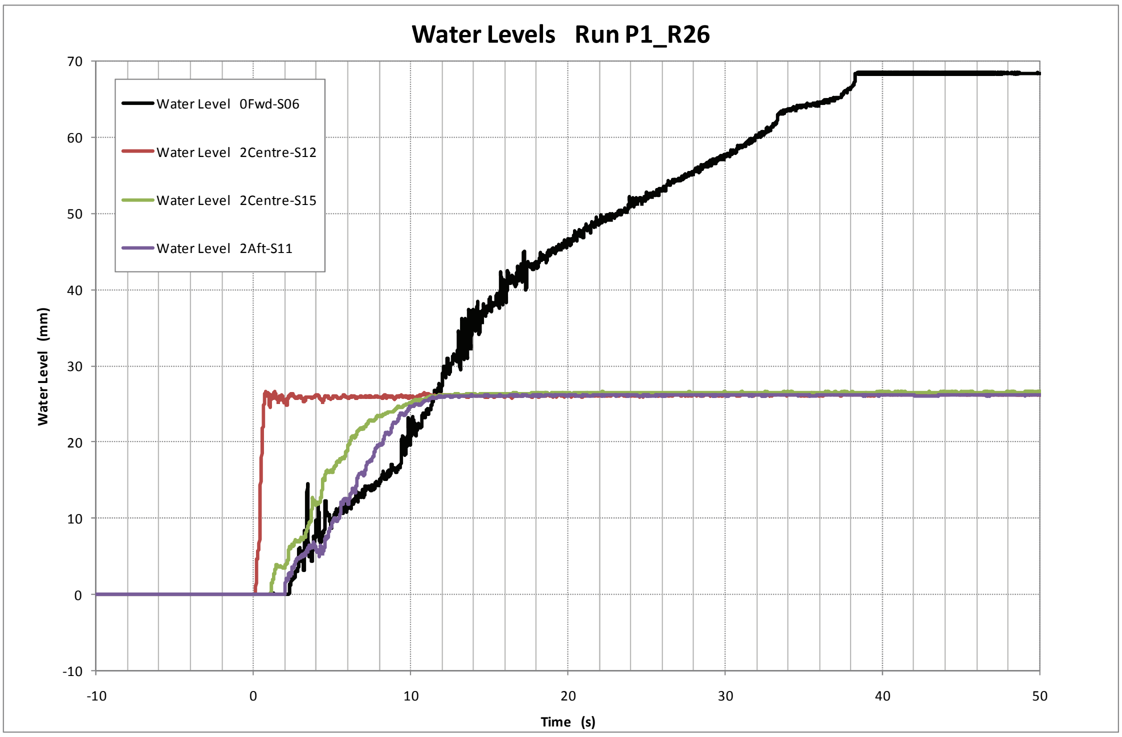

Figure 3 Water levels in compartments as a function of time

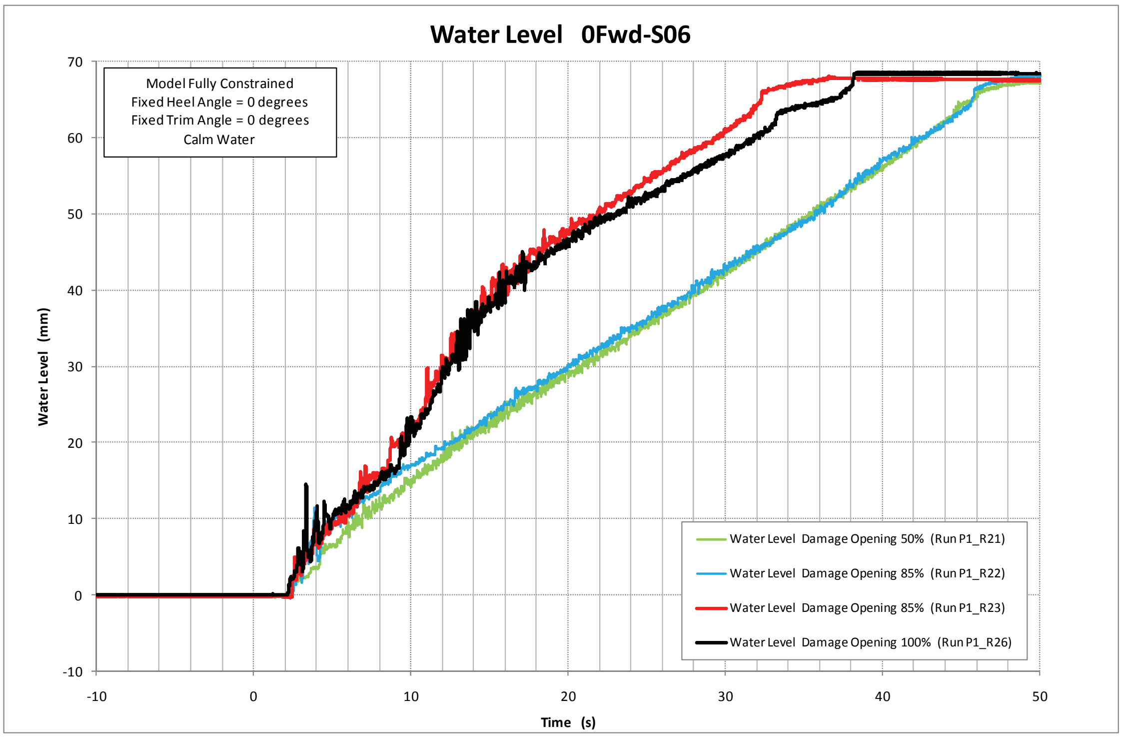

Figure 4 Water level at 0Fwd-S06 as a function of time

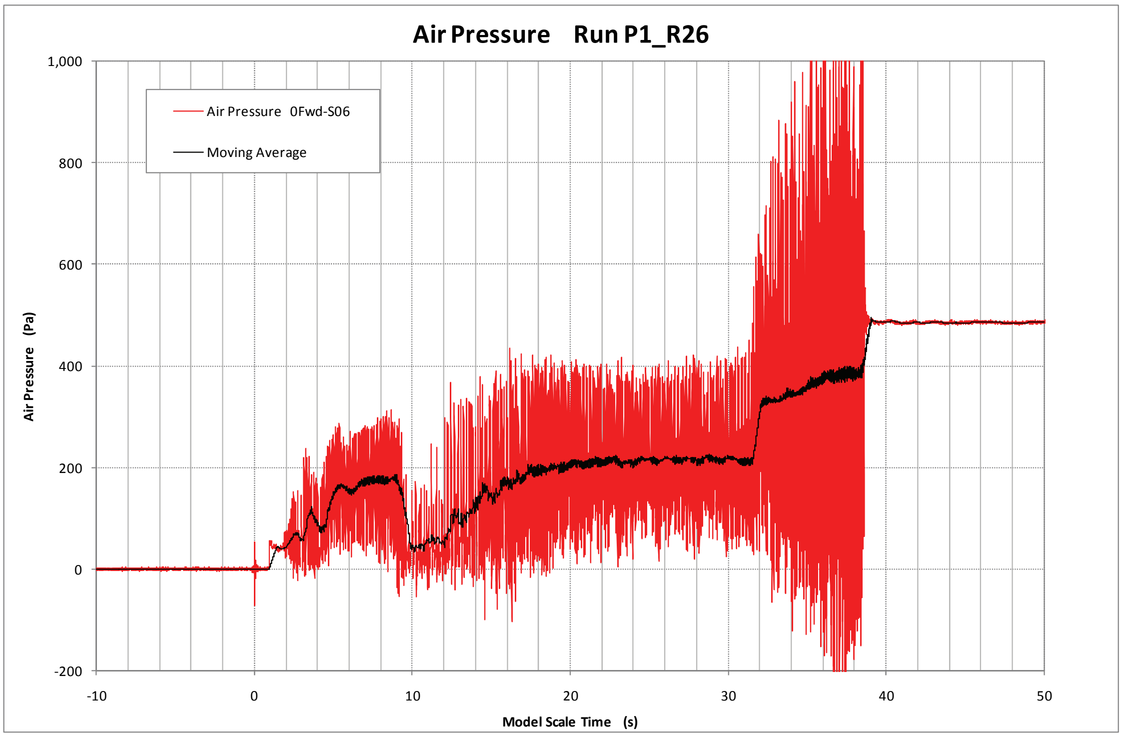

Figure 5 Air pressure in tank 0Fwd-S06 as a function of time

Figure 5 is a plot of the change in air pressure as a function of time within compartment 0Fwd-S06, which was located in the forward lower starboard tank (see Figure 1). As can be seen, there was considerable noise in the signal as water was entering the tank, however the signal noise level dramatically decreased as the water level within the tank reached equilibrium after just over 38s. This appeared to coincide with a reduction in the level of bubbles that were occurring as this tank filled up through the hatchway, which were visible in the video footage. To provide a clearer picture of how the air pressure changes, a moving average curve has been added, as shown in black (period of moving average = 100 samples).

4.2 EFFECT OF AREA OF DAMAGE OPENING ON COMPARTMENT WATER LEVELS

The area of the damage opening was varied from 50% up to 100%, as shown in Table 2, to investigate what influence this has on the flow of water into the compartments and provide experimental data for the purpose of validating numerical codes. Note that 100% damage was assumed to be the full length of damage opening multiplied by a height of damage opening up to the static waterline for the design draught. In Table 2, the top of each diagram corresponds approximately to the waterline.

The water levels in the centre tank on the starboard side (2Centre-S12) are plotted as functions of time in Figure 6. Here the levels all rise very quickly, with only the result for the 50% damage opening (Run P1_R21) being slightly slower. All reach the same approximate equilibrium position, as this wave probe is in the free flooding space close to the damage opening. This small effect that the 50% damage opening has on the filling rate can also be seen in Figure 9, where the water levels within tank 2Centre-S12 at time t = 10s are plotted. At this point in time, the water level is about 3mm lower than the cases where at least 85% of the damage area is open.

The water levels in the two compartments on the 2nd deck on the port side (2Centre-S15 and 2Aft-S11) are plotted as functions of time in Figures 7 and 8 respectively. With the exception of the smallest damage opening (Run P1_R21, 50%) these results are very similar for the forward of these two compartments (2Centre-S15).

For the aft compartment on the 2nd Deck (2Aft-S11) the damage opening had a slight influence on when the water first reached the wave probe, with the water level taking slightly longer to reach the wave probe when the area of the damage opening was reduced. The damage opening appears to have affected the water level in tank 2Aft-S11 for both the 50% and 85% damage opening cases as they are lower than the 100% case, as can be seen in Figure 9. It should be noted that in all these cases there was a reduction in damage opening area at the aftermost part of the damage opening (thus the incoming water had further to travel to this aft compartment).

4.3 EFFECT OF WAVES ON COMPARTMENT WATER LEVELS

The water levels in compartments 0Fwd-S06, 2Aft-S11, 2Centre-S12, 2Centre-S15 and 2Fwd-S16 from a test in calm water are compared against results from a test in regular beam seas with nominal wave height of 50mm and wave frequency of 0.9Hz, see Figures 10 to 14, respectively. For all these tests the damage opening is facing the oncoming waves and the model is fixed at level heel.

As can be seen in Figure 10, there is very little difference between the calm water and regular beam sea cases for the tank 0Fwd-S06. Water entering this tank does so through a down-flooding hatch so the water level does not oscillate in the same manner as the compartments on the 2nd Deck. Thus, the results in regular beam seas appear to be similar to those from the equivalent calm water tests.

As expected, the incident waves cause the water level in the compartments to also oscillate, which generally occurs at wave frequency, although the variation in water elevation is more complicated due to wave reflection and refraction within the compartments. The magnitude of the oscillations in water level tends to be greatest within those compartments that have more direct access to the damage opening. For example, wave oscillations of up to approximately 40mm occur within compartment 2Centre-S12, which is fully exposed to the damage opening, whereas this reduces to as low as approximately 10mm for 2Centre-S15 and 5mm for 2Aft-S11 (the incident wave height was 50mm). Both of these compartments are located on the port side of the model where the waves need to travel through open doors and adjoining compartments.

Of particular note, there appears to be a build up, or 'set-up', of water inside each of the compartments on the 2nd Deck. The result of this is that the mean equilibrium water level in the regular beam sea cases is higher than the equivalent calm water case. This is particularly noticeable for the two compartments on the port side, 2Aft-S11 and 2Centre-S15.

Further calm water and beam sea tests were conducted with the model at fixed heel angles of 5 and 10 degrees (both to starboard – *i.e.* towards the damage, which is facing the oncoming waves). Figure 15 presents a cross-plot of the equilibrium water levels as a function of heel angle. As can be seen, a set-up in water level of similar magnitude occurs at both port-side compartments (2Aft-S11 and 2Centre-S15) at each of the three fixed heel angles (0, 5 and 10 degrees).

However, this set-up appears to reduce at 5 degrees of heel and is not present at all for 10 degrees of heel for the wave probe located along the model centreline (2Fwd-S16) and the probe on the starboard side near the damage opening (2Centre-S12). This reduction in water level set-up at these two locations appears to be approximately linear with increasing heel angle. Note that the equilibrium water level during the regular beam sea tests is assumed to be the mean of the oscillations.

Further investigation is required to determine what effect wave frequency and/or wave height may have on these results.

Run Number	Damage Opening (%)	Damage Opening (unshaded area indicates damage opening)
P1_R21	50%	
P1_R22	85%	
P1_R23	85%	
P1_R26	100%	

Table 2 Details of damage openings

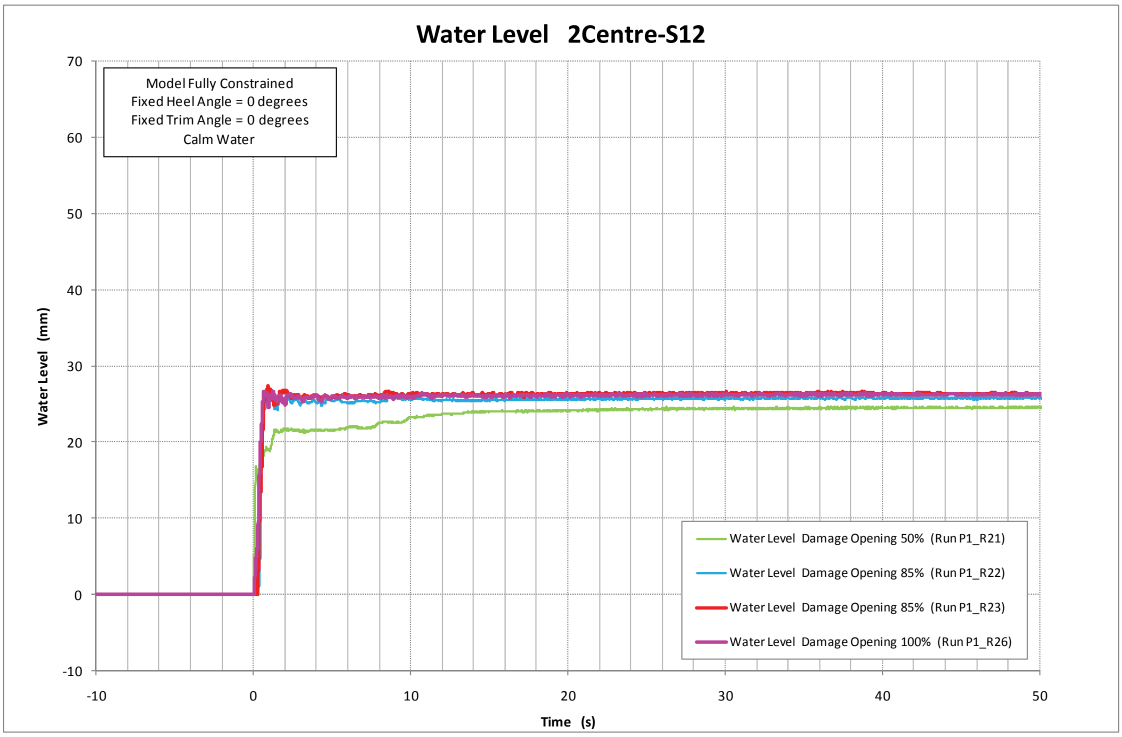

Figure 6 Water level at 2Centre-S12 as a function of time

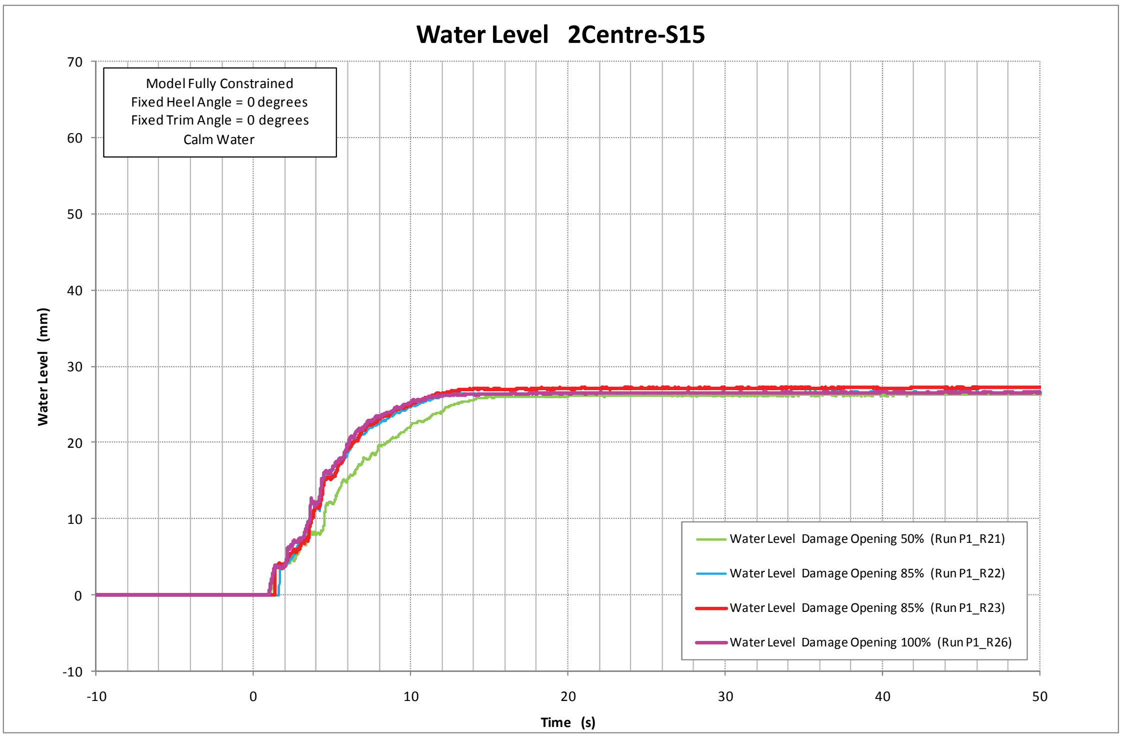

Figure 7 Water level at 2Centre-S15 as a function of time

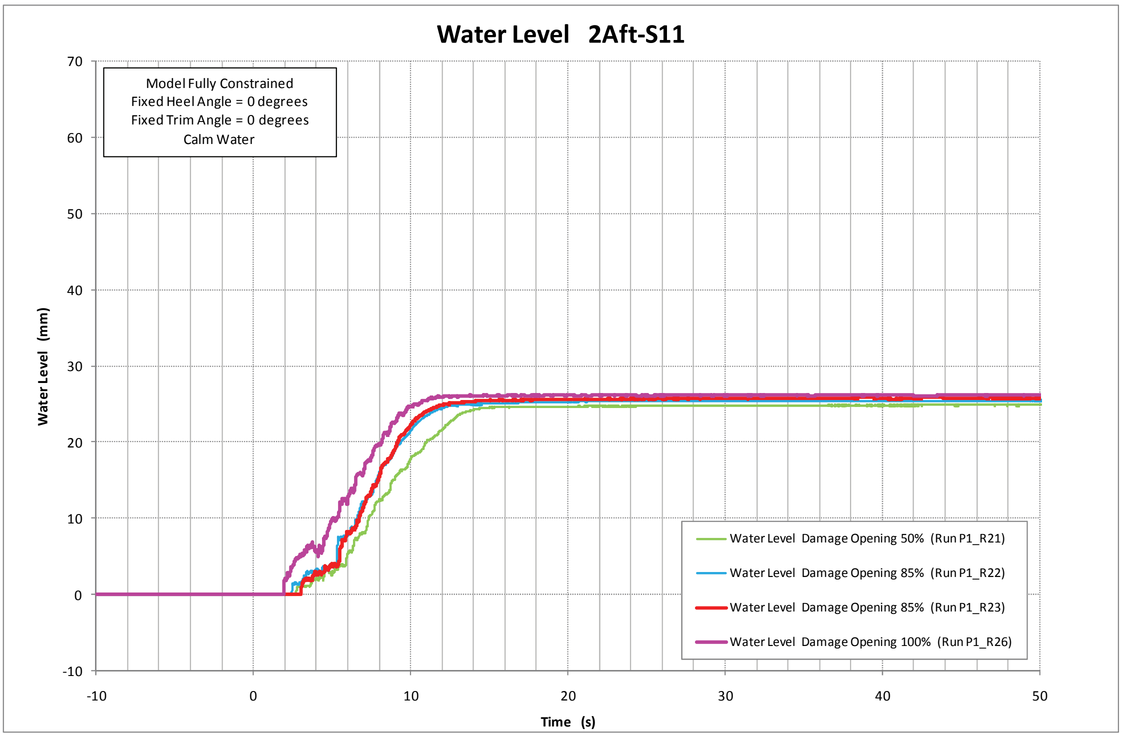

Figure 8 Water level at 2Aft-S11 as a function of time

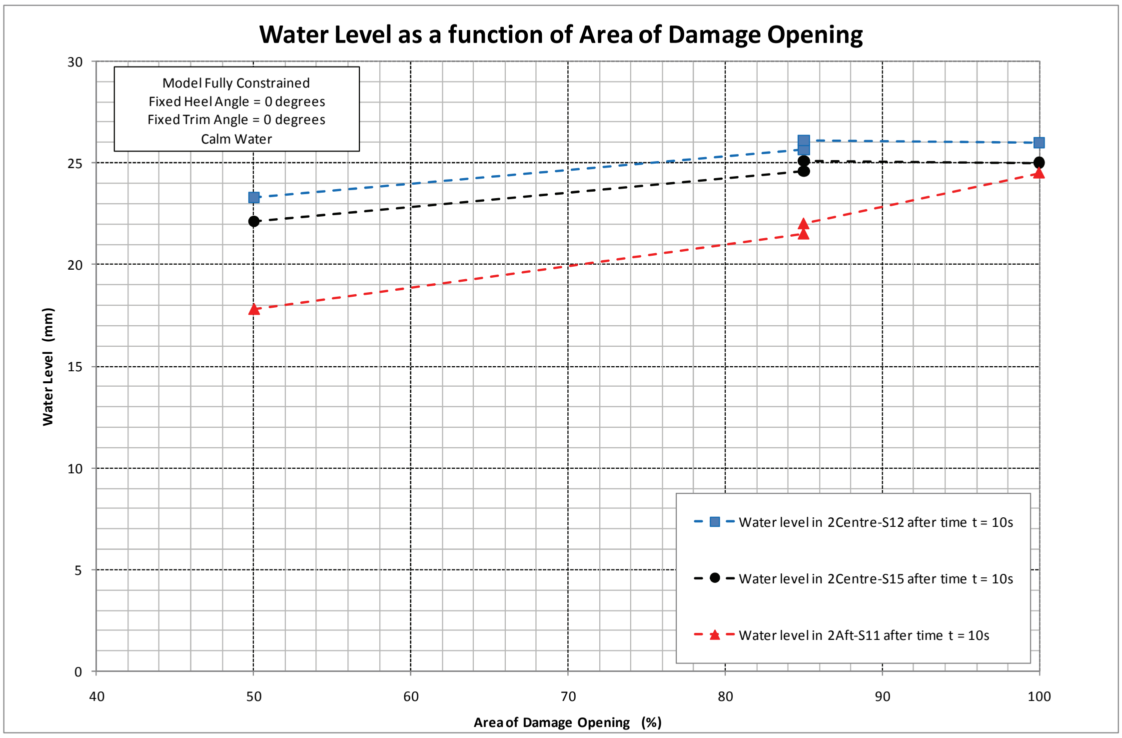

Figure 9 Water level as a function of area of damage opening

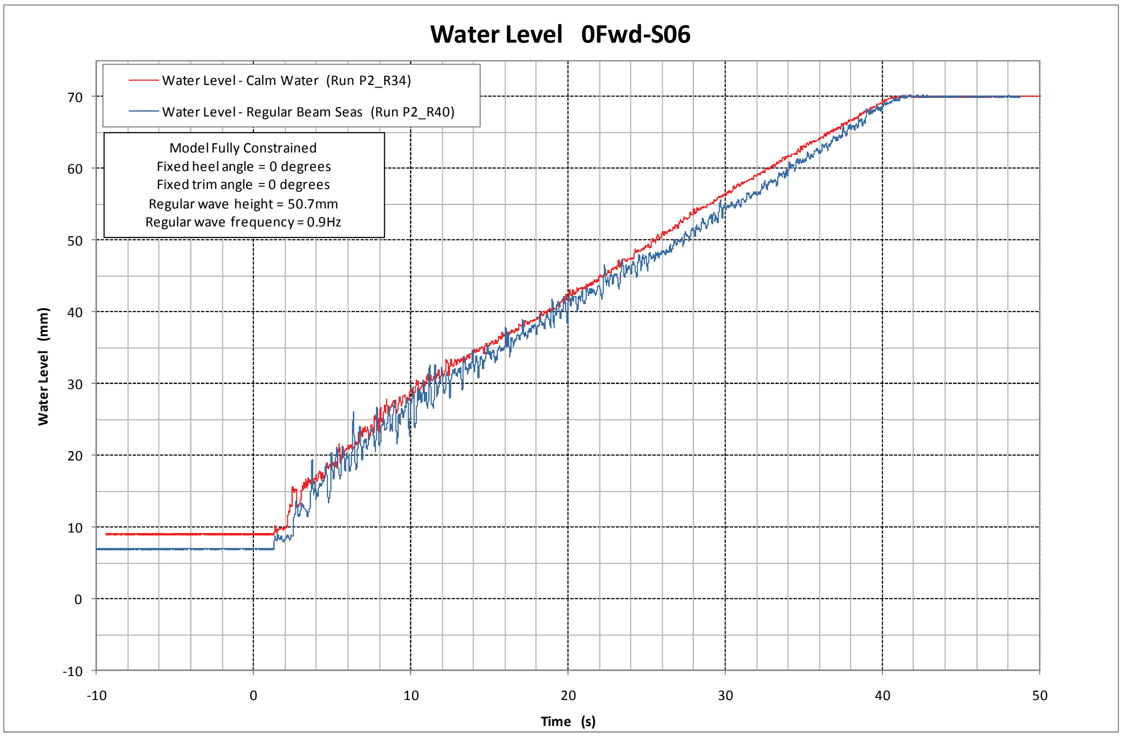

Figure 10 Water level at 0Fwd-S06 as a function of time

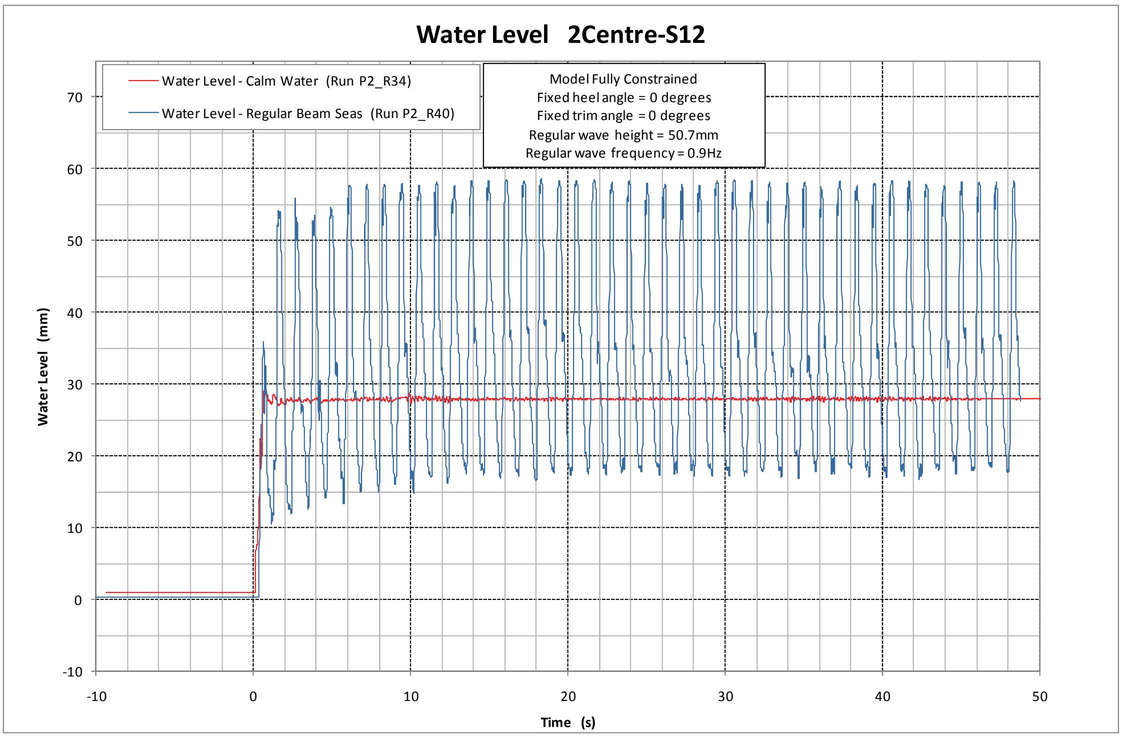

Figure 11 Water level at 2Centre-S12 as a function of time

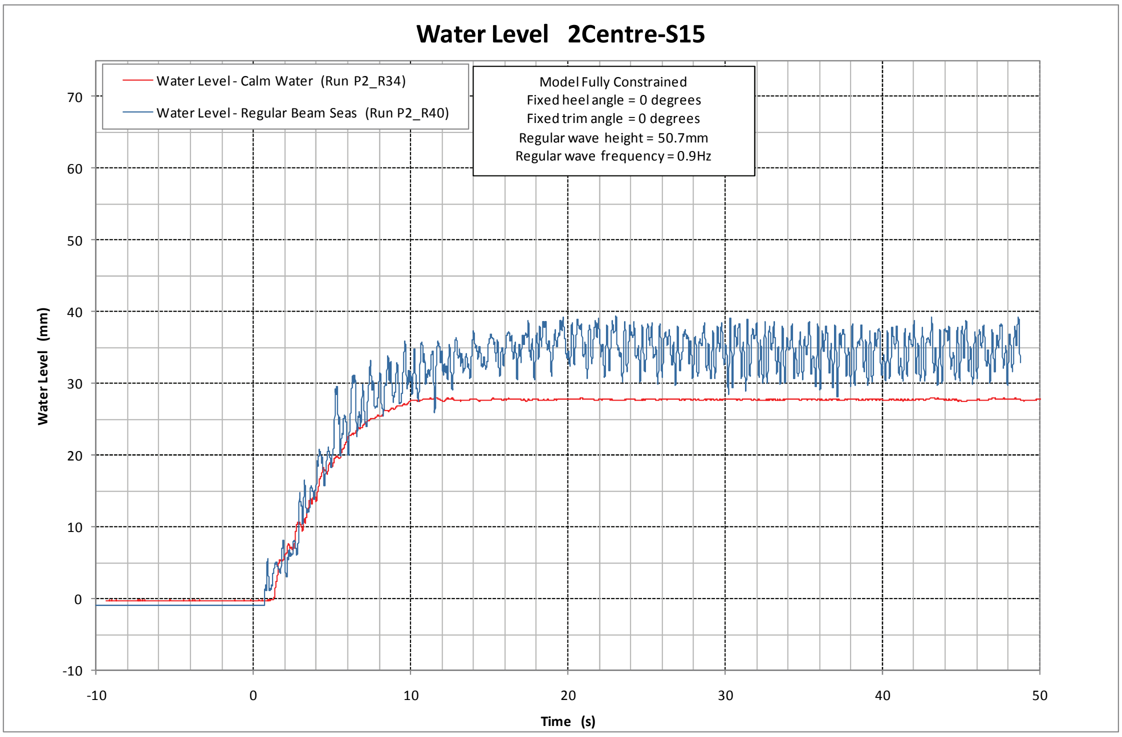

Figure 12 Water level at 2Centre-S15 as a function of time

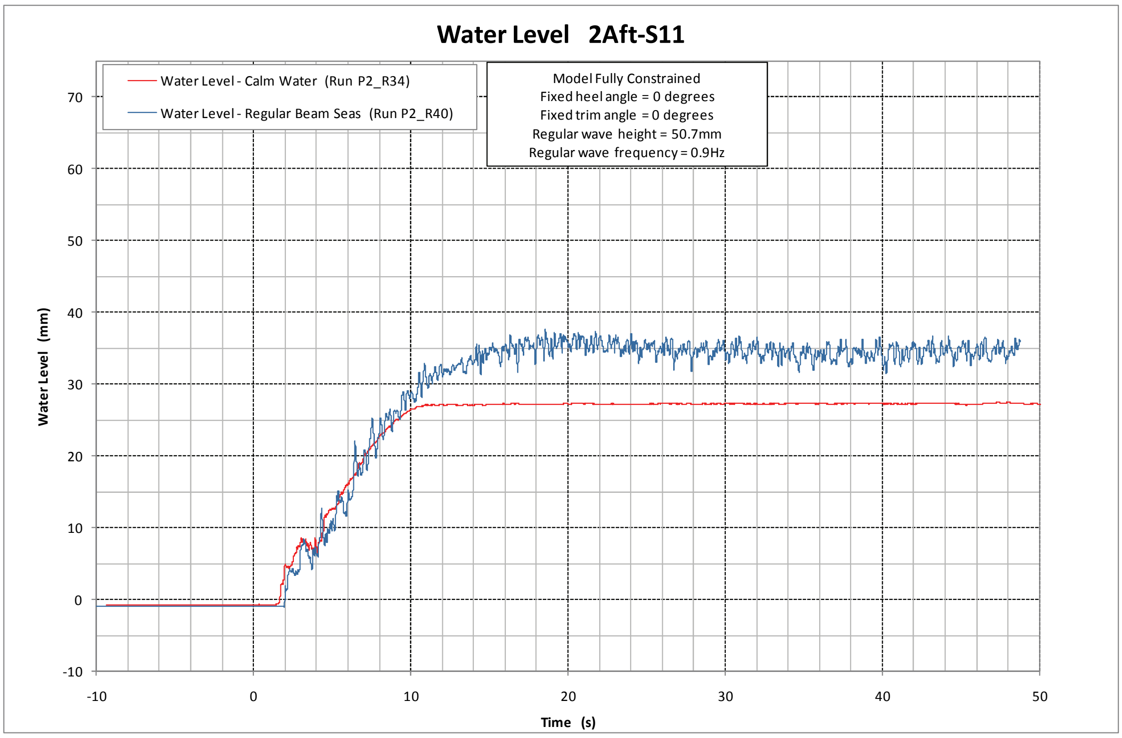

Figure 13 Water level at 2Aft-S11 as a function of time

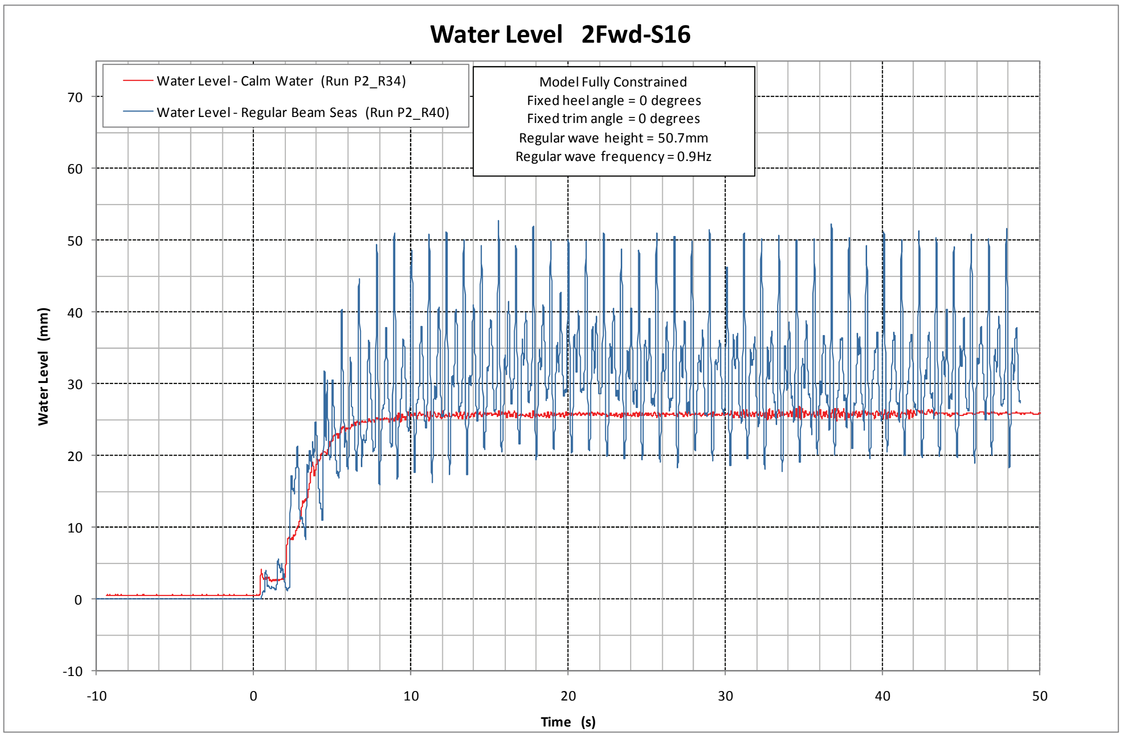

Figure 14 Water level at 2Fwd-S16 as a function of time

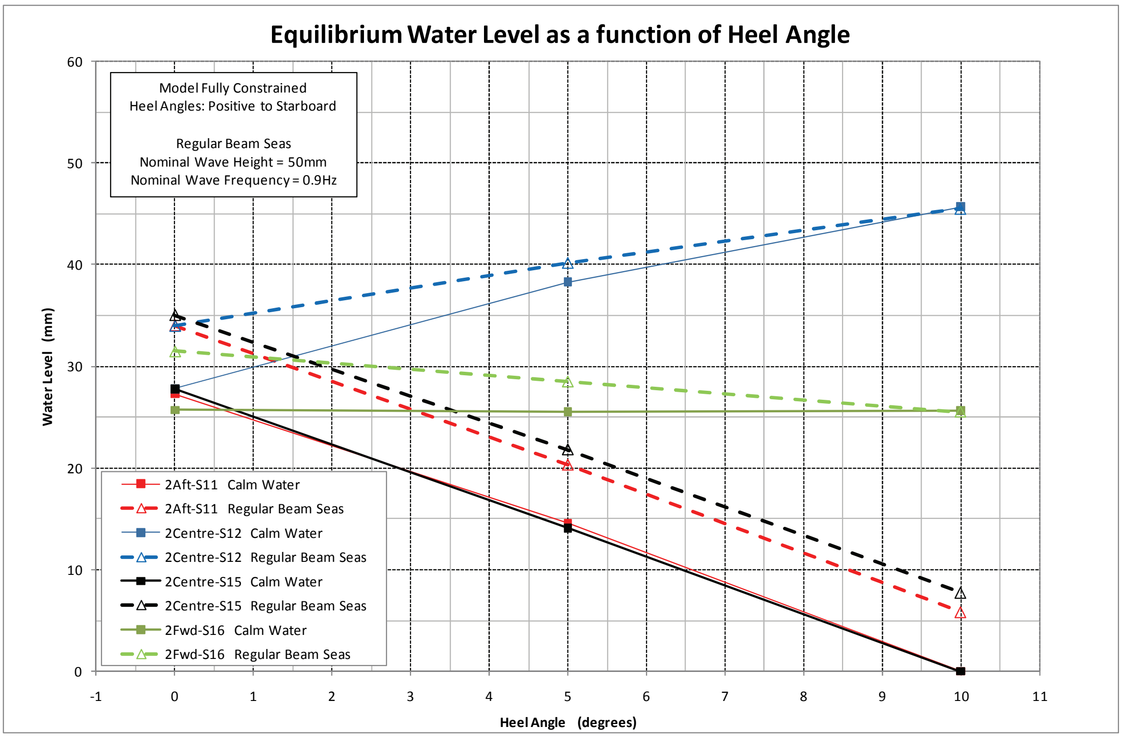

Figure 15 Equilibrium water level as a function of heel angle

6 CONCLUDING COMMENTS

A series of experiments has been conducted in calm water and regular beam seas on a 3.268 metre long model of a generic destroyer hull form to investigate the progressive flooding in a complex geometry in order to further validate the progressive flooding model in a non-linear time domain ship motions code. With the model fully constrained, a rapid damage event was generated, and the water levels and pressures in some of the internal compartments measured, as functions of time.

The effect of the area of the damage opening was investigated by conducting calm water tests with damage opening extents ranging from 50% to 100%. When the damage opening was only 50% the rate of rise of water in each of the compartments on the 2nd Deck was slower than for the greater damage extents. The results for the case with 85% damage opening were similar to those for the 100% case, with the greater damage extent generally resulting in only a marginal increase in the rate of water level rise. This may be worth further, more systematic, investigation.

Tests were also conducted with the model fully constrained in regular beam seas. The incident waves caused the water levels in the tanks to oscillate, with the oscillation levels greater in magnitude on the starboard side (nearer the damage) than on the port side.

Of particular note, there appears to be a set-up of water inside each of the compartments on the 2nd Deck. The result of this is that the mean equilibrium water level in the regular beam sea cases is higher than the equivalent calm water case. This is particularly noticeable for the two compartments on the port side, 2Aft-S11 and 2Centre-S15.

It was found that a set up of similar magnitude also occurred at both port-side compartments (2Aft-S11 and 2Centre-S15) when the model was fixed at heel angles of 5 and 10 degrees. However, this set-up appeared to reduce at 5 degrees of heel and is not present at 10 degrees of heel for the wave probe located along the model centreline (2Fwd-S16) and the probe on the starboard side near the damage opening (2Centre-S12). This reduction in water level set-up at these two locations appeared to be approximately linear with increasing heel angle.

Further investigation is required to determine what effect wave frequency and/or wave height may have on these results.

The results for the fully constrained model presented here form one phase of several undertaken as part of the validation process for the non-linear time domain code, FREDYN. Macfarlane et al. (2010) presented results for the fully unconstrained model in calm water. Preliminary findings from both phases have provided encouraging results regarding the validation of this code, as described by Ypma and Turner (2010).

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