Study of Davit-Launched Lifeboats During Lowering, Water Entry, Release and Sail-away Phases

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Abstract

This paper presents the results of the Davit-Launched Lifeboat Project (DLLBP). The project was initiated by the Norwegian Oil Industry Association (OLF) in December 2009, and was executed as a joint effort between OLF and The Norwegian Shipowners' Association (NSA). The project is a continuation of NSA LAP (Life-saving Appliances Project) and lessons learned in OLF Free Fall Lifeboat Project. The project was organised in six Work Packages (WPs) and was completed in June 2011.

The studies in the project covered the following phases during lifeboat evacuation; (1) lifeboat lowering, (2) water entry, (3) release of wire falls and (4) sail-away. Findings and recommendations related to each of the four phases are presented in this paper.

The members of the Norwegian Lifeboat Network, consisting of representatives from authorities, unions, suppliers, OLF and NSA, were informed during the course of the project.

Introduction

In 2005 a free-fall lifeboat on the Veslefrikk field was subjected to a full-scale test. The test revealed several weaknesses. Since then, The Norwegian Oil Industry Association (OLF) and the Norwegian Shipowners' Association (NSA) have performed many investigations, tests, simulations and improvements mainly related to the free-fall lifeboats. The work has focused on development of regulations (new design standard for free-fall lifeboats), hull capacities (slamming), safety of occupants (acceleration levels), forward movement and sail-away to a safe area, Ref. /1/.

On the basis of the findings for free-fall lifeboats, OLF initiated the Davit-launched Lifeboat Project (DLLBP) in December 2009 to investigate the status of similar issues for davit-launched lifeboats. In addition, several findings and recommendations for further work from the NSA Life-saving Appliances Project (LAP) have been brought forward into the DLLBP. The DLLBP was a joint effort between OLF and NSA.

At the time the project started, the number of davit-launched lifeboats on the Norwegian Continental Shelf was 170 boats of 16 types.

Considerable effort has been taken to ensure that the basis for the work is sound and accurate. However, some assumptions and simplifications have been made. Also, some effects are not included and will introduce uncertainties. The uncertainties will influence the results and how they are interpreted. This should be considered when reading this paper. Evident trends from the results have been used to identify areas for improvement.

The methodologies for generation of accelerations pulses and sail-away simulations have been subjected to third-party verification as these provided key results for the project.

In order to provide a clear transition between the phases, specific descriptions of the start and end of each phase were defined:

Lowering phase:	starts as the coxswain initiates lowering of the lifeboat from its stowed position in the davits, and ends as the boat comes in contact with the sea.
Water entry:	starts as the lifeboat comes in contact with the sea and ends when the lifeboat is waterborne. This phase may also be referred to as *landing*.
Release phase:	starts as the boat is waterborne and ends when the wire falls are released.
Sail-away phase:	starts when the wire falls are released and ends when the lifeboat has reached a safe area.

The sail-away simulations are based on a spectre of weather conditions, while the remaining simulations are based on severe regular waves in a 100-year condition.

This paper is based on the DLLBP Summary Report, Ref. /8/, which again is based on the detailed reports from various sub-activities, mainly Refs. /9/ to /24/. Note that the actual lifeboat names have been anonymised in the text and also in the references.

Lowering Phase

Lowering Basics

Before going into the specifics of the work performed for the lowering phase, the reader should consider some basics for launching of a davit-launched lifeboat.

Figure 1 below shows a simplified case for the lowering of a lifeboat in a regular wave with height of 13 m and a period of 11 s moving towards the left. The figure shows the vertical position of the wave and the boat as function of time. The special case in the figure is a case where the boat barely misses the peak. The three lines shows how the lowering speed affects the landing position (hit point) in the wave. For a lowering speed of 1.5 m/s the lifeboat lands deeper in the wave trough than the two other lowering speeds. The figure shows that the slope of the lines is in general smaller than the slope of the wave. In severe weather with steep waves, the lifeboat will always land in a zone where the wave is moving upwards. This observation is independent of wave direction.

A portion of the wave has been marked red to roughly indicate the start and end of the landing zone. The release window[1] is shown to be 4.2 s, 3.2 s and 2.5 s for the three different lowering speeds. As the boat lands on the water, it will move horizontally with the waves creating a diagonal on the wire falls. If the lifeboat is not released from the wire falls before the end of the release window, the wave will move downwards and the weight of the lifeboat will be transferred back onto the wire falls, also called ‘re-entry’. This happens because the vertical wave particle velocity in severe weather is larger than the lowering speed the lifeboat. Since the lifeboat has moved horizontally, it will swing backwards upon re-entry and may have a totally different landing position on its next landing.

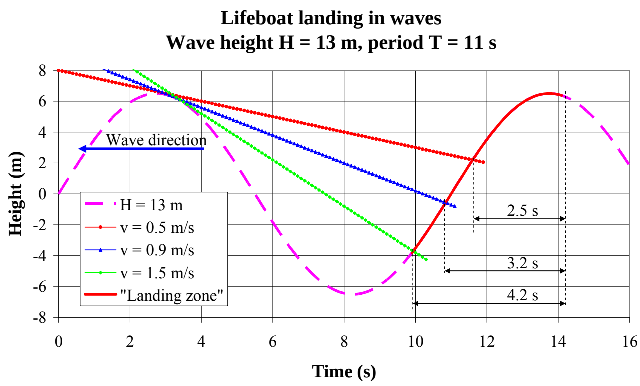


Figure 1 Simplified case 1: Hit point and release window as function of lowering speed for wave H = 13 m and T = 11 seconds.

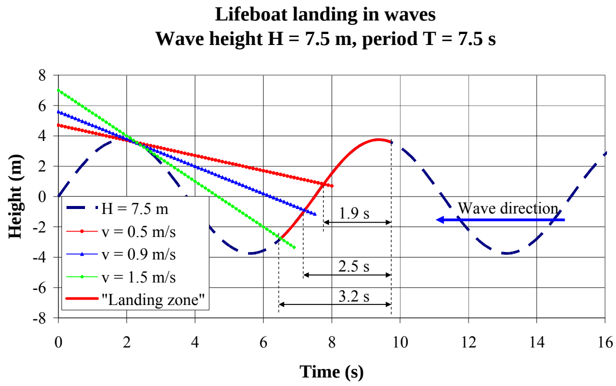


Figure 2 Simplified case 2: Hit point and release window as function of lowering speed for wave H = 7.5 m and T = 7.5 seconds.

[1] Release window: time period available between landing and possible re-entry.

As stated above, the case in Figure 1 is simplified. In reality, the lifeboat can land anywhere in the red part of the wave depending on the lowering velocity and time of launching. In the cases where the lifeboat lands just before the wave peak, the release window will be too short for a release of the wire falls, thus resulting in a re-entry. The re-entry of these cases is less severe as the horizontal movement is less which again results in a smaller pendulum effect. Another favourable element is that the lifeboat will continue its descent and land deeper in the next wave compared to a lifeboat which barely misses the wave peak, as the simplified cases in Figure 1. And by landing deeper into the second wave, the release window is increased.

Figure 2 shows another simplified case for a lower wave height with a shorter wave period. The figure shows that the release window is smaller for this wave than for the larger wave shown in Figure 1. This means that it can be more difficult to release the wire falls in small waves than in large waves since the release window is smaller.

Although Figure 1 and Figure 2 represent simplifications, they demonstrate the term “re-entry” and the effects of lowering speed and wave period on the release window.

Description of Simulations

In the lowering phase the lifeboat is subjected primarily to self-weight and wind loads. Pull & go[2] launching is used as basis for these simulations, so dynamic loads from use of hold brake is disregarded. However, the resistance from a typical centrifugal brake is included. Parameters such as lowering speed, lowering height and lifeboat weight have been included in the study. Table 1 below gives an overview of the simulations and parameters in the lowering simulations performed in MOSES[3].

Table 1 Simulation matrix for lowering simulations.

Loading conditions	Lowering height	Lowering speed	Beaufort force	Wind direction	Number of simulations
Full	22 m	0.5, 0.9 and 1.5 m/s	10, 11 and 12	175, 135 and 90 deg	2700
Full	50 m	0.5, 0.9 and 1.5 m/s	10, 11 and 12	175, 135 and 90 deg	2700
Full	80 m	0.5, 0.9 and 1.5 m/s	10, 11 and 12	175, 135 and 90 deg	2700
Empty	22 m	0.9 m/s	10, 11 and 12	175, 135 and 90 deg	900
Empty	80 m	0.9 m/s	10, 11 and 12	175, 135 and 90 deg	900

Note on wind directions:
0 deg is following sea, 90 deg is beam sea to starboard and 180 deg is head sea

The simulation starts with the lifeboat hanging in the wire falls. At start of simulation the keel of the lifeboat located 6.0 m beneath the davit points. The wind forces are gradually applied during the first 20 seconds of simulation to prevent transient effects (pendulum motion due to suddenly applied

[2] Launching of a lifeboat without braking; the lowering is performed in one continuous movement from its stowed position in the davits until it is waterborne.
[3] By Ultramarine, http://www.ultramarine.com/

loads). When the wind force is fully applied, the lowering starts. The lowering speed is gradually increased from zero to desired speed during the first 5 seconds of lowering.

Post-processing of the results is carried out by first determining the time instant for water contact. This is taken as the instant the origin of the boat (located on the keel, midway between the hooks) touches the wave surface. The *x*-axis points towards the stern of the vessel, *y*-axis points towards starboard and *z*-axis points upwards.

At the time instant of water entry the lifeboat yaw angle and location of three points is reported. One point is located at the origin of the boat, one point is at the stern, and one point is located at the bow.

The *x*, *y* and *z* coordinates of the boat trajectory is reported starting when the wind forces are fully applied. The reporting of the trajectory is stopped at the time instant of water entry.

Various environmental conditions have been established by using the Beaufort scale as basis. Wind and wave parameters corresponding to Beaufort force 10 to 12 are given in Table 2.

Table 2 Overview of sea states and wind speeds included in lowering simulations.

Beaufort force	Mean wind speed at 10 m	Significant wave height	Wave peak period	Gamma factor	Average steepness (S_p)
10	26 m/s	8 m	11 s	3.6	1/24
11	31 m/s	11 m	13 s	3.5	1/24
12	37 m/s	16 m	17 s	2.4	1/28

It is not straight forward to establish a relation between wind speed, wave height and wave period. This is because the waves will build up gradually as the wind continues to blow, which means that the duration of the wind state is an important parameter which is disregarded here. Table 2 represents well developed conditions. Wave peak period is selected such that each sea state is in the steep range of the scale. The average steepness (S_p) as defined in DNV-RP-C205, Ref. /5/, is given in the table for reference. The average steepness is given by:

$$S_p = \frac{2\pi}{g}\frac{H_s}{T_p^2}$$

where T_p is the peak period and H_s is the significant wave height.

Summary of Results for Lowering Phase

Figure 22 in Annex A shows an example of results from the lowering simulations. The data point with rank 91 (of 101) is selected in the cumulative distribution plots and reported in Table 14, Table 15 and Table 16 (also in Annex A). This data point is an estimator for the 90% probability of non-exceedance (91/101=90%). The *x*-offset is the offset towards the platform and is considered to be the critical parameter. The main conclusions are:

1. Pendulum motions may be reduced by increasing the lowering speed.
2. Lifeboat lowering from great heights (more than 50 m) in strong wind may lead to large pendulum motions and large position and heading offsets. The situation becomes worse if the lifeboat is lightly loaded.

A higher lowering speed gives higher slamming loads and thus higher acceleration levels during water entry. A higher lowering speed will also increase the release window. The tendency may be less clear in irregular waves and, when lowering from large heights, in strong wind. On the other side, a lower lowering speed will give smaller acceleration levels during landing, but at the same time reduce the release window. In general, a lowering speed of around 1.0 m/s appears to be a sound compromise between acceleration levels and release window requirements.

Evaluation of Pull & Go

In general, DLLBP recommends pull & go launching of davit-launched lifeboats as described in NORSOK R-002 A.3.4.3, Ref. /3/. The basis for this recommendation is:

- Simplified launching procedure; the crew does not need to hold the pilot wire and is not expected to halt lowering to target a suitable wave or avoid debris;
- Focus is shifted towards the important tasks of rapid release and limiting setback which are crucial for a successful outcome;
- Non-stop launching reduces the oscillation compared to a stop in launching in strong wind;
- Dynamic loads when breaking during lowering are avoided;
- Use of gravitational breaks (and no hold break) will reduce the dynamic loads in case of re-entry;
- The pull & go approach is more in line with the launching of free-fall lifeboats which can be launched without consideration to debris or other floating objects.

The project acknowledges that there is a conflict between the LSA code and the requirements of NORSOK R-002 and also the recommendations from this project. This will mainly be an issue for mobile offshore units which are under maritime regulations. However, the advantages of pull & go launching of davit-launched lifeboats are such that pull & go launching is strongly recommended by this project.

Water Entry Phase

The studies of the water entry phase mainly covered two important aspects: The first is human aspects like "What is the injury potential of acceleration peaks during water entry?" The second aspect is related to estimation of the slamming capacities (structural strength) of two typical lifeboat hulls.

Peak Accelerations

A large number of acceleration pulses were generated as input to biomechanical studies. Some acceleration pulses were generated at an early phase to allow biomechanical engineers to perform a validation study and a parameter study. The majority of the acceleration pulses, consisting of 21 000 pulses, were generated from 3 500 computer simulations. These were used in a comprehensive biomechanical study of the landing phase, see below. The 3 500 computer simulations in MOSES were based on the following input parameters:

- 5 boats (called Boats A, B, C, D and E)
- 2 lowering speeds (0.9 m/s and 1.5 m/s)

- 5 wave directions (0, 45, 90 (beam sea), 135, 180 (head sea) degrees)
- 7 wave conditions (see Table 3) – regular waves
- 10 landing positions within each wave

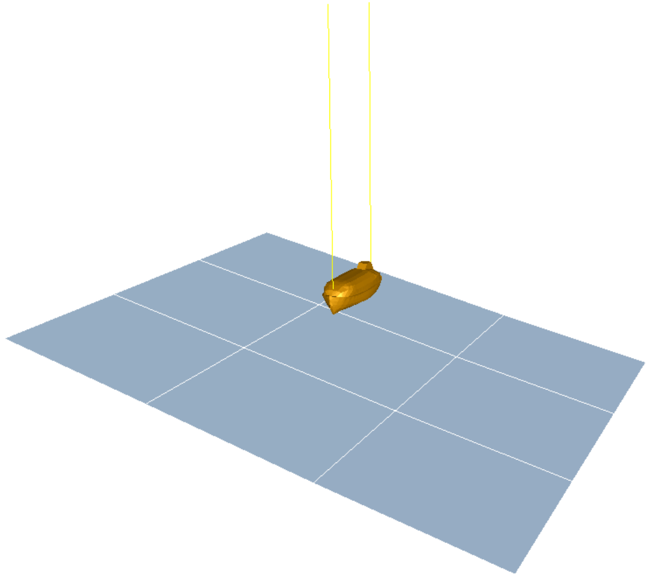


Figure 3 Screen capture from simulation.

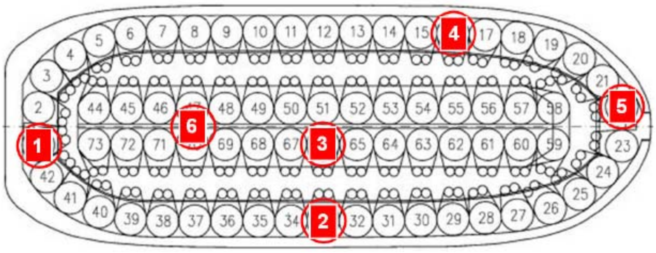


Figure 4 Typical seat selection for evaluation of occupant injuries.

Figure 3 shows a screen capture from one of the MOSES simulations. The lowering height is 30 m for all these simulations. Seat accelerations were reported for six seats for each simulation, one being the driver's seat. The other five seats were spread over the boat covering outer starboard seat bench, centre seat bench, most forward seat and most aft seat. A typical selection of seats is shown in Figure 4.

A set of irregular sea states were selected as basis for the simulations. These sea states, expressed by a significant wave H_s height and a peak period T_p, are all on or close to the 100-year contour in a typical H_s–T_p diagram for the Northern North Sea. From the selected irregular sea states, the height of representative waves were selected as the average of the one tenth highest waves, $H_{1/10} \approx 1.27 \cdot H_s$. Corresponding wave period T is selected so that there is a 10% chance of having a steeper wave, given the wave height.

The representative waves used for generating the acceleration pulses are listed in Table 3 and visualised in Figure 5. The non-linear waves were used in the simulations.

Table 3 Irregular sea parameters and representative regular waves for water entry simulations.

Peak period	Avg. steepness	Sign. height	H	T	Phase velocity	Wave length	Steepness	Velocity *)	Acceleration *)
T_p [s]	S_p [-]	H_s [m]	[m]	[s]	[m/s]	[m]	[-]	[m/s]	[m/s^2]
16.0	1/25	15.99	20.3	13.7	21.4	292	1/14	4.66	2.14
15.0	1/25	14.05	17.8	12.8	20.0	257	1/14	4.37	2.14
14.0	1/23	13.41	17.0	12.6	19.7	249	1/15	4.24	2.11
13.0	1/21	12.56	16.0	12.3	19.2	236	1/15	4.08	2.08
12.0	1/19	11.56	14.7	11.4	17.8	203	1/14	4.04	2.23
10.0	1/17	9.22	11.7	8.9	13.9	124	1/11	4.13	2.92
8.0	1/15	6.66	8.5	7.1	11.1	79	1/9	3.73	3.30

Notes:
*) Amplitude evaluated at mean water level (Airy wave – deep water)

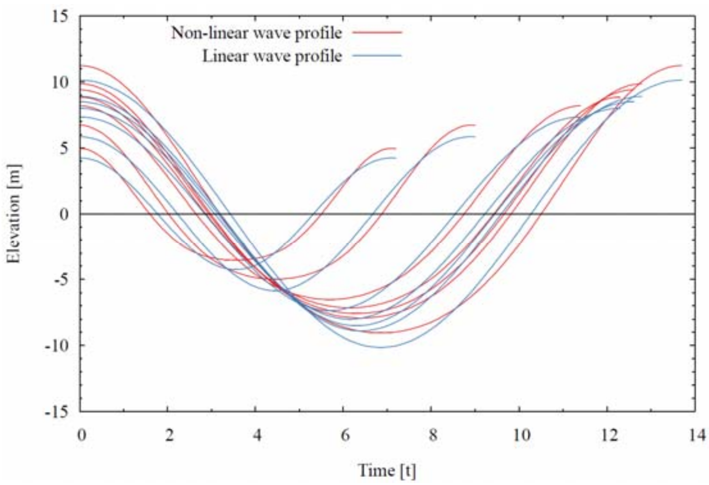


Figure 5 Non-linear wave profiles used in the simulations plotted over linear wave profiles.

Forces on Lifeboat Occupants during Water Entry

Numerical simulations were performed in MADYMO[4] using the acceleration pulses generated as described above. The simulations were used to investigate the occurrence of injuries for occupants in six positions in three different lifeboats. The safety level provided by the actual lifeboats was evaluated using a standardised crash dummy (RID^{3D}) in the simulation set up as a replacement for a real 50^{th} percentile human male occupant.

Acceleration pulses for three of the five lifeboats simulated in MOSES were selected for biomechanical simulations. The acceleration pulses for the remaining two lifeboats were in general enveloped by the other three. Also, of the ten hit points for each wave, only the set with the highest average CAR[5] value was used in the biomechanical simulations.

An inversed validation sled test series was performed in a laboratory for an outer seat in a 3 m test drop, which showed that in general the simulated (numerical) injury responses matched the measured injury responses. Figure 6 shows an example image from the laboratory tests side by side with an image from the numerical simulations (corresponding time instants).

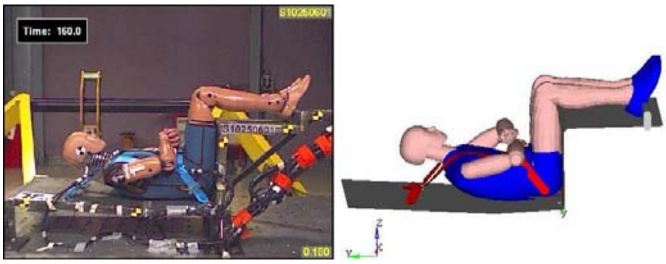


Figure 6 Example: Comparison of kinematic images between the sled test (left) and the simulation (right).

The set-up used for the simulations is as currently present in three actual lifeboats. The dummy in the occupant seats is restrained by the actual belt systems in the boat (2-point or 4-point belt systems). The reference setup for all seats in the biomechanical simulations is a rigid seat in which the dummy sits upright with braced arms. The driver and occupants are holding on to the shoulder belts, if present. The 4-point belt consists of a pelvis belt and two shoulder belts attached to a horizontal belt at the upper attachment points. In the simulations, the 4-point belt system for ‘Boat A’ has adjustable shoulder belts, while the 4-point belt system for ‘Boat C’ has non-adjustable shoulder belts.

Injury criteria established by the LBP2 SOL sub-project, Ref. /2/, have been used. This set of injury criteria are in general expressed by lower limits and upper limits for selected parameters. The lower limit represents no or minor injuries, while the upper limit corresponds to severe injuries. Both lower and upper limit represent low risks of respective injuries, targeted at $< 25\%$ risk of that injury to occur. The assessment of the limits take into account that an injury that is serious in the AIS scale, see Table 4 below, may be fatal in lifeboat evacuation due to circumstances preventing emergency medical assistance.

[4] By TASS (TNO Automotive Safety Solutions), http://www.tass-safe.com/

[5] Combined Acceleration Ratio, see Ref. /4/.

Table 4 Abbreviated Injury Scale (AIS), from Ref. /4/.

AIS code	Injury	Example of characteristics and indications	
		Brain/head injuries	**Skeletal injuries**
0	Non-injured		
1	Minor	Headache	Bruise or minor fracture
2	Moderate	Loss of consciousness for less than 1 hour	Moderate fractures, for example 2 rib fractures
3	Serious	Loss of consciousness between 1 and 6 hours	Not life-threatening, such as a crushed foot
4	Severe	Loss of consciousness between 6 and 24 hours	4 or more rib fractures on one side, 2 to 3 rib fractures with hemothorax or pneumothorax
5	Critical		Fatal in the short term, such as caused by a broken neck
6	Untreatable	Unsurvivable	Immediate death, such as caused by decapitation

Table 5, Table 6 and Table 7 summarizes the results from the study. Each coloured cell in the tables represents one simulation. If the cell is green, then the injury level is below the lower value (AIS level 0 and 1). If the cell is yellow, then the injury level is between the lower and the upper limit (AIS level 2 to 3). A red cell indicates that the injury level is above the upper limit (higher than AIS level 3 to 4).

The three tables contain mostly green cells. In general, it is only for some seats in beam sea that the cells are non-green. Also, the number of non-green cells is higher for a lowering speed of 1.5 m/s than for a lowering speed of 0.9 m/s.

Since all occupant seats in the ‘Boat B’ have a 2-point belt system, the upper body is not restrained and can move into the seating space of other occupants. To investigate whether this could lead to injuries, two simulations have been performed with two dummies possibly interacting with each other. Although not directly observed in the simulations, the uncontrolled motion of the upper body due to the absence of shoulder belts, could lead to possibly injurious contacts.

For ‘Boat A’ and ‘Boat C’ the cases that did predict an injury risk (exceeding lower limit) were related to neck posterior forces. In four beam sea cases for ‘Boat C’ the high injury values were caused by the head hitting the seatback during rebound. Especially for the ‘Boat C’ with a ‘loose’ 4-point belt system with fixed shoulder belt length, the injury responses may decrease when an optimized 4-point belt system is used with adjustable shoulder (and pelvis) belts.

Considering that the acceleration pulses used in these numerical simulations are based on severe waves in a 100-year sea state, and that they are expected to be the worst out of the ten simulated hit points averaged over the six selected seats, the overall risk of being injured during the landing phase is very low.

To investigate to what extent the CAR value can be used to predict injury levels or to select worst case conditions; the correlation between CAR and the maximum normalised injury value (F_{max}) for any of the criteria has been investigated. In general there is a positive trend between the CAR value and F_{max} for the evaluated cases, showing that higher injuries in general are related to higher CAR values. The CAR value correlates to the F_{max} with a coefficient of determination R^2 of 0.84, 0.61 and 0.45 for 'Boat A', 'Boat B' and 'Boat C', respectively. Since a significant spread in F_{max} can be observed with similar CAR values for all three boats, the CAR value can only be used to obtain a very rough indication of the injury level to be expected. For a detailed injury risk prediction numerical simulations remain required.

Table 5 Summary of results for 'Boat A'.

FollowingSea	lowering speed 0.9							lowering speed 1.5						
waveheight	20.3	17.8	17	16	14.7	11.7	8.5	20.3	17.8	17	16	14.7	11.7	8.5
1OCseat01Rear														
2OCseat10Outside														
3OCseat24Center														
4OCseat52Outside														
5OCseat58Front														
6HSseat60														

SternQuarteringSea	lowering speed 0.9							lowering speed 1.5						
waveheight	20.3	17.8	17	16	14.7	11.7	8.5	20.3	17.8	17	16	14.7	11.7	8.5
1OCseat01Rear														
2OCseat10Outside														
3OCseat24Center														
4OCseat52Outside														
5OCseat58Front														
6HSseat60														

BeamSea	lowering speed 0.9							lowering speed 1.5						
waveheight	20.3	17.8	17	16	14.7	11.7	8.5	20.3	17.8	17	16	14.7	11.7	8.5
1OCseat01Rear														
2OCseat10Outside														
3OCseat24Center														
4OCseat52Outside														
5OCseat58Front														
6HSseat60														

BowQuarteringSea	lowering speed 0.9							lowering speed 1.5						
waveheight	20.3	17.8	17	16	14.7	11.7	8.5	20.3	17.8	17	16	14.7	11.7	8.5
1OCseat01Rear														
2OCseat10Outside														
3OCseat24Center														
4OCseat52Outside														
5OCseat58Front														
6HSseat60														

HeadSea	lowering speed 0.9							lowering speed 1.5						
waveheight	20.3	17.8	17	16	14.7	11.7	8.5	20.3	17.8	17	16	14.7	11.7	8.5
1OCseat01Rear														
2OCseat10Outside														
3OCseat24Center														
4OCseat52Outside														
5OCseat58Front														
6HSseat60														

Table 6 Summary of results for 'Boat B'.

FollowingSea	lowering speed 0.9							lowering speed 1.5						
waveheight	20.3	17.8	17	16	14.7	11.7	8.5	20.3	17.8	17	16	14.7	11.7	8.5
1HSseat														
11OCseatOutside														
18OCseatOutside														
35OCseatOutside														
37OCseatCenter														
70OCseatCenter														

SternQuarteringSea	lowering speed 0.9							lowering speed 1.5						
waveheight	20.3	17.8	17	16	14.7	11.7	8.5	20.3	17.8	17	16	14.7	11.7	8.5
1HSseat														
11OCseatOutside														
18OCseatOutside														
35OCseatOutside														
37OCseatCenter														
70OCseatCenter														

BeamSea	lowering speed 0.9							lowering speed 1.5						
waveheight	20.3	17.8	17	16	14.7	11.7	8.5	20.3	17.8	17	16	14.7	11.7	8.5
1HSseat														
11OCseatOutside														
18OCseatOutside														
35OCseatOutside														
37OCseatCenter														
70OCseatCenter														

BowQuarteringSea	lowering speed 0.9							lowering speed 1.5						
waveheight	20.3	17.8	17	16	14.7	11.7	8.5	20.3	17.8	17	16	14.7	11.7	8.5
1HSseat														
11OCseatOutside														
18OCseatOutside														
35OCseatOutside														
37OCseatCenter														
70OCseatCenter														

HeadSea	lowering speed 0.9							lowering speed 1.5						
waveheight	20.3	17.8	17	16	14.7	11.7	8.5	20.3	17.8	17	16	14.7	11.7	8.5
1HSseat														
11OCseatOutside														
18OCseatOutside														
35OCseatOutside														
37OCseatCenter														
70OCseatCenter														

Table 7 Summary of results for 'Boat C'.

FollowingSea	lowering speed 0.9							lowering speed 1.5						
waveheight	20.3	17.8	17	16	14.7	11.7	8.5	20.3	17.8	17	16	14.7	11.7	8.5
1OCseat30Rear														
2OCseat23Outside														
3OCseat47Center														
4OCseat10Outside														
5OCseat15Front														
6HSseat														

SternQuarteringSea	lowering speed 0.9							lowering speed 1.5						
waveheight	20.3	17.8	17	16	14.7	11.7	8.5	20.3	17.8	17	16	14.7	11.7	8.5
1OCseat30Rear														
2OCseat23Outside														
3OCseat47Center														
4OCseat10Outside														
5OCseat15Front														
6HSseat														

BeamSea	lowering speed 0.9							lowering speed 1.5						
waveheight	20.3	17.8	17	16	14.7	11.7	8.5	20.3	17.8	17	16	14.7	11.7	8.5
1OCseat30Rear														
2OCseat23Outside														
3OCseat47Center														
4OCseat10Outside														
5OCseat15Front														
6HSseat														

BowQuarteringSea	lowering speed 0.9							lowering speed 1.5						
waveheight	20.3	17.8	17	16	14.7	11.7	8.5	20.3	17.8	17	16	14.7	11.7	8.5
1OCseat30Rear														
2OCseat23Outside														
3OCseat47Center														
4OCseat10Outside														
5OCseat15Front														
6HSseat														

HeadSea	lowering speed 0.9							lowering speed 1.5						
waveheight	20.3	17.8	17	16	14.7	11.7	8.5	20.3	17.8	17	16	14.7	11.7	8.5
1OCseat30Rear														
2OCseat23Outside														
3OCseat47Center														
4OCseat10Outside														
5OCseat15Front														
6HSseat														

Parameter Study

The main goal of the parameter study was to investigate the risk of injuries to occupants in different lifeboats under various emergency evacuation scenarios at or around time of water impact. The work started by performing numerical investigation of the occurrence of injuries for occupants situated on an arbitrary seat in a 'Boat A' lifeboat varying several parameters like dummy posture, belt system and the presence of cushions under two loading conditions.

The reference setup for all seats in 'Boat A' in the parameter study was a rigid seat in which the dummy sits upright with loose arms and is restrained by a 4-point belt system, consisting of a pelvis belt and two shoulder belts attached to a horizontal belt at the upper attachment points. The parameter study was performed with two similar acceleration pulses; One acceleration pulse, also obtained from lifeboat landing simulations, had a high value in the horizontal direction and the other had a high value in the vertical direction. The driver's seat was assessed in particular.

The acceleration pulses used in the parameter study were more severe than the pulses used in the boat-specific simulations above. However, these results still hold for seats in general:

1. For the 5 occupant seats included in the study it was found that the existing/reference setup provided the most desirable responses, with the exception that the bracing arms position is better than loose arms. The braced arms position prevents the arms from impacting other, non-simulated, structures or occupants in the boat.
2. In general, 2-point belt systems are not advised due to large movements in upper body and head.
3. Bending forward did not improve the injury responses for 2-point belt systems. However, some limitations in the

possible postures of the specific dummy may leave this conclusion open.
4. Adding a face mask to a 4-point belt system may be beneficial for rearward and frontal impacts, but not for lateral impacts. It is not advisable to implement face masks as the dominant direction of the accelerations is unknown.
5. Adding cushions on the occupant seats in general lowers the injury responses, however, not substantial enough to manufacture cushions and place them in all existing lifeboats.
6. Some seats having attachments for shoulder belts located high (at openings and some inner seats), should where possible, have these attachment points lowered to the same level as for the remaining seats, see Figure 7.

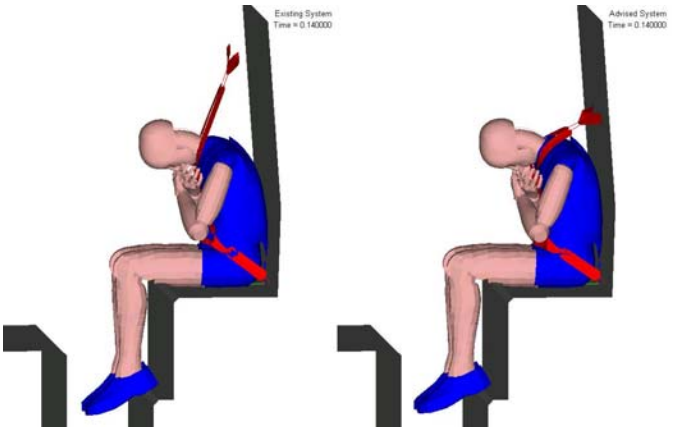


Figure 7 Example of attachment points for shoulder belts; located high (left) and located optimally (right).

The results for the driver's seat are:

1. A 4-point belt system is advised compared to a 2-point belt system.
2. It is advised to implement cushions for the headrest.
3. Some driver's seats have the attachment points for the pelvis belts too much forward. These should be moved backwards and upwards. Optimal attachment points are close to the transition from seat base to seat back.
4. Bracing arms is recommended.

Dummy-Dummy Contact Study

The dummy-dummy contact study involved numerical investigation of the risk of contact between two occupants in three seated arrangements for a 2-point belt system under three different load conditions, see Figure 8. The pulses used in the study represented following sea, stern quartering sea and beam sea.

From the simulations performed in this study, it can be stated that when two occupants are seated next to, opposite to or with their backs to each other this may influence the injury values compared to a single seated occupant with no neighbours. Both occupants may impact each other with their head, thorax, pelvis, arms and/or legs possibly resulting in more severe injuries. Purely based on this analysis, in order to prevent impact between dummy heads and upper bodies, it is recommended to use shoulder belts.

Seating arrangement scenerio		Joints	Seatback plane
Next	Dummy1 Dummy2	Free Free	Yes
	Dummy1 Dummy2	Free Locked	Yes
Opposite	Dummy1 Dummy2	Free Free	Yes
	Dummy1 Dummy2	Free Locked	Yes
Back	Dummy1 Dummy2	Free Free	Yes
	Dummy1 Dummy2	Free Free	No

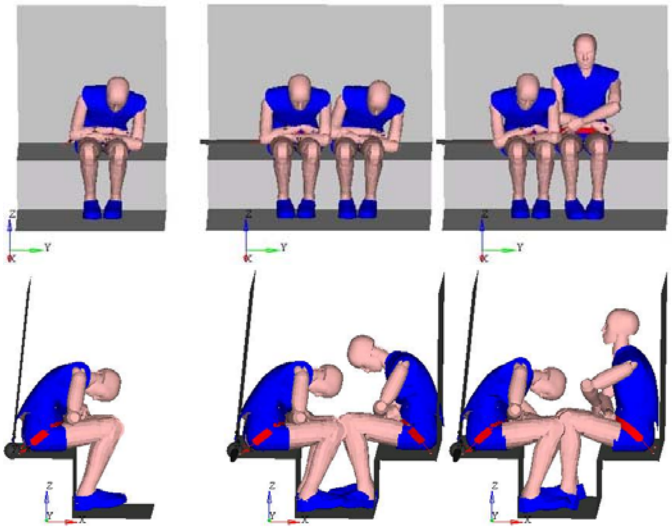


Figure 8 Dummy-dummy contact study: Seating scenarios and joint fixities.

Some other specific results from the study are:

1) Side-by-side scenario:
   a) Both dummies free to move: injury values are comparable to a single seated dummy.
   b) Only one dummy free to move: different behaviour and worse injury values for some injuries. These may be prevented by use of shoulder belts.

2) Front-to-front scenario:
   a) Same behaviour seen in kinematics when comparing the outside dummy with the single seated dummy. Initial contact exists between the legs of both dummies which may result in injuries during the impact phase (leg and head impact). Head impacts may be prevented by use of shoulder belts.

3) Back-to-back scenario:
   a) On the centre benches of the boat, the same behaviour for the dummies is seen for the simulations with a seatback plane between the dummies when comparing with a single seated dummy.
   b) When no seatback plane is between both centre benches, both dummies impact each other resulting in higher impact speeds of one of the two dummies with the pelvis belt. This results in a faster and further forward movement of the upper body of the dummy

which resulted in lower rotational head accelerations, indicating for this specific case an injury risk reducing advantage of dummies contacting each other. However, it may result in a head impact with an opposite dummy. When shoulder belts are implemented, the forward movement would be prevented and no head impact would be possible.

Although not simulated as part of the study, one should be aware that large persons sitting close to each other in a boat with a 2-point belt system have a higher risk of injury caused by hitting each other than smaller persons.

Occupant Size Variation

Most of the biomechanical studies have been using a standardised crash dummy (RID^{3D}) as a replacement for a 50th percentile human male occupant. A separate study was performed to investigate the influence of occupant size variation (different anthropometries). The study covered three different sizes in three different seats for three different waves (same wave direction) in one selected boat ('Boat C'). Figure 10 below contains some key characteristics of the human models used in the study. The belt system used was a 4-point belt system, consisting of a pelvis belt and two non-adjustable shoulder belts. Acceleration pulses corresponding to a lowering speed of 1.5 m/s were used.

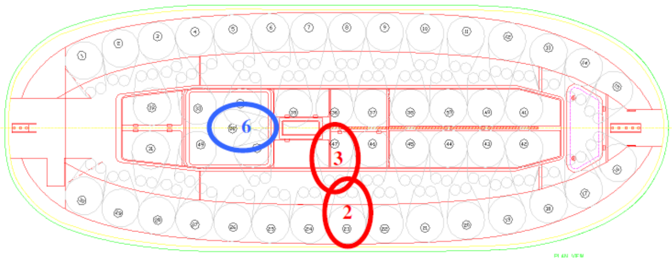
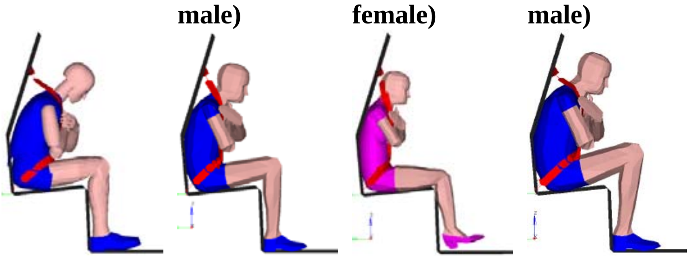


Figure 9 Selected seats in study of occupant size variation.

RID^{3D} dummy model	Dummy size male (50th percentile male)	Small female (5th percentile female)	Hercules size (about 99th percentile male)



	1.74 m tall 78.0 kg	1.43 m tall 48.8 kg	1.97 m tall 120.0 kg

Figure 10 Simulation setups in seat 2 showing the RID^{3D} and human models.

Overall, the comparison between dummy size human male model and RID^{3D} dummy model showed a very similar behaviour. One of the largest differences between the dummy and the human model is the spine construction, which in the human is more flexible compared to the dummy. The different initial position and difference in spine stiffness result in differences in motion of the human compared to the dummy during impact phase. In general, the human models bend more forward and sideward compared to the dummy model.

Overall, the behaviour of the 5th percentile female, dummy size male and Hercules is similar in identical load cases. Only for the driver seat (seat 6) the simulations with the Hercules show a different behaviour compared to 5th percentile female and dummy size male. This is related to the fact that the position of the Hercules is not the same as for the smaller occupant sizes, because it does not fit between the bars of the driver seat.

In none of the simulated load-cases with the human models the injury parameters exceed the upper limit. In 10 out of 27 simulated load-cases with human models injury values above the lower limit can be noticed. All seats show injury values above the lower limit for at least one simulated load-case.

Especially for 'Boat C' with a 4-point belt system with fixed shoulder belt length, the injury responses may decrease when an optimized 4-point belt system is used with adjustable shoulder (and pelvis) belts. Besides, the occupant may impact structures in the boat during lifeboat launch, which were not all simulated.

In the evaluated belt configuration the top attachments points of the shoulder belts are not height adjustable, but have a fixed height. Previous research showed that the height of the shoulder belt attachment points has an effect on the injury prediction, especially when taking into account different occupant sizes. The ability to have height adjustable top attachments points of the shoulder belts might reduce the injuries.

Structural Capacity of Lifeboat Hulls

Slamming loads and structural capacity for two boats, 'Boat F' and 'Boat G'. have been predicted using Computational Fluid Dynamics (CFD) and Finite Element (FE) software tools. The method used is adopted from the method which was developed and applied for free-fall lifeboats, with proper adjustments.

The two boats were selected because they represent the biggest boats in the project. A large and heavy boat will yield larger slamming forces. Also, the two boats represent two different suppliers and two different manufacturing methods.

The methodology can be summarized as follows:

1. Perform selection of design loads and load factors. This involves selection of the design wave, wave headings, lowering speed and hit point.
2. Establish skin model of lifeboat with indicator panels.
3. Perform CFD analyses giving pressure on indicator panels. Select time instances of peak pressures to be included in the structural analyses.
4. Prepare structural model of lifeboat.
5. Perform load mapping of pressure from CFD analyses onto structural model.
6. Perform evaluation of stress and deflection.

Three different waves with different characteristic load were applied to the 'Boat F', whereas only one wave ("Wave 1") was applied to 'Boat G' in order to probe the actual slamming capacity of the lifeboat. The characteristics of the design waves are given in Table 8. For each wave, a total of 5 launch events were simulated by CFD (Star-CCM+[6]) and 10 structural load cases were analyzed in NX I-DEAS[7].

Table 8 Design waves for structural evaluation.

Wave ID	"Wave 0"	"Wave 2"	"Wave 1"
Wave height	17 m	20.3 m	16.0 m
Wave period	10.4 s	13.7 s	12.3 s
Steepness S_p	1/10	1/14	1/15
Vertical wave particle velocity	5.1 m/s	4.7 m/s	4.1 m/s

A load factor of 1.0 was used for existing boats. The material factor was set to 1.75 (matrix dominated laminates).

Results for 'Boat F'

For all three design waves the results from the structural load cases for 'Boat F' show capacity below requirement in large parts of the structure. The global analysis shows three areas in the boat, which are characterized by high stress levels. This is the aft hull area, the side of the hull and large areas in the canopy. The high stress level in the canopy is caused by large global deformations.

The structural analyses show that the boat may be subjected to global structural failure. The analysis also shows that the CSM (Chopped Strand Mats) layers in the laminates fail first. The results for beam sea display large sideways deflections of the canopy relative to the hull. These deflections may injure passengers.

It should be noted that there are a number of uncertainties related to modelling of structural details. The owners of this type of lifeboat should evaluate these uncertainties with assistance from the lifeboat manufacturer.

Results for 'Boat G'

There are only two load cases with stress levels near or above capacity. These were load cases 3 and 6. Load case 3 is a launch event with stern quartering sea. The analysis shows high utilization, but it is not expected to give progressive failure. Load case 6 is from a launch event with a wave hitting the hull from the side. The structural analysis of this event shows high stress levels in the bottom hull structure, inner liner, buoyancy foam and canopy laminate. This load case also has a high deformation between hull structure and canopy structure that may injure the passengers onboard the lifeboat. Maximum deflection in the non-linear analysis is 206 mm. Both global sideways and global vertical deflections are large and may, as for 'Boat F', injure passengers. The lifeboat owner should with assistance from the lifeboat manufacturer evaluate possible reinforcements.

Release Phase

Release Systems

In the following the NORSOK R-002 definition of 'release systems', Ref. /3/, is used:

Release System combination of release mechanism and activation system.

where

release mechanism parts of the means of connection that are moveable for the purpose of disconnecting the lifesaving equipment from its launching and recovery appliance.

activation system interconnected parts necessary for powered or manual opening of the release mechanism, including the power supply and control system or manual control device.

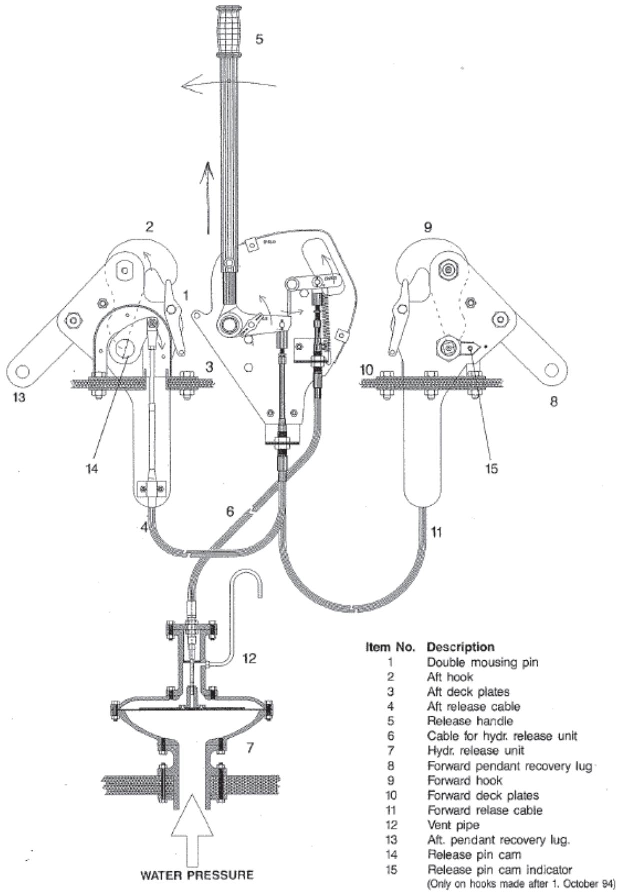


Figure 11 Typical conventional release system.

Figure 11 shows a typical conventional release system (on-load). The system consists of a hydraulic release unit which is located at the keel in the middle of the boat. The unit is open to sea on one end and water will enter when the boat lands on the sea. The hydrostatic pressure will then create a force on a membrane in the release unit and move the centre of the membrane upwards. A cable link is attached to the membrane on one end and is terminated at a lock in the other end. As the bottom of the cable is pushed upwards, the lock is released, making it possible for the lifeboat driver to operate the release handle. As the handle is rotated, two more cables are being pulled which in turn releases the forward and aft hooks. Figure 12 shows some examples of release mechanisms.

Two surveys of release systems were performed by collecting information about lifeboat release systems. The actual performance of release systems was established by preparing a test procedure and collecting results from time-to-release tests. A gap analysis was performed by first identifying

[6] By CD-adapco
[7] By Siemens PLM Software.

requirements to release systems given by NORSOK R-002 preliminary edition April 2010, and then systematically comparing each system against these requirements. Finally, an overall evaluation was performed by reviewing the systems identified by the surveys and evaluating them.

Figure 12 Examples of release mechanisms.

The conclusions from the survey of release systems are:

1. At the time the work was performed, there were no lifeboat release systems, neither existing nor novel, which comply fully with the preliminary NORSOK R-002 standard. Hence, product development is required if the current requirements are maintained in the final revision of the standard.
2. Results for time-to-release tests show that some systems are capable of releasing within 1.5 seconds, while other systems need typically 3 to 4 seconds. The importance of rapid release is discussed further in the following sub-section.

Study of Delayed Release

The study involved 3600 time domain computer simulations to examine the effect of lowering speed and delayed release on slamming loads, wire tensions and corresponding boat accelerations. The following parameters have been investigated:

- Two lifeboats (‘Boat A’ and ‘Boat B’)
- Two lowering heights (28 m and 80 m)
- Three lowering speeds (0.5 m/s, 0.9 m/s and 1.5 m/s)
- Six wave conditions
- Five wave directions
- Ten different landing positions (hit points) in each wave

For each simulation, 4 different delays in the release mechanism have been investigated; 1, 3 and 5 seconds. The simulations are also based on use of pull & go; the winch is modelled as a friction brake with no hold brake.

A set of representative (regular) waves were selected as input to the simulations, see Table 9. The height of these waves was set to be the average of the one tenth highest waves, typically H ≈ 1.27·H_s. The steepness S_p of the waves is 1/15 for peak period $T_p \leq 8$ s and 1/25 for $T_p \geq 15$ s and interpolated linearly between the boundaries.

In the simulations a special algorithm is used to detect if the keel centre of the boat is submerged for a period of time lesser or greater than the specified release delays (1, 3 or 5 seconds). Each simulation is defined as a successful release provided that the wire falls are released before the simulation ends, regardless of numbers of boat water-entries. The simulation time was typically between 20 to 40 seconds.

The results seem insensitive to boat type. The slamming forces are sensitive to wave particle velocity and the wire snatch loads are sensitive to wave particle acceleration. This means that the highest waves are not necessarily the worst, but rather an unfavourable combination of wave height and wave period.

The results show that the time from initial water contact to release of wire falls is a critical parameter. This time period is the sum of the duration of several events during the release phase:

1. Inherent reaction time of the hydraulic release unit: This safety device may be either mechanical or an electronic sensor. A mechanical solution requires a certain water pressure over a period of time to disengage. An electronic sensor must be able to detect that the lifeboat is waterborne and not trigger by spurts.
2. Reaction time of the coxswain: Most release systems require the coxswain to be ready and react on a signal or an indicator. Stress, distractions and boat movements may increase the reaction time of the coxswain.
3. Duration of the operation required by the coxswain.

If the sum of the durations of these events is too large, then it will in certain situations be difficult to release the boat. Increased lowering speed does not seem to be a sufficient mean to compensate. Efforts should be made to reduce the time from water contact to release of wire falls. This can be done by reviewing all components involved in the process of releasing the wires. Any delays in the system should be reduced as much as possible and coxswain operations should be fast and simple.

Figure 13 is a cumulative distribution plot of the time from water contact to release for lowering speeds of 0.9 m/s and 1.5 m/s. The figure shows that for a time to release of 3 seconds, the lifeboat was released on the first wave in about 71% of the simulations. For a time to release of 5 seconds the lifeboat was released on the first wave in 22% of the simulations for lowering speed of 0.9 m/s, and in 31% of the simulations for lowering speed of 1.5 m/s. Figure 13 also shows that for a release delay of 1 second, the lifeboat was released in the first wave in almost all simulations (97%).

In Figure 13 the red graph corresponding to a time to release of 5 seconds does not climb all the way to 100%. The reason for this is that the duration of the simulations was limited to a certain length, typically 20 to 40 seconds, to keep the simulation time within a practical range. Had the simulations been longer the boat would have been released a later point in time.

Figure 13 shows a dramatic increase in non-successful releases as the delay in the release mechanism increases. The figure also demonstrates that an increased lowering speed will increase the release window and thereby reduce the risk for re-entry, as discussed in ‘Lowering Basics’ above. This can be seen by comparing the plots of the two different lowering speeds for release delays of 3 and 5 seconds, as the number of releases on the first wave is higher for the highest lowering speed.

Figure 14 is a cumulative distribution plot of the maximum tension in one of the two wire falls before release when assuming a delay in the release mechanism of 1, 3 and 5 seconds. It can be observed that 85% to 90% of the simulations yield wire tensions below 30 tonnes for a time to release of 3 seconds. A wire tension of 30 tonnes is selected as the limiting value in the re-entry assessment below. This corresponds to a load 6 times the nominal load (if the lifeboat weighs 10 tonnes, this gives nominally 5 tonnes on each wire), and is typically close to the braking load of the wire. For more detailed assessments it is recommended to identify the weakest component in the launching arrangement / release system and use this value as the threshold.

Figure 14 also indicates that increased lowering speed does not seem to reduce the risk of snatch loads in the wires. This can be seen by comparing the left and right plots for 0.9 and 1.5 m/s lowering speed; there are only small differences between the two graphs.

From the simulated results, a time to release of 5 seconds is clearly not acceptable since there is a high risk of overloading the wires/davits due to snatch loads after landing on water (re-entry). In roughly 50% of the simulations, wire tensions above braking load are reported, see Figure 14.

Table 9 Selected sea states and representative regular waves for studies of delayed release.

Selected sea states			Representative regular waves						
H_s (m)	T_p (s)	S_p* (-)	H (m)	T (s)	Phase vel. (m/s)	Wave length (m)	Steepness (-)	Velocity** (m/s)	Accele-ration** (m/s^2)
16.0	16.0	1/25.0	20.0	16.0	25.0	400	1/20	3.93	1.54
14.0	14.9	1/24.8	18.0	15.0	23.4	351	1/20	3.77	1.58
12.0	12.4	1/20.1	15.0	12.5	19.5	244	1/16	3.77	1.89
10.0	10.6	1/17.7	13.0	10.5	16.4	172	1/13	3.89	2.33
8.0	9.0	1/15.9	10.0	9.0	14.1	126	1/13	3.49	2.44
6.0	7.6	1/15.0	7.5	7.5	11.7	88	1/12	3.14	2.63

* S_p = Average wave steepness
** Amplitude evaluated at mean water level (Airy wave – deep water)

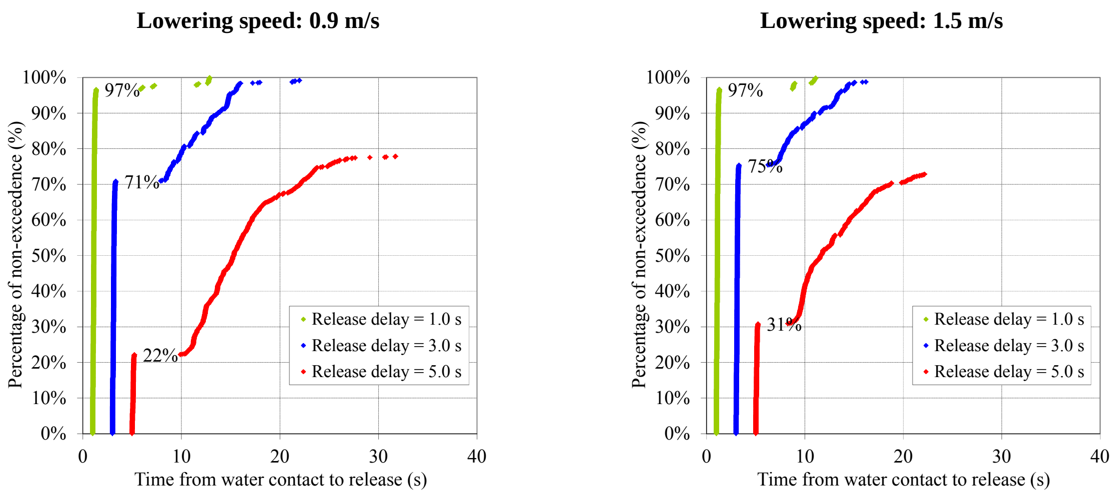


Figure 13 Cumulative distribution plot of time to release for lowering speeds of 0.9 m/s and 1.5 m/s.

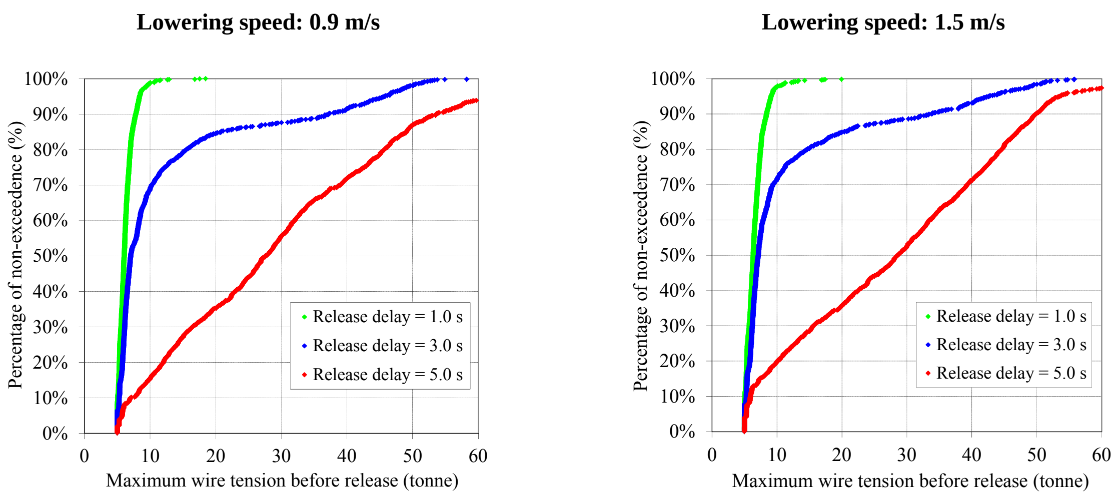


Figure 14 Cumulative distribution plot of maximum wire tension (in one of the two wires) before release for lowering speeds of 0.9 m/s and 1.5 m/s.

Effects of Extreme Re-entry Accelerations on Occupants

A set of acceleration pulses from simulations with about 30 tonnes wire force was prepared as input to biomechanical simulations of extreme re-entry loads. These loads are considered extreme because they are upper-fraction values established from severe representative (regular) waves in 100-year sea states. An overview of these runs is given in Table 10. Provided that the wire falls are released rapidly, these should be considered as extraordinary loads with a low likelihood of occurrence. The accelerations during re-entry are primarily caused by the abrupt transfer of the weight of the lifeboat from the wave back onto the wires as the wave moves downwards.

Table 10 Overview of runs for generation of acceleration pulses for assessment of severe re-entry loads.

Run	**Description**	**Max CAR**	**Seat**	**Max wire tension (of the two wires)**
9929	Wave from starboard	0.99	35	34 tonnes
9939	Wave from starboard/bow (quartering)	1.17	35	30 tonnes
9955	Wave from aft	1.43	37	32 tonnes
9966	Wave from starboard/aft (quartering)	1.62	37	32 tonnes
9991	Wave from bow	1.44	37	33 tonnes

Figure 24 in Annex B is an example of an acceleration pulse. The figure shows how the linear and rotational accelerations vary with time.

The reference setup for all seats in the biomechanical simulations is a rigid seat in which the dummy sits upright with braced arms. In the initial assessment the current belt system is used, i.e. a 2-point belt system (pelvis belt) for the occupants and a 4-point belt system (pelvis and shoulder belts) for the driver. Later on also a 4-point belt, consisting of a pelvis belt and two shoulder belts attached to a horizontal belt at the upper attachment points is investigated for the occupant seats. The driver and occupants are holding on to the shoulder belts, if present. A total of 55 simulations have been performed as part of this sub-activity.

The results from the study are:

1. With the current 2-point belt system injury values exceeding the upper limit were found in a number of the simulations. The other evaluated scenarios showed, due to the extremely large acceleration loads outside of the validation range of both dummy as well as numerical dummy model, extreme dummy behaviour resulting in an unrealistic injury risk assessment. As such, based on the severe dummy behaviour, it can be expected that the 2-point belt occupant scenarios result in a risk of severe injuries. It should, however, be noted that these scenarios are very unlikely to happen. If the extreme re-entry loads happen, a 4-point belt system is better than a 2-point belt system.
2. In all simulated scenarios of a driver with a 4-point belt system the injury responses are exceeding lower limits or even upper limits. In 4 out of 5 simulated driver seat scenarios, injury responses are exceeding one or more of the upper limit injury thresholds. Finally, the occupant seats are evaluated with a 4-point belt system, this however still results in a large amount of scenarios exceeding lower and upper limits. The simulations with 4-point belt system show more realistic and less severe dummy model behaviours, however, many are still exceeding the upper limit.
3. The comparison was made between the first water impact and the selected re-entry accelerations in order to assess the difference in dummy behaviour between the two possible phases during an emergency evacuation. The main differences between the two are the magnitude and duration of the accelerations (and therefore also the maximal CAR values and included energy in the pulses) which are in general higher/longer for the re-entry pulses than for first water impact. As such, these higher and longer pulses can be considered the primary cause of more severe dummy model behaviour and therefore also in a more severe injury response for the re-entry pulses.
4. Although all injury responses might be below their lower limits for first water impact, the risk of injuries during a re-entry phase is much higher. Regardless of the restraint system (2- or 4-point belt system) the simulated re-entry scenarios result in very high injury values for both driver and occupants. Therefore it is advised to assure that the probability of severe re-entry loads occurring is reduced as much as possible.

The kinematic images in Figure 23 in Annex B show examples of dummy behaviour for re-entry loads.

Structural Assessment of Extreme Re-entry Loads

A structural assessment of severe re-entry loads was also performed for two boats; 'Boat F' and 'Boat G'. The given loads are six times the static weight of the boat and the pulses have typical durations between 0.6 and 1.2 seconds.

These re-entry loads are treated as quasi-static and equally distributed at the front and aft hooks on the boat. The elements around the hook areas are refined in the re-entry model. The hooks are represented in the model by a combination of increased thickness of the shell elements and a rigid link up to the wire connection. The rigid link is connected to the shell elements at the bolt locations.

The analyses were performed in NX I-DEAS.

<u>Results for 'Boat F'</u>

The re-entry simulation of 'Boat F' shows that large areas in the front and aft of the boat will experience severe stresses above the laminate's capacity. The results show that the boat will have laminate or rip-out failure mode if it is subjected to maximum re-entry load as applied in the analysis. It is not possible to predict which area that fails first. The failure mode is dependent on the first failure.

Rip-out may occur if the shear stress around the hook fastening is above the laminate capacity. Laminate failure in the surrounding areas may occur if the shear stress is above the capacity.

The hook is fastened to the boat with steel plates and bolts. An analytical calculation is performed with an assumption that the re-entry force is completely taken by the horizontal plate at the hook box. With an equally distributed load around the steel plate, this will give a shear stress of 18.62 MPa in the laminate. The transverse shear capacity in the laminate is 26.2 MPa.

The analytical calculations show that the shear stress is within the shear capacity of the laminate for the given ideal load condition. However, this load condition with the evenly distributed load is not likely to occur. It is not possible to predict which failure mode that takes place first without doing a progressive failure analysis.

Results for 'Boat G'

The re-entry analyses for 'Boat G' also used a load of six times the weight of the boat. This extreme re-entry load case gives stress levels near the global capacity of the boat. The analysis shows two areas in some distance away from the hook foundation which have high stress levels. This may be due to local or global buckling. The analysis also shows high utilization near the fore and aft hook foundation. Excess capacity may be present in these areas since the FE model is somewhat coarse.

Sail-away Phase

Simulation of Propulsion and Sail-away

Simulations of the sail-away phase have been performed to assess the positive headway of a typical lifeboat under various conditions. A Monte Carlo approach was applied in the simulations since the wave elevation and wind speed were random variables. 100 simulations were carried out for each set of conditions (lowering height, wind speed, etc.). One single wave or wind train was used for the 100 simulations. Randomness was ensured by selecting 100 random time instants in the range 0–3600 s. These time instants represent start times for lowering the lifeboat, so that the boat lands in 100 different locations in the wave train.

The simulation of lifeboat sail-away starts with lifeboat lowering. For all simulations a full lifeboat was considered using a lowering height of 22 m and lowering speed of 0.9 m/s.

Irregular wave trains were generated from JONSWAP sea spectra using wave height, period and gamma factor from Table 11. Long-crested waves were used. A Picard estimate of the nonlinear pressure term was used in the computation of wave elevation. Wave kinematics was computed from the elevation. Infinite water depth was used.

Table 11 Overview of sea states and wind speeds included in simulations.

Beaufort force	Mean wind speed at 10 m	Significant wave height	Wave peak period	Gamma factor	Average steepness (S_p)
5	10 m/s	2 m	5 s	5.0	1/20
6	13 m/s	3 m	6 s	5.0	1/19
7	16 m/s	4 m	7 s	5.0	1/19
8	19 m/s	5 m	8 s	5.0	1/20
9	22 m/s	6 m	9 s	4.6	1/21
10	26 m/s	8 m	11 s	3.6	1/24
11	31 m/s	11 m	13 s	3.5	1/24

The thrust used in the simulations was 0.3, 0.5 and 0.8 tonnes. These numbers correspond roughly to a small motor (27/29 hp) a medium motor (70 hp) and a larger motor (100 hp). The lifeboat was a generic lifeboat for 70 persons with a total weight of 9 tonnes.

Figure 15 shows a screen capture of a sail-away simulation. The two lines from the bow represent the boat heading and the desired course.

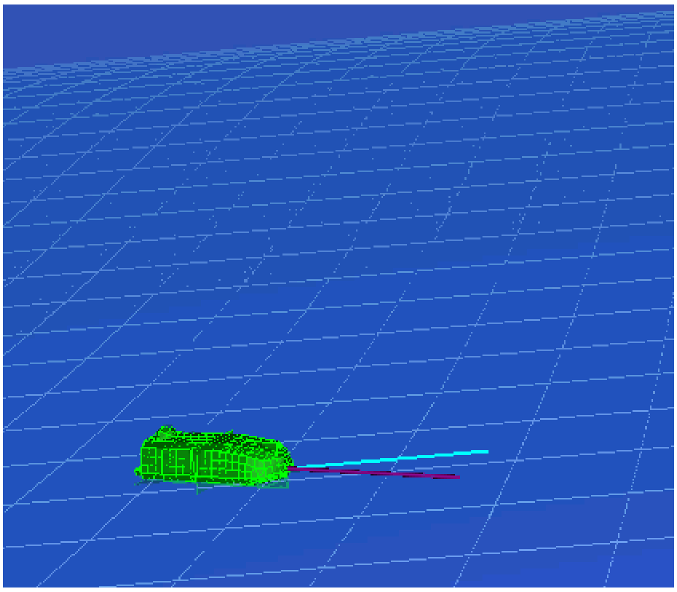


Figure 15 Screen capture of sail-away simulation.

In order to account for rudder action, a constant force was applied at the bow of the lifeboat, and this force was always pointing along the desired course. This force would, when the boat is off course, generate a yaw moment that steered the boat towards the desired course, similar to a rudder, see Figure 16. This resembles a control system with proportional control only (P controller). In the simulations 30% of the available thrust was used as steering 'rudder force' while the remaining 70% was used as 'thrust'. This simplified controller caused a relative large steady state course error for rough weather conditions. Typically, in a more sophisticated control system steady state error is reduced by increasing the proportional gain, or more effectively by introducing an integral term in the controller. In some of the lifeboat trajectories the steady state course error was increasing with increasing wind. The steady state error is a weakness of the control system. It does not mean that the lifeboat is incapable of holding the course.

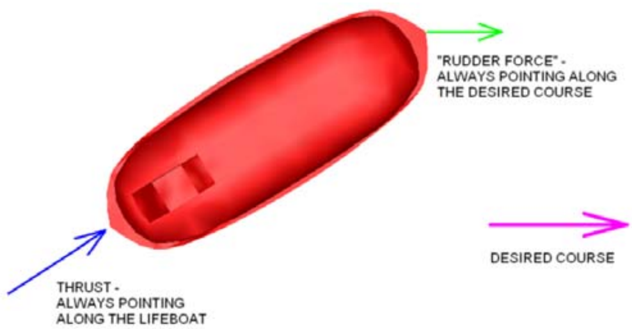


Figure 16 Rudder model.

The main focus for this study was to investigate the performance of the lifeboat in the first few seconds after landing as the set-back is a key parameter for successful evacuation. The simplified control system is considered adequate for this.

For the sail-away simulations environmental conditions corresponding to a Beaufort range of 5 to 11 have been considered. There were 2800 basic simulations (100 simulations for each Beaufort condition and direction), which were carried out to establish start conditions for the sail-away simulations. An entire simulation from start of lowering to end of sail-away was split up in a basic simulation and a sub-simulation. The basic simulation represents the part from lowering to water entry, while the sub-simulation represents the part from water entry to end of simulation. In general there were multiple sub-simulations for each basic simulation. This way it was ensured that the each sub-simulation got identical start conditions. This is beneficial when comparing the effect of parameters like thrust and course; Identical start conditions make comparison easier. Multiple sub-simulations were carried out by first carrying out a basic simulation up to the time instant of water entry. Then, the simulation was "saved" so that it could be re-started again. One run was re-started several times with different run parameters (e.g. thrust, course, etc.). Basic simulation parameters and sub-simulation parameters are given in Table 12 and Table 13.

There are three important events that are defined for each simulation:

1. Water entry: This is the time instant when the boat origin becomes submerged. When this happens the wind yaw moment acting on the boat is reduced to 80% of the in-air value. (Surge and sway wind force is automatically reduced since the submerged portion of the drag plate model does not attract wind forces.)
2. Release: This is the time instant when the wire falls are deactivated in the simulation. Also, the time step is changed from 0.01 seconds to 0.05 seconds.
3. Propulsion: This is the time instant when the thrust is applied in the simulation.

In addition, there is an important time instant which is found during post-processing of the lifeboat trajectories. This is the time instant when the lifeboat is in the most "critical" position. The algorithm used for finding the most critical position is given in the following (see Figure 17):

1. Remove the parts of the trajectory which have *y*-coordinate greater than +50 m and less than -50 m from target drop point (border indicated with red, dotted lines).
2. Remove the parts of the trajectory which have *x*-coordinate greater than +100 m from target drop point (border indicated with red, dotted line).
3. In the trajectory enclosed by red dotted lines, find the position with greatest *x*-values and mark this time instant as critical (cross markings in the figure).

The above algorithm allows the lifeboat to move outside the borders of a 100 m x 100 m "installation" without reporting the position as critical.

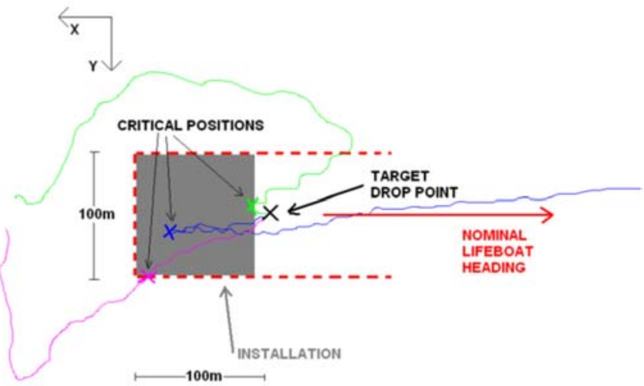


Figure 17 Definition of critical positions. Trajectories outside red, dotted lines are discarded when finding critical position.

Table 12 Run parameters for the basic sail-away simulations.

Run number	Beaufort force	Wind direction*	Number of basic simulations	Sub-simulations	Total number of simulations
30000-30699	5, 6, 7, 8, 9, 10 and 11	175	700	a, b, c, d, e, f and g	4900
30700-31399	5, 6, 7, 8, 9, 10 and 11	135	700	a, b, c, d and e	3500
31400-32099	5, 6, 7, 8, 9, 10 and 11	90	700	a, b, c, d and e	3500
32100-32799	5, 6, 7, 8, 9, 10 and 11	45	700	a	700

Notes:
* 0 deg is following sea, 90 deg is beam sea to starboard and 180 deg is head sea

Table 13 Run parameters for the sail-away sub-simulations.

Sub-run	Desired course relative to nominal lifeboat heading	Thrust	Time from water entry to release	Time from entry to propulsion
a	Straight ahead	0.3 tonnes	3 s	5 s
b	Straight ahead	0.5 tonnes	3 s	5 s
c	Straight ahead	0.8 tonnes	3 s	5 s
d	45 degrees port	0.5 tonnes	3 s	5 s
e	Straight ahead	0.5 tonnes	0.1 s	0.2 s
f	Straight ahead	0.3 tonnes	3 s	0.3 s
g	Straight ahead	0.5 tonnes	3 s	0.5 s

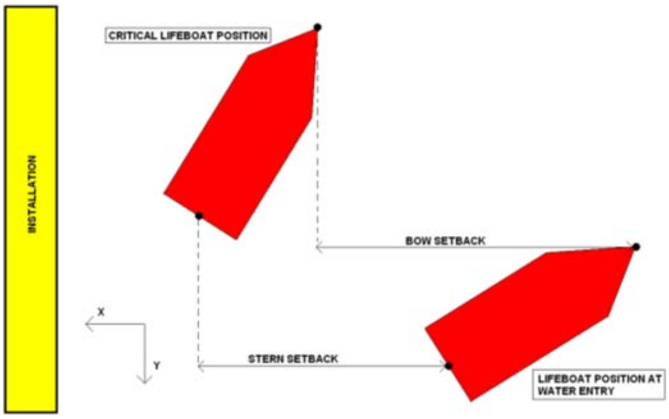


Figure 18 Definition of setback.

A full set of results are given in the report on for the sail-away simulations, Ref. /9/. The main results are presented in Figure 19 and Figure 20. These graphs are based on data points with rank 91 from the cumulative distribution plots. These data points are estimators for the 90% probability of non-exceedance (91/101=90%).

The main conclusions drawn from the sail-away simulations are:

1. The setback in head waves may be substantial even in moderate weather conditions (BF 7).
2. In moderate weather conditions, propulsion should be engaged as soon as possible to prevent large setback.
3. In moderate weather conditions, the setback is sensitive to when propulsion is engaged, and not so sensitive to engine size.
4. In heavy weather conditions the setback is sensitive to motor size and not so sensitive to when propulsion is engaged.
5. In bow quartering waves, the setback is smaller than in head waves.
6. In beam waves and stern quartering waves the setback is small.
7. With a medium sized motor (70 hp) and quick engagement of propulsion the risk of collision is dramatically reduced compared to a small motor (29 hp) and delayed propulsion.

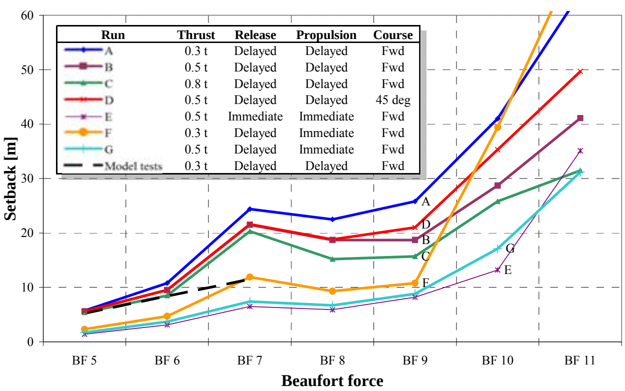


Figure 19 Set-back in <u>head sea</u> (90th percentiles) vs. Beaufort force. Dotted line is based on results from Candian model tests, Ref. /25/.

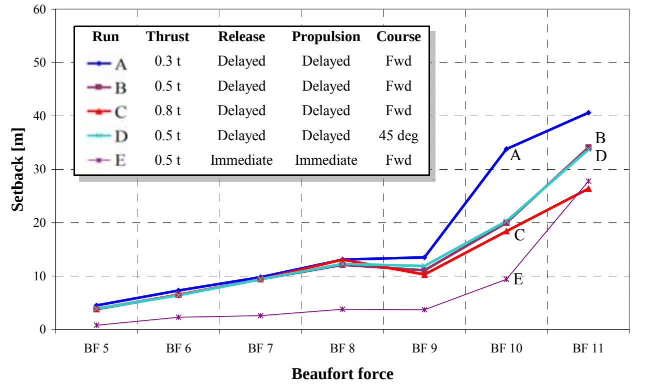


Figure 20 Set-back in <u>bow quartering sea</u> (90th percentiles) vs. Beaufort force.

Recommended Procedure for Test Run of Lifeboat Engines

One finding in the NSA-LAP project was that there were differences in how the owners performed test runs of lifeboat engines. The objective of this study was therefore to establish a common procedure for how to test run lifeboat engines. This activity therefore involved reviewed relevant regulations and data provided from lifeboat user manuals, existing test procedures from lifeboat owners and the NSA-LAP Design report, Ref. /26/. A meeting was held with lifeboat owners and engine producers, and some additional inquiries were made.

Figure 21 Typical lifeboat engine

From the considerations made, it is concluded that testing of lifeboat engine (and also of the sub systems) is important to ensure that full power will be delivered in an evacuation scenario.

It is concluded that the optimal interval for testing is every second week.

It should be noted that floating rigs are obliged to follow SOLAS-regulations (Ref. /6/) according to the Life Saving Regulation (Ref. /7/). The SOLAS-regulation states that weekly test runs of engine are imperative. The work-meeting concluded that test run every second week is a better alternative, given that all idle-running of the lifeboat engine will cause soothing that may impair the engines maximum output. However, as long as no changes are made in the regulations weekly test runs should be performed. In any case, idle running time should not exceed 3 minutes.

Fixed installations, not bound by the SOLAS regulation, should follow the recommendation of test running every second week.

Conclusions

The main conclusions drawn from the project for each of the four phases are:

Lowering phase:

1. A lowering speed of around 1.0 m/s is recommended.
2. Implementation of 'pull & go' launching of davit-launched lifeboats is recommended.

Water entry phase:

3. There is a minor risk of injury to lifeboat occupants during water entry. The largest risk occurs in beam sea conditions, mainly related to high loads on head and neck.
4. The CAR index can only be used to obtain a very rough indication of the injury level to be expected. For a detailed injury risk prediction numerical simulations are required.
5. Structural reinforcements of hull and canopy should be evaluated to improve hull slamming capacities.

Release phase:

6. Severe re-entry loads should be avoided by either ensuring rapid release of wire falls, or in other ways preventing high accelerations. Such loads may cause serious injuries on lifeboat occupants and damages to the lifeboat.
7. Development of release systems is required to provide equipment which fulfils the requirements of NORSOK R-002.

Sail-away phase:

8. The setback of conventional lifeboats in head sea and bow quartering sea may be substantial. Care should be taken when launching lifeboats in head sea or in bow quartering sea in severe weather. This is in particular important for offshore units where the clearance is limited by jacket legs or bracings.
9. The setback during launching may be reduced by optimising the bollard pull and the launching procedure.

Other:

10. The findings from this project should be implemented in coxswain training programs.
11. Idle running of lifeboat engines should not exceed 3 minutes to prevent soothing. The optimal interval for engine test runs is every second week.

Acknowledgements

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ANNEX A – Sample result plots and tabular data from lowering simulations

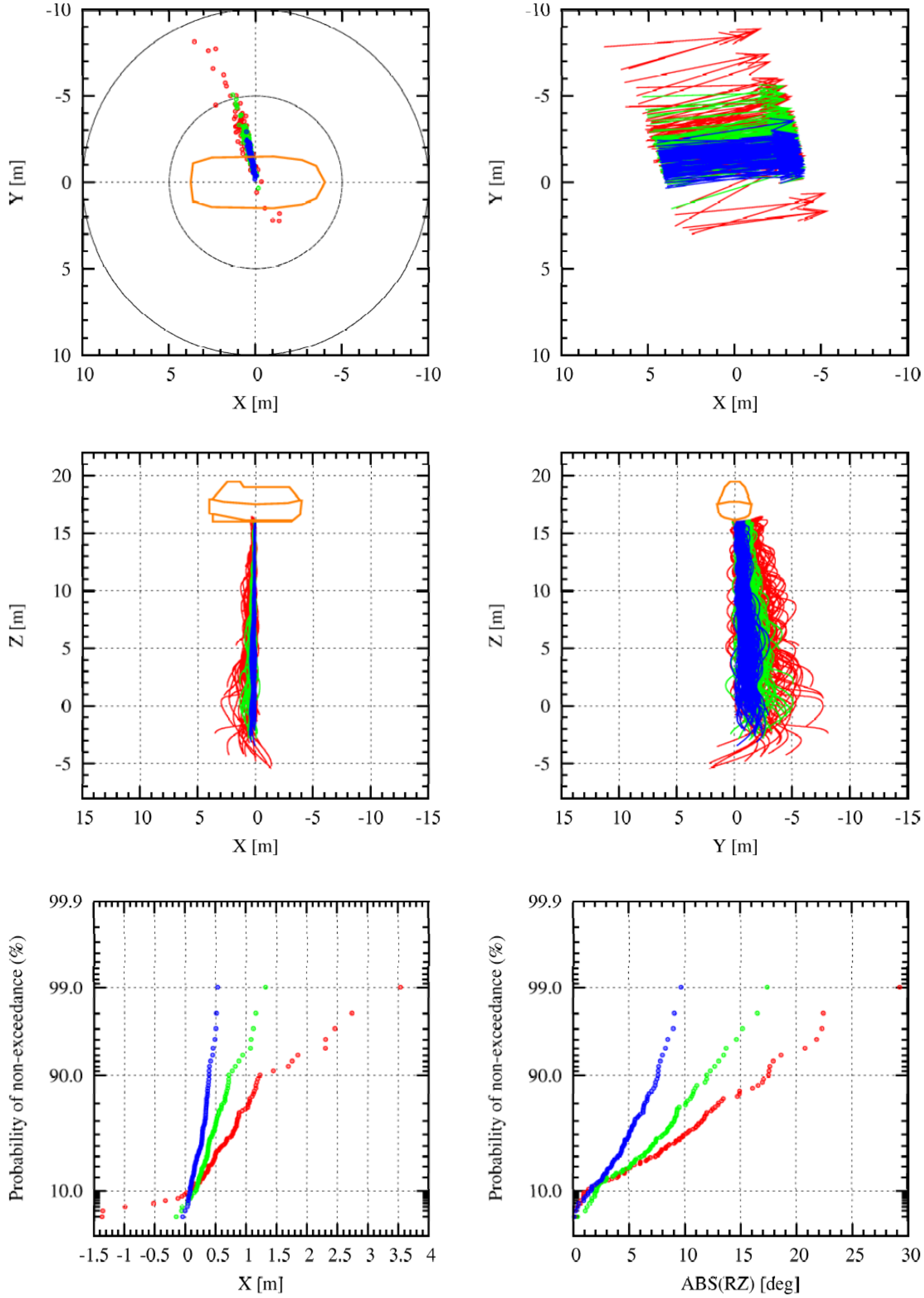

Figure 22 Example of plots from lowering simulations; 'Boat B', fully loaded, 22 m lowering height, 0.9 m/s lowering speed, bow quartering wind; BLUE = BF 10, GREEN = BF 11, RED = BF 12.

Table 14 90th percentile positional and heading offsets during lifeboat launch in head wind
BLUE = BF 10 (26 m/s), GREEN = BF 11 (31 m/s), RED = BF 12 (37 m/s).

Loading condition	Lowering height	Lowering speed	X-offset at landing			Y-offset at landing			Heading offset at landing		
Full boat	22 m	0.5 m/s	0.3 m	0.5 m	0.8 m	-0.3 m	-0.5 m	-0.8 m	2°	2°	3°
		0.9 m/s	0.3 m	0.4 m	0.6 m	-0.3 m	-0.4 m	-0.7 m	1°	2°	4°
		1.5 m/s	0.3 m	0.5 m	0.6 m	-0.3 m	-0.5 m	-0.7 m	1°	2°	4°
	50 m	0.5 m/s	0.9 m	1.4 m	3.6 m	-1.1 m	-2.0 m	-6.3 m	5°	12°	27°
		0.9 m/s	0.8 m	1.4 m	4.5 m	-1.0 m	-2.1 m	-6.7 m	5°	9°	25°
		1.5 m/s	0.7 m	1.0 m	3.3 m	-0.8 m	-1.5 m	-6.0 m	5°	8°	24°
	80 m	0.5 m/s	2.3 m	8.7 m	20.6 m	-3.5 m	-10.5 m	-11.4 m	16°	45°	88°
		0.9 m/s	1.7 m	4.4 m	19.2 m	-2.7 m	-6.6 m	-14.8 m	12°	43°	80°
		1.5 m/s	1.6 m	4.2 m	19.4 m	-2.7 m	-5.5 m	-10.9 m	11°	29°	73°
Empty boat	22 m	0.9 m/s	0.6 m	0.9 m	2.6 m	-0.8 m	-1.2 m	-4.6 m	3°	6°	15°
	80 m	0.9 m/s	22.5 m	27.9 m	27.3 m	-12.1 m	-14.0 m	-18.8 m	74°	110°	154°

Table 15 90th percentile positional and heading offsets during lifeboat launch in bow quartering wind
BLUE = BF 10 (26 m/s), GREEN = BF 11 (31 m/s), RED = BF 12 (37 m/s).

Loading condition	Lowering height	Lowering speed	X-offset at landing			Y-offset at landing			Heading offset at landing		
Full boat	22 m	0.5 m/s	0.4 m	0.9 m	1.2 m	-2.3 m	-3.7 m	-4.4 m	9°	15°	18°
		0.9 m/s	0.4 m	0.7 m	1.2 m	-2.1 m	-3.2 m	-4.6 m	8°	12°	18°
		1.5 m/s	0.4 m	0.6 m	1.2 m	-2.2 m	-2.9 m	-4.2 m	8°	11°	17°
	50 m	0.5 m/s	2.2 m	4.7 m	9.0 m	-6.4 m	-10.1 m	-14.2 m	21°	31°	46°
		0.9 m/s	2.2 m	3.6 m	7.6 m	-5.7 m	-8.8 m	-12.4 m	21°	29°	39°
		1.5 m/s	1.6 m	3.5 m	6.3 m	-4.8 m	-8.0 m	-11.1 m	18°	28°	35°
	80 m	0.5 m/s	5.7 m	7.0 m	16.9 m	-11.6 m	-11.8 m	-18.3 m	35°	48°	90°
		0.9 m/s	4.5 m	6.9 m	17.7 m	-9.9 m	-13.7 m	-20.9 m	30°	42°	58°
		1.5 m/s	3.8 m	6.4 m	12.6 m	-9.0 m	-12.2 m	-17.2 m	29°	34°	46°
Empty boat	22 m	0.9 m/s	1.6 m	2.6 m	5.8 m	-5.3 m	-6.9 m	-9.5 m	18°	22°	30°
	80 m	0.9 m/s	14.4 m	20.1 m	29.8 m	-19.3 m	-22.2 m	-25.9 m	54°	100°	150°

Table 16 90th percentile positional and heading offsets during lifeboat launch in beam wind
BLUE = BF 10 (26 m/s), GREEN = BF 11 (31 m/s), RED = BF 12 (37 m/s).

Loading condition	Lowering height	Lowering speed	X-offset at landing			Y-offset at landing			Heading offset at landing		
Full boat	22 m	0.5 m/s	0.0 m	0.0 m	0.0 m	-3.1 m	-4.1 m	-6.6 m	0°	0°	0°
		0.9 m/s	0.0 m	0.0 m	0.0 m	-2.8 m	-4.5 m	-6.2 m	0°	0°	0°
		1.5 m/s	0.0 m	0.0 m	0.0 m	-2.9 m	-3.7 m	-5.8 m	0°	0°	0°
	50 m	0.5 m/s	0.0 m	0.0 m	0.0 m	-8.0 m	-11.6 m	-17.0 m	0°	0°	0°
		0.9 m/s	0.0 m	0.0 m	0.0 m	-6.8 m	-10.8 m	-15.0 m	0°	0°	0°
		1.5 m/s	0.0 m	0.0 m	0.0 m	-6.6 m	-9.0 m	-14.0 m	0°	0°	0°
	80 m	0.5 m/s	0.0 m	0.0 m	0.0 m	-13.2 m	-15.3 m	-29.2 m	0°	0°	0°
		0.9 m/s	0.0 m	0.0 m	0.0 m	-13.1 m	-15.4 m	-25.6 m	0°	0°	0°
		1.5 m/s	0.0 m	0.0 m	0.0 m	-9.8 m	-16.0 m	-22.3 m	0°	0°	0°
Empty boat	22 m	0.9 m/s	0.0 m	0.0 m	0.0 m	-6.1 m	-8.7 m	-12.3 m	0°	0°	0°
	80 m	0.9 m/s	0.0 m	0.0 m	0.0 m	-24.0 m	-30.5 m	-37.5 m	0°	0°	0°

ANNEX B – Sample motion sequence plots and acceleration pulse plot for extreme re-entry simulations

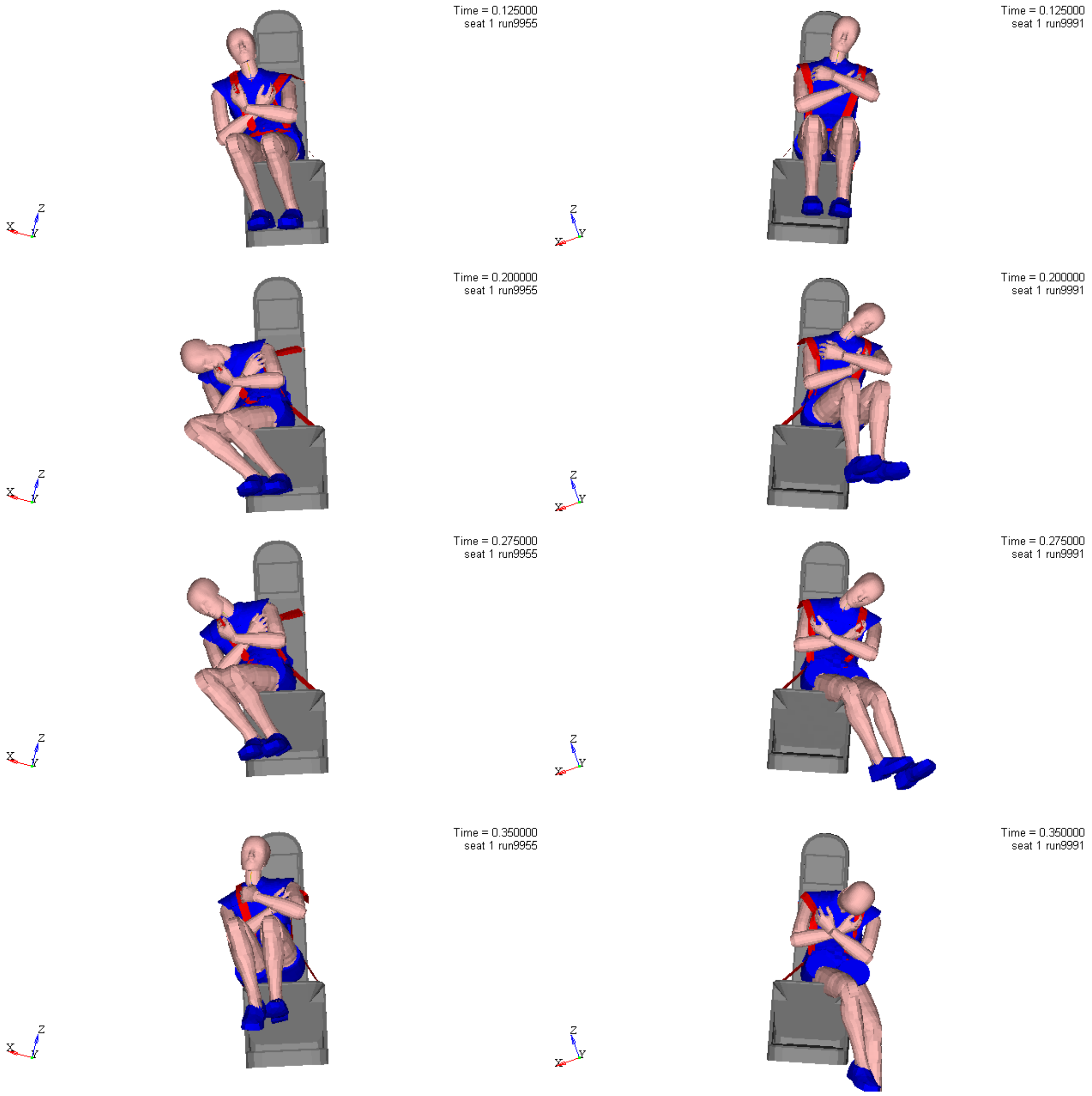

Figure 23 Example of motion sequence in an extreme re-entry pulse of seat 1 for following sea (run9955) and head sea (run9991) at 125, 200, 275 and 350 ms.

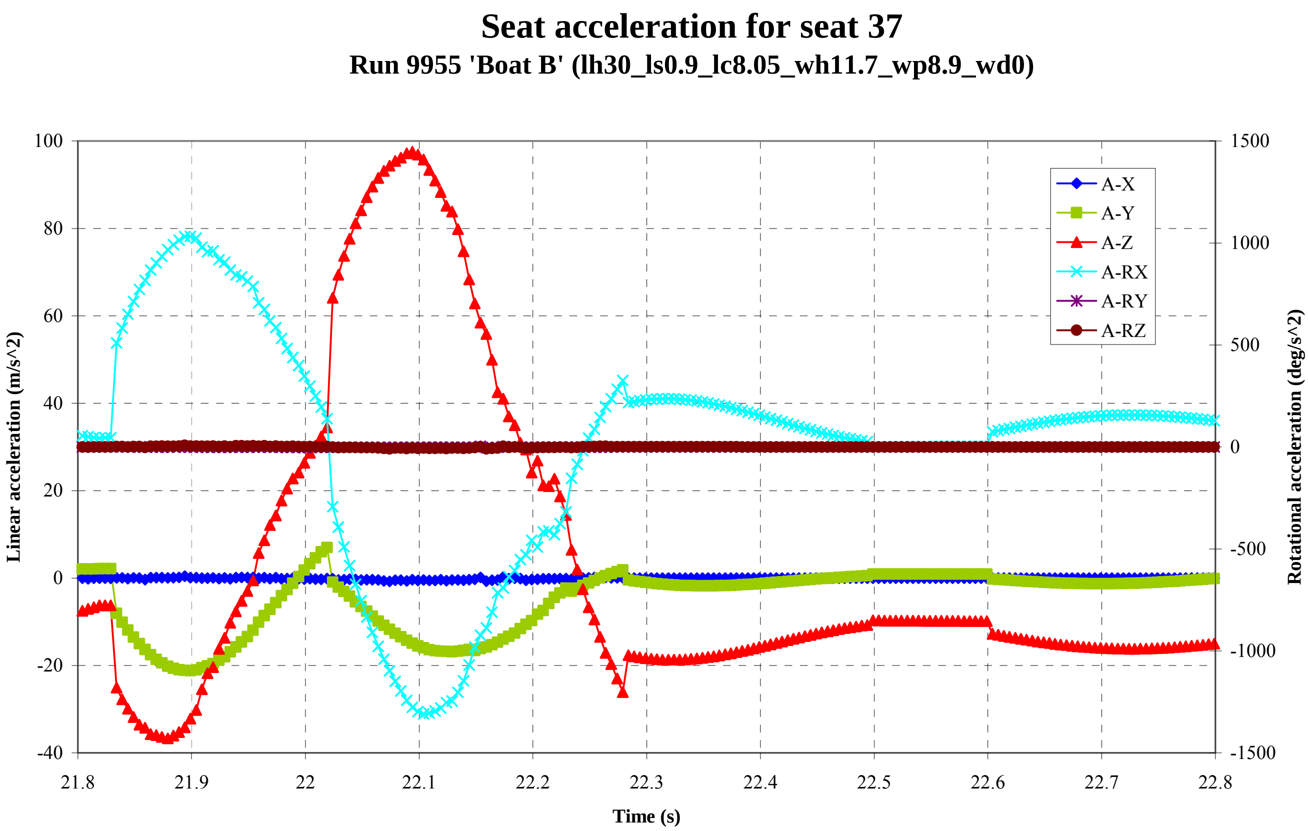

Figure 24 Re-entry example: Seat accelerations for seat 37, run 9955; 0.9 m/s lowering speed, wave height 11.7 m, wave period 8.9 sec, following sea.

Annex C – Tabular setback results

Table 17 Setback in head sea (90th percentiles) for various combinations of thrust, courses and sea states.

Run	Thrust	Release	Propulsion	Course	BF 5	BF 6	BF 7	BF 8	BF 9	BF 10	BF 11
a)	0.3 t	Delayed	Delayed	Fwd	5.7 m	10.8 m	24.4 m	22.5 m	25.8 m	41.0 m	64.1 m
b)	0.5 t	Delayed	Delayed	Fwd	5.6 m	9.5 m	21.5 m	18.7 m	18.7 m	28.7 m	41.1 m
c)	0.8 t	Delayed	Delayed	Fwd	5.4 m	8.5 m	20.3 m	15.2 m	15.7 m	25.8 m	31.5 m
d)	0.5 t	Delayed	Delayed	45 deg	5.6 m	9.5 m	21.6 m	18.8 m	21.0 m	35.3 m	49.7 m
e)	0.5 t	Immediate	Immediate	Fwd	1.4 m	3.1 m	6.5 m	5.9 m	8.2 m	13.2 m	35.1 m
f)	0.3 t	Delayed	Immediate	Fwd	2.3 m	4.7 m	11.9 m	9.3 m	10.8 m	39.4 m	72.2 m
g)	0.5 t	Delayed	Immediate	Fwd	1.7 m	3.7 m	7.4 m	6.7 m	8.8 m	17.1 m	31.2 m

Table 18 Setback in bow quartering sea (90th percentiles) for various combinations of thrust, courses and sea states.

Run	Thrust	Release	Propulsion	Course	BF 5	BF 6	BF 7	BF 8	BF 9	BF 10	BF 11
a)	0.3 t	Delayed	Delayed	Fwd	4.5 m	7.3 m	9.8 m	13.1 m	13.5 m	33.8 m	40.6 m
b)	0.5 t	Delayed	Delayed	Fwd	3.9 m	6.5 m	9.4 m	12.1 m	11.1 m	20.0 m	34.1 m
c)	0.8 t	Delayed	Delayed	Fwd	3.8 m	6.5 m	9.4 m	13.1 m	10.3 m	18.4 m	26.4 m
d)	0.5 t	Delayed	Delayed	45 deg	3.9 m	6.4 m	9.4 m	12.3 m	11.9 m	20.3 m	33.7 m
e)	0.5 t	Immediate	Immediate	Fwd	0.8 m	2.3 m	2.6 m	3.8 m	3.7 m	9.4 m	27.8 m

Table 19 Setback in beam sea (90th percentiles) for various combinations of thrust, courses and sea states.

Run	Thrust	Release	Propulsion	Course	BF 5	BF 6	BF 7	BF 8	BF 9	BF 10	BF 11
a)	0.3 t	Delayed	Delayed	Fwd	0.0 m	0.1 m	0.1 m	0.1 m	0.3 m	1.2 m	6.8 m
b)	0.5 t	Delayed	Delayed	Fwd	0.0 m	0.1 m	0.1 m	0.1 m	0.2 m	0.8 m	5.9 m
c)	0.8 t	Delayed	Delayed	Fwd	0.0 m	0.1 m	0.1 m	0.1 m	0.2 m	0.8 m	5.3 m
d)	0.5 t	Delayed	Delayed	45 deg	0.0 m	0.1 m	0.1 m	0.1 m	0.2 m	0.8 m	5.9 m
e)	0.5 t	Immediate	Immediate	Fwd	0.0 m	0.0 m	0.0 m	0.0 m	0.0 m	0.0 m	0.0 m

Table 20 Setback in stern quartering sea (90th percentiles).

Run	Thrust	Release	Propulsion	Course	BF 5	BF 6	BF 7	BF 8	BF 9	BF 10	BF 11
a)	0.3 t	Delayed	Delayed	Fwd	1.8 m	2.8 m	3.2 m	3.1 m	4.3 m	4.3 m	2.8 m

Annex D – Tabular overview of simulations

Phase(s)	Scope of work / Objective	Description of parameters	Number of simulations / Software
Lowering/release	Effect of delayed release and lowering speed on slamming, wire loads and CAR index	Two boats: 'A' and 'B' Two lowering heights: 28 and 80 m Three lowering speeds: 0.5, 0.9 and 1.5 m/s Five directions: from stern to bow Six representative regular waves: 7.5, 10, 13, 15, 18 and 20 m Ten hit points per wave	3600 / MOSES
	Study of pendulum and heading offset effects as function of lowering height and total weight	One boat: 'B' – full and nearly empty Three lowering heights: 22, 50 and 80 m Three wind speeds: 26, 31 and 37 m/s Three wind directions: 175, 135 and 90 degrees 100 repetitions (different points in time)	9900 /MOSES
Water entry	Establish peak accelerations	Five boats: 'A', 'B', 'C', 'D' and 'E' Seven representative waves: 8.5, 11.7, 14.7, 16.0, 17.0, 17.8 and 20.3 m Five directions: from stern to bow Two lowering speeds: 0.9 and 1.5 m/s Ten hit points per wave Six seats per boat	3500 (yields 21000 acceleration pulses) / MOSES
	Evaluation of hull slamming capacities	Boat 'F': Three waves: H1=17 m, T1=10.4 s H2=20.3 m, T2=13.7 s H3=16 m, T3=12.3 s Five directions: from stern to bow Boat 'G': One wave: H3=16 m, T3=12.3 s Five wave directions: from stern to bow	20 CFD analyses / Star-CCM+ 40 structural analyses / NX I-DEAS
	Biomechanical parameter study: belt systems, postures	One boat: 'A' Six seats Two acceleration pulses Thirteen configurations	156 / MADYMO
	Interaction between occupants with 2-point belt systems	One boat: 'B' Three configurations: opposite, back-to-back and side-by-side Two combinations of either free or locked joints Three wave directions: following sea, beam sea and stern quartering sea One lowering speed: 1.5 m/s	18 / MADYMO
	Boat specific numerical simulations	Three boats: 'A', 'B' and 'C' Seven representative waves: 8.5, 11.7, 14.7, 16.0, 17.0, 17.8 and 20.3 m Five directions: from stern to bow Two lowering speeds: 0.9 and 1.5 m/s One hit point per wave Six seats per boat	1260 / MADYMO
	Comparison of numerical simulations of dummy model and human models	Three body sizes: 5th percentile female (small female), dummy size male (50th percentile male) and Hercules size (about 99th percentile male) Three seats Three wave heights: 8.5, 14.7 and 20.3 m One wave direction: beam sea One lowering speed: 1.5 m/s	27 / MADYMO
Release	Establish re-entry accelerations for use in biomechanical simulations	One boat, five directions, one lowering speed (0.9 m/s), two waves (11.7 m and 20.3 m), six seats	5 (30 acceleration pulses) / MOSES
	Structural analysis of extreme re-entry forces on hull	Two boats: 'G' and 'F' One load	2 / NX I-DEAS
	Study of injury potential of extreme re-entry loads	Six different seats Two belt systems: 2- and 4-point Five acceleration pulses/wave directions: following sea, stern quartering sea, beam sea, bow quartering sea and head sea	55 / MADYMO
Sail-away	Simulation of setback and propulsion in a range of sea states	One boat: Simplified 'Boat B' Seven sea states: BF 5, 6, 7, 8, 9, 10 and 11 Four weather directions: 175, 135, 90 and 45 degrees Three bollard pulls: 0.3, 0.5 and 0.8 tonnes Two times to release: 3 and 0.1 s Two times to propulsion: 0.5 and 5 s	12600 / MOSES