SURVIVABILITY OF A DAMAGED FRIGATE IN WAVES - A PROBABILISTIC APPROACH

Lionel Palazzi, MARIN, (The Netherlands)
Jan de Kat, MARIN, (The Netherlands)

Abstract

This paper provides an overview of the work carried out to validate a time domain simulation program for a damaged frigate with cross flooding arrangements. This concerns roll decay tests in calm water and the dynamics in regular and irregular waves. To assess the survivability of this frigate for several damage scenarios in a variety of sea states, a probabilistic ‘operability-type’ of analysis has been applied on the basis of extensive numerical simulations. To illustrate the methodology, three different mission requirements have been investigated and compared for the damage scenarios. The results suggest that it is feasible to study the influence of mission requirements on damage survivability in a quantitative sense.

1. INTRODUCTION

The need for rational stability criteria and ship safety assessment methods led the Cooperative Research Navies (CRNAV) group[1] to the development of a numerical model that is capable of simulating the behaviour of intact and damaged frigates in extreme wave conditions.

Extensive validation of the simulation model has taken place over the last years. For damaged frigates the model has reached a sufficient degree of accuracy to be used for stability safety assessment purposes.

This paper describes model test and simulation results for a damaged frigate with cross flooding arrangements. This comprises roll decay tests (intact and damaged) in calm water and the dynamics in regular and irregular waves. To assess the survivability of this frigate for several damage scenarios in a variety of sea states, a probabilistic ‘operability-type’ of analysis is applied on the basis of extensive simulations. To illustrate the operability methodology, three different mission requirements have been investigated and compared for the damage scenarios.

The paper aims to open discussion for possible approaches which can be used in the development of stability standards.

2. NUMERICAL SIMULATION MODEL

The background for predicting large amplitude ship motions with the numerical model (FREDYN) and validation for a damaged frigate have been described in [1] and [2]. The derivation of the equations of motions for a ship subjected to flooding through one or more damage openings is based on the conservation

---

[1] Members comprise US Navy, Canada, France, UK, RAN, RNN, US Coast Guard and MARIN.

of linear and angular momentum for six coupled degrees of freedom. The fluid inside the ship is considered as a free particle with concentrated and time-varying mass; the fluid level is assumed to be horizontal at each time instant.

The wave pressure is calculated over the instantaneous wetted surface. This accounts for a large part of the nonlinearities that affect the ship response. The added mass and damping are treated in the time domain through memory effect integrals. Wind forces, manoeuvring drag forces and appendage forces are included as well in the equation of motion. During damage simulations the time varying mass and inertia of the damage fluid are also accounted for when solving the equation of motion.

To estimate the flow rates of water entering a compartment, the flooding model is based on the Bernoulli equation, see [6]. This analysis is applied to each damage opening or openings between compartments. Based on the difference in pressure head, the velocity through a damage opening is calculated. Air flow and air compression effects are modelled using the appropriate gas laws.

3. VALIDATION FOR THE LEANDER FRIGATE

3.1 Model Tests

Model tests were performed at QinetiQ, Haslar, using a Leander type frigate model to provide validation data [1] for CRNAV simulation purposes. The Leander model is shown in figure 1. Figure 2 shows the model fitted with a generic set of floodable compartments, representing a 3-compartment damage amidships. Tests were performed for two loading conditions (intact GM = 0.73m and GM = 0.28m) with and without cross flooding arrangement. Note that for the low GM case the ship does not comply with the naval stability criteria; this condition was included to determine whether capsizing would occur. The tests included intact and damaged calm water decays as well as damaged tests in regular and irregular waves. More details on this test program can be found in [1] and [2].

The generic interior consisted of four floodable compartments:

- Two large compartments from bottom to main deck
- Forward symmetric compartment
- Center starboard side compartment

Two small wing tanks on the side were connected by a cross duct equipped with a valve to turn the cross flooding arrangement on or off. These tanks were located below the water line on the damage side.

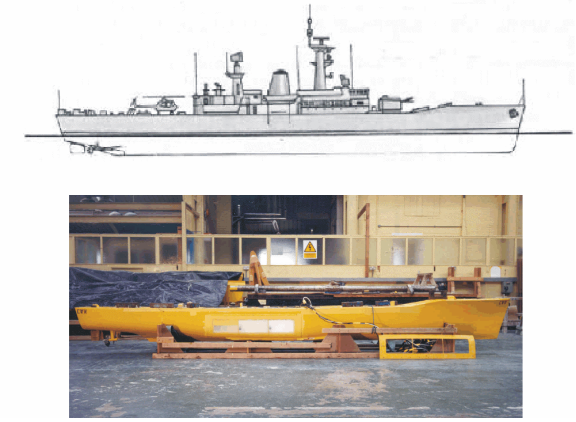


Figure 1: Scale model of the Leander Frigate

All compartments were vented with small holes in the main deck. For the wing tanks pipes were used to allow air escape. The damage opening was created instantly over the full length of the compartments by puncturing a latex sheet.

Figure2: Floodable compartments of frigate

3.2 Simulation results

The validation based on the model tests focussed mainly on roll behaviour; the observed agreement between tests and simulations ranged from reasonable to very good.

The most important observations were as follows:

- The roll decay simulations show that the natural roll period of the damaged ship is smaller than in the intact case, as observed in the model tests. However, the simulated roll period exceeds the actual roll period to some extent, as shown in figures 3 and 4. A discrepancy was observed for the low GM case with regard to the final heel angle; this is attributed to the high sensitivity of damaged ship attitude to small discrepancies between the physical and simulated internal geometry.

- The roll motion of the damaged vessel is accurately predicted in regular waves for the high GM case and is reasonable for the low GM, as illustrated in figures 5 and 6. The RAO given in figure 5 shows that the simulated resonance peak occurs at a longer period than in the model test, which is due to the overestimation of the natural roll period.

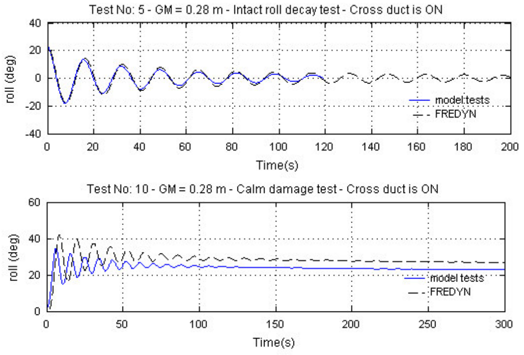


Figure 3. Intact roll decay and damage decay test (GM = 0.28 m)

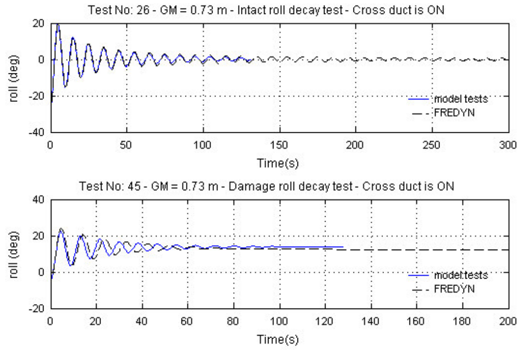


Figure 4. Intact decay and damage test (GM = 0.73 m)

- Compressed air flow provides a damping mechanism of internal fluid motion, which affects motion of the ship [2]. In this case the accuracy of the modeling does not appear to be crucial. Variation of the size of the air vent (thus air flow) does not change the motions significantly as long as air compression and air escape can occur.

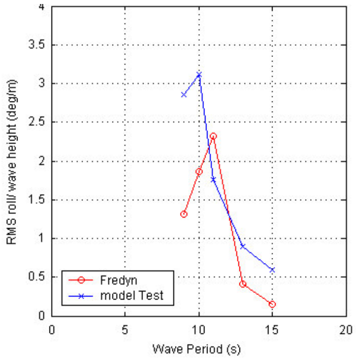


Figure 5. Roll RAOs - Tests in regular waves GM = 0.28 m

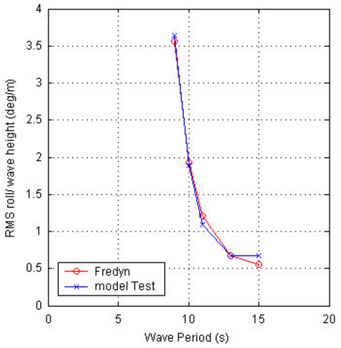


Figure 6. Roll RAOs - Tests in regular waves GM = 0.73 m

Irregular wave tests were carried out in a variety of sea states up to Hs = 5.0 m. The model started in the intact condition in beam seas, and the damage opening was created at an arbitrary point in time. The roll motion after the transient damage response was analyzed; Table 1 shows the root mean square (RMS) values of the simulated and measured roll time series. This table and figure 7 suggest that the roll motion after damage is predicted reasonably well in terms of standard deviations and maxima.

Table 1. RMS roll motion after damage in irregular waves:

RMS roll - after damage (deg)		GM = 0.28 m		GM = 0.73 m	
		Cross duct			
		ON	OFF	ON	OFF
Hs (m)	Tp (s)	M.test / Simul.	M.test / Simul.	M.test / Simul.	M.test / Simul.
1.88	8.8	3.7 / 3.7	4.4 / 2.6	4.6 / 3.8	5 / 3.3
3.25	9.7	6.5 / 5.8	6.0 / 4.5	6.0 / 5.0	6.1/4.8
5.0	12.4	6.8 / 5.7	6.2 / 3.5	6.3 / 5.2	7.1/5.1

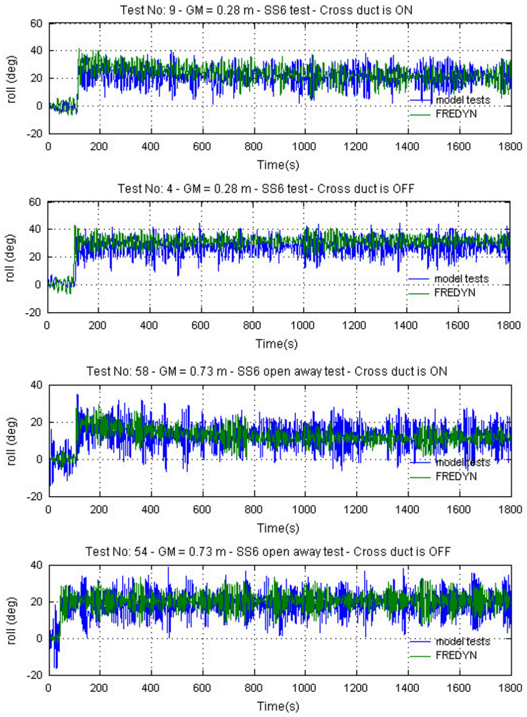


Figure 7. Roll motion during damage tests in irregular sea state (Hs =5 m) compared with simulations for GM = 0.28 m and 0.73 m, with and without cross ducts

- The influence of the cross flooding ducts is simulated quite accurately compared with the model test results. With open ducts it took about 500 seconds for final equalization to occur after the damage event.

It was concluded that the simulation program provides overall satisfactory results and that it could be used to study the survivability of a damaged frigate in waves.

4. ASSESSMENT OF CAPSIZE BOUNDARIES

4.1 Naval stability criteria

The design of naval ships focuses on combat survivability. If intact stability criteria are also applied, in most cases the damage stability criteria determine the design limitations. Present stability criteria are based on empirical and statistical assessment made from analysis of damaged war ship dating back to the World War II era. The criteria are typically based on hydrostatic considerations and heeling energy balance in wind and waves. Although a significant number of navies follow the Sarchin and Goldberg criteria, there are some differences on a detailed level [4].

As is the case for intact ships, it would be possible to formulate performance requirements for a damaged naval ship. Based on considerations of "Float-Fight-Move" it is possible to distinguish different mission scenarios and related requirements. As an example of combat capability, the following requirements may apply [4]:

- the ship must continue to fight following one hit by an anti-ship cruise missile with a nominal one metric ton warhead;
- the ship must survive two anti-ship cruise missile hits;
- survivability design must allow a ship to empty its magazines.

The current stability criteria are not a scientific and rational translation of such operational requirements; their primary aim is to ensure ship survivability for a worst case scenario based on hydrostatic considerations and wind heeling.

Having the ability to simulate the behaviour of a damaged ship in different sea state conditions, it should be feasible to make a step forward toward developing rational design criteria.

4.2 Simulations of damaged ship in irregular waves

The advantage of a fast time domain program is that it can be used repeatedly over a large range of conditions to provide the designer with a more or less complete picture of the ship's operability. However the quantities that must be used to provide the most relevant information for the designer or the rule maker are not yet defined. No damage criteria have been defined yet in terms of limiting motion or flooding and/or maximum allowable percentages of failing certain performance requirements (analogous to the concept of 'down time' in operability analysis).

In this initial phase of the study, it was decided to carry out a large number of simulations with the Leander frigate as described above and to extract motion parameters that could be relevant for assessing the ship performance.

In the study, the following assumptions have been made:

- One damage configuration is investigated (same floodable compartments as in model tests)
- Beam sea at zero forward speed
- Damage opening facing toward weather side
- Analysis was applied to four cases (two GM conditions with and without cross duct)

Ninety six irregular sea states of 30 minutes each (real scale) were simulated and were repeated 5 times with different random wave realizations. It corresponds to 480 damage simulations per design case. The sea states were based on the annual wave statistics for the North Atlantic Ocean. The majority of simulations were carried out in waves only; the effect of wind was investigated for a limited set of conditions

4.3 Roll motion characteristics of damaged ship

The figures below illustrate some typical time series of roll motion obtained during simulation of the damaged Leander in random waves. The dark line drawn through the time series represents the mean heel position (list) based on a running average for a lapsed time of three minutes.

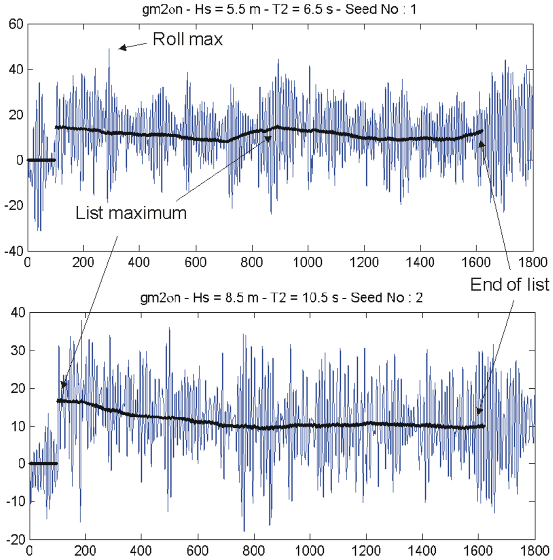


Figure 8: Parameters of interest for analysis of roll motion characteristics of damaged ship

For each time series, the following quantities were analysed:

- the maximum roll angle
- the standard deviation after damage

- the maximum list
- the list at the end of the simulation

The analysis could easily be extended to include other motion parameters such as heave, sinkage, or relative motion at openings. Here only the roll motion is considered to illustrate the approach.

The above roll parameters were derived for the 96 different sea states and different wave realizations. For each design scenario a database was created with the relevant motion parameters, which could be used to conduct an overall operability assessment.

Figure 9 shows the content of the database as a function of sea condition (zero crossing period and significant wave height) for one of the design cases (GM = 0.28 m, open cross duct).

The roll motion database shows that the maximum of the list is rather constant. For this design case it is governed by the calculated list around the initial transient response position (immediately after the damage is created). The transient angle after damage is more or less independent of the sea state.

Absolute maximum angles tend to increase with the steepness of the sea although trends are difficult to observe with maximum value as is described in section 4.5. Capsizing (roll = 90 deg) is observed for the steepest wave conditions. Note that most of these steep conditions are not realistic, i.e., they have a very low probability of occurrence. They have been calculated to ensure that every relevant condition is covered.

The roll standard deviation is a function of wave height and wave period. Highest values are obtained when the mean wave period matches the natural period of the damaged ship.

4.4 Influence of wind

Regarding the mean roll angle in figure 9, it is noted that the quantities are more or less constant. This is mainly because wind was not accounted for in the simulations.

The influence of wind action is illustrated in figure 10, showing recalculated results for the damaged ship with GM = 0.73 m.

Last of mean roll angle

Hs (m)											
11.5					-	-	26	22	19	16	22
10.5					-	-	18	21	20	20	20
9.5				-	-	-	20	19	20	20	20
8.5				-	-	24	18	19	22	22	20
7.5				-	-	19	18	20	20	20	21
6.5			-	-	28	19	19	19	20	21	20
5.5			-	26	18	19	19	20	20	21	21
4.5			16	18	18	19	20	20	21	21	21
3.5		16	18	19	20	20	20	21	22	22	22
2.5		17	19	21	21	22	22	23	23	23	23
1.5	19	21	23	23	23	23	24	25	24	26	24
T2 (s)	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5

Maxroll angle

Hs (m)											
11.5					90	90	90	55	54	-69	44
10.5					90	90	-90	51	54	44	43
9.5				90	90	90	59	51	54	43	42
8.5				90	90	90	57	52	55	43	41
7.5				90	90	60	50	49	54	43	40
6.5			-90	90	60	51	50	47	54	42	40
5.5			-90	54	59	50	51	45	53	41	39
4.5			55	47	48	50	50	44	52	41	39
3.5		62	41	43	46	49	49	42	50	41	38
2.5		45	39	39	46	47	47	41	46	40	39
1.5	43	40	42	40	40	44	44	41	43	39	40
T2 (s)	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5

Max of mean roll angle

Hs (m)											
11.5					-	-	27	28	29	29	29
10.5					-	-	28	29	29	29	29
9.5				-	-	-	28	29	29	29	30
8.5				-	-	29	29	29	30	30	30
7.5				-	-	29	28	30	29	30	30
6.5			-	-	30	29	29	29	30	30	30
5.5			-	28	31	29	29	29	30	30	30
4.5			28	28	29	29	29	29	30	30	30
3.5		28	28	29	29	30	30	30	30	29	29
2.5		29	29	29	30	30	30	29	30	29	30
1.5	29	29	29	29	30	30	30	29	30	29	29
T2 (s)	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5

Roll standart deviation after damage

Hs (m)											
11.5					-	-	15	12	11	9	8
10.5					-	-	13	12	10	9	8
9.5				-	-	-	13	11	9	8	7
8.5				-	-	15	12	10	9	7	6
7.5				-	-	11	11	9	8	6	6
6.5			-	-	10	10	10	8	7	6	5
5.5			-	7	7	9	9	7	6	5	5
4.5			9	6	6	7	7	6	5	4	4
3.5		10	5	4	5	6	6	4	5	4	3
2.5		6	4	3	4	5	4	3	4	3	3
1.5	3	3	2	3	3	3	3	3	3	2	2
T2 (s)	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5

Figure 9. Roll motion database for damaged ship - GM = 0.28 m, Cross duct on - wave realization no 1

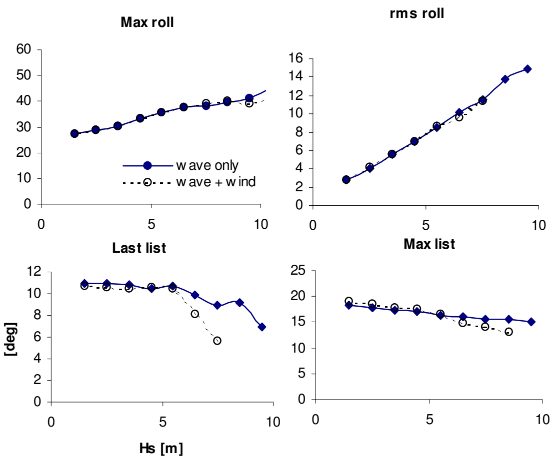


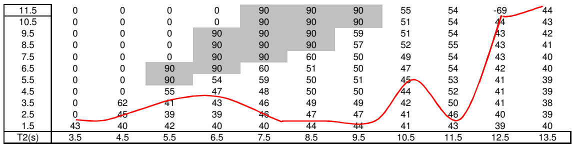
Figure 10: wind effect - GM = 0.73m - cross duct on - T2 = 8.5 s

The following (Kruseman) wind wave relationship was used to determine the mean wind velocity:

$$V_w = 372\,(H_s^{1.829})/(T_p^{2.66}) \qquad \text{m/s}$$

For this case wind has a very limited influence. Only the last heel position (last list or last mean roll angle) is influenced by the wind. It is noted that the damage scenario results in a steady heel angle toward the damage side, i.e., toward the incoming wind and waves. Any effect of wind would result in a slight decrease of the mean heel angle.

Even in the absence of wind, the last value of the mean roll angle decreases with increasing wave steepness (apart from sea states close to capsize). This could be related to the drift velocity, which increases with the wave steepness and which creates a drag force acting on the hull. It is expected that this drag provides a counteracting moment that can reduce the list. More research will be directed at assessing the influence of wind.

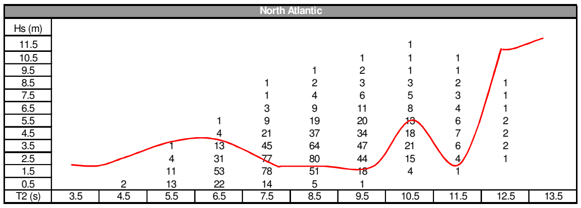


11.5	0	0	0	0	90	90	90	55	54	-69	44
10.5	0	0	0	0	90	90	90	51	54	44	43
9.5	0	0	0	90	90	90	59	51	54	43	42
8.5	0	0	0	90	90	90	57	52	55	43	41
7.5	0	0	0	90	90	60	50	49	54	43	40
6.5	0	0	90	90	60	51	50	47	54	42	40
5.5	0	0	90	54	59	50	51	45	53	41	39
4.5	0	0	55	47	48	50	50	44	52	41	39
3.5	0	62	41	43	46	49	49	42	50	41	38
2.5	0	45	39	39	46	47	47	41	46	40	39
1.5	43	40	42	40	40	44	44	41	43	39	40
T2(s)	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5

Figure 11. Maximum roll angle over 30 minutes: GM = 0.28 m, Cross duct ON

4.5 Criteria and downtime

It is possible to determine "capsize boundaries" or more precisely conditions where motion criteria are exceeded. For instance one might consider the sea states where a critical roll angle has been exceeded. As an example, figures 11 and 12 show the conditions where a specified maximum roll angle is reached for one of the design cases during 30 minute duration. Note that the figure corresponds to only one wave realization for each sea state (for identical wave period the time series of the waves are always the same and are proportional to the wave height).



North Atlantic											
Hs (m)											
11.5								1			
10.5							1	1	1		
9.5						1	2	1	1		
8.5					1	2	3	3	2	1	
7.5					1	4	6	5	3	1	
6.5					3	9	11	8	4	1	
5.5				1	9	19	20	13	6	2	
4.5				4	21	37	34	18	7	2	
3.5			1	13	45	64	47	21	6	2	
2.5			4	31	77	80	44	15	4	1	
1.5			11	53	78	51	18	4	1		
0.5		2	13	22	14	5	1				
T2 (s)	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5

Figure 12. Criteria boundaries: maximum roll = 45 deg

The line in figure 12 depicts the sea states where a specified limit of 45 degrees maximum roll angle has been reached. The cells in the figure reflect the probability of occurrence of the sea state in the North Atlantic area (data extracted form Global Wave Statistics - All directions - All seasons).

By counting the number of occurences above the line, one obtains the downtime related to the criterion: *maximum roll angle = 45 deg*. In this case the down time is found to be around 61%.

Note that the statistical confidence in this number is low. The reason is that it concerns a maximum value that is obtained in only 30 minutes exposure. When the same criterion is applied using other wave realizations, large differences in the boundaries are observed as illustrated in figure 13. The down time ranges then from 13% to 61%.

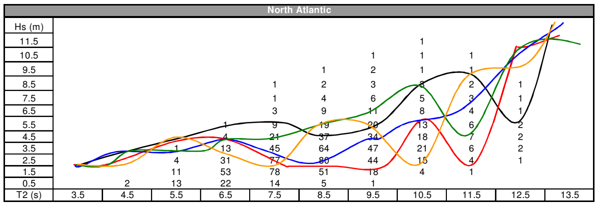


Figure 13. Maximum roll angle - 45 deg for five wave realizations - average down time = 36.3%

These large differences stress the difficulty to deal with maximum values in irregular waves. This difficulty is the reason why Mc Taggart and De Kat [3] chose to determine the short term probability to reach the criteria (probability of capsize) in each sea state. The technique consists of an estimation based on an extrapolation to the longer term of the probability distribution of the roll motion obtained with a sufficient number of simulations per case.

For the illustration purpose of this study, we assume that the down time average obtained over five realizations provides a reliable figure. More research will be carried out to investigate the application of the probabilistic method as given in [3] and [5].

4.6 Mission performance estimation

Once the procedure to determine down time figures has been established, one can define mission types that must fulfill a set of multiple criteria. A mission is then considered as a success when none of the criteria are exceeded. The total down time corresponding to each mission type can be obtained. The difficulty is now to define which motion criteria should apply to a mission or combat situation and which downtime level can be accepted for each mission type. The intention is to develop mission requirements and criteria for the CRNAV group through close interaction with the Naval Stability Standards Working Group (NSSWG) and the Operator Guidance and Training Working Group (OGTWG). The NSSWG consists of navy representatives who are responsible for the stability standards, and the OGTWG consists of navy officers who are responsible for naval training and fleet operations.

To illustrate mission requirements with multiple criteria, we assume that the following requirements are applicable.

<u>Mission requirement no 1:</u>

- max. roll < 60 deg
  - $\sigma_{roll} < 5$ deg
  - max list < 20 deg
  - end list < 20 deg

<u>Mission requirement no 2:</u>

- max. roll < 75 deg
- $\sigma_{roll} < 8$ deg
- max list < 40 deg
- end list < 40 deg

<u>Mission requirement no 3:</u>

- max. roll < 30 deg
- $\sigma_{roll} < 2$ deg
- max list < 15 deg

- end list < 15 deg

Of course the number of requirements could be increased. The criteria could also include onboard accelerations, relative motion at key location, sinkage, or loss of reserve buoyancy.

These criteria are applied to the following Leander damage cases:

design A : GM = 0.28 m - cross duct ON
design B : GM = 0.28 m - cross duct OFF
design C : GM = 0.77 m - cross duct ON
design D : GM = 0.77 m - cross duct OFF

Table 2 provides the down time figures (% failure of criteria) for Mission no. 1.

Table 2. Mission requirements No 1 - % of failure

Design alternatives	Maximum	Max of mean	Last of mean	rms after damag	All of them
A	2.1%	100.0%	66.9%	43.1%	100.0%
B	5.5%	100.0%	100.0%	30.8%	100.0%
C	0.6%	0.3%	0.3%	51.6%	51.6%
D	0.7%	56.6%	32.5%	54.4%	99.3%
Criteria	60	20	20	5	

Design cases A and B would largely fail the mission no. 1 because the mean roll angle is always higher than what is considered acceptable. Note that design case C (with cross duct) results in an acceptable list angle at the end of the simulation.

Table 3. Mission requirements No 2 - % of failure

Design alternatives	Maximum	Max of mean	Last of mean	rms after dama	All of them
A	1.2%	0.4%	0.4%	10.8%	10.9%
B	3.2%	0.5%	2.4%	6.0%	6.3%
C	0.3%	0.3%	0.3%	12.2%	12.2%
D	0.4%	0.3%	0.3%	13.4%	13.4%
Criteria	90	40	40	8	

Mission no. 2 downtimes (representing capsize risk in table 3) are much better since the allowable criteria are higher. The total downtime is mainly governed by the motion amplitude (rms after damage).

Table 4 - Mission requirements No 3 - % of failure

Design alternatives	Maximum	Max of mean	Last of mean	rms after damag	All of them
A	99.8%	100.0%	66.9%	10.8%	100.0%
B	99.8%	100.0%	100.0%	6.0%	100.0%
C	60.4%	0.3%	0.3%	12.2%	60.6%
D	78.3%	56.6%	32.5%	13.4%	99.5%
Criteria	30	20	20	8	

Down times associated with mission requirement no. 3 (table 4) are the highest mainly because of the criteria on maximum angle.

Finally, considering the total down time (the mission fails if any of the criteria is exceeded), the percentage of successful missions is obtained as shown in table 5.

Table 5. Design performance - Mission Success percentages

% of success	Design case			
	A	B	C	D
Mission No. 1	0.0%	0.0%	48.4%	0.7%
Mission No. 2	89.1%	93.7%	87.8%	86.6%
Mission No. 3	0.0%	0.0%	39.4%	0.5%

The benefit of this approach is that it clearly points out which design alternative has the highest performance. Note that in our example the result is obvious since the design with the highest GM and cross flooding arrangement should be the most attractive.

5. FUTURE DEVELOPMENTS

Instead of only four different design alternatives it would have been possible to perform a parametric variation of KG. A guess of expected results is given in figure 14. The same type of graph could then be produced as a function of other hydrostatic parameters such as those used in the existing rules.

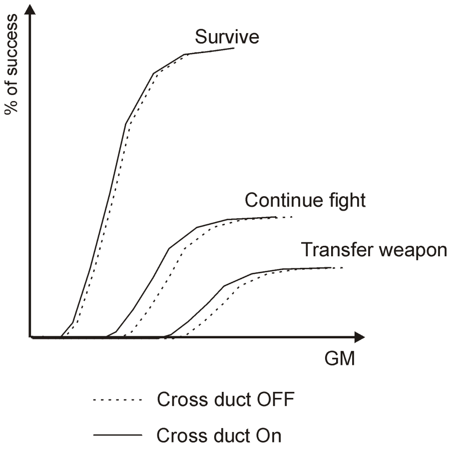


Figure 14: GM influence on mission performance

Repeating the same procedure with other internal arrangements and/or other ships might give trends toward acceptable percentage of success. As part of future efforts, however, several questions will need to be answered:

- What is an acceptable level of success?
- What is the influence of the simulation accuracy to this percentage?
- What motion criteria define a mission type and what mission type shall be considered?
- What is the relevant weighting of mission types in the design process?

A variety of problems and limitations need to be addressed before it is possible to arrive at a generalized and probabilistic design framework.

6. CONCLUSIONS

It has been demonstrated that it is possible to simulate the behaviour of a damaged frigate in waves with reasonable accuracy when compared to model tests.

Using simulations and specified motion criteria it is possible to obtain 'down time' figures for a damaged vessel in a variety of sea states. Initial results suggest that the influence of wind is limited.

The paper illustrates the possibility to assess ship survivability in a probabilistic sense on the basis of mission performance requirements with multiple criteria.

7. ACKNOWLEDGEMENTS

The work presented in this paper is part of ongoing research supported by the Cooperative Research Navies Dynamic Stability (CRNAV) group. Any opinions expressed in this paper are those of the individual authors.

8. REFERENCES

[1] De Kat, J.O., and Peters A.J., "Model experiments and simulation of a damaged frigate", *Proc. IMAM Congress,* Rethymnon, Crete, May 2002

[2] Palazzi, L. and De Kat, J.O., "Model Experiments and Simulations of a Damaged Ship with Air-Flow Taken into Account", *Proc. 6th International Ship Stability Workshop*, Webb Institute, New York, Oct. 2002

[3] Mc Taggart, K. and De Kat, J.O., "Capsize risk of Intact Frigates in Irregular Seas", *Transactions, Society of Naval Architects and Marine Engineers, 2000*

[4] Surko, S.W., An Assessment of Current Warship Damaged Stability Criteria, Naval Engineers Journal, May, 1994.

[5] Harmsen E. and Krikke M., "A Probabilistic Damage Stability Calculation Method for Naval Vessels", 7th International Conference on Stability of Ships and Ocean Vehicules, Tasmania, 2000

[6] Van ' t Veer, R. and De Kat, J.O., "Experimental and Numerical Investigation on Progressive Flooding and Sloshing in Complex Compartment Geometries", *Proceedings of the 7th International Conference on Stability for Ships and Ocean Vehicles, STAB 2000, Vol. A,* Launceston, Tasmania, Feb. 2000, pp. 305-321