Forensic Research into the Loss of Ships by Means of a Time Domain Simulation Tool

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ABSTRACT

The present paper describes forensic research in to the loss of the trawler MFV Gaul. The research focuses on water ingress through openings in the vessel when operating in a hind cast sea state. The ship, environmental conditions and basics of the FREDYN time domain simulation tool are described. Simulation results are discussed which clearly indicate that certain combinations of heading, speed and resulting water ingress can be threatening to the survivability of the ship. Scale model test results confirm these findings. Finally, a possible loss scenario is presented.

Keywords: MFV Gaul, loss of trawler, forensic hydrodynamic research, time domain simulations, model tests

1. INTRODUCTION

The Hull based trawler MFV Gaul was lost with all hands in heavy seas off the North Cape of Norway in February 1974. Its wreck lying on the seabed was discovered in 1997. Underwater surveys by the UK Marine Accident Investigation Branch (MAIB) performed in 1998 and 2002 have shown amongst others that the lids of the duff and offal chutes were open, see MAIB (1999). These chutes are positioned on the starboard side of the vessel at approximately 1.6 m above the SWL and serve to remove waste from the factory deck. Furthermore, the steering nozzle was at its maximum angle and the propeller was at a high pitch setting, indicating that the vessel was manoeuvring prior to sinking. Following the findings of the underwater survey, the UK's Secretary of State for the Department for Transport ordered a re-opening of the Formal Inquiry into the vessel's loss.

A multi-disciplinary team of experts was formed to prepare a joint report on possible loss scenarios for the Re-opened Formal Inquiry (RFI) held in late 2003 through early 2004. Results of a investigations in the 1970's are discussed by Morrall, see Ref. [6]. The present paper focuses on the results of investigations in to the dynamic stability of the Gaul in intact and partially flooded conditions. These investigations have been performed by MARIN in close cooperation with TMC (Marine Consultants) and Burness Corlett Ltd. The main objective of the investigations was to assess the behaviour of the vessel in the sea state believed to be present at the time of the loss. The performance of the vessel was determined by means of model tests and numerical simulations. Conditions included straight course sailing, turning and zig-zag manoeuvres and free drifting in beam waves, in regular and irregular waves. The purpose was to assess the susceptibility towards capsizing, surfing and broaching and to measure the amount of water ingressing through the chutes and the factory space access door. An additional objective of the tests was to provide data to validate numerical predictions.

The present paper is a follow up on a more general paper by Bowman et al. (2006), and focuses on the model testing and numerical simulations. A similar investigation into the loss of the Arctic Rose fishing vessel has been performed in the USA, see Johnson and Borlase (2003).

2. THE GAUL

The Gaul was designed as a 66 m factory freezer stern trawler for the North Atlantic and Barents Sea fishing grounds, and built in 1972 by Brooke Marine of Lowestoft UK as the Ranger Castor under Lloyds Register Class. The vessel was not built under Load Line rules and did not satisfy Load Line protocols with respect to freeboard deck identification and closure arrangements for openings in and below the weather and freeboard decks. A General Arrangement is shown in Fig 1 while Table 1 lists the main particulars.

Table1. Main particulars of the Gaul (DoT loading condition)

Lwl	60.544 m
Bwl	12.192 m
Tf	2.831 m
Ta	5.295 m
Displacement	1571 tons
GM	0.850 m
Nat. roll period	10.9 s
Maximum GZ	0.53 m at 43 deg
Range of pos. stability	approx. 75 deg
Number of crew	36

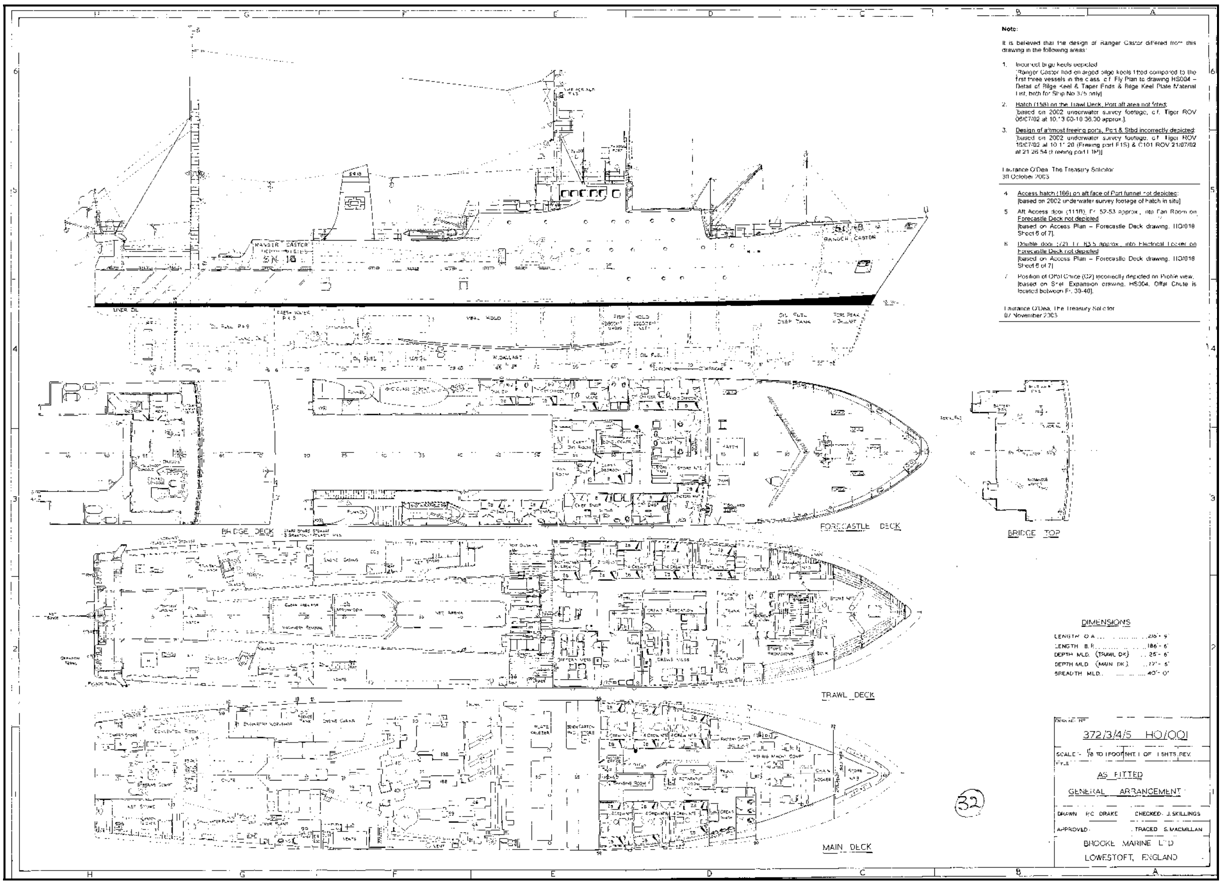

Figure 1 General arrangement Gaul

For propulsion and steering a Kort steering nozzle was fitted with a controllable pitch propeller.

During operation, the catch was released to the factory deck through two flush hatches at the aft trawl deck. The full beam factory deck accommodated various types of processing machinery. There were two side shell openings from this space, the duff and offal chutes, which were used to dispose of waste material. The factory space was accessible from the trawl deck through a door and staircase.

3. ENVIRONMENTAL CONDITIONS

The panel of experts involved in the investigation into the loss of the Gaul ordered a hind cast study into the most likely wave conditions present at the location and time of the loss, see Cardone (2003). Figure 2 shows the wave characteristics at the loss position for a ten day period. The rapid increase in wave height on February 8th suggests the presence of steep, breaking waves. At the assumed time of loss the significant wave height was about 9.0 m with a period of 12 seconds. A corresponding wind speed (Bf 9) and direction have been selected as well for the simulations.

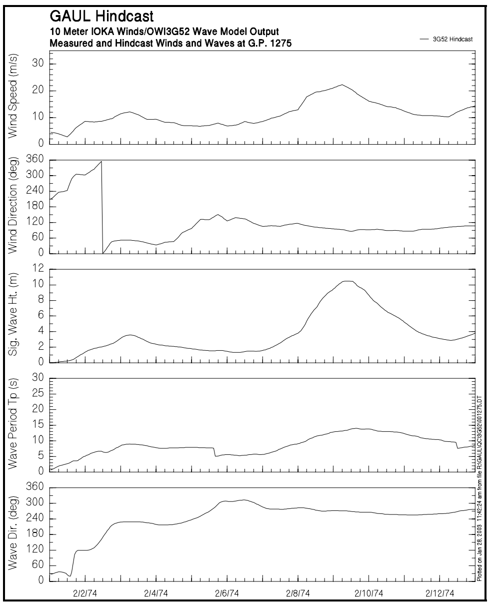

Figure 2 Hind cast data

Figure 3 shows the wind speeds for noon February 8th. The loss position is just above the North Cape. It seems likely that the Gaul tried to reach the area with low wind speeds in lee of the Norwegian coast. This would suggest that the wave directions were from the port beam to stern quarter.

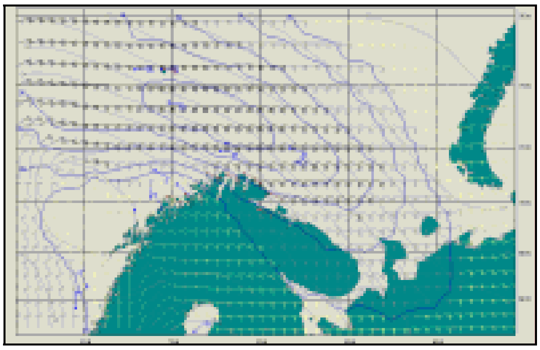

Figure 3 Wind speed plot at 1200 GMT

4. THE FREDYN SIMULATION TOOL

FREDYN is a simulation tool in six degrees of freedom for ships operating in waves from arbitrary directions. Its fundamentals are discussed in De Kat and Paulling (2001). It can be used for ships sailing on a straight course relative to the waves as well as for simulating ship manoeuvres such as zig-zags and turning circles. It is also capable to compute the ingress of water through openings in the hull and superstructure.

The model consists of a non-linear strip theory approach, where linear and non-linear potential flow forces are combined with manoeuvring and viscous drag forces. The non-potential force contributions are of a non-linear nature and based on (semi)empirical models. The following force components are taken into account:

- Froude-Krylov (non-linear)
- Wave radiation (linear)
- Diffraction (linear)
- Viscous (manoeuvring, non-linear)
- Thrust and resistance (non-linear)
- Appendages: rudders, skeg (non-linear)
- Wind (non-linear)
- Internal fluid (non-linear)

The derivation of the equations of motions for a ship subjected to flooding through one or more openings is based on the conservation of linear and angular momentum for six coupled degrees of freedom. Here the fluid inside the ship is considered in a dynamics sense as a free particle with concentrated mass. With this assumption, classical rigid body dynamics can be used to derive the equations of motion, see e.g. Umeda et al. (2000) and Van't Veer and De Kat (2000), for a structure with a time varying mass.

The following equations of motion for a damaged vessel in the ship-fixed coordinate system can be derived:

$$([\mathbf{M_0}]+[\mathbf{a}_\infty]+[\mathbf{M_f}])\cdot\ddot{\mathbf{x}}_G = \begin{pmatrix}\sum F_x\\ \sum F_y\\ \sum F_z\\ \sum M_x\\ \sum M_y\\ \sum M_z\end{pmatrix} + \underbrace{\begin{pmatrix}(m_0+m_f)\cdot(w_G q - v_G r)\\ (m_0+m_f)\cdot(u_G r - w_G p)\\ (m_0+m_f)\cdot(v_G p - u_G q)\\ (I_{zz,0}-I_{yy,0})qr\\ (I_{xx,0}-I_{zz,0})pr\\ (I_{yy,0}-I_{xx,0})pq\end{pmatrix} - [\dot{\mathbf{M}}_f]\cdot\dot{\mathbf{x}}_G +}_{\text{additional terms}} \quad (1)$$

The matrix $[\mathbf{M_0}]$ is the generalized mass matrix of the intact ship, $[\mathbf{a}_\infty]$ is the added mass matrix that is part of the linear radiation forces, $[\mathbf{M_f}]$ is the 6x6 matrix containing all ship-acceleration related, time-dependent inertia terms associated with the flood water, including non-zero off-diagonal terms. The state vector is represented by x_G and an over dot indicates differentiation with respect to time. The summation signs in the RHS represent the sum of all external force contributions, as for the intact case (including the presence of damage fluid).

Additional terms in the RHS of the equations of motion stem from cross products, which appear when expressing the conservation of momentum in a ship-fixed coordinate system, and from the motion of the fluid relative to the ship.

To estimate the flow rates of water entering a compartment, the flooding model is typically based on the Bernoulli equation, see Umeda et al. (2000). This analysis is applied to each damage opening or holes between two compartments. It assumes stationary flow conditions and no loss of energy due to friction or increased turbulence. Based on the difference in pressure head, the velocity through a damage opening can be calculated. Figure 4 presents a sketch for the flow through an orifice where the discharge velocity is given by:

$$v_2 = \sqrt{2g(H_1 - H_2)} \quad (2)$$

H_2 equals zero for the free discharging orifice. The height H_1 is considered as the height from the free surface plane to the center of the hole. The flow over a weir (which for example applies when the opening is partly above the waterline) is calculated this equation as well, with H_2 equal to zero.

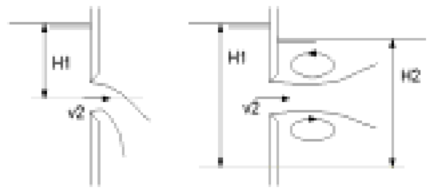

Figure 4 Flow through a free discharging orifice (left) and through a fully submerged orifice (right)

To obtain the total discharge through an opening, the following empirical formulation is used:

$$Q = C_d v_2 A \quad (3)$$

where A is the area of the opening and C_d is the discharge coefficient. This coefficient accounts for a combination of several effects (such as friction losses) and can be found in hydraulics textbooks. For a sharp-edged orifice a typical value is around 0.60, which is valid for high Reynolds numbers.

Based on the computed inflow and outflow of fluid through all openings, the fluid mass inside a compartment is known at each time step. A simple yet practical approach is to assume that the water level of the flood water inside any compartment remains horizontal (earth-fixed) at all times. This implies that the sloshing fluid maintains a purely vertical force (due to gravity and inertia) on the ship and that all dynamic effects are neglected. The associated ship-fixed force and moment components can be determined through the appropriate transformations and are added to the RHS of the equations of motion; this applies to forces and moments acting on a ship during transient flooding in a variety of compartments and during forced oscillations. This approach gives adequate results for engineering purposes, as long as sloshing is not dominant. This may not be so for instance during a sudden turning manoeuvre and may also neglect sloshing effects on roll.

5. INITIAL SIMULATION RESULTS

Initial numerical investigations into the behaviour of the Gaul in the selected environmental conditions were performed using the FREDYN simulation tool. The purpose of these simulations was to identify the most relevant test conditions for the model test programme. In a later stage FREDYN predictions were validated on basis of the model test results which led to some tuning of the calculation method. Finally, a series of simulations with a long duration and various flooding arrangements were performed to obtain a more complete insight in the performance of the Gaul in the given conditions.

The hind cast wave spectrum was discretised into 80 wave components with a random frequency step, in combination with a random phase angle. Random numbers were uniformly distributed. The irregular wave train could then be obtained by summation of the individual regular wave components. This approach assured that the repetition time of the generated wave train was beyond the simulation duration. Note that for simulations with transient effects such as flooding, repetition of a wave train would not be necessarily undesirable.

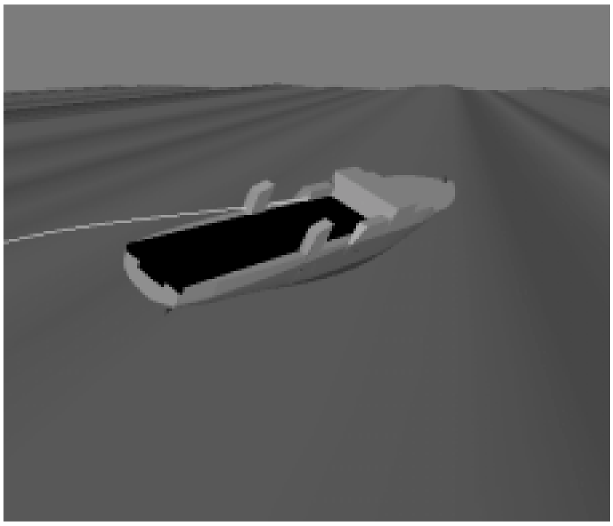

Figure 5 FREDYN animation of a Gaul simulation

Figure 5 shows an animation of the Gaul during a FREDYN simulation and Figure 6 shows the floodable compartments including accumulated flood water.

The duff and offal chutes are the small black squares in the starboard side of the vessel. The trawl deck is also modelled as a floodable compartment including entrance door and staircase to the factory space.

The initial FREDYN results indicated that down flooding through the two chutes was substantial when the ship operates in beam to stern quartering seas and that progressive down flooding can lead to a capsize. Water accumulation on the trawl deck was relatively insignificant.

Figure 7 shows the amount of water ingress during 20 minute simulations for a series of heading angles with respect to the wave direction. Head waves are at 180 deg. The plot shows that for port stern quartering seas (300 deg) with the duff and offal chutes on the leeward side, the amount of floodwater reaches a maximum of 120 tons. For waves approaching the starboard side the down flooding is insignificant.

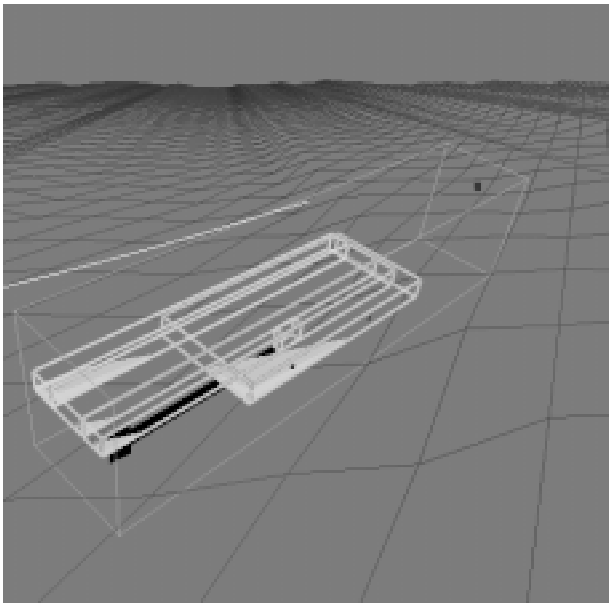

Figure 6 Floodable compartments

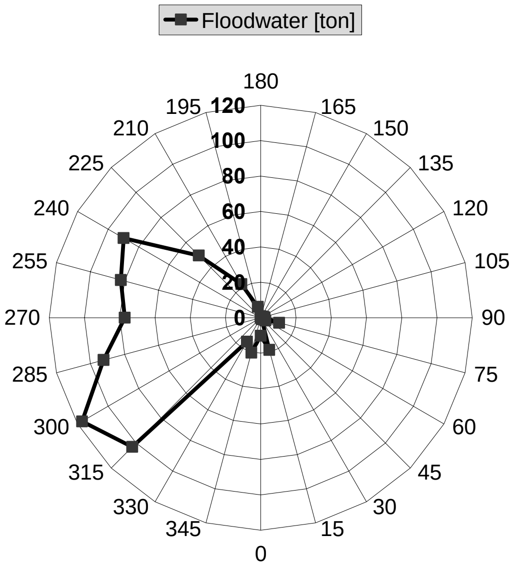

Figure 7 Down flooding as a function of heading angle with respect to wave direction

6. MODEL TESTS

The purpose of the model tests was to investigate the motions of the vessel and the ingress of water in the sea state believed to be present at the time of the loss. MARIN's Seakeeping and Manoeuvring Basin (170 m x 40 m x 5 m) was used for these tests.

The model was built to a 1:24 scale, as shown in Fig 8, with particular attention to

Figure 8 Gaul scale model

obstructions on the trawl and factory decks. Propulsion was provided by a propeller in a steerable nozzle, similar to the vessel.The modelling of the down flooding points created by the duff and offal chutes included a Perspex reservoir capable of holding the influx from one wave. This discharged into a larger reservoir positioned so as to have minimal effect on heel and trim for the duration of each test. The reservoir was emptied after each test run and the amount of water was weighed. This made each run a “snapshot” for determining down flooding rates in an irregular sea state. The vessel was run intact, and with two initial amounts of floodwater (50 and 100 tons) so as to assess cumulative flooding effects.

The model was free running and steered through an autopilot system, using a light umbilical for data transmission. Position fixing was achieved through a Krypton infra red system, referenced to the main and sub-carriages which latter was also equipped with a range of cameras. The carriages operated in following mode, i.e. their position was controlled to follow the free running model.

Test conditions included free drifting, two forward speeds, five wave directions including bow quartering, beam, stern quartering to following seas whereby the model was to follow a straight (mean) course as well as turning and zig-zag manoeuvring in waves. Figure 9 shows a photo taken during a manoeuvre in irregular seas and Figure 10 shows the model being hit by a breaking beam wave.

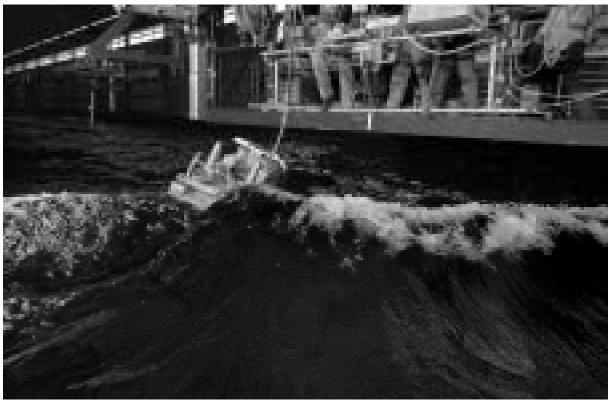

Figure 9 Gaul model during manoeuvre

Figure 10 Gaul model in beam seas

The Gaul model showed quite good seakeeping characteristics in relation to the heavy seas generated. The vessel was not at risk in the intact condition.

Despite its favourable seakeeping characteristics, absolute values of the motions were high in the heavy conditions tested. Typical operability criteria based on acceleration components and roll angles were exceeded during virtually all test conditions, indicating that performing normal duties must have been very difficult for the crew. In beam and stern quartering waves the probability of exceeding a safety roll angle limit of 16 degrees is 20% to 60% for intact conditions, and almost 100% for flooded conditions. Roll angles up to 45 degrees have been measured.

Transverse accelerations exceed the safety limit of $0.10g$ by a factor two to three in beam and stern quartering seas. In partially flooded conditions the safety limits are more seriously exceeded. Therefore, with progressive down flooding the crew must have had great trouble in staying upright and were likely to be impaired in their tasks or even sustain injury.

Down flooding through the duff and offal chutes during straight course runs was strongest in port stern quartering seas. Down flooding rates of about 1 ton/min were recorded for intact conditions and up to 8 tons/min for flooded conditions, indicating that progressive down flooding was likely to occur when the ship operated under these conditions. In beam waves down flooding through the chutes was less and in bow quartering waves it was almost absent.

When a disabled (no steering or propulsion) ship was simulated by a freely drifting model, it drifted with its bow turned away from wind and waves. This results in a stern quartering wave direction with accompanying high down flooding rates for partially down flooded conditions (4-6 tons/min). In regular waves down flooding rates per meter wave height were about two times higher than in irregular waves with the same average (significant) properties.

The water level in the reservoirs and the submersion of the chutes was recorded continuously during all tests. No apparent relationship could be found between the instantaneous submergence of the chutes and the resulting flow rate. This was probably due to the heavy sloshing of the flow volume in the reservoir and the time delay between the ingress at the chute and the instant that the flow arrives in the collecting tank.

Down flooding had a “threshold” character. This is important because exceedance of the threshold is likely to be a rare occurrence in the operation of the vessel, as it happens only under particular conditions.

The results show that in the normal “laid and dodging" mode (which involves taking bow seas and occasionally running down weather to maintain position) there would be negligible down flooding. However, from beam to stern quartering seas the duff and offal chutes allowed substantial ingress.

7. FREDYN VALIDATION

The model did not capsize during the tests. This may have partly been because flooding was confined to the main factory space, whereas subsequent re-examination of the survey tapes suggested that doors into adjacent spaces on the starboard side had been left open, which would have increased the loll angle. At the same time, the number of conditions that could be investigated by means of model tests were limited due to cost and time considerations. It was therefore more cost-effective to carry out an additional investigation into possible capsize scenarios by means of the FREDYN simulation tool which was validated and tuned for this purpose using the available experimental results.

With respect to tuning, two items are relevant: the manoeuvring method and the discharge coefficient value for the flow through the chutes, both being of a general, empirical nature. The course keeping had to be improved by enlarging the skeg area by 25%, which also enhanced the roll damping. The bilge keel height was enlarged by 20% to further increase the roll damping to the desired level based on roll decay in calm water.

With respect to down flooding through the chutes, the discharge coefficients were adjusted to result in approximately the same flow rates as measured during the model test program. For the chutes relatively large flow losses were present due to the two square and sharp edged openings and internal ducting. Discharge coefficients of 0.25 were used here for the two square openings while the default values in FREDYN are 0.50 to 0.60 for openings with a single square entrance without ducting.

Finally, the steerable nozzle was represented by an equivalent large area rudder in FREDYN.

During the experiments, the model was equipped with a down flooding arrangement that excluded progressive down flooding during a run. The combined duration of all runs within a test (combination of speed and wave condition) was 30 minutes full scale time. A series of ten FREDYN runs have been performed for each selected condition. Each run had a duration of three minutes so that progressive down flooding effects were insignificant.

Figures 11 through 14 compare experimental (Exp) and FREDYN (Frd) results for motions in bow and stern quartering seas and the intact and partially down flooded initial conditions. The motions are normalised with respect to the wave height and are defined as the standard deviation of the motions divided by the standard deviation of the wave height. The roll motion is of primary importance with respect to capsizing, next in ranking is the yaw motion (course keeping ability) while the heave and pitch are of secondary importance.

Calculated motions are seen to be in fair agreement with the experimental results for both intact and partially flooded conditions. An exception is the roll motion in bow quartering seas, which is over-predicted by FREDYN. A further increase in roll damping could improve the prediction here, but might also worsen the roll prediction for other conditions. Since bow quartering seas are of little importance for the survivability of the Gaul, this was not further investigated.

Figures 15 through 17 show the time averaged down flooding rates through the chutes for several conditions. The Figures are plotted with the same vertical scale to show the dependency on wave direction. The Figures show that the trends with wave direction and initial down flooding state are adequately predicted by FREDYN. Per condition, the relative difference between FREDYN and experimental results can be substantial, when the flood rates are low. For simulations with progressive down flooding this is however of little consequence.

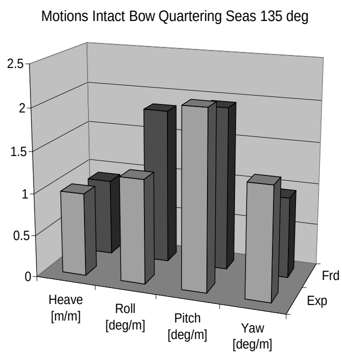

Figure 11 Motions in bow quartering seas

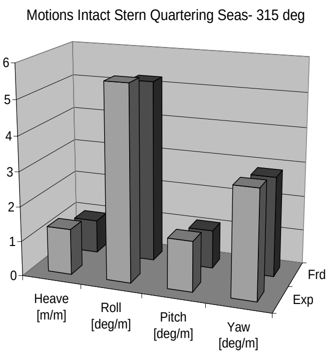

Figure 12 Motions in stern quartering seas

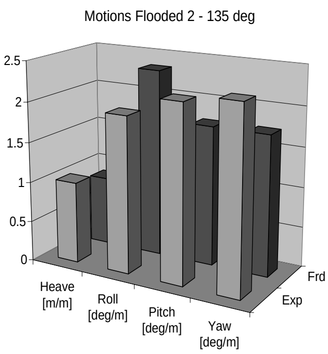

Figure 13 Motions in bow quartering seas – Flooded 2

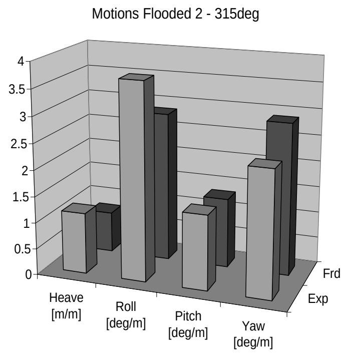

Figure 14 Motions in stern quartering seas – Flooded 2

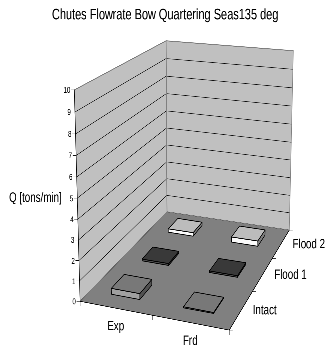

Figure 15 Flow rates bow quartering seas

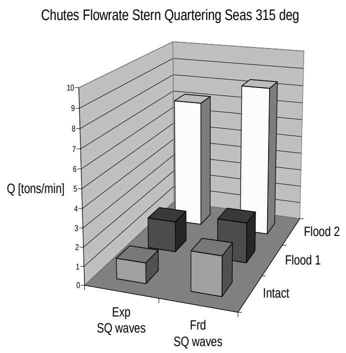

Figure 16 Flow rates stern quartering seas

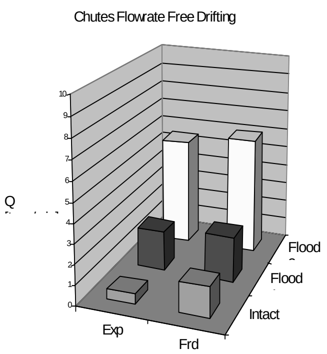

Figure 17 Flow rates free drifting

8. FINAL FREDYN SIMULATIONS

The main objective of the simulations was to investigate if there were combinations of wave heights and directions, ship speed, down flooding state and operational modes (straight course, drifting and manoeuvring) in which the ship is likely to capsize. Furthermore, it was required to assess the mechanism causing the ship to capsize and also to determine how soon the ship capsizes in a certain condition. In view of the randomness of waves some insight on the repeatability of simulation results was required as well. In other words, does the ship always capsize in a certain condition or does this depend on a rare and particular sequence of waves?

At a late stage of the investigation it became apparent that the door in the factory space giving access to the liver and chill water plant compartments was open. The door in the chill water plant compartment giving access to the net store was known to be open as well. It also became clear that the fish loading hatches on the trawl deck might have opened when a substantial amount of water was present on the trawl deck.

Therefore, some additional simulations have been performed with open fish hatches and the additional liver and chill water plant compartments. Besides modelling the fish hatches as openings in the trawl deck, the fish chute was modelled as well, leading flood water from the hatches to the factory space.

The duration of simulations corresponded to 60 minutes for each condition, excluding a two minute start-up period. This duration is generally more than sufficient to obtain statistically accurate results for wave induced motions. However, for extreme events such as capsizing it is difficult to derive statistics. To get some insight in the probability of capsizing, simulations for some critical conditions have been repeated five times with a different wave seeding. When capsizing is sensitive to a particular wave sequence, the ship may capsize in one wave realisation, while it may not capsize in another.

The maximum roll angle in the simulations has been set to plus or minus 75 degrees. This corresponds approximately to the angle of vanishing stability in calm water. At higher roll angles the ship is considered to be lost. It should be noted that there does not exist a well defined, exact roll angle above which a ship is considered to be lost. Factors like shifting cargo and equipment, additional down flooding through immersed superstructure openings and crew injuries start playing a role at large roll angles and a critical roll angle definition is subject to debate.

The panel of experts suggested a criterion for the disablement of the ship, by which is meant the angle at which the combination of list (mean heel angle) and roll makes it impossible for the crew to operate. This will sooner or later lead to the loss of the ship. The criterion takes into account the fact that a single large roll angle by itself is less serious than repeated rolling to a lower angle on top of a list as follows:

$$\varphi_d = 65 - \varphi_m / 2 \tag{4}$$

where φ_m is the list and φ_d is the disablement angle. This criterion will be used in the discussion of results.

All results shown here concern the ship sailing on a straight course, except for a special type of simulation that consists of a combination of a straight course followed by a turning manoeuvre. As mentioned before, it was suggested that the fish loading hatches might have started to open automatically by the pressure of water sloshing on the hydraulic control panel. Large amounts of water occasionally wash over the stern during the simulations. Once this happens, the water on the trawl deck is allowed to flood the factory space through the fish chute. The opened fish loading hatches effectively seal off the openings from behind. This is modelled as well in FREDYN by making a subdivision in the centre trawl deck compartment at the position of the hatch hinges. This subdivision can be open or closed as desired in FREDYN, where use is made of an assumed threshold associated with the external fluid pressure. Fifteen seconds after down flooding through the fish hatches has started, a crew action is simulated: full power and rudder are given to turn the ship with its bow into the waves. This scenario is consistent with the findings of the wreck survey: full rudder was given and the propeller had maximum pitch.

9. STRAIGHT COURSE SIMULATIONS AT 6 KT

A review of the simulations and the main results are given in Table 2. The largest roll angles occur for port beam to stern quartering seas (285 - 300 degrees) and have a magnitude of about 60 degrees which is not far off the 75 degree capsize limit.

In starboard quartering to beam seas (45 -90 degrees) roll angles approach 55 degrees, despite the fact that the amount of flood water in the factory space is limited to a few tons. These large roll angles are due broaching. During the model tests no broaching was witnessed. However, the runs during the model test program were limited in duration and since broaching occurs on average only one or two times per hour, the occurrence of broaching in the FREDYN simulations cannot be ruled out.

For port beam to stern quartering seas the ingress of water is significant with as much as 147 and 148 tons for the 300 and 315 degrees wave direction respectively. It should be noted that when there is over 100 tons of flood water present in the factory space, water starts to flow out through the chutes when the water level in the factory space is higher than that outside of the hull, at the chutes. Consequently, the amount of flood water is limited to about 150 - 200 tons. When considering the static stability the ship does not capsize due to 200 tons of flood water in the factory space; it has sufficient reserve static stability to cope with this amount. When considering the dynamic stability, things are different as will be shown hereafter.

Table 1. Main simulation results 6 kt

Run	Heading [deg]	Max Roll [deg]	Flood water [ton]	Duration [min]	Disabled
101	0	14.6	23.7	60	0
102	15	16.9	2.2	60	0
103	30	32.2	1	60	0
104	45	54.6	2.2	60	0
105	60	48.8	0.8	60	0
106	75	53.2	3.9	60	0
107	90	46.4	6.7	60	0
108	105	45.5	2.9	60	0
109	120	33.3	0.6	60	0
110	135	30.9	0.1	60	0
111	150	25.6	0	60	0
112	165	14.2	3.1	60	0
113	180	0.4	3.2	60	0
114	195	14.7	24	60	0
115	210	35	95.3	60	0
116	225	37.9	125	60	0
117	240	39.5	129.5	60	0
118	255	44.8	127.1	60	0
119	270	55.4	140.1	60	0
120	285	60.7	138.2	60	0
121	300	62.9	146.9	60	4
122	315	52.1	148.2	60	0
123	330	36.7	119.9	60	0
124	345	22.4	51.2	60	0

The crew gets disabled 4 times during the 300 deg wave direction simulation, while crew disablement does not occur for the other wave directions.

Table 3 shows results for five wave seeds for the port stern quartering wave direction (315 degrees). Time traces of the amounts of flood water in the factory space and the roll motion are given in Figures 18 and 19 respectively. The variations in maximum roll angle and flood water are relatively modest. The variation in the number of times that the disablement criterion is exceeded is relatively large.

Table 2. Main simulation results wave seeds

Run #	Seed #	Max Roll [deg]	Flood water [ton]	Duration [min]	Disabled
301	1	50.2	139.8	60	3
302	2	51.2	134.6	60	0
303	3	49.2	138.6	60	0
304	4	58.8	132.1	60	7
305	5	63.1	142.8	60	9

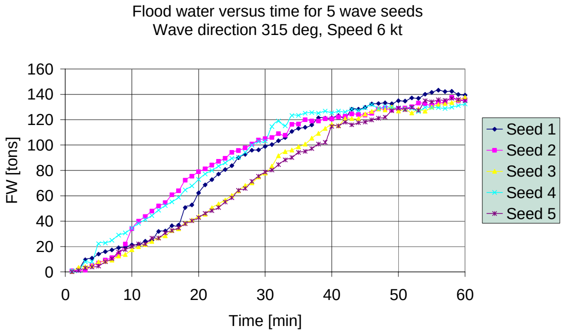

Figure 18 Flood water versus time

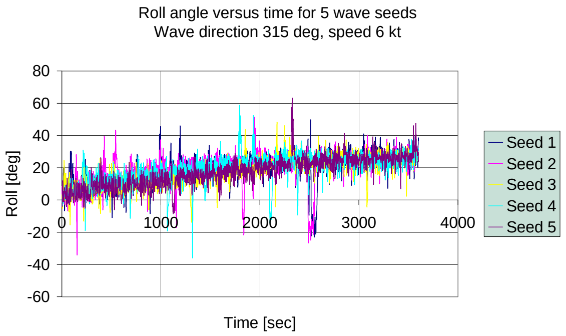

Figure 19 Roll angle versus time

10. STRAIGHT COURSE SIMULATIONS AT 14 KT

Table 4 shows the results for these simulations. In starboard stern quartering seas (60 degrees) the maximum roll angle is 67 degrees while only 15 tons of water is present in the factory space. Such a high roll angle is caused by broaching in high and steep waves.

A case where the roll exceeds 75 deg occurs in near following seas (345 degrees) with 160 tons of water in the factory space. For port beam to following seas (270 – 360 or 0 degrees) roll angles and flood water quantities are high as well.

The high roll angles in port stern quartering to following seas are primarily caused by down flooding through the chutes. The flood water in the factory space causes the ship to trim with its stern down, the mean list to starboard further reduces the height of the starboard side of the stern above the water surface. When the ship meets a sequence of high, steep waves the trawl deck gets immersed relatively easily. An additional reason for capsizing is due to the 14 knots calm water speed, for which the wave encounter frequency is much lower than for a 6 knot calm water speed, causing the roll response to be significantly higher since water surface disturbances simply last longer giving the ship more time to react to losses of stability.

Disablement of the crew appears for the broach at a starboard stern quartering wave direction and for four conditions with port beam to stern quartering waves. For run 122, crew disablement occurs 39 times which is considered as a very substantial amount.

Table 5 show results for 5 wave seeds for the 315 degrees wave direction. Time traces of the amounts of flood water in the factory space and the roll motion are given in Figures 20 and 21 respectively.

Together with the original runs in Table 4, the ship exceeds the 75 deg roll limit in 9 out of 44 simulations, so in about 20% of the cases. It should be noted that for a number of conditions the maximum roll is still close to 75 degrees. The amount of flood water in the factory space varies considerably between 80 and 190 tons. The number of instances that the crew gets disabled varies considerably as well, from a single occurrence to 88 occurrences. The single occurrence is for a run with a duration of only 15 minutes, where a single large roll exceeds the 75 degree limit. Still, comparing the runs 101 and 105 for the 315 degree wave direction, which both have a duration of 60 minutes, there is about a factor two difference in the number of exceedances of the disablement criterion. This indicates that exceeding the disability criterion is a phenomenon that does not respond to linear wave theory, rather it is depending on the joint probability of high and steep waves and a the susceptibility of the vessel to such waves (speed, heading, list, etc.).

Table 3. Main simulation results 14 kt.

Run #	Heading [deg]	Max Roll [deg]	Flood water [ton]	Duration [min]	Disabled
101	0	50.5	132.9	60	0
102	15	53	37.5	60	0
103	30	40.4	6.6	60	0
104	45	50.7	0.3	60	0
105	60	67.1	15.3	60	4
106	75	54	14.3	60	0
107	90	45.1	6.7	60	0
108	105	41.7	4.5	60	0
109	120	37	0.6	60	0
110	135	30.3	0.4	60	0
111	150	27.7	1.2	60	0
112	165	17.8	2.5	60	0
113	180	0	2.8	60	0
114	195	17.4	21.2	60	0
115	210	31	89.1	60	0
116	225	39.5	121.5	60	0
117	240	54.8	140.6	60	0
118	255	53.6	138.3	60	0
119	270	60.1	146	60	1
120	285	59.7	136.2	60	0
121	300	62.2	145.6	60	10
122	315	67.8	158.9	60	39
123	330	45.9	129	60	0
124	345	75.1	160	57	2

Table 4. Main simulation results wave seeds

Run #	Seed #	Max Roll [deg]	Flood water [ton]	Duration [min]	Disabled
301	1	70	162.9	60	42
302	2	75.3	164.6	58	35
303	3	75.2	80.6	15	1
304	4	75	151.8	36	28
305	5	74.2	166.5	60	88

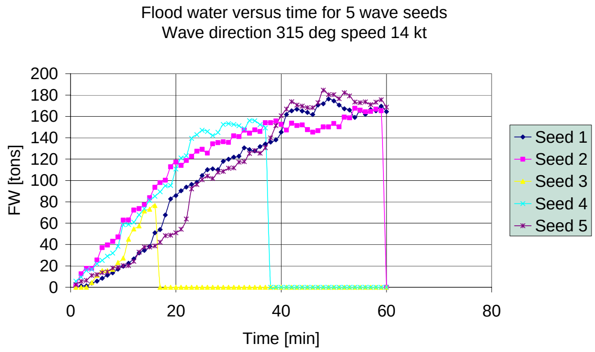

Figure 20 Flood water versus time

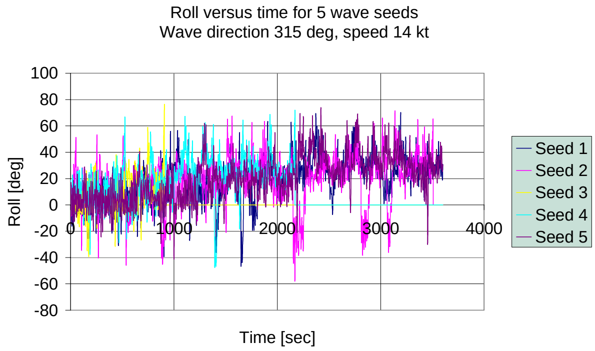

Figure 21 Roll angle versus time

11. STRAIGHT COURSE PLUS TURNING

This final case includes flooding through the fish hatches at the aft trawl deck. As explained earlier, the ship initially operates with the fish hatches closed at a 315 degree heading at a 6 knot calm water speed. The fish hatches open at the first instant with a significant amount of water on the trawl deck. A little later (15 sec) maximum power and full port rudder angle (30 deg) are commanded. Once the course is at 225 degrees this heading is maintained until the end of the simulation (30 minutes). Six simulations are performed for the earlier used amounts of initial flood water in the factory spaces. The purpose of these simulations is to find out if a possible opening of the fish hatches may cause the ship to capsize rapidly.

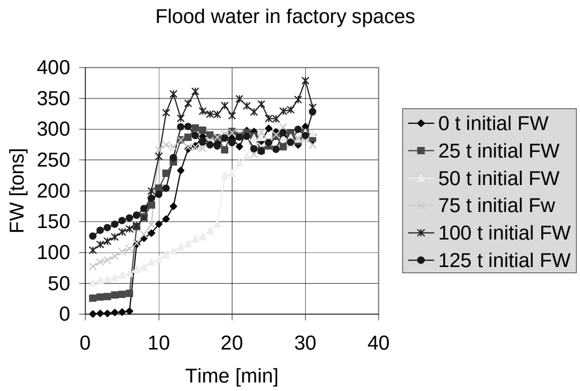

Figure 22 Flood water versus time

Figures 22 and 23 show time series for the amounts of flood water and the roll motion. The flooding through the fish hatches is clearly visible as a sudden increase of the amount of flood water. For all cases the amount of flood water in the factory spaces after flooding through the fish hatches is quite high: 275 to 350 tons. After this event, the amounts of flood water remain approximately constant, despite the high list to starboard of about 50 deg. This is due to the change in heading towards bow quartering seas for which progressive flooding through the chutes and access door is limited in extend. Figure 24 depicts the ship in final flooded condition at a particular instant in time during a run shown in Figure 23.

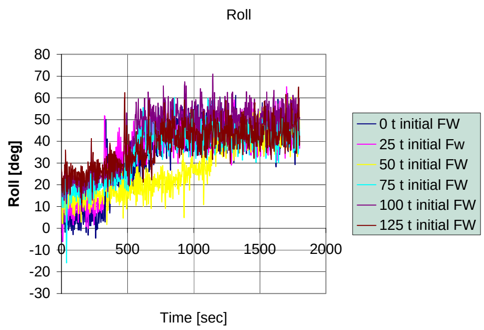

Figure 23 Roll angle versus time

Table 5. Main simulation results

Run #	Initial FW [tons]	Max roll [deg]	Floodwater [tons]	Duration [min]	Disabled
301	0	62.0	282.4	30	247
302	25	65.3	285.6	30	275
303	50	60.2	292.7	30	119
304	75	60.2	274.3	30	266
305	100	71.2	337.4	30	1093
306	125	65.1	328.0	30	242

Table 6 shows that maximum roll angles are in-between 60 and 70 degrees. The number of instances that the crew gets disabled is very high. This is obviously caused by the high list for the remainder of the simulation after the turning manoeuvre is completed. Still, it shows that the ship might have survived down flooding through the fish hatches but that the crew would have little chance to bring the ship in safety afterwards. Furthermore, shifting cargo and equipment and additional flooding through the ventilation ducts on the starboard funnel and through immersed superstructure openings might well have caused the vessel to sink.

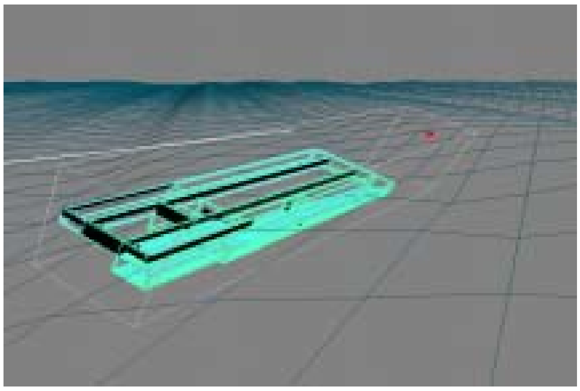

Figure 24 Final down flooding condition

12. A POSSIBLE LOSS SCENARIO

The combination of physical and numerical modeling described above was crucial to the identification of the most likely source of flooding and cause of loss. Without such evidence, it would have been difficult to predict the high rates of ingress through openings well above the still water line.

The FREDYN simulations were the principal evidence the panel of experts used to conclude that out of all the numerous suggested loss scenarios, the most likely was as follows:

Although flood water on the factory deck could have been present from the internal water supply, the initial source of flooding was probably ingress through the duff and offal chutes, found open during the 2002 survey.

The sea-state was severe with relatively steep waves, and the ship was in a relatively light condition, probably trimmed by the stern. This proved to be an unfortunate combination.

On several headings in these circumstances, but particularly when encountering port stern quartering seas, water would intermittently enter the factory deck through the open duff and offal chutes.

Although, ingress at first would have been relatively slow, it would have accelerated as the flood water caused the vessel to roll to higher angles and trim further by the stern, submerging the chutes longer and to a greater depth.

If the two pumps located on the factory deck were not running or were blocked, enough water could accumulate on the factory deck to seriously compromise the vessel's stability in less than an hour.

The quantity cannot be stated with precise accuracy but it could have been over 100 tons when encountering stern quartering seas. To put this into perspective, if the vessel were upright with level trim the depth of flood water would have been about 0.5m above the deck.

The door to the liver oil plant located on the aft starboard side of the factory deck was not secured shut so water would enter this space when the level reached the top of the sill of this door about 600mm above the deck.

The aft end of the liver oil plant room gave access to the net store and another door led to the steering gear space. Both had low sills of 150mm and were not WT so flood water would eventually flow through them into the net store and steering gear space.

With this amount of water lying predominately aft and to starboard, the vessel would roll about a large angle of loll to starboard which, because of wave action, would cause the duff and offal chutes to be submerged for about half the period of each roll cycle.

We surmise that someone discovered the flooding and reported to the bridge.

The natural reaction would be to head the vessel into the waves by sharply turning to port at full power. This would have increased the starboard list during the turn, causing the flood water to slosh starboard.

In this condition waves were also likely to break over the trawl deck. In these circumstances the vessel would not recover but roll over heavily to starboard with a rapidly increasing angle of list resulting in all loose equipment sliding to starboard, adding to the list.

Rolling about a starboard angle of loll of around 20 – 30° and reaching an extreme starboard roll angle of about 60° the vessel would have been effectively lost. In all probability the crew would have been disabled, and unable to communicate.

With waves continually breaking over the trawl deck, further water would flood through the door access to the factory.

Lying on her starboard side, waves would also break over the exposed port side. Water ingress would occur through the starboard engine room ventilators.

Remaining buoyancy would rapidly be lost most likely from aft forward, causing the ship to sink steeply by the stern on her starboard side.

13. CONCLUSIONS

1. The model of the MFV Gaul showed good seakeeping characteristics in proportion to the heavy seas tested. Roll responses are low in bow quartering seas, moderate in

beam seas and are relatively high in stern quartering seas. Course keeping was possible for all conditions tested and no broaching occurred. In stern quartering seas course keeping was more difficult than in beam and bow quartering wave directions.

2. Despite its favourable seakeeping characteristics, absolute values of the motions are high in the heavy conditions tested. Operability criteria based on acceleration components and roll angles are exceeded during virtually all test conditions, indicating that performing normal duties must have been very difficult for the crew. In partially flooded conditions the safety limits are obviously more seriously exceeded. With progressive down flooding the crew must have had great trouble in staying upright and were likely to get injured.
3. Down flooding through the duff and offal chutes during straight course runs is strongest in stern quartering wave directions. Down flooding rates of about 1 tons/min were recorded for intact conditions and up to 8 tons/min for flooded conditions, indicating that progressive down flooding was likely to occur when the ship operated under these conditions.
4. Initial FREDYN simulations showed the same observations in a qualitative sense.
5. A comparison between tuned FREDYN predictions and experimental results shows that the FREDYN predictions are adequate for the present investigation, for those conditions where the capsize risk is largest.
6. Extensive FREDYN simulations show that high roll angles occur during operation at a straight course in beam to stern quartering wave directions. The predominant mechanism is that due to flooding of the factory space through the chutes, increasing the stern immersion which increases the risk of water on the trawl deck. Substantial amounts of water may then enter the trawl deck in an unfavourable sequence of relatively high and steep waves. Once this happens, the ship loses stability and may roll over to angles up to 75 degrees, which is the angle of vanishing stability and defined as the capsize angle in the present investigation.
7. In terms of dynamic stability, the critical combination of water in the factory space and an unfavourable wave sequence may occur sooner or later, or not at all during the simulations. A large number of simulations are required to derive probabilistic information on the time to reach critically high roll angles, given specific initial conditions.
8. For high speed operation (i.e. at maximum power) the maximum roll angles and therefore the probability of capsizing are clearly higher than for low speed operation. This is mainly the result of the lower wave encounter frequency in stern quartering seas and prolonged stability reduction in the wave crest, which causes larger roll motions and more ingress of water.
9. A second near-capsize mechanism is found for operation in starboard following to stern quartering seas at both low and high speeds. This is much more related to broaching than to progressive down flooding.
10. Disablement of the crew occurs quite frequently in port stern quartering seas at high speed. Adding additional floodable compartments to the factory space significantly increases the number of occasions that the crew would be disabled. Simulation of down flooding through opened fish loading hatches in combination with crew actions to bring the ship into safety shows that the list and heel are such that the crew would be unable to do so. Furthermore, shifting of cargo and equipment and additional down flooding through ventilation ducts and immersed superstructure openings might well have led to the loss of the ship.

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