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Consequence analyses of collision-damaged ships — damage stability, structural adequacy and oil spills

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ABSTRACT
A ship collision accident may pose a threat to human lives, the environment and material assets. A damaged ship can suffer from the loss of ship stability, reduced global structural strength, and the loss of the integrity of internal tanks carrying polluting liquids. This study presents a methodology as a framework that can be used to analyze the related consequences of ship-ship collision events using simulations and evaluations. The methodology includes nonlinear finite element analyses of the collision event, a METOCEAN data analysis module, damage stability simulations, analyses of the damaged ship's ultimate strength and structural integrity, oil spill drift simulations, and finally, an evaluation of the three abovementioned consequences. A case study with a chemical tanker subjected to collision demonstrates the methodology. The collision event was assumed to occur in the Kattegat area (between Sweden and Denmark) at a ship route intersection with high ship traffic density.

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Consequence analysis; ship collision; damage stability; ultimate strength; oil spill

Nomenclature

Greek notations

η	Structural adequacy [-]
θ	Roll angle [deg]
κ_L	Labour utilisation [hours]
Φ	Edge function [-]

Latin notations

a_{roll}	Acceleration of roll motions [m/s^2]
a_y	Lateral acceleration [m/s^2]
B	Breadth [m]
c	Hourly operating costs [USD/hour]
C	Structural capacity to withstand bending moment [Nm]
C_{cargo}	Cargo loss cost [USD]
C_{DT}	Downtime cost [USD/day]
C_{pr}	Pollution response operation cost [USD]
C_{repair}	Repair cost [USD]
$C_{repair,direct}$	Direct repair cost [USD]
C_{rt}	Recovery trip cost [USD]
$C_{salvage}$	Salvage operation cost [USD]
C_{SAR}	Search and Rescue operation cost [USD]
C_{ship}	Ship loss cost [USD]
C_{social}	Social cost [USD]
D	Bending moment demand [Nm]
d_R	Vertical distance from the ship's rotation centre to the navigation deck [m]
d_{site}	Travel distance between coast station and vessel in distress [nm]
DWL	Design water level [m]
DWT	Deadweight [tonnes]
g	Acceleration of gravity [m/s^2]
GDP	Gross domestic product [USD/person]
H_S	Significant wave height [m]
$ICAF$	Optimum acceptable implied cost of averting a fatality [USD/person]
KG	Vertical centre of gravity [m]
LCG	Longitudinal centre of gravity [m]
L_E	Life expectancy [years]
LOA	Length overall [m]
LPP	Length between perpendiculars [m]
LQI	Life quality index [-]
M_H	Horizontal bending moment [Nm]
M_V	Vertical bending moment [Nm]
N_{crew}	Number of crew members [person]
P_d	Ship price decrease rate [USD/year]
P_{DT}	Downtime cost [USD/day]
P_{labor}	Labour price [USD/hour]
P_{oil}	Oil price [USD/barrel]
P_{ship}	Economic value of a ship [USD]
$P_{ship,new}$	New-built price of a ship [USD]
Q_{oil}	Amount of oil spilled [tonnes]
q_{or}	Oil recovery capacity [m^3/hour]
RMS	Root mean square
S	Number of fatalities [persons]
T	Draft [m]
T_{age}	Ship's age [years]
T_p	Peak period [s]
t_{aware}	Awareness time [hours]
t_m	Time required for mooring [hours]
t_{pr}	Pollution response operation time [hours]
t_{repair}	Repair time [days]
t_{rescue}	Time required to rescue one person [hours]
v	Speed [knots]
V_{oil}	Volume of spilled oil [m^3]
V_{ot}	Recovered oil tank capacity [m^3]
w	Proportion of life spent in economic activity [-]

Abbreviations

3D	Three-dimensional
ELS	Elastic Limit State
FEA	Finite Element Analysis
RoPax	Roll-on/Roll-off Passenger Vessel
RoRo	Roll-on/Roll-off Cargo vessel
SAR	Search and Rescue

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SCG Swedish Coast Guard
SGISc Second Generation Stability Criteria
ULS Ultimate Limit State

1. Introduction

Statistics from EMSA (2021) and JTSB (2022) show that ship-ship collisions, contacts and grounding/stranding are the dominating events among maritime accidents worldwide and represents more than 50% of casualty events to cargo ships. Most of these accidents originate from navigation errors or loss of power and maneuverability. The consequences are often injured humans, loss of human lives, loss of property, cargo and ships, and pollution from oil or other liquid cargo spills into the ocean environment. While research and development aim to propose mitigation actions that reduce the occurrence of these accidents, methods and models will always be needed that can recommend prevention and response planning, e.g. rescue operations of crew and passengers, salvage operations of damaged ships, and actions that can minimise harmful pollutions and negative impact on the environment.

There are three major categories that can define severe consequences for a collision-damaged ship (EMSA 2021): exceedance of the ultimate strength, loss of stability, and spillage of hazardous cargo and liquid transported by the damaged ship. Each of them can result in the negative consequences mentioned earlier — to various extents for different ship types — and the sum of their effects is obviously greater than their individual effects. Thus, consequence analysis of ship-ship collisions and groundings should incorporate all three categories.

The residual ultimate strength of collision-damaged ships has been studied by, e.g. Fujikubo et al. (2012), Kuznecovs et al. (2020), Paik (2018) and Parunov et al. (2020). The shape, size and location of the structural damage govern the ultimate limit state (ULS) capacity, as well as the age of the vessel, i.e. the remaining corrosion margin. Kuznecovs and Ringsberg (2021) presented a 3D ultimate-strength-capacity method that accounts for a change in capacity along the length of a ship, the remaining corrosion margin and a damage opening in the hull if the ship has been involved in a collision accident. This method includes the effect of waves on the section forces and the changes in the mass distribution of the damaged ship that result from either the outflow of cargo or the inflow of seawater. Ćorak and Parunov (2020) presented a structural reliability analysis of an Aframax oil tanker damaged in collision and exposed to combined bending moments. The study emphasises the structural response and variation of section forces due to wave actions, but the influence of outflow of oil or inflow of seawater is not incorporated. Their method presents a histogram of safety indices for many collision scenarios using one case study ship and several sea state conditions. The method was found to have practical use for maritime authorities, as it can be used in performance assessments of damaged ships for salvage operations, e.g. tankers, containers, and cargo ships.

The stability of ships with damaged hull structures was studied by Schreuder et al. (2011) and Spanos and Papanikolaou (2014). Both studies targeted ship types where flooding accidents can lead to loss of the ship within a short time after flooding initiation, e.g. RoPax and RoRo ships. The numerical simulations present how the time to capsize is affected by the sea state conditions and the wave encounter direction. The methods have practical use, as they can be used to analyze and propose the most effective operational and design measures that lead to improved survivability of a damaged ship and to enhance the safety of the people onboard. De Vos et al. (2020) studied damage stability requirements for autonomous ships based on equivalent safety. It was found that because of the absence of people on board, the associated safety measures can result in a more efficient design, but amendments in the existing regulatory framework may be needed.

The concern for the negative environmental consequences of oil outflow from collision-damaged or grounded tankers has been studied by a large number of researchers. Tavakoli et al. (2011, 2012) presented numerical models that were validated by experiments on oil leakage from damaged ships due to collision and grounding. The models allowed for different opening shapes and sizes in the inner and outer hull structure, and the physics with couplings between (i) inflow of seawater and outflow of oil related to filling grade of oil in the cargo tank, (ii) the ballast water condition in the ballast tanks, (iii) and positions of the damages with reference to the sea water level. Wang et al. (2016) continued the work by Tavakoli et al. (2012) and proposed a method that calculates the coefficient of discharge, an important parameter for initial estimation of flooding rate, for different damage opening shapes and sizes with flat and petalled orifice plates. Kollo et al. (2017) refined the hydraulic modelling proposed by Tavakoli et al. (2012) and integrated it in an oil outflow assessment tool presented in Tabri et al. (2018), where the pollution response of grounded tankers was studied. Lu et al. (2019) studied the effectiveness of oil spill recovery using a Bayesian network model, where the Seatrack Web tool (Ambjörn et al. 2014) was used to simulate the oil drift to estimate the consequences of oil spills. The methods and models presented in these studies have practical use, especially the Accidental Damage and Spill Assessment Model (ADSAM, 2022) presented in Tabri et al. (2018). It was developed to provide rapid assistance to the strategic planning of response to oil spills.

Depending on the ship types involved in an accident, the severity of the three categories of consequences (exceedance of the ultimate strength, loss of stability, and spillage of hazardous cargo and liquid transported by the damaged ship) will vary as well as how they can be mitigated. Intuitively, collision-damaged RoPax and tanker vessels have different proportions of consequences, and therefore, the outcome of their consequence analyses, e.g. monetary terms, is different. This study presents a methodology as a framework for the consequence analysis of collision-damaged ships independent of the ship type. The three previously mentioned categories of consequences are evaluated by calculating the damaged ship's structural adequacy, damage stability conditions, and environmental impact from oil spills and drift. Section 2 presents the methodology and the numerical codes used herein, followed by a description of the consequences and how they are analyzed. Section 4 presents a case study that demonstrates the methodology. The results of the case study are presented in Section 5, followed by the conclusions in Section 6.

2. Methodology

The methodology and an overview of the simulation procedure are outlined in Figure 1. The ships involved in the collision accident must first undergo a finite element analysis (FEA) of the accident. The calculated shape, size and location of the damage opening in the struck vessel are transferred to the damage stability and structural integrity analyses. A METOCEAN analysis module is integrated into the methodology, which is based on probability analyses of the metocean conditions at the geographical location of the accident. The output from the metocean analysis is used as input to the ship stability simulations. The environmental impact simulations of oil spills and drift are

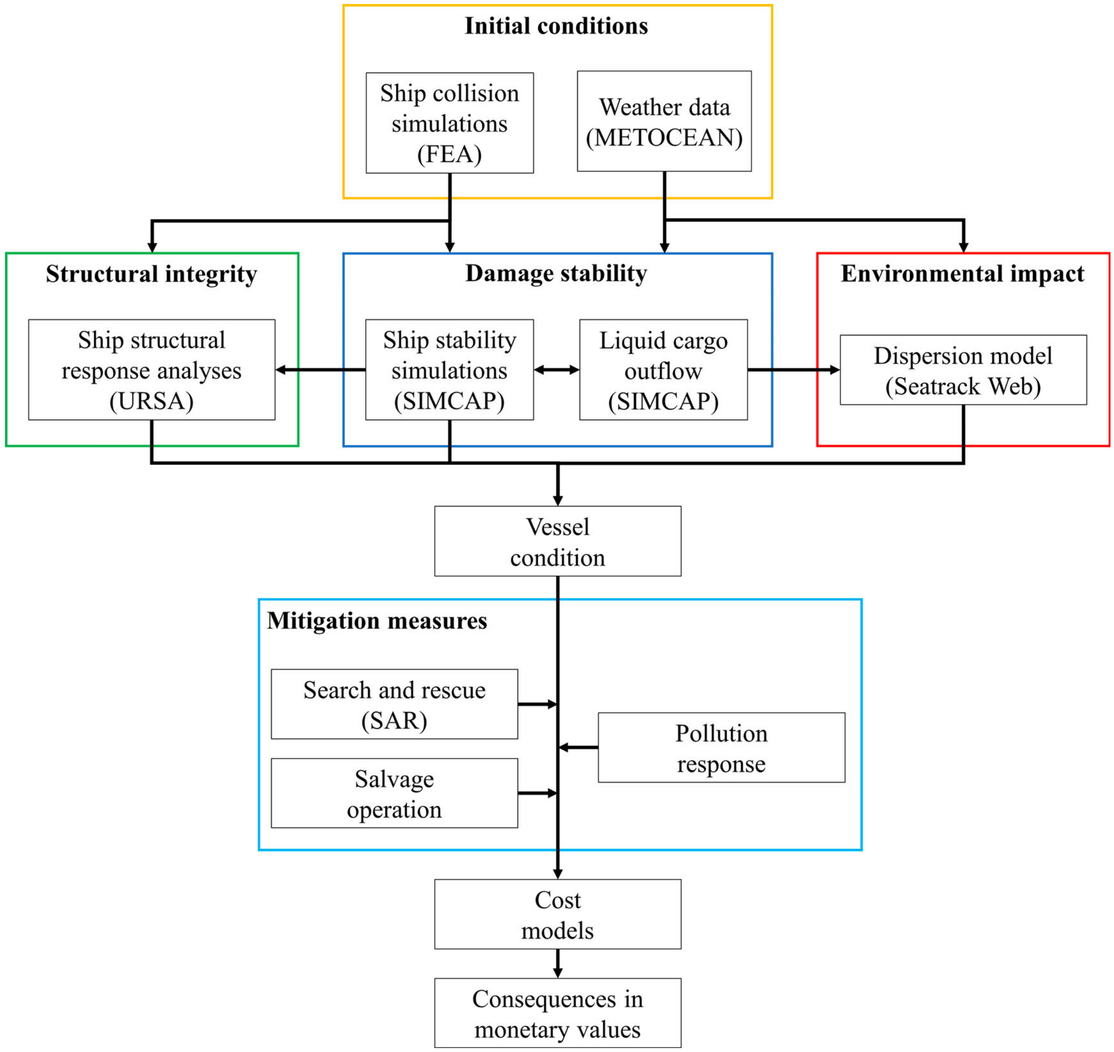

Figure 1. A schematic of the methodology (This figure is available in colour online.)

based on the calculated oil outflow from the damage stability simulations.

From the structural integrity, damage stability and oil outflow analysis results, the severity of the collision accident is evaluated with respect to various limit states, and the actual vessel condition is determined. Based on the condition of a vessel that is operational, with impaired operability, abandoned, or foundered, relevant consequences, mitigation measures and associated costs are estimated.

The study is limited to consequence analyses of struck ships, which are often more severely damaged than striking ships. The current version of the methodology is not rapid enough to be used as a tool that can assist in, e.g. rescue or salvage operations. Its current purpose is the analysis of proactive measures by analyzing plausible collision events and locations and by that means to increase the awareness of the three consequences to see if the preparedness both onshore and on ships is sufficient when it needs to be activated. This knowledge can be important for future and safer marine traffic planning in dense ship traffic areas. The results from the methodology are of practical use for the crew on ships since they may indicate possible measures to mitigate the consequences.

The following subsections present a brief description of the modules and codes that form the methodology: nonlinear FEA of the collision accident, metocean analysis in METOCEAN, damage stability simulations in SIMCAP, structural integrity analysis in URSA, environmental impact simulations in Seatrack Web, and finally, a module where the consequences are assessed and compared.

2.1. FEA: simulation of ship-ship collision events

The collision event is defined by the analyst who designs and generates the geometry and FE models of the ships involved in the collision. All parameters that normally define a collision event should be specified by the analyst, e.g. the ships' speeds, draughts, heading directions, and location of impact on the struck ship. After that, the simulation setup can be defined based on justified assumptions and limitations.

In the current study, hull damage due to ship collision was obtained by running nonlinear explicit FE simulations using the commercial software Abaqus/Explicit (DSS 2022). The modelling and simulation procedures that should be carried out are well documented in the literature; see Kuznecovs et al. (2020) and Ringsberg et al. (2018) for details referring to the authors' previous work and detailed descriptions. The results from the FEA are transferred to the other modules and codes in the methodology. The shape, size and location of the damage opening must be calculated with sufficiently high accuracy since they affect all following simulations, e.g. the damage stability

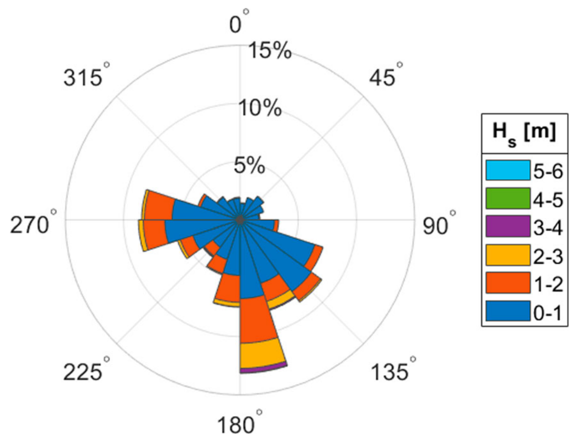

Figure 2. A rose plot of the probability of significant wave heights H_S for different sectors of wave directions for the location of the case study collision site; see the text for details (This figure is available in colour online.)

calculations; see Hogström and Ringsberg (2012) for an example. In the structural integrity analysis in URSA, information about the hull opening, the plastically deformed structure, and the degree of plastic deformation is needed to perform the structural adequacy analysis.

2.2. METOCEAN: identification and analysis of plausible metocean conditions

Since one of the purposes of the methodology is that it should be used as a prevention measure to reduce negative consequences from ship-ship collisions, a METOCEAN conditions analysis module is integrated to identify plausible sea state conditions at the geographical location specified by the analyst. The METOCEAN module is an in-house code that collects and post-processes historical metocean conditions at a given geographic location by retrieving time-variant wave data from Copernicus Marine Service (CMEMS, 2022). The analyst can study monthly, seasonal, and annual statistics at the specified latitude and longitude. The code presents statistics and probabilities of the wave directions, significant wave heights, and ocean current directions and magnitudes. The intervals/ranges of these properties are defined and plotted for visualisation in rose plots. Figure 2 presents an example of the probability of the significant wave height for different intervals of wave directions. The struck ship is in the centre, and the sectors indicate which direction the waves are coming from. The results are plotted for latitude 57.61° and longitude 11.51° in Kattegat (between Sweden and Denmark) and are based on metocean statistics for the spring season between 2016 and 2020; the 0°-direction represents geographic north.

The METOCEAN module is used to identify the sea state conditions that should be simulated in the SIMCAP code for the damage stability assessment (see Figure 1). It should be emphasised that the choice of the studied sea state also has a direct coupling to the ship's structural response through the URSA code. It interacts with the SIMCAP code through, among others, the section forces in a coupled time-variant ship motion-structural response procedure.

2.3. SIMCAP: simulation of ship motions, damage stability and oil spill

SIMCAP is a code developed by Schreuder (2014) for dynamic ship stability simulations for both intact and damaged conditions. SIMCAP can be used to simulate, analyze and obtain the motion responses to incident waves, section hydrodynamic forces along the hull and change in total mass distribution caused by interexchange of outboard water and liquid cargo through an eventual damage opening.

This code can be used directly to evaluate a damaged ship's stability conditions, e.g. the roll motions of the ship and how they change due to flooding and acting waves. The time-varying section hydrodynamic forces along the hull and the change in total mass distribution (see above) are coupled to the URSA code in a sequentially coupled approach. By doing so, the structural response assessment and the hull's structural adequacy account for the change in section forces due to the ship's motions and change in mass distribution. This coupling is highly relevant for the consequence analysis of the damaged ship's structural integrity. To get representative results of ship motions and damage stability especially in case of extreme events, multiple realizations of irregular waves should be considered. However, in this study for the purpose of showcasing the framework, a single realisation of irregular waves for stability simulations was considered as sufficient and direct assessment of threshold values' exceedance (see below) was employed.

For simulation cases where liquid cargo outflows from the damaged compartments, the SIMCAP code can provide results such as total outflow volume and rate. The transient oil outflow model implemented in SIMCAP is based on Bernoulli's principle and was validated against the tests carried out by Tavakoli et al. (2011). The liquid interexchange model considers compartment arrangement, liquid types (e.g. oil cargo and outboard seawater) and pressure gradients including the effect from acting waves. This information can be used in the proposed methodology using Seatrack Web in the environmental impact assessment; see Section 2.5 and Figure 1.

The vessel conditions and limit states with respect to stability are defined using criteria representing various severity levels. The vessel's safe operation is assumed to be impaired if the RMS value of lateral accelerations a_y at the highest point on board the ship with crew exceeds the operational limit for merchant vessels of $0.12\,g$ (NORDFORSK 1987). The lateral acceleration a_y is found according to Equation (1) (DNV GL 2020), where g is the acceleration of gravity, θ is the roll angle, a_{roll} is the directly measured acceleration of roll motions in SIMCAP, and d_R is the vertical distance from the ship's rotation centre to the navigation deck.

$$a_y = -g \cdot sin\theta + a_{roll} \cdot d_R \tag{1}$$

Considering the requirements for the direct stability assessment procedures specified in the Second Generation Intact Stability criteria (IMO 2020), the stability failure event is defined when either lateral acceleration of 9.81 m/s^2 or critical roll angle of 40° are exceeded at least once during simulation. Requirements associated with the angles of vanishing stability in calm water or submergence of unprotected openings of an intact ship are neglected, since these values will no longer be of relevance after a collision damage is introduced. If any of the stability failure criteria are met at any step of a SIMCAP simulation, it is assumed that the ship's crew is endangered, and the vessel has been abandoned. Moreover, the vessel is considered foundered if capsized. The time to capsize is also available in SIMCAP for the following consequence analysis for estimation of the time available to rescue the crew. All criteria defining the stability limit states are summarised in Table 1.

Table 1. Summary of hazard criteria and associated vessel conditions.

		Criteria		
Vessel condition	Hazards	Structural	Stability	Environmental
Foundered	Hull collapse	$\eta = 0$		
	Capsize		$90° < \theta$	
Abandoned	Severe local damage	$0 < \eta \leq 0.8$		
	Excessive accelerations 2		$g \leq a_y$	
	Critical roll angle		$40° \leq \theta$	
Impaired operation	Significant local damage	$0.8 < \eta < 1.0$		
	Excessive accelerations 1		$0.12\ g \leq RMS(a_y)$	
	Oil discharge			$0 < Q_{oil}$
Operational	Minor local damage	$\eta = 1.0$		

2.4. URSA: simulation of structural response and assessment of structural adequacy

URSA is an in-house code developed for rapid and accurate ultimate and residual strength assessment of intact/damaged hull girders. It has been developed and verified against FE simulations in Kuznecovs (2020). In URSA, the demand is computed as a longitudinal distribution of shear forces and bending moments for each time step of the SIMCAP simulation (Kuznecovs et al. 2021). The demand is compared against the longitudinally varying biaxial bending capacity of the structure represented by one 3D elastic limit state surface and one 3D ultimate limit state surface (Kuznecovs and Ringsberg 2021); see Figure 3. Through this comparison, URSA evaluates the safety level and integrity of the structure for SIMCAP-simulated ship motions and dynamic conditions.

The structural integrity of a collision-damaged hull is assessed in terms of the structural adequacy η (Paik 2018), which characterises the capability of a hull structure to withstand still water and wave-induced biaxial bending moments. Here, the procedure for the calculation of the structural adequacy proposed in Kuznecovs and Ringsberg (2021) was modified so that $\eta = 1$ represents the

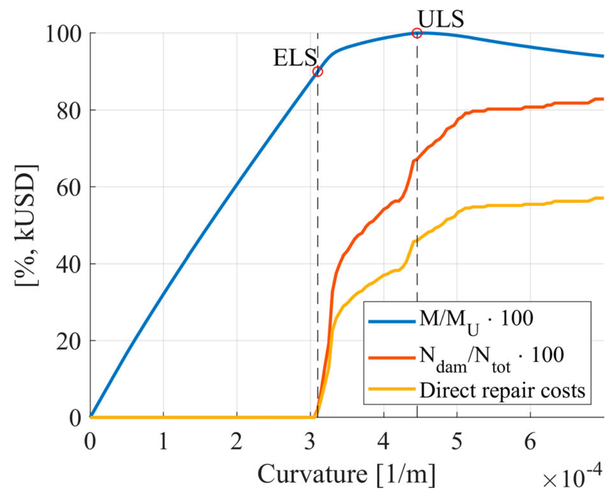

Figure 4. Bending curvature-moment curve with indication of ELS ($\eta = 1$) and ULS ($\eta = 0$), failure progress as a proportion of the structural members that have collapsed and associated direct repair costs (This figure is available in colour online.)

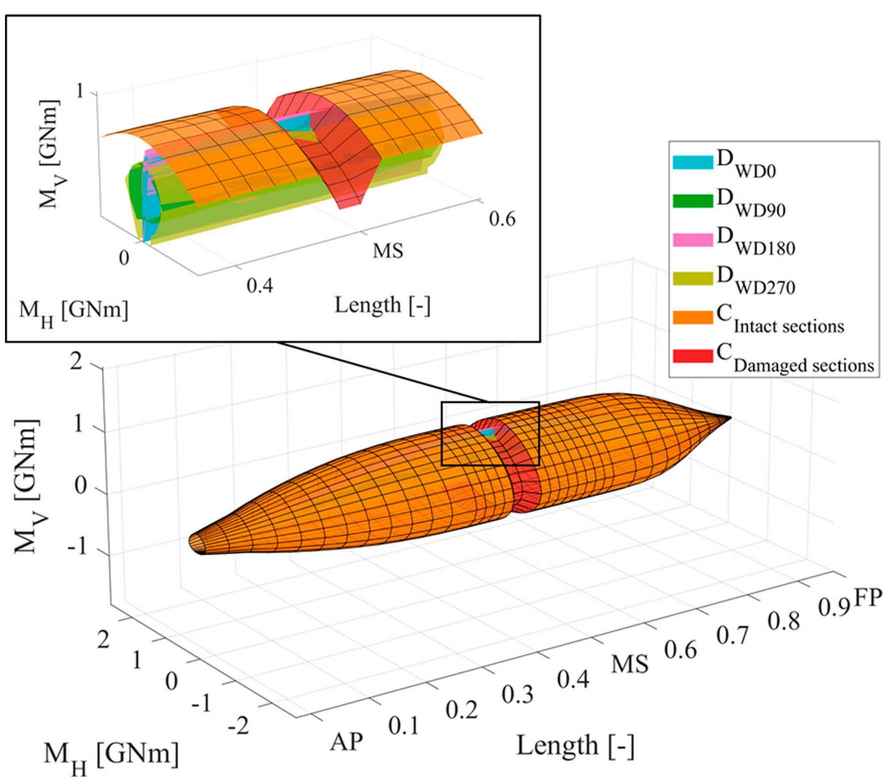

Figure 3. Example of ultimate capacity surface *C* and bending load demands *D* for different sea states from Kuznecovs and Ringsberg (2021) (This figure is available in colour online.)

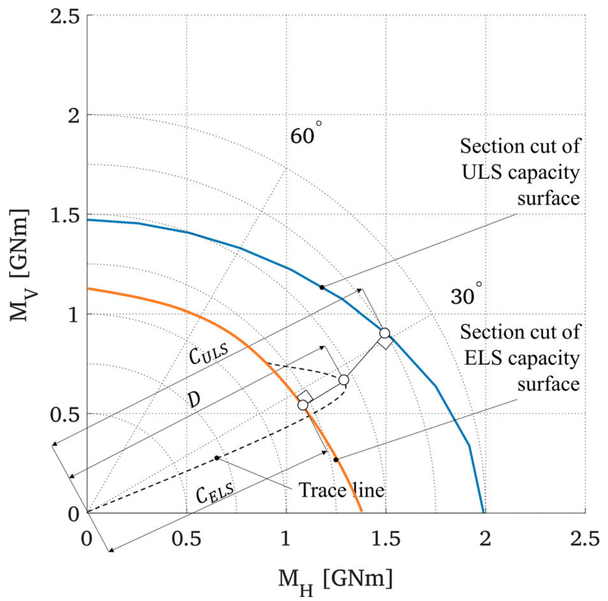

Figure 5. Definition of the demand *D* and capacity *C* values (This figure is available in colour online.)

proportional limit of the bending curvature-moment curve or elastic limit state (ELS) that depicts the hull condition just before irreversible local collapse of the structural members due to bending-induced stresses (see Figure 4). The value $\eta = 0$ reflects the total collapse of the hull when its ULS is reached. Structural adequacy values between 1 and 0 indicate intermediate states with different levels of local damage due to progressive collapse caused by bending.

The formal definition of the modified structural adequacy parameter is given by Equation (2), where D is the biaxial bending load demand, C_{ELS} and C_{ULS} are the elastic and ultimate hull bending load bearing capacities, respectively, and Φ is the edge function. The demand and capacities are evaluated at various section cuts of the 3D elastic and ultimate limit state surfaces (see Figure 5), and the structural adequacy of a ship for certain loading conditions is represented by the lowest η value among all sections.

$$\eta = \Phi(C_{ULS},\ D)\left(1 - \Phi(D,\ C_{ELS})\left(\frac{D - C_{ELS}}{C_{ULS} - C_{ELS}}\right)\right) \tag{2}$$

$$\Phi(x, y) = \begin{cases} 0{:}x < y \\ 1{:}x \geq y \end{cases}$$

The vessel condition with respect to its structural adequacy is defined according to Table 1. If $\eta = 1$, the damage due to collision is considered minor, and further operation of the vessel for certain weather conditions is safe. The ship's further operation is considered to be impaired due to significant local damage if η is in the range between 0.8 and 1. The hull structure is at high risk of reaching its ULS if $\eta < 0.8$, and the ship must be abandoned. In the worst-case scenario, if there is no structural adequacy left and $\eta = 0$, the ship is assumed to be totally lost due to hull collapse.

2.5. Seatrack Web: simulation of oil spills and drifting of oil

Ambjörn et al. (2014) developed the Seatrack Web tool (SMHI, 2022) for the simulation and assessment of oil spills and drift. The oil drift model is a Lagrangian particle-spreading model where the substance or object being simulated is represented as a cloud of particles. The trajectory of each particle is calculated based on time- and space-varying flow fields. Particles are affected by boundaries such as the coastline, the bottom or the sea surface. Forecasted flow and wind fields force substances or objects to move and spread. At present, the area covered by Seatrack Web is the Baltic Sea, the straits between Sweden and Denmark, the Kattegat and the Skagerrak, and the North Sea to approximately longitude 3° east.

Tabri et al. (2018) integrated Seatrack Web in the ADSAM tool. In the current study, however, it is run as a stand-alone tool where the total amount of oil spilled Q_{oil} from the collision event is approximated by SIMCAP. If a collision accident resulted in an oil spillage and $Q_{oil} > 0$, the struck vessel's operability was assumed to be impaired (see Table 1). In Seatrack Web, the analyst defines the discharge date and time, discharge outlet depth, discharge location (latitude and longitude), the duration for the simulation, the type of oil being discharged, and the volume and duration of the discharge. METOCEAN forecast models determine the oil drift trajectory. Examples of results from a simulation are the percentage of the total outflow of oil that ends up on the sea floor, floats on the sea surface, or reaches the coastline. One simulation takes only a few minutes, which makes the tool suitable for parameter studies and rapid consequence analyses of environmental impacts from oil spills.

3. Consequence analyses

Negative consequences from ship collision accidents can be related to oil spills, insufficient damage stability, structural adequacy, or a combination of these. These consequences may pose threats to the crew and passengers, the environment and material assets. To provide common means for comparison purposes, all consequences are assessed in monetary values. The consequence costs are assumed to depend on the post-accident vessel condition, and the cost components are defined through scenarios associated with the respective condition according to Table 2. Therefore, the final costs vary with the severity of the collision accident's consequences.

The overall oil spill costs comprise response-, socioeconomic- and environmental damage-based costs (Etkin 2004). In the current study and methodology, only the events and operations that arise due to the discharge of oil to sea waters along with the impact measure and financial loss incurred due to non-reusable oil after clean-up are considered. The remaining parts of the oil spill costs will be addressed in the future development of the methodology.

3.1. Social costs

The social burden of an accident is depicted by the costs of injuries and losses of human lives associated with the accident. For

Table 2. Cost components associated with the respective vessel condition.

					Mitigation measures		
Vessel condition	Social	Repair	Ship loss	Cargo loss	SAR	Salvage	Pollution response
Foundered	X		X	X	X		X
Abandoned	X	X		X	X	X	X
Impaired operation	X	X		X		X	X
Operational	X	X					

Table 3. Severity of accidents, their effects on ships and humans according to (IMO 2018) and the respective vessel conditions assigned in the study.

Vessel condition	Accident severity	Effects on ship	Effects on humans	Equivalent number of fatalities, S
Foundered	Catastrophic	Total loss	Multiple fatalities	10
Abandoned	Severe	Severe damage	Single fatality or multiple severe injuries	1
Impaired operation	Significant	Non-severe damage	Multiple or severe injuries	0.1
Operational	Minor	Local equipment damage	Single or minor injuries	0.01

Table 4. Direct repair cost components (Rahman and Caldwell 1995).

Cost, [USD]	Description	Formula
C_{plate}	Cost of materials for plating	$W_p P_{steel}$
C_{stiff}	Cost of materials for stiffeners	$(W_{ls}C_{lm} + W_{tf}C_{fm})P_{steel}$
C_{weld}	Cost of welding for stiffeners	$(lC_{ls} + sC_{wf})P_{labor}$
$C_{intersect}$	Cost of intersections between longitudinal stiffeners and transverse frames and preparation of brackets and joints	$(C_{is} + C_{bj})P_{labor}$
$C_{electric}$	Cost of electricity, electrodes, and fabrication cost of longitudinal stiffeners	$lC_{ee}P_{labor}$

simultaneous consideration of both injuries and loss of lives, the equivalent fatality concept (IMO 2018) is adopted, according to which 1 fatality equals 10 severe injuries or 100 minor injuries. The equivalent number of fatalities S depends on the severity of an accident and its consequences (see Table 3).

In Equation (3), the social cost of an accident C_{social} is defined as the equivalent number of fatalities S times the optimum acceptable implied cost of averting a fatality $ICAF$ (Skjong and Ronold, 1998). $ICAF$ is a threshold measure based on the life quality index (LQI) and depends on the gross domestic product per person per year GDP, life expectancy L_E and the proportion of life spent in economic activity w; see Equation (4). Economic activity w is defined as the ratio between labour utilisation κ_L (expressed in hours worked per capita population) and the total number of hours in one year.

$$C_{social} = S \cdot ICAF \tag{3}$$

$$ICAF = \frac{GDP \cdot L_E}{4} \cdot \frac{(1-w)}{w} \tag{4}$$

3.2. Repair costs

Repair costs are assumed to consist of direct repair, $C_{repair,direct}$, and indirect downtime, C_{DT}, costs associated with construction and the loss of earnings during the repair period, respectively.

$$C_{repair} = C_{repair,direct} + C_{DT} \tag{5}$$

3.2.1. Direct repair costs

The direct repair costs of the hull structural elements damaged either in collision or during excessive bending loads are estimated with the cost method proposed by Rahman and Caldwell (1995). Structural elements damaged by collision are identified by comparing the intact and damaged structures directly after impact. Additional structural members collapsed during the bending loads either in compression or tension were recorded during the ULS analyses. The total direct repair cost $C_{repair,\ direct}$ is then the sum of the repair costs of all damaged elements given by Equation (6). A description of the direct repair cost components is provided in Table 4. The cost parameters used in the model were adopted from Rigterink et al. (2013) and are given in Table 5.

Table 5. Direct repair cost model parameters (Rigterink et al. 2013).

Coefficient	Description	Value
W_p	Weight of plate [tonnes]	–
P_a	Material price [USD/tonne]	700
W_{ls}	Weight of longitudinal stiffeners [tonnes]	–
C_{lm}	Increase in cost of prefabricated longitudinal stiffeners [-]	1.25
W_{tf}	Weight of transverse stiffeners [tonnes]	–
C_{fm}	Increase in cost of prefabricated transverse stiffeners [-]	1.4
l	Transverse stiffener spacing [mm]	–
C_{ls}	Labour required for welding longitudinal stiffeners to plate [hr/mm]	0.0024
s	Longitudinal stiffener spacing [mm]	–
C_{wf}	Labour required for welding transverse stiffeners to plate [hr/mm]	0.0024
P_s	Labour price [USD/hr]	27
C_{is}	Labour required for welding longitudinals to transverses [hr]	1.15
C_{bj}	Labour required connecting longitudinals to transverses [hr]	0.6
C_{ee}	Labour-equivalent cost for welding supplies and consumables [hr/mm]	0.0009

$$C_{repair,direct} = \sum_{i=1}^{N_{dam}} C_{plate} + C_{stiff} + C_{weld} + C_{intersect} + C_{electric} \tag{6}$$

3.2.2. Downtime costs

In addition to the direct costs, the repair of a vessel involves indirect costs associated with the downtime and lost economic revenue during the repair; see Equation (7). The economic losses or downtime cost P_{DT} per day the damaged vessel is idle are estimated based on the ship's deadweight (COWI 2008) in prices for 2007 and with an applied annual inflation rate of 3%. To provide a common means of comparison between collision impact and bending-induced damage, the time required for repair is estimated according to the total mass of all structural elements requiring replacement. The relation between mass and repair time t_{repair}, presented in Table 6, was estimated from a comparison of damaged areas (COWI 2008) and the masses of corresponding damaged elements for different collision scenarios presented in Kuznecovs et al. (2021).

$$C_{DT} = P_{DT} t_{repair} \tag{7}$$

3.3. Ship loss cost

If the ship has foundered, it is assumed that its total economic value, P_{ship}, is lost and will constitute the cost associated with ship loss, C_{ship}. The economic value of a ship is considered to be time-dependent and decreasing from the newly built price $P_{ship,new}$ with the vessel's age T_{age} at a rate P_d; see Equation (8). This simple linear relation is applied to reveal situations when owners of old and badly maintained vessels may be less willing to stand the costs related to salvage, rescue, and other mitigation measures. Indirect costs associated with ship loss, such as loss of

Table 6. Repair time as a function of damaged structural elements' total mass.

Total mass of structural elements to be replaced [tonnes]	< 0.5	0.5–5.0	5.0–10.0	> 10.0
Repair time, t_{repair} [days]	2	7	14	21

earnings, reputational losses, etc. are disregarded in the current methodology.

$$C_{ship} = P_{ship} = P_{ship,new} - P_d T_{age} \tag{8}$$

3.4. Cargo loss cost

If the collision impact resulted in breach of watertight integrity of cargo tanks, oil leakage is of concern. This implies extra costs for the ship contractor in terms of lost cargo that depend on the volume of spilled oil V_{oil} and its price per barrel P_{oil} on the market; see Equation (9). For the special case of a lost ship, the amount of cargo lost is assumed to be equal to the deadweight of the foundered vessel.

$$C_{cargo} = 7.33 P_{oil} V_{oil} \tag{9}$$

3.5. Mitigation measures

In the current study, search and rescue (SAR), and salvage and pollution response operations are considered active mitigation measures to reduce consequences associated with a collision accident. The operations are assumed to be coordinated by the Swedish Coast Guard (SCG) and that all available and suitable assets based on the closest SCG coast station are involved. The list of available assets and their technical specifications at the Gothenburg coast station (Kustbevakningen 2021) are presented in Table 7. The awareness time t_{aware}, i.e. the time required for decision making and preparation of an asset before starting the mitigation operation is taken as 0.5 h.

The presented mitigation measure examples are designed in cooperation with and for the SCG and include their level of detail and actions to prevent impacts to the marine environment due to an oil spill. Consequently, a computed monetary value defines the consequence 'oil spill' in the study.

3.5.1. Search and rescue (SAR)

A SAR operation is required when it is no longer safe for the crew of a ship involved in an accident to stay aboard, which corresponds to abandoned and foundered vessel conditions (see Table 7). The SCG assets involved in the SAR operation are the combination vessel KBV001 and the surveillance aircraft KBV500, which is active during the whole operation time.

The total cost for a search and rescue operation C_{SAR} is based on the sum of costs associated with the operation duration time that depends on the awareness time t_{aware}, the travel distance d_{site} between the closest coast station and a vessel in distress, speed of the vessel v, the time required to rescue one person t_{rescue} and the number of crew members N_{crew} of the abandoned ship. In this study, it was assumed to take 0.25 h to take one crew member aboard the rescue vessel. The total cost is then hourly costs c_{KBV001} and c_{KBV500} of the rescue vessel and the aircraft involved in the operation, respectively, times the total operation time (see Equation (10)).

$$C_{SAR} = (c_{KBV001} + c_{KBV500}) \left(\frac{2d_{site}}{v_{KBV001}} + t_{rescue} N_{crew} + t_{aware} \right) \tag{10}$$

3.5.2. Salvage

A salvage operation is required when either the vessel's further safe operation is impaired or when the vessel must be abandoned. In the current study, the salvage operation is assumed to be a towing operation carried out by the SCG with the KBV001 combination vessel. The salvage cost is defined by the travelling time to the collision site, towing of the struck vessel to a safe harbour and the time required for mooring t_m; see Equation (11). The v_{tow} is taken as 4 knots here as a typical safe towing speed, and the safe harbour is assumed to be near the coast station.

$$C_{salvage} = c_{KBV001} \left(\frac{d_{site}}{v_{KBV001}} + \frac{d_{site}}{v_{tow}} + t_m \right) \tag{11}$$

3.5.3. Pollution response

In the case of oil spillage, the SCG must intervene with the pollution response operation to recover the spilled oil at sea and prevent its deposition on the shore to minimise the environmental impact and oil clean-up costs. In the pollution response operation, all surface vessels with oil recovery capabilities based at the coast station are involved, i.e. the KBV001 combination and the KBV010 environmental protection vessels (see Table 7). The pollution response operation time t_{pr} is obtained through an incremental calculation procedure in which each vessel i is assumed to perform as many oil recovery trips as required until all spilled oil of volume V_{oil} is cleaned up. Every recovery trip consists of (i) travelling to the location of oil spillage, (ii) oil recovery at the site, (iii) return to the coast station, and (iv) discharge of the recovered oil. The times for oil intake and discharge are assumed to be the same and depend on the oil recovery capacity q_{or} and recovered oil tank capacity V_{ot} of the respective vessel i. Travel times are found in a manner similar to that of the SAR operation, and the cost for every recovery trip C_{rt} is given by Equation (12). Moreover, the total time t_{pr} includes the awareness time t_{aware}.

$$C_{rt} = c_i t_{rt} = 2c_i (t_{travel} + t_{recovery}) = 2c_i \left(\frac{d_{site}}{v_i} + \frac{V_{ot,i}}{q_{or,i}} \right) \tag{12}$$

In addition to oil recovery vessels, the surveillance aircraft is deployed during the operation. Therefore, the total pollution response cost C_{pr} is defined as the sum of the costs for every recovery trip and the airborne surveillance cost during the total pollution response operation time t_{pr}, Equation (13).

$$C_{pr} = \sum C_{rt} + c_{KVB500} t_{pr} \tag{13}$$

Table 7. Swedish Coast Guard assets available for mitigation measures.

		Speed, v [knots]	Hourly costs, c [USD/hr]	Oil recovery capacity, q_{or} [m^3/hr]	Recovered oil tank capacity, V_{ot} [m^3]
Combination vessel	KBV001	16	2,580	400	1,100
Environmental protection vessel	KBV010	13	1,608	400	312
Surveillance vessel	KBV312	31	696	–	–
Surveillance aircraft	KBV500	–	4,833	–	–

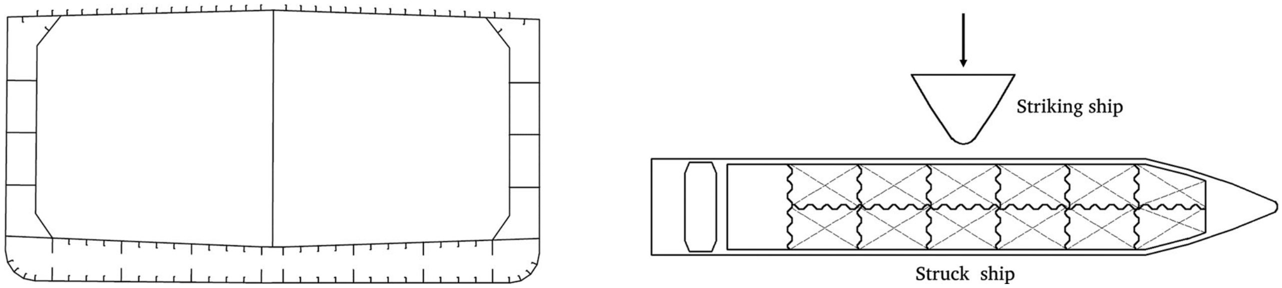

Figure 6. (Left) Midship section of the tanker and (right) collision setup and cargo hold arrangement.

Table 8. Principal particulars of the tanker.

Parameter	Value	Units
Length overall, *LOA*	139.9	m
Length between perpendiculars, *LPP*	134.0	m
Breadth, *B*	21.5	m
Draft, *T*	7.4	m
Longitudinal position of the centre of gravity from aft, *LCG*	69.3	m
Vertical distance between the keel and the centre of gravity, *KG*	5.0	m
Vertical distance between the keel and the navigation deck	25.0	m
Crew number, N_{crew}	15	–
Deadweight, *DWT*	11,500	tonnes
Total displacement	16,200	tonnes

4. Simulation cases

The case study vessel for the struck ship was a coastal double-hull oil tanker with 12 cargo tanks arranged in starboard-port-side pairs and midship sections according to Figure 6. Its principal particulars are summarised in Table 8. The striking ship was a similar-sized chemical product tanker with a total displacement of 16,200 tonnes. These vessels were chosen because of the typical sizes and types of ships in the Kattegat region. The struck tanker was studied with structural degradation due to corrosion, representative for an age of 25 years. Ship hull corrosion was considered by full corrosion margin deduction, and local geometry changes (due to pitting) were considered through adjustment of the constitutive properties of the materials. In addition, increased friction coefficients were applied for the FE simulation of collisions with the aged tanker. For details regarding corrosion modelling, see Ringsberg et al. (2018).

The vertical coordinate of the ship roll motion centre is assumed to coincide with the ship's vertical centre of gravity given by *KG*. For the case study tanker $KG = 5$ m, the distance from the keel to the navigation deck is equal to 25 m, which gives the vertical distance from the ship's rotation centre to the navigation deck = 20 m.

4.1. FEA: ship-ship collision simulations

The collision accident is simulated with an idle struck vessel and a moving striking bow with an attached mass. The bow of the striking ship was allowed to deform, and the impact was assumed to occur amidships between transverse bulkheads and web frames (see Figure 6), while the relative draft of the vessels was selected with both keels aligned. The setup assures progressive flooding through a large damage opening in a cargo hold and a drastic reduction in the section modulus at a longitudinal location where the largest bending moments are usually attained. A detailed description of the design of the nonlinear FE models (i.e. the struck and the striking ships) is presented in Kuznecovs et al. (2020).

4.2. SIMCAP and URSA: damage stability and structural adequacy simulations

The damage obtained by the FE collision simulations was mapped to the SIMCAP and URSA codes to study the damage stability and structural adequacy of the struck vessel. The size and shape of the damage were quantified by the projected area of the opening on undeformed planes of the inner and outer plating. It should be emphasised that accurate collision damage modelling is necessary for reliable damage stability simulations and assessment of the ship's residual strength.

To present the sea state conditions and ship heading directions for which specific limit states may be reached, dynamic ship stability simulations in SIMCAP were carried out for the damaged vessel in headings from 0° (following seas) to 315° in 45° increments. In the simulations, irregular sea states according to the JONSWAP spectrum with significant wave heights, H_S, between 1 and 6 metres and a peak period of $T_p = 4\cdot\sqrt{H_s}$ were simulated. The damage stability simulations were running for at least 30 min in real time after complete flooding process. Consequently, URSA computations for the specified sea states were carried out, and the results are presented in the form of polar diagrams. For the following consequence analyses, the limit states can be directly read off from the polar diagrams for specific weather conditions obtained from the METOCEAN data at the geographical location of the collision event.

4.3. Seatrack Web: oil spill and drifting of oil

The oil distribution from the oil spill source is simulated using the Seatrack Web; see Section 2.5. As the damaged vessel was a tanker, the outflow cargo was assumed to be a medium oil (100-1000 cSt) with a density of 0.876 tonnes/m^3. The amount of oil spilled is determined from the total capacity of the breached cargo tanks, and oil discharge is assumed to be instant. The oil drift simulations were carried out in the absence of any intervention measures by the SCG. The weather conditions were selected to be representative of the spring season according to the metocean analyses. On the selected date for oil drift simulations, waves mainly approached from the south-southeast, and significant wave heights were between 1 and 3 m (see Figures 2 and 12).

4.4. Consequence analysis

The study was carried out as part of the Swedish research project SHARC (https://research.chalmers.se/en/project/9203), where marine traffic around the Swedish coast is of particular interest. The Kattegat region of the North Sea was studied, as the major sea routes in this region intersect at multiple locations with a high risk of collision between ships. Therefore, for the consequence analysis in this region, a location outside the port of Gothenburg

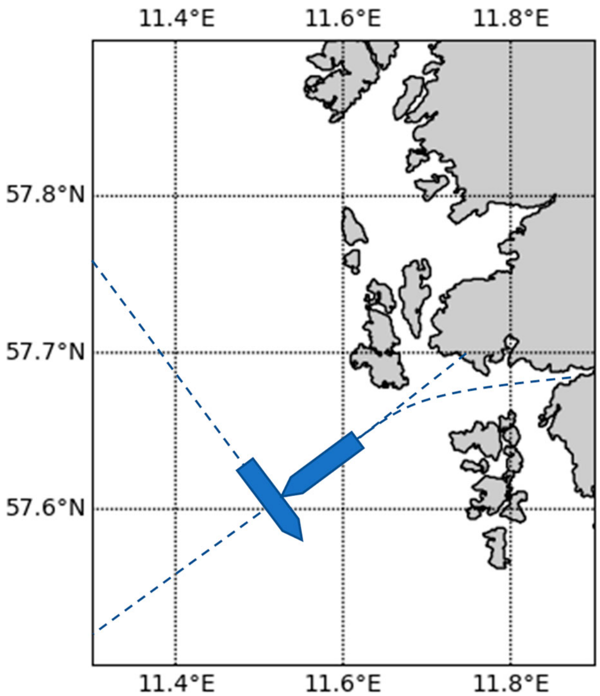

Figure 7. Collision location and orientation of the vessels involved in the case study accident (This figure is available in colour online.)

near the intersection of shipping routes at coordinates latitude 57.61° and longitude 11.51° was selected (see Figure 7) since ship-ship collisions and near misses have occurred here within the last 5 years (Swedish Accident Investigation Authority 2016, 2017). The struck vessel was assumed to head southeast following the 140° course, and collision occurred with a right-angled impact at the port side at a speed of 5 knots.

The optimum acceptable implied cost of averting a fatality for the applied economic parameters is found to be $ICAF = 8.97$ MUSD. The newly built price of the case study tanker is estimated to be $P_{ship} = 48$ MUSD (Mulligan 2008), and the price decrease rate is $P_d = 1.59$ MUSD/year based on the average tanker fleet age of 17 years and the average selling price of tankers of similar sizes of 21 MUSD (COWI 2008). The economic losses due to downtime for the tanker of 11,500 DWT in 2021 are estimated as $P_{DT} = 25{,}000$ USD per day (COWI 2008). The rest of the cost parameters necessary for the consequence analysis of the collision scenario are summarised in Table 9.

5. Results

In this section, the results from the FE collision analysis, damage stability, structural adequacy and oil drift simulations together

Table 9. Cost parameters for the consequence analysis.

Parameter	Value
Life expectancy, L_E [years][(a)]	80.6
Gross domestic product, GDP [USD/person] [(a)]	42,055
Labour utilisation, κ_L [hr][(a)]	754.9
Steel price, P_{steel} [USD/tonne] [(b)]	700
Labour price, P_{labor} [USD/hr] [(b)]	27
Oil price, P_{oil} [USD/barrel] [(c)]	55

[(a)]For EU countries in 2018, (OECD 2021).
[(b)]Rigterink et al. (2013).
[(c)]5-year average (2016-2020) crude oil import price for OECD countries (OECD 2021).

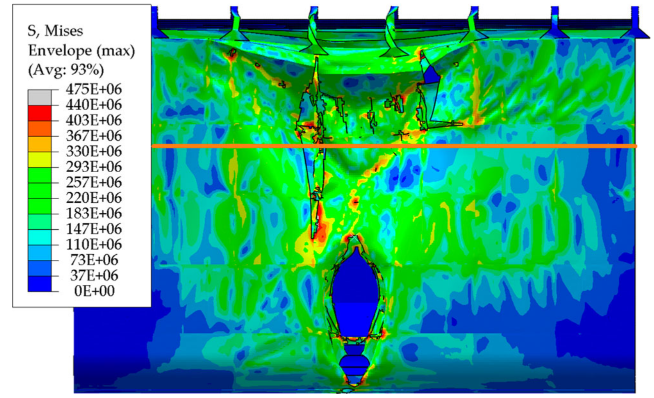

Figure 8. Collision damage pattern and stress distribution in [Pa]. The orange line marks the design water level (This figure is available in colour online.)

with the consequences of the case study collision scenario are presented.

5.1. FEA: shape, size and location of damage hull

The FE analysis of the collision accident revealed a breach of the outer and inner hull plating below the design water level DWL with a total opening area of 8.8 m^2. Besides the shape and size of the damage opening, the collision simulation revealed extensive plastic deformations in the upper part of the shell plating near the weather deck. The damage pattern and residual stresses are presented in Figure 8.

The total mass of the structural elements damaged due to collision that required repair was estimated to be 5.9 tonnes. Since the largest portion of the damage opening is located below the DWL and close to the keel level, the amount of spilled oil is estimated to be 1,340 tonnes based on the volume of the breached cargo tank.

5.2. SIMCAP: damage stability

The results from the SIMCAP simulation with the case study tanker for the sea states and heading directions defined in Section 4.2 are summarised in Figure 9. From the polar plots of lateral accelerations and roll angle, it is observed that the vessel experiences the largest roll motions in beam waves. The operational limit for lateral accelerations is reached already at beam seas with waves of 2 m height. Moreover, exceedance of the operational criterion is observed for the bow seas.

The 40° roll angle stability failure criterion is reached when 6 m waves approach the damaged port side (marked by the dot in the figure). The asymmetry in responses is attributed to the heel angle toward the port side caused by the redistribution of masses due to flooding.

Similar to the roll angle results, the SIMCAP analyses revealed stability failure during operation in high beam seas due to exceedance of the lateral acceleration criterion of 9.81 m/s^2. The most dangerous accelerations are found when the vessel is subjected to waves higher than 4 m approaching from the starboard side at a right angle. The observed phenomena can be partially justified by the increased restoring forces due to instant immersion of the hull sides during high roll angles.

The vessel condition with respect to stability is determined by the worst limit state found through simultaneous consideration of all stability criteria. As a result, the tanker must be abandoned if subjected to beam seas with significant wave heights above 4 m. In

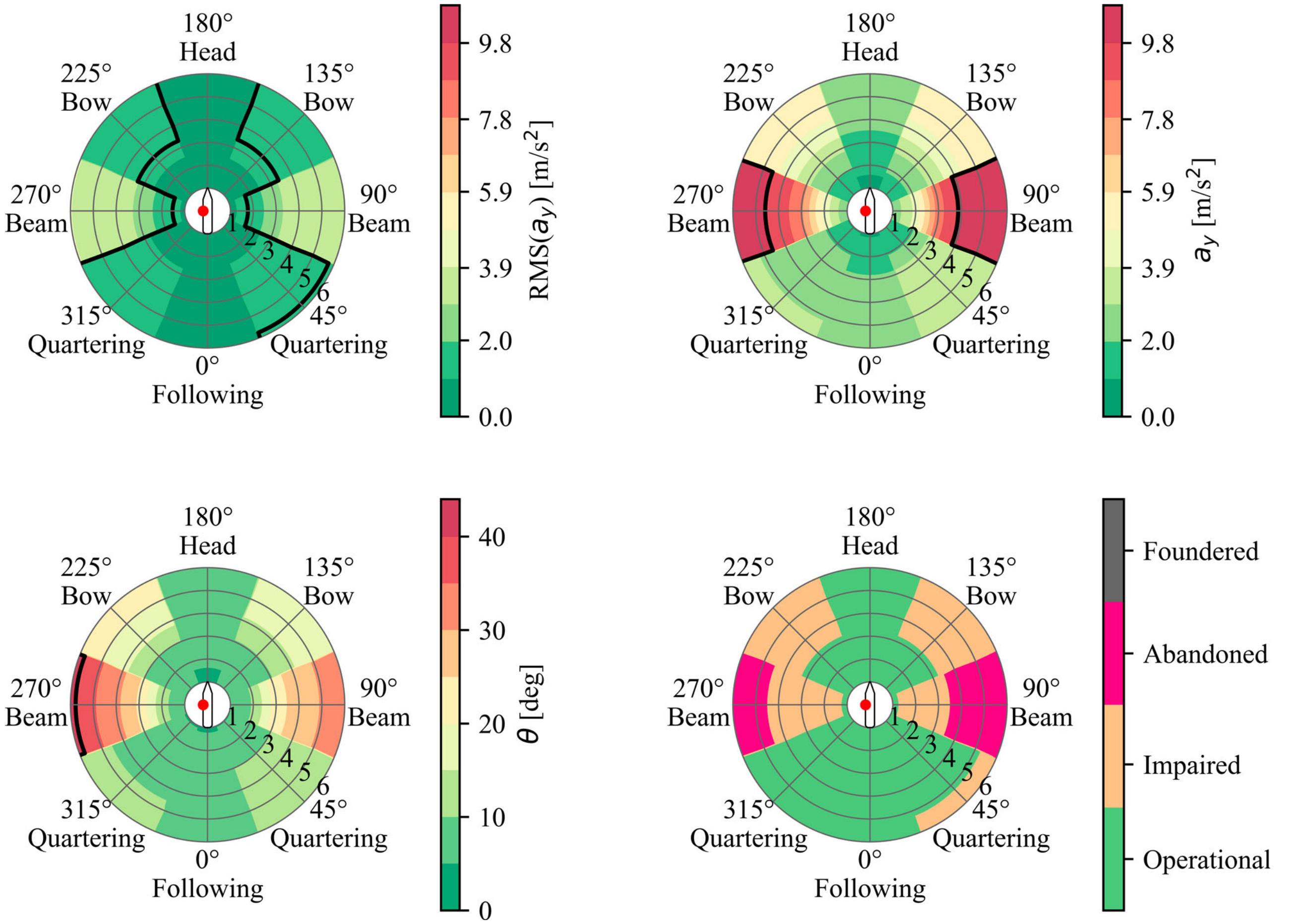

Figure 9. Polar plots of (upper left) RMS of lateral acceleration, (lower left) roll angle, (upper right) lateral acceleration peak values and (lower right) vessel condition with respect to stability limit states for different wave-encountering directions and significant wave heights. The red dot indicates the location of the damage opening (This figure is available in colour online.)

addition, safe operation might be impaired even in less demanding weather conditions in both beam and bow seas. Finally, the analyses reaffirmed that capsize is rarely a threat to vessels with full hull shapes and large block coefficients, and the case study tanker never reached the foundered condition under the investigated sea states.

5.3. URSA: structural adequacy

The URSA code is sequentially coupled with SIMCAP: time histories of motions and section forces from damage stability simulations are utilised in load and response structural analyses. Therefore, the structural safety of the ship hull in bending was assessed for the same sea states and wave-encountering directions as the ship stability. The struck vessel's 3D ULS capacity surface was obtained assuming the collision damage opening to span over one bay between two bulkhead frames, cf. Figures 3 and 8. Figure 10 exemplifies the biaxial bending loads (moments) acting on the hull structure and elastic and ultimate limit state capacities at the location of the collision damage.

Examination of the loads and their ranges reveals the importance of considering hull bending for a collision-damaged ship as a biaxial problem. Already for head and following waves, the bending deviates from pure vertical bending due to the asymmetry of the cross-section and developed heel angle. Moreover, as seen from the capacity plots in Figure 10, the collision damage in the double-side structure resulted in a large reduction of the strength for loading conditions different from pure vertical bending. It implies that both vertical and horizontal bending moment components are of importance and their combination may pose a threat for a

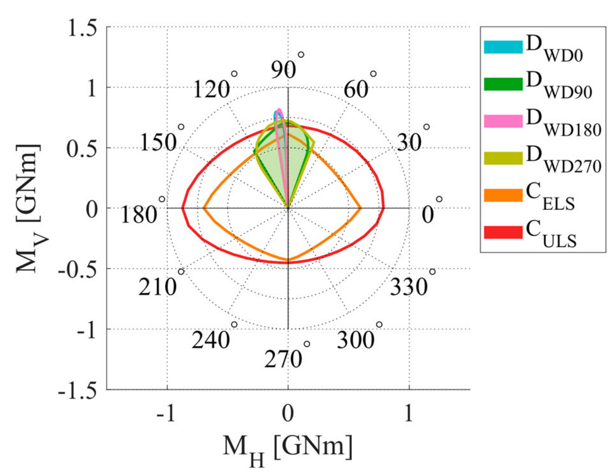

Figure 10. Section cut of 3D ULS and ELS capacity (*C*) surfaces at the location of the collision damage and relevant demand (*D*) or bending load ranges (i.e. envelopes of all loads encountered) for sea state with significant wave height of 6 m and four different wave-encountering directions (WDs) (This figure is available in colour online.)

collision-damaged vessel in beam waves – a condition usually disregarded in structural analyses.

The safety results are quantified in terms of structural adequacy and are presented in the form of polar diagrams (see Figure 11). In addition to the initial damage caused by the collision impact, the extra damage induced by excessive bending loads is referenced as local damage in the structural state polar diagram in Figure 11. The vessel conditions defining relevant consequences and costs are found in accordance with the definition of the structural limit states in Section 2.4.

It is observed that a large reduction in the structural adequacy is maintained not only when the vessel is operating in head or following seas – usually regarded as the only critical loading condition from a structural perspective – but also in beam and bow seas due to large amplitudes of roll motion and horizontal bending moment as a consequence. Actually, for the sea states with H_S up to 3 m, the hull will suffer larger local damage in the beam seas. Moreover, waves approaching the damaged port side of the vessel are as dangerous as head or following waves from a ULS perspective.

In general, collision impact with a severely corroded ship structure, such as the case study tanker, is very dangerous since the residual strength of the structure is adequate only for calm weather conditions. Harsh weather conditions imply the negative consequences of either large local damage or even ULS attainment and global structural failure, i.e. the crew will be endangered, or the ship will be lost. If undesired loading conditions are unavoidable, the negative structural consequences may be reduced if the vessel is oriented to meet quartering waves (see Figure 11).

5.4. Seatrack Web: drifting of oil

The oil drift simulations were carried out with Seatrack Web for May 23, 2021 between 12:00 and 20:00. Trajectories of oil drift at selected time frames and respective weather conditions are presented in Figure 12. Note that the weather conditions used in the current case study are based on the actual historical weather data available in the Seatrack Web. Weather conditions for the selected time frame correlates well with some of the most probable sea states from METOCEAN module, see Figure 2, but also represent the volatile sea behaviour during longer time periods. For the selected date with mild waves and winds from the south, the spilled oil slowly drifted northward as a single cluster and did not reach the neighbouring coastline within the 12-hour period since the assumed spillage outbreak. Therefore, for the selected date it was presumed that all the oil spilled could be recovered during pollution response operation.

5.5. Consequence analyses and mitigation actions

Consequence analyses were carried out with simultaneous consideration of all three components: damage stability, structural adequacy and oil spillage. Through evaluation of the worst possible scenario with respect to each of the aspects, general polar diagrams for vessel conditions and associated costs at different sea states were obtained (see Figure 13). Due to oil leakage, the severity of accident consequences for the struck tanker is at least impaired operability under any loading condition. In general, the consequence costs increased with the severity of the accident, and the highest costs were obtained if the vessel was considered foundered.

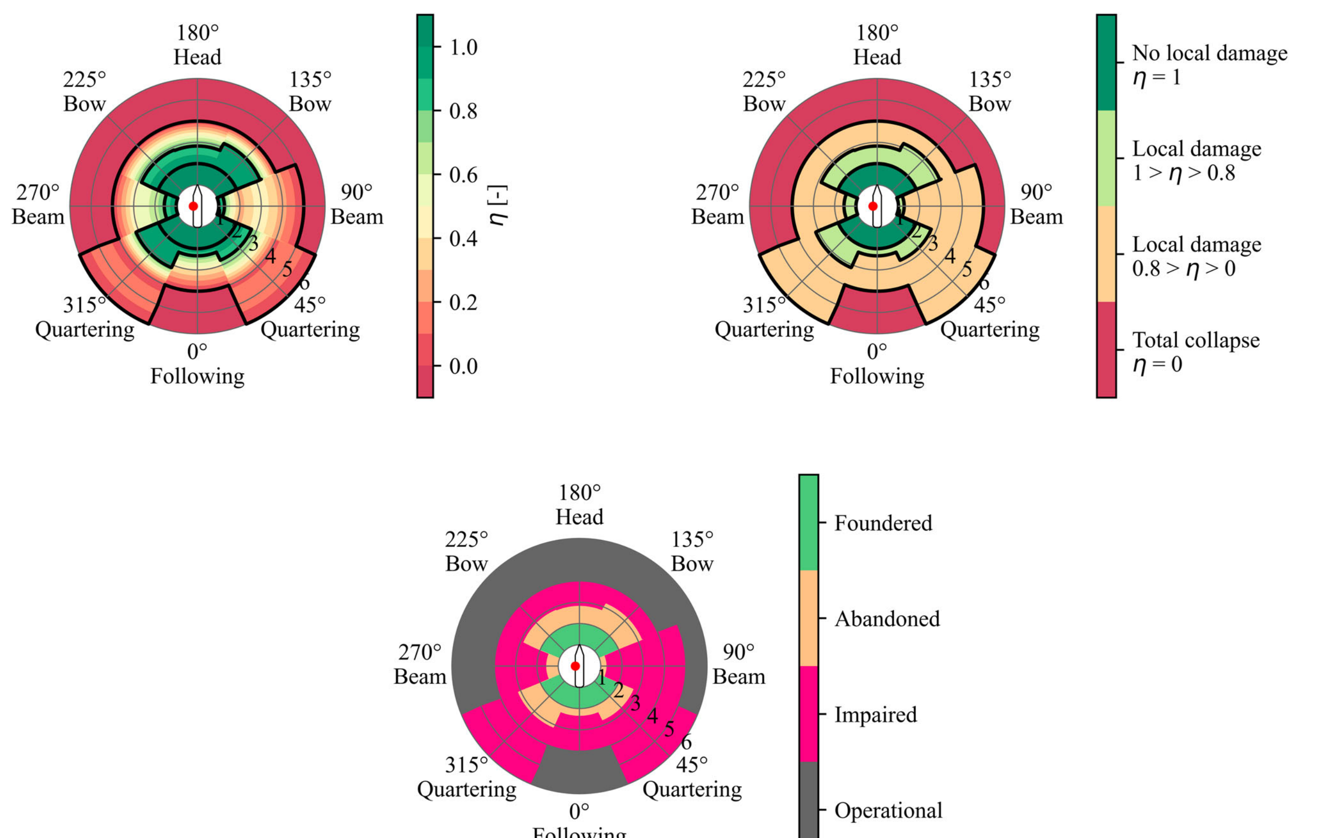

Figure 11. Polar plots of (upper left) structural adequacy, (upper right) structural state and (lower) vessel condition with respect to structural limit states for different wave-encountering directions and significant wave heights (This figure is available in colour online.)

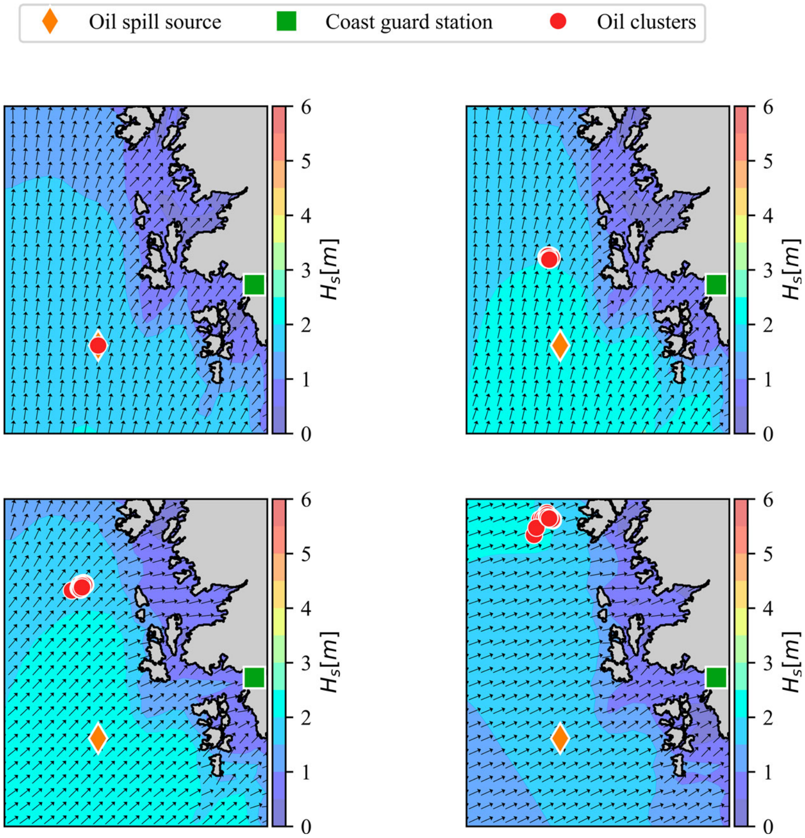

Figure 12. Sea states and drifting trajectories of spilled oil at the collision location at (upper left) the moment of collision at 12:00, (upper right) 16:00, (lower left) 20:00 and (lower right) 24:00 on May 23, 2021 (This figure is available in colour online.)

Consequence cost breakdown was performed for the same period as the oil drift simulations. For the specified collision date and time, significant wave heights were up to 2.3 m, and the wave-encountering direction for the struck vessel remaining on its original course of 140° changed from 126° to 94° (i.e. from bow to beam seas) within the 8-hour time span. In the latter sea state the ship had to be abandoned which resulted in a total consequence cost of 10.1 MUSD. The results from the cost breakdown analysis are shown in Figure 14.

Since free drifting of oil was found to be rather slow (see the results from the Seatrack Web simulations in Section 5.4), it was assumed that the SCG's preventive measures to stop further

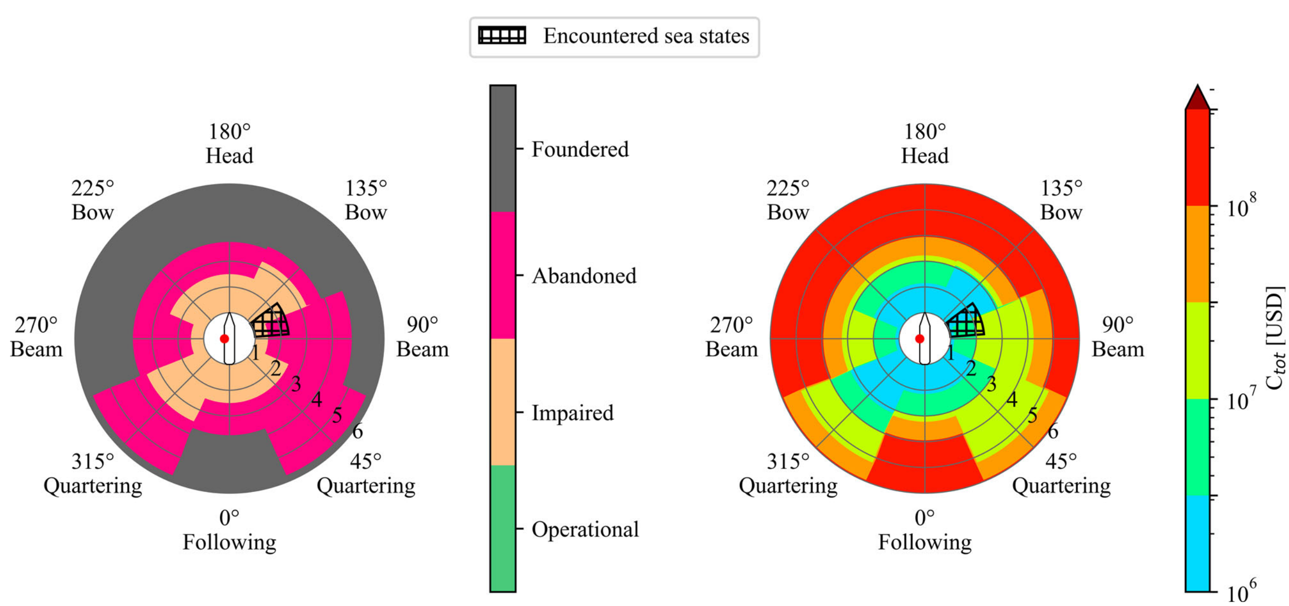

Figure 13. Polar diagrams of (left) vessel condition and (right) total costs of associated consequences. Encountered sea states during the study case are marked by a hatch (This figure is available in colour online.)

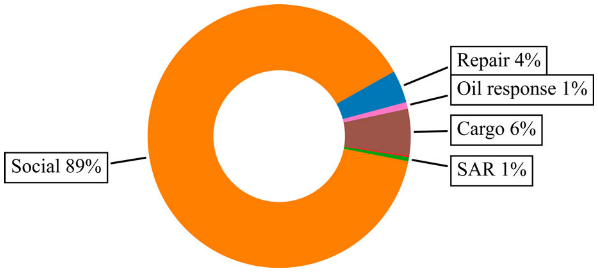

Figure 14. Cost breakdown for the consequences of the case study collision accident (This figure is available in colour online.)

spreading of oil were successful and that all of the spilled oil was cleaned up near the location of the collision accident. With this assumption, the oil response operation was estimated to take 8.6 h from the time of the accident and cost approximately 83,000 USD. Together with a SAR operation, the total costs for the SCG's mitigation measures do not exceed 2%.

The direct repair costs due to collision damage alone for the case study tanker are estimated to be 17,000 USD. To repair the additional damage caused by excessive bending loads will cost 37,000 USD. The total repair costs including downtime are 403,000 USD and constitute 4% of the overall costs. The oil cargo lost was worth 577,000 USD. The largest cost components are associated with crew safety making up to 89% of the total costs due to high accident severity and corresponding equivalent number of fatalities, see Table 3.

6. Conclusions

This paper presented a methodology for the assessment of consequences associated with ship-ship collision accidents at sea. The proposed methodology considers negative consequences related to oil spills, insufficient damage stability, structural adequacy, or a combination of these. Scenarios of the events following an accident, relevant consequences, necessary mitigation measures and associated costs are estimated based on the actual vessel condition that is evaluated with respect to limit states defined for each of the hazard categories: stability, structure, and the environment.

The proposed methodology was demonstrated with a case study chemical tanker struck in a collision. The outcomes of the consequence analyses are practical polar diagrams and cost breakdown analysis. The polar diagrams indicate potentially dangerous conditions and, together with cost assessment results, can act as guidance for operational decision making. Additionally, since all consequences are assessed in monetary values, the severity of different hazards can be compared, and thus, areas requiring improvements to sustain the necessary safety level for specific vessels can be identified.

The framework of the methodology consists of interchangeable modules and models that allow the tool to be tailored for specific needs. Therefore, the proposed methodology is believed to have potential for further development for consequence and risk analyses of ships under pre- and post-accident conditions.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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