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COMMITTEE V.1

ACCIDENTAL LIMIT STATES

COMMITTEE MANDATE

Concern for accidental scenarios for ships and offshore structures and for their structural components leading to limit states. Types of accidental scenarios shall include collision, grounding, dropped objects, explosion, and fire. Attention shall be given to hazard identification, accidental loads and nonlinear structural consequences including strength reduction, affecting the probability of failure and related risks. Uncertainties in the use of accidental scenarios for design and analysis shall be highlighted. Consideration shall be given to the practical application of methods and to the development of ISSC guidance for quantitative assessment and management of accidental risks.

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KEYWORDS

Accidental situations Limit states; Abnormal environmental event; Collision; Grounding; Explosion Fires; Emergency Response Service; Benchmark on grounding simulation

CONTENTS

1. INTRODUCTION 4

2. SCENARIOS FOR THE DESIGN OF MARINE STRUCTURES 4
   2.1 Probability of occurrence of a scenario 5
   2.2 Consequences of exposure to a given scenario 5
   2.3 Characteristics of scenarios for limit states design 6
      2.3.1 Scenarios for verifications of ULSs 7
      2.3.2 Wave loads scenarios for ULS 7
      2.3.3 Scenarios for verifications of SLSs 9
      2.3.4 Scenarios for verifications of FLSs 9
   2.4 Accidental and abnormal environmental situations 9
   2.5 Uncertainties in accidental scenarios....................10
   2.6 Design accidental/abnormal scenarios 10
   2.7 Design Standards 11
   2.8 Status of existing design standards for ships in relation to accidental scenarios 11

3. ABNORMAL ENVIRONMENTAL EVENTS 12
   3.1 Abnormal waves 12
   3.2 Abnormal wave design loads for offshore structures....................13
   3.3 Comments to offshore scenarios....................14
   3.4 Possible definition of abnormal wave scenarios for ships 15

4. METHODS AND PROCEDURES FOR THE ANALYSIS OF ALS....................15
   4.1 Introduction....................15
   4.2 Modelling details and response evaluation 17
      4.2.1 Analytical methodology on response evaluation 17
      4.2.2 Numerical simulation methodology 19
   4.3 Present application and recent development in current standards 20
   4.4 Material models to be used in FEM 21
      4.4.1 Metallic Shipbuilding Materials....................21
      4.4.2 Composites....................23
      4.4.3 Foam....................24
      4.4.4 Rubber....................26
      4.4.5 Ice....................26
      4.4.6 Soil 27

5. COLLISION....................28
   5.1 Ship collision categories 28
      5.1.1 Ship-ship collision 28
      5.1.2 Ship-offshore collision 29
      5.1.3 Ship-bridge collision....................30
      5.1.4 Ship-ice collision 31
   5.2 Most critical/relevant condition and design/analysis methods 32
   5.3 Acceptance criteria/consequence evaluation....................33

6. GROUNDING 34
   6.1 Introduction....................34
   6.2 Most critical/relevant condition....................35
   6.3 Analysis methods 37
      6.3.1 Experiments 37
      6.3.2 Statistical models 38

6.3.3 Numerical models 38
6.3.4 Empirical and regression models 39
6.3.5 Analytical models 40
6.4 Acceptance criteria/consequence evaluation 40

7. FIRE AND EXPLOSION 41
7.1 Introduction 41
7.2 Prescriptive vs performance based codes 41
7.3 Fire and explosion analysis: General 42
7.4 The Risk of Fire and Explosion accidents 43
7.4.1 Action effects and modelling 43
7.4.2 Accidental scenario and probability 44
7.5 Design Requirements of Fire and Explosion Accidents for LNG Ships 45
7.5.1 Fire and explosion design for LNG carriers and FSRU 45
7.5.2 Fire and explosion design for Gas fuelled ships 45
7.6 Fire and explosion analyses for LNG ships 46
7.6.1 Fire and explosion analyses for LNG carriers and FSRUs 46
7.6.2 Fire and explosion analyses for LNG fuelled ships 49

8. MARITIME SAFETY AND RESCUE SERVICES 49
8.1 Emergency Response Services - ERS 50
8.2 ERS Functionality 50
8.3 Basis for decisions making 51

9. BENCHMARK STUDY 52
9.1 Introduction 52
9.2 Experiment 52
9.3 Input data 53
9.4 Results 54
9.5 Sensitivity studies 55
9.5.1 Sensitivity for friction coefficients 55
9.5.2 Sensitivity to failure strain values 56
9.5.3 Sensitivity to mesh refinement 56
9.6 Summary 56

REFERENCES 58

ANNEX 70

1. INTRODUCTION

The term of Accidental Limit States design in technical language indicates a design procedure accounting for accidental situations in terms of specific initial states, actions and/or final states for the structure. The characteristic features of accidental situations in comparison to other scenarios considered in structural checks are discussed in chapter 2, where the motivations for the introduction of this class of scenarios are discussed, too.

Chapter3 reports a brief overview of the current and possible applications to ships and off shore structures design of the specific category of abnormal environmental situations, in which the event activating the scenario is represented by extraordinary wave events

The other typical accidental situations (collision, grounding, explosion and fire) are covered by chapters 5 to 7, where the various aspects of each specific scenario are analysed with the aim of providing a state of the art of the procedures available for investigations. When possible, reference is made in particular to ship structures.

Chapter 4 contains a discussion of tools available for the structural analysis of various of the following scenarios.

Chapter 8 touches upon a subject correlated to accidents, i.e. the Emergency Response Services, that are aimed at managing on the field accidental situations, thus limiting consequences.

Finally, the last chapter (n.9) includes a benchmark study carried out by some of the committee members and regarding a grounding event for which model scale experiments were available from literature. The force and the energy exchanged between an obstacle with a simple but realistic shape and a medium size specimen resembling the double bottom of a ship are derived by FEM simulation and compared to experimental surveys.

2. SCENARIOS FOR THE DESIGN OF MARINE STRUCTURES

Ships and offshore structures are subjected to various operational situations, from frequent and/or normal to extreme and/or accidental ones. In design, the main objective is to obtain a structure able to withstand these situations with an adequate probability of resisting them with limited unwanted effects. In other words, the target of design is to control the risk of operating the structure.

A key step for setting up a design procedure, therefore, is represented by the selection of a number of situations able to represent effectively the whole spectrum of hazards to which the structure is subjected during its life. In more details, this implies:

- to select the classes of scenarios that generate the largest contributions to risk of the structure,
- to identify examples of those scenarios in quantitative terms (selecting characteristic values for the elements of the scenario) and
- to use those scenarios to evaluate the implied risk and to control it.

Each relevant scenario allocates a certain risk contribution: the total lifetime risk, represented by the sum of all contributions, is to be kept within acceptable limits.

In this process, elements for the definition of the relevant scenarios are the probability of occurrence of the scenario itself, the initial state of the structure and the actions to which the structure is exposed. A further element for the evaluation of the risk inherent to the scenario is the final state of the structure, evaluated through the probability of exceeding specific limit states. Exceeding these limits has a direct influence on the consequences of the exposure.

In formal terms the risk allocated to a structure subjected to scenario S_i of exceeding the limit state Lj thus generating consequences Cj can be expressed in terms of Eq. 1

$$R_{j,i} = \quad C_j \, P\left(L_{j,i}\right) = C_j \, P\left(L_j \,\middle|\, S_i\right) P(S_i) \tag{1}$$

Where

$P(S_i)$ = probability of occurrence of scenario Si
$P(L_jS_i)$ = conditional probability of exceeding the Limit State L_j given occurrence of scen. S_i
$P(L_{j,i})$ = probability of exceeding the Limit State L_j in scenario i
C_j = consequence of exceeding limit state j
$R_{j,i}$ = risk due exceeding limit state j in scenario i

Summation of the various contributions is carried out generally first within the single scenario and later among scenarios (Eq.2)

$$R = \sum_i R_i = \sum_i R \,\middle|\, S_i \cdot P(S_i) = \sum_i \left[\sum_j C_j \, P\left(L_j \,\middle|\, S_i\right)\right] P(S_i) \tag{2}$$

R = total risk
R_i = risk incurred in scenario i
$R \,|\, S_i$ = risk conditional to scenario i

In the following, a few general characteristics of the most typical scenarios adopted for structural verifications are recalled, with the aim of focusing later on accidental ones.

2.1 *Probability of occurrence of a scenario*

A key quantity of a scenario for design verification is represented by its probability of occurrence $P(S_i)$ in Eq. (1) and Eq. (2) and/or the expected number of times it will occur in the life of the structure. This is important because the risk evaluated in the scenario (i.e. conditional to the occurrence of the scenario) is to be weighted according to such probability (Eq.2). The probability of the scenario depends on the probability of the initial state featured by the system under consideration and on the probability of occurrence of the actions described in the scenario, which, in turn, may be conditional to that initial state. In the following, a quick review of how the concept is applied in various classes of scenarios is presented.

2.2 *Consequences of exposure to a given scenario*

When evaluating the effect of the exposure to a given scenario, the response of the structure (i.e. its final state) is to be modelled. In order to carry out an evaluation of consequences, the concept of limit state is widely used. A limit state defines the border of a region in the space of the possible states of the structure. Inside the region, the structure fulfils a given criterion, while, outside it, the state of the structure belongs to a different category of states, with significant differences in performances from the region inside the border.

The above border is expressed through the limit state equation, which, in turn, is formulated in terms of those state variables that are needed to identify the specific limit (or criterion). In structural design, these variables may refer to loads or other actions on the structure, to responses (stress, strain, displacement, etc.) or other variables, regarding the mechanical, thermal or any type of behaviour that may be of interest for checking the performance of the structure. Criteria may refer to performances like maintaining the structural integrity, the fitness for use, durability, fatigue resistance or other requirements. During the last two decades, the so called limit state design (LSD) has been increasingly applied in engineering, since a rigorous design should be obtained evaluating directly all the various final states the structure can end up to, because of the different exposures experienced during its operational life.

Three types of limit states (LS) have been considered for a long time for steel structures (as already mentioned in Czujko et al. 2012): Ultimate Limit State (ULS), Serviceability Limit State (SLS) and Fatigue Limit State (FLS). The criteria at the basis of the formulation of the LSs characterize the reference scenario to such an extent, that, in common language, the type of analysis and the whole check situation is identified by the term indicating its (final) limit state. In the following, the characteristics of the three LSs (here intended in their narrower and more precise meaning) are summarized, while in the next paragraphs the corresponding scenarios are briefly recalled. A forth category (accidental scenarios), which is the main object of this report, is discussed from §2.4 onwards.

Serviceability Limit States (SLS): are used to check the adequacy of the structure during normal operation. SLS criteria in design may address for instance limits of deflection, vibration, motions, durability considerations, and similar.

Fatigue Limit States (FLS): refer to damages induced by repeated load cycles on the structure. Checks according to this criterion aim at ensuring that the structure has an adequate fatigue life for its anticipated operations. The predicted fatigue life can also be a basis for planning efficient inspection programs during operation of the structure. Formulations of this limit state may be based on two alternative models: Miner's Rule and Fracture Mechanics. The selection of the model reflects into different formulations and different choices of the relevant state variables.

Ultimate Limit States (ULS): refer to irreversible changes in the state in the system, associated with failure. Failure may be represented by structural collapse and, in this case, the limit state is often expressed in terms of those variables that characterise the stress-strain field in specific points of the structure or global loads and capacity of the whole structure. The loss of structural capacity may be related to collapse of individual strength members or collapse of the entire structure due to for instance buckling and plastic collapse of plating, stiffened panels and support members. On the other hand, failure can be represented by other criteria, very much dependent on the type of structure and on the scenario. For a floating structure, it could correspond to loss of water tightness or to exceedance of a given heeling angle (above which evacuation is impaired); for a structure subjected to thermal loads it could be represented by reaching a given surface temperature (above which an excessive decay of load carrying capacity is implied, etc.).

A structure designed by a LS is proportioned to sustain all actions likely to occur during its service life, and to keep on fulfilling the condition expressed by the LS, with an appropriate level of reliability for each limit state. The various types of limit states may be checked against different levels of probability of exceedance and such probability, not to be exceeded for a particular type of limit state, is in turn fixed in dependence of the foreseen consequences of going beyond the limit. The target is the control of the risk coming from that specific scenario. Limit states are therefore an important aspect in the characterisation of the situations foreseen for structural verifications.

2.3 Characteristics of scenarios for limit states design

As mentioned above, the probability for a structure to go beyond a specified limit state is to be computed with reference to the initial state and to the actions foreseen in the scenario under investigation. In the following, the characteristics of scenarios for ULS, SLS and FLS checks will be recalled, with the aim of introducing later those inherent to accidental situations.

2.3.1 Scenarios for verifications of ULSs

Typical strength verifications correspond to initially intact structures subjected to suitably chosen action levels. The final state is compared with an ULS resistance formulation.

The initial intact state is characterised by the absence of localised damages. Minor and diffused degradation effects, like corrosion, wearing or other material defects are sometimes included in the model. The probability associated with this initial state is very high (close to 1) because the structure will be intact (in the sense above mentioned) for most of its life.

For a structure subjected to a time variant load, the probability of exceeding a limit state in a given time period corresponds to the probability that the extreme load amplitude in that period exceeds the capacity of the structure. In general, therefore, the action level to be considered for reliability evaluations corresponds to the extreme value distribution of the action in the reference time for the analysis.

In a full reliability analysis, the extreme action as well as the resistance of the structure are treated as random variables.

The probability distribution of the extreme value of the action depends on the characteristics of the distribution of the action and on the reference time on which the extreme is evaluated (i.e. on the average number of times the action is occurring).

If the load is accounted for by the variable corresponding to the extreme value in the same reference time adopted for reliability evaluations, the probability that the structure will be exposed to such load in that time period is, by definition, 1 and this exposure will occur once. This means that the probability of exceeding the ULS computed with this load does not need to be weighted by the probability of occurrence of the load scenario (both initial state and loads feature a unit probability). The above probability of exceeding, therefore, can be directly multiplied by the consequences in order obtain the risk contribution by the scenario.

2.3.2 Wave loads scenarios for ULS

For wave loads, the average period of each single cycle is quite short, so the number of applications results to be quite large for any reference period chosen for the analysis. This is not the typical situation for other types of events, likes fires, explosions collisions or grounding, which are intrinsically rare and may not occur at all in the lifetime of a structure. Because of the high number of repetitions, for waves the distribution of single cycle amplitudes is well defined and described by continuous distributions un-limited to the right (see Figure 2). Accordingly, the distribution of extreme values is, too, un-limited to the right, showing progressively higher mean values for longer exposure periods. Again, this does not apply to the other types of hazards, for which probability distributions are in general not available and the procedure to find an extreme value among a multiple number of occurrences on the single structure does not apply.

In design checks at a lower level of analysis (e.g. in checks based on a LRF or Partial Safety Factor formats), single characteristic values, instead of probability distributions, are representative of each variable. This is presented in Figure 1 for the load and resistance variables sketched, and in Figure 1 for different choices of the characteristics values for wave loads. For ships, typical characteristic values for sea related actions are taken at levels with a 10^{-8} exceeding probability (referred to any single cycle). This is based on an average number of load cycles of 108 in the design life of ships, corresponding to 25 years. The same value corresponds to a probability of 1/25 (4%) of being exceeded by the annual extreme value (based on the corresponding number of $4\ 10^{6}$ cycles/year). In 25 years, the same 10^{-8} value features an exceeding probability of 63% (coming from the application of basic hypotheses of the theory of extreme values).

In similar checks for offshore platforms, the characteristic value is defined with reference to the annual extreme distribution, with an exceeding probability of 10^{-2}. This value features in 100 years an exceeding probability again of 63%, while in 25 years (which could be a reasonable design lifetime also for an offshore installation) the exceeding probability is about 22%. The different ways of characterising wave actions are sketched in Figure 1 below.

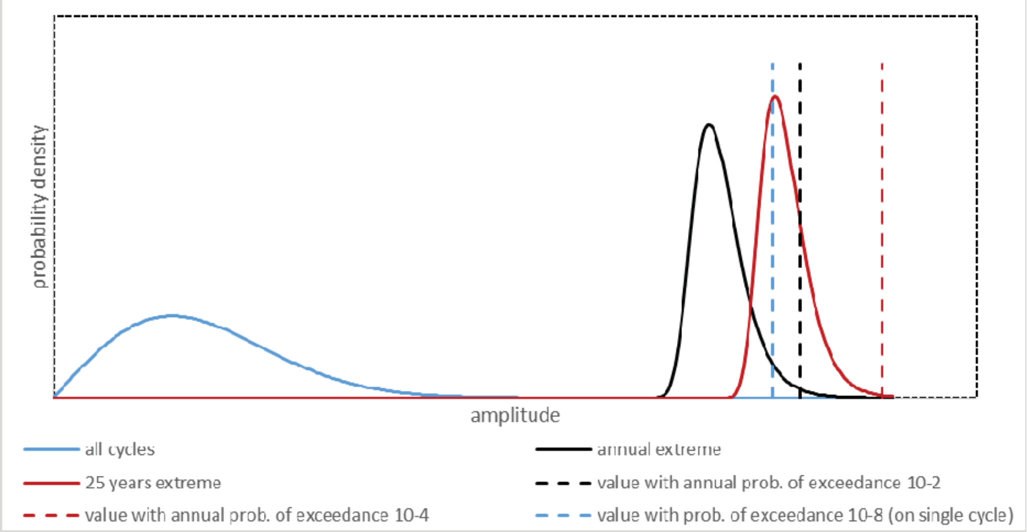


Figure 1: Different scenarios for wave actions

The above figure also indicates characteristic waves with a return period of 104 years (annual probability of exceedance of 10^{-4}). They are used in checks for abnormal environmental situations (see later). In this case the exceeding probability in 25 years is $2.5\ 10^{3}$.

It is here marginally noted that, for a more precise comparison between characteristic values of loads for ships and for platforms (which is beyond the scope of the present report), other relevant aspects should actually be mentioned. Ships are not exposed for 365 days a year, but are considered to be sheltered from waves for about 15% of the time (in port or at dock), so the same design life corresponds anyway to a different number of exposure cycles (smaller for ships: about 85% of what is expected for platforms). Other differences are related to the fact that ships move and therefore experience in the same sea state a different wave encounter frequency than platforms.

In other types of checks for ships the concept of equivalent design waves is introduced. When checking the structural adequacy of the hull structure of ships, a set of load cases with different design waves is defined (see IACS 2017). In that case, the characteristics of design waves are selected in order to reproduce characteristic values of the wave effect (e.g. long term predictions of extreme values of the wave induced bending moment with exceeding probability of 10^{-8} during 25 years, see above).

When dealing with design waves for structural checks, a definition based on extreme values of the wave height (i.e. a characteristic value of the action, instead of the action effect) may also apply, based on the assumption that the effect is proportional to the wave height. This, however, should be checked carefully in those cases in which strong nonlinearities apply. In these cases, the average effect of a set of very high waves may be by far larger than the effect of a single wave with an average height computed on the same set.

2.3.3 Scenarios for verifications of SLSs

When the capability of maintaining a full operability of the structure is to be evaluated, the scenarios adopted are based in general on an initial intact state similar to that adopted for ULS checks, but on environmental loads corresponding to a shorter exposure time and on more restrictive criteria. The contribution to the risk is to be evaluated taking into account that these limits will be exceeded in the structure lifetime several times. The inherent consequences will therefore occur for the expected number of times (greater than 1) in which the limit is exceeded.

2.3.4 Scenarios for verifications of FLSs

Also in the case of fatigue verifications, the initial state is intact (an initial distribution of small defects may apply). When modelling the exposure by means of a long term prediction of the distribution of the load cycles amplitude, the reference time duration is the structure lifetime. Limits corresponding to fatigue collapse are set (different definitions may apply). The probability of this scenario is again 1, as the fatigue strength of the structure will definitely be put into trial by the lifetime distribution of the load cycles amplitude. Accordingly, the consequences of exceeding the limit do not need to be weighted.

In simplified checks, on the other hand, conservative load stress histories may be adopted. In this case, a lower probability of occurrence would apply.

2.4 Accidental and abnormal environmental situations

The situations to which the above three categories of LS are applied all are characterized by an initial intact condition of the structure and by a probability of occurrence of 1 of the scenario (Eq. 1 and 2), when a full reliability analysis is carried out. In addition to those situations, other scenarios have been recognized more recently to be relevant for design purposes. A further class is represented by those situations in which the structure, because of specific external actions, is in damaged conditions (with specific degradation effects concentrated in parts of the structure). These situations will not necessarily occur in the lifetime of all structures, but, as they imply large consequences, they need to be considered at the design stage. This class of low probability situations, corresponding to accidental and very rare (abnormal) events, is the object of the present report. Their distinctive features are therefore related to the presence of a localised damage (due to various types of hazards) and to the low probability of occurrence (typically a return period of a couple of orders of magnitude longer than the lifetime foreseen for the structure).

Accidental situations refer to hazards such as fire, explosion, collision, dropped objects or very rare environmental events. Checks are aimed at achieving that the main vital functions of the structure are not impaired (beyond a certain probability level) during any accidental event or within a certain time period after the accident. The analysis of these scenarios includes the evaluation of the immediate consequences of the event and/or the evaluation of the probability of occurrence of an escalation of events that, starting with the accident, may lead to a progressive collapse (exceeding various types of limit states). Such analyses have for several years been required for the design of offshore structures, where they are considered with reference to accidental limit states, ALSs. A quality of a structure relevant for such analyses is robustness, characteristics related to the ability of preventing progressive collapse of the structure following an initiating damage event.

This report is focused on accidental/abnormal situations and inherent characteristics. These scenarios imply in general an exceptional action, giving rise to an initial damage state, which needs to be characterized. The situation may imply further actions (e.g. environmental actions) on the damaged structure with specific characteristics in terms of amplitude, exposure times and resistance capabilities of the structure. The criterion for assessing the state of the structure after damage is often related to ULS, even though the large variety of situations, different from each other, implies a variety in the definitions of the inherent LSs.

In accidental scenarios, loss of capacity of individual members and subassemblies may take place, but the focus is on maintaining main safety functions that prevent total collapse. This means that individual members can be subjected even to loads larger than from normal use (SLS and FLS) and extreme loads (ULS).

2.5 Uncertainties in accidental scenarios

In the assessment of the adequacy of a structure to accidental/abnormal scenarios, several uncertainties arise, due to the approximate nature of the methods for determining actions and action effects. Further uncertainties apply to the knowledge of the system characteristics (e.g. the material strength). The above uncertainties apply to any scenario for structural verification, but they are enhanced in the case of accidental scenarios, because of their characteristics. In particular: low probability of occurrence (i.e. difficulties in obtaining statistical data) and extreme variability in the types of situations (with particularly large complexity of the models involved in the performance prediction) and variety of limits states adopted for the assessment.

2.6 Design accidental/abnormal scenarios

Accidental scenarios for the design and assessment of structures and associated performance criteria should be set on the basis of risk assessment for a given type of structure. The first step is to perform a Quantitative Risk Assessment (QRA), which is a formalised specialist method for calculating individual, environmental, employee and public risk levels for comparison with regulatory risk criteria.

This should be done for all types of hazards/abnormal environmental events, identifying the probability of occurrence and the magnitude of actions, of action effects and of consequences. For each relevant category of scenarios, one or more specific scenarios or situations is to be defined for design purposes. For example, for a ship-ship collision scenario, a specific situation must be specified such as e.g a bow impact of a striking ship in the side of a struck ship. To proceed with the analysis, a further step is necessary, in which a quantification of the main variables is carried out (ex: impact angle, impact energy) in order to define a design situation. This is illustrated in Figure 2.

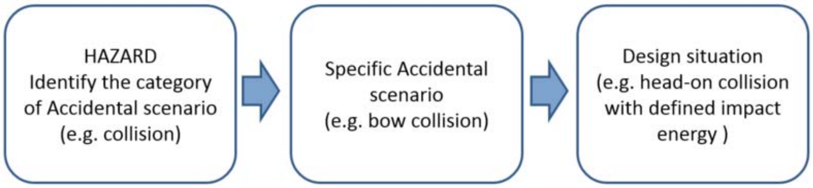


Figure 2: Flowchart for definition of design situation in ALS.

A design situation is meant to be representative of a wider class of real situations and should be chosen in such a way that the performance of the structure in that situation is as much as possible representative of the performances in the whole class of real situations. In the above example, the spectrum of possible ship-ship collisions is much wider, including impacts on different parts of the hull, with different angles and different relative velocities, but for design purposes, a discrete number of scenarios is considered.

In principle, the equivalence should be evaluated in terms of risk. In other words, the risk in the single design condition should be similar to the risk for the whole class of similar ‘actual’ situations. A way of ensuring such result is to select, as design case within a class, a specific scenario which allocates a major (or at least a large) part of the risk associated to the whole class and to attribute to that specific case the probability of occurrence of the whole class. A similar procedure is suggested in (Rizzuto et al., 2010) for the case of a tanker in grounding conditions. The same concept was later refined in (Prestileo et al., 2013) with the use of a Bayesian Network to identify the damage case allocating the highest probability of failure for the hull girder of the ship.

2.7 Design Standards

Design standards, among other tasks, are meant to provide guidelines on how to determine the capacity of the structure to resist various types of scenarios, inclusive of accidental ones. In this context, they cover the definition of design scenarios, the evaluation of the response of the structure to the scenario and the assessment of such response. The latter is to be based in principle on a risk analysis including the classical three types of consequences: loss of life in the structure or the surrounding area, pollution of the environment and loss of property or financial exposure.

Guidelines may be provided on how to investigate a given scenario both using simplified solutions with explicit formulas or with more advanced numerical simulations. Since the computer resources are increasing continuously, it is more and more common to use advanced numerical simulations. The most usual tools and methods for advanced numerical simulations are Finite Element Method (FEM) for assessing the action effects and Computation Fluid Dynamic (CFD) analysis for assessing the external actions/loads. Advanced numerical simulations are very general and can be adopted for cases that are not properly covered by simplified solutions with explicit formulas. However, numerical simulations require experienced users and several factors must be accounted for in order to achieve reliable results. These factors can typically be material model, solution procedure, mesh refinement, etc. which are discussed in more detail in the following chapters with reference to accidental scenarios.

2.8 Status of existing design standards for ships in relation to accidental scenarios

All major standards for offshore structures offer a practical implementation of an explicit design approach against accidental and abnormal actions, even though the degree of details in characterizing actions and action effects may be different for the various situations. As stated in (Czujko et al. 2015) this approach has not yet been widely adopted by the shipbuilding industry, largely due to a conservative approach of this industry, which developed its know how by experience over hundreds of years. Another peculiarity is represented by the fact that accidental scenarios for ships are very case dependent on the ship design and type of operation. Also acceptance criteria can be formulated in quite different ways: safe return to port, safe evacuation, resistance to flooding, containment of oil spilling, etc.

A more traditional approach followed for ships is the development of prescriptive rules, derived from past experience and related studies and covering implicitly accidental criteria. Prescriptive provisions of this type are e.g. for all ships: the requirements about number and characteristics of watertight bulkheads (against flooding) and free board requirements against green water effects (when dealing with the encounter of extreme waves). For tankers, requirements are set about presence and dimensions of a double hull (against oil spilling caused by collision and grounding events).

A growing interest is shown, however, in the use of direct analysis to explore design solutions and this is also being pushed by IMO's long term target for Goal Based Standards. In this context, a few examples of requirements are present, where specific aspects related to accidental scenarios are considered (in particular for collision and grounding).

One example is the check for hull girder residual strength after a grounding or collision event that is incorporated into the Common Structural Rules for Bulk Carriers and Oil Tankers. In this check, a damage extent in the bottom and side is specified for grounding and collision, respectively.

In other cases, direct computations of accidental scenarios are applied for the assessment of alternative designs:

- Marpol collision and grounding equivalence: According to Marpol Annex I (IMO 2004a), comprehensive non-linear FE analyses can be used to demonstrate equivalence with regards to collision and grounding resistance of a combination carrier compared to a similar sized reference oil tanker. If strength equivalence or better can be shown, a less restrictive requirement to mean outflow parameter is accepted.
- Equivalent study for reduced minimum distance between outer skin to LNG tank: The safety against an impact of the tanks is dependent on the strength of the ship side, and FE analysis can be used to demonstrate that equivalent safety is kept for a strengthen ship side with reduced minimum distance between outer skin to LNG tank.
- FE analysis with dropped objects from crane operations that hit fender protections for LNG fuel tanks.

Another accidental scenario that can be relevant for ships is explosion, and not only related to the presence of hydrocarbon on board. In the recent years, there is more focus on the environment, and battery systems for electric propulsion ships (for instance on ferries, offshore vessels, etc.) is considered as an effective climate mitigation action. However, with battery systems there is a risk for fire and explosions, and for instance Norwegian Maritime Authority (NMA) now requires additional documentation such as fire extinguishing philosophy and explosion analysis.

In the following chapters, analysis procedures of what is presently available for the analysis of the main categories of accidental scenarios is presented, with particular focus, when possible, on ships.

3. ABNORMAL ENVIRONMENTAL EVENTS

In addition to the ‘classical’ accidental situations corresponding to collision, grounding, fire, explosion and similar, which are characterised by rare events with so large consequences that they cannot be neglected, it is also relevant to consider situations associated with rare environmental actions.

Actions due to environmental loads are included in other scenarios, like those to be checked against SLS, ULS and FLS (see chapter 2 above). The justification for introducing a new class of scenarios regarding environmental effects stands in the activation of a different risk generation mechanisms due to the presence in abnormal events of different phenomena in the actions themselves and/or of different effects in respect to those produced in the other scenarios.

For marine structures, abnormal environmental actions are mainly represented by extremely high waves. They feature, in comparison to the (relatively) lower waves relevant for ULS design, more severe kinematics near the free surface and also a different type of wave-structure interaction (for example: a wave hitting the deck has a different effect than one impacting only on the legs of a platform).

The models adopted for describing waves and their effects within ULS, FLS and SLS checks are not able to capture these different aspects, which need to be treated in a specific way with different models. The very low probability of occurrence of the abnormal wave events and their characteristics and effects justify the classification of these situations within the ‘accidental’ (in a broad sense) scenarios.

3.1 Abnormal waves

Rare events with long return periods are in principle included in the tails of the probability distributions of the extreme crest height used in ULS analysis. As Figure 1 shows, even a limit corresponding to the height of a wave with return period of 10 000 year can be exceeded with a non-negligible probability in 25 years. However, the major contributions to the probability of exceeding the ULS come from waves with return periods of the order of magnitude of the design lifetime of the structure. For checks formulated in LRF or PSF formats, as mentioned above, characteristic values for wave and wave effects are set with typical return periods of 25 and 100 years for ships and platforms, respectively. Models of wave loads aimed at describing events with those return periods are unable to capture the wave in deck load and local pressures near the wave crest, typical of events with a much longer return period. Abnormal occurrences can also result in wave events that are steeper and higher than the surrounding waves.

The need for proper models of larger wave events has indeed focused the attention of the scientific and technical community, also because detailed experimental records were obtained for a number of very high single wave events in the last twenty years. These records shed a new light on previous reports of other extraordinary waves and of extraordinary damage events occurred to ship structures around the world. These data have prompted an intense research activity aimed at modelling in a proper way the mechanism of generation, the frequency and the characteristics of those events. The details of these discussions are quite complicated and fall outside the mandate of this committee. They have been documented extensively for instance in the last reports of the Committee I.1 of ISSC ‘Loads’ (see Bitner-Gregersen et al., 2012, 2015 and 2016).

3.2 Abnormal wave design loads for offshore structures

As reported in Czujko et al. (2015), in simplified checks for offshore platforms, based on characteristic values of wave height, abnormal environmental loads are defined with reference to events with a yearly probability of exceedance of 10^{-4} (as for other accidental scenarios), see ISO (2007) and NORSOK (2007). Slightly different approaches were originally used to determine the necessary design airgap in the above standards for the 10^{-4} wave event. More recently, a general concern for a worsening of sea conditions also due to climate changes has necessitated stricter design requirements. Thus, STATOIL introduced an internal conservative design requirement for the air gap of platforms accounting for the 10 000 year wave elevation increased by 10%. According to simple patterns like those of Figure 1, this 10% increase in the characteristic value corresponds to lowering the exceeding probability to about $1.5\ 10^{-5}$ in 25 years (if computed on the same base distribution of wave heights).

A recent formulation is contained in NORSOK (2017). Also in this case, to design the air gap between the sea surface and the deck of fixed platforms, it is strongly recommended to use a value of at least 1.1 times the 2nd order crest height (with probability 10^{-4}), plus the combined tide and storm surge. Another option to satisfy the same requirement of positive air gap, is to evaluate higher order wave effects and spatial statistics of wave elevation in detail. Alternatively, wave-in-deck scenarios are to be applied.

The effect of climate changes on permanent facilities with a planned service life of more than 50 years is considered, too. The motivation is that future wave, wind and sea level conditions are predicted with considerable uncertainty by the current models. In lack of more detailed information, the following increase in metocean characteristic values for predictions 50 years ahead is recommended in NORSOK (2017):

- extreme wave heights: +4% on characteristic values
- extreme wind speeds: +4% on characteristic values
- sea level: +0.25 m

The increase is to be applied for both the 100 years return period wave (design scenario for ULS verifications) and for the 10,000 years return period (design scenario for ALS verifications).

In the cases reported above, more restrictive requirements are set (in terms of a 10% increase in the height of the deck over the still water level) in order to improve, in respect to previous prescriptions, the safety of the structure as regards water on deck events. A question is raised, however, about the foreseen probability of exceeding the new limit. Currently, there is no definite answer to this (see later).

The increments in the platform height required by the most recent requirements are apparently justified as a consequence of new knowledge about actual wave events (now recognised to be higher than what before modelled, because of new effects included in wave models and/or of climate changes). No mention was found to a modification in exceeding probabilities. This can be interpreted as an indication that the new requirements are meant to re-establish the original probability of exceedance (10^{-4} in a year, 2.5 10^{-3} in 25 years) in the presence of a more severe distribution of wave heights. On the contrary, these requirements could have had in part also the implicit aim of reducing such probabilities.

3.3 Comments to offshore scenarios

The trend of research in the field of wave models is to obtain a comprehensive model for sea waves, able to capture effectively the whole spectrum of wave events, including the most rare ones, and to predict correctly their characteristics and frequency of occurrence. The improvement of wave models imply changes in the description not only of the crest elevation, but also of all the characteristics of the wave field (kinematics, steepness, etc.) that are essential to model the effects on the structure. A key point for a proper consideration of the scenario corresponding to an abnormal wave event remains however linked with the wave hitting or not the deck and the modelling of this situation.

It is to be noted that when designing the airgap of fixed platforms, the underlying idea is to move the event of a water impact on the platform deck in the region of 'negligible risk' by reducing so much the probability of occurrence that even a large consequence would not contribute significantly to risk. This way, a proper evaluation of the consequences of water on deck can be avoided. In principle, however, any platform, designed with any air gap, is subject to the possibility that a rogue wave reaches the deck and this would imply consequences, both for the global and local response of the structure. The probability for this to occur may be very low (and a good model is needed to evaluate it), but it will never be null. The risk associated with this situation is limited by the low probability of occurrence of the wave but, on the other hand, may be easily enhanced by large consequences. An exceeding probability of 10^{-4}, like that of the base event on which the present requirements on air gap seem still to be based, is low, but not low enough to consider negligible the corresponding risk (and to avoid a consequence evaluation of the exceedance). Consequences evaluation is actually carried out for other hazards at similar probability levels (fire, explosions, collision, dropped objects, grounding). The assumption that a proper consequences analysis can be avoided by compliance with the above airgap provisions appears therefore questionable in the context of a risk oriented design.

A consequence analysis of waves hitting the deck would provide the possibility of carrying out a cost benefit analysis on the design air-gap, and also the possibility of investigating the robustness of the structure to these events (and of increasing it, if applicable).

The possible introduction of an accidental scenario for waves hitting the deck of a fixed platform should include a wave actually reaching the deck. A possible way of formulating this scenario would be to take, as representative wave, one corresponding to a given height of water over the deck. The probability of occurrence of this scenario should of course be evaluated as an important characteristic, but also consequences and possible escalation of consequences should be quantified and can provide important information for design improvements.

3.4 Possible definition of abnormal wave scenarios for ships

A possible update of the currently used wave models (that are basically the same for ships and platforms) would imply an update also in the probability distributions of wave effects on ships. In particular, the increased frequency of occurrence (confirmed by theoretical analysis) of waves steeper than those provided by earlier models could suggest (in parallel with what already happened for the air gap of platforms) a revision of the present free board prescriptive requirements for ships. It is interesting to note that, due to the different response of floating structures, the worst situation refers to waves with a length similar to that of the vessel and not to longer waves (that are in general higher). Accordingly, free-board provisions do not contain explicitly parameters referred to waves, but only to the ship geometry.

In parallel with the situation of fixed platforms, a significant non-linearity in the structural response of ships to wave action is surely occurring both when the seawater floods the deck (green water event) and when the ship bottom hits the water surface (slamming event, possibly followed by a transient response of the hull girder: whipping). Both these events (which have a different probability of occurrence) have implications in terms of global and local response of the ship structure and may give rise to significant risk contributions.

Presently, these aspects are covered in an implicit way by design and operational prescriptive requirements issued by Class Societies. Minimum values are set and checked during the loading process for the free board (distance between the weather deck and the water plane in loaded conditions and for the draft of the ship). Bow and forward bottom impact loads are also considered since long time in Class Societies Rules in the context of ULS scenarios for local checks of the hull scantlings. Empirical values of green water pressures are set as well for the structural checks of exposed decks, bulkheads, hatchways and outfitting placed on the weather deck (see e.g. IACS 2017).

Explicit accidental scenarios dedicated to extreme weather events, however, have not been included so far in the design process of ships. They could be effectively adopted, and described in terms of actions, taking advantage of the recent progress achieved in wave model and above briefly mentioned. Also, as regards the models of effects, new possibilities of accounting for the non-linear effects of green water on deck in the context of hull girder loads have been reported, as well as the development of CFD techniques able to describe the dynamics of waves breaking on the deck. Some recent developments, referred to the EU funded EXTREME SEAS project are summarized in Bitner-Gregersen et al. (2016). Without going into more details on the development of these models, which is beyond the scope of the present text, it is here outlined that establishing accidental scenarios dedicated to extreme wave events seems to be possible in the near future. This would allow a more systematic exploration of innovative solutions aimed at risk reduction (possibly involving trade-offs between increases in free board and in deck scantling).

4. METHODS AND PROCEDURES FOR THE ANALYSIS OF ALS

4.1 Introduction

By definition, accidental limit state (ALS) and ALS design refer to structural integrity following an undesired situation, such as crash, impact, fire, collision or explosion. Due to the complexity of the situation and the physical size of the structures involved in such conditions, full-scale experiments are seldom performed. The usual approach for handling this is by performing numerical analysis and validation with scaled down experimental replications. This is showing that the correct Finite Element Method (FEM) analysis is crucial. Material models, definition of the loads and the boundary conditions require extra attention due to the nature of such accidental conditions with high strain rates or extreme conditions.

The analysis of extreme events on ship structure inherently involves plasticity and fracture. A key challenge is that both are inherently local material-scale or plate-scale phenomena and yet the analyses of interest typically have a length scale of tens of meters or more due to the large size of the structures of interest. Furthermore, planar shell elements are utilized for the vast majority of ALS analyses and these elements must be larger than the thickness of the plate structural member. Fortunately, since the typical analysis of an ALS seeks to capture gross structural behaviour, final deflections, and the gross extent of fracture and damage, only quantities that effect the overall structural response, i.e. material stress-strain and strain at failure, must be captured to address these disparate length scales. It is noted that for analysis cases where local structural details dominate the response modes, e.g. the analysis of connection details for internal explosions, a highly-refined FEM model of the relevant details is usually required. Such FEM's, due to the dramatic increase in computational power, have the potential to capture the details material response such as crack initiation and propagation.

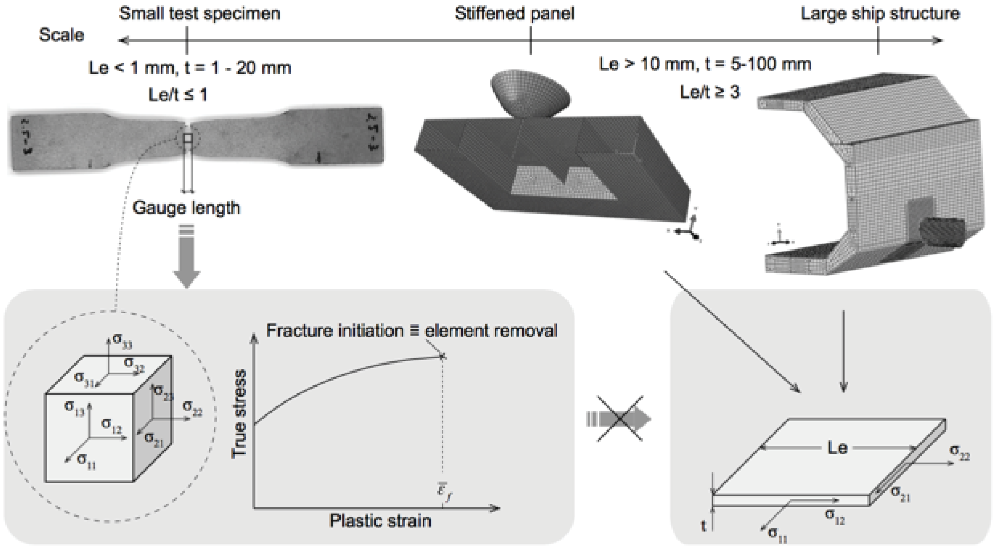


Figure 3: Illustration of the different scales in fracture analysis:
small test specimen, stiffened panel and large-scale ship structure.

When only the energy absorbing capacity of a ship during an impact event is needed, analyses can be limited to either FEM analyses up to failure or analytical or empirical solutions. For instance, the most well-known simplified empirical approach to collision analysis was made probably by Minorsky. In (Zhang and Pedersen, 2016) a simplified method for energy absorption is presented, based on plastic tension damage and crashing and folding damage. The rupture strain of the material is obtained from standard uniaxial tensile tests.

However, using the last couple of decades, the requirements related to the crashworthiness of ship structures were often broadened and involve hazards linked with pollution, stability in damaged condition and ultimate strength of a damaged ship. Further, there was a shift from deterministic methodologies to probabilistic methodologies, which are used both for the assessment of the crashworthiness of a structure as well as the effectiveness of risk control options.

These concepts also set different requirements to the methodologies that are used for the simulation of the impacts: it is, therefore, no longer appropriate to use a rupture criterion "uncoupled" with the simulation, but it is necessary to integrate the criterion in the FE software to simulate the propagation of rupture. This is now essential, because the required output, which is subsequently used for the calculation of oil outflow, the time to capsize and the ultimate strength, is the description of the damage rather than the energy absorption capacity of the structure until rupture. For the determination of the extent of the rupture and damage in case of impact, it is not considered appropriate to use methodologies based on plastic collapse mechanisms, because such methodologies do not simulate the propagation of rupture other than the tearing of plate structures, when they are penetrated by an impactor moving parallel to the plate.

For all materials of interest, the analytical description of material behaviour consists of a constitutive model, which relates stress and strain, and a fracture model that describes the point of rupture. More advanced models couple the fracture and constitutive model to achieve a unified description of material behaviour. Since the fracture process has a length scale that is smaller than the resolution of the analysis, a mesh dependency of the fracture criteria is also required.

Within this chapter both developments and currently commercially available material models for several materials, such as steel, composites, foam, rubber, ice and soil, are discussed. First recent developments in modelling details and response evaluations are given. Furthermore, developments in standards are discussed. Looking at the applicability of material models for ALS, models of course include non-linear material behaviour and progressive failure.

4.2 Modelling details and response evaluation

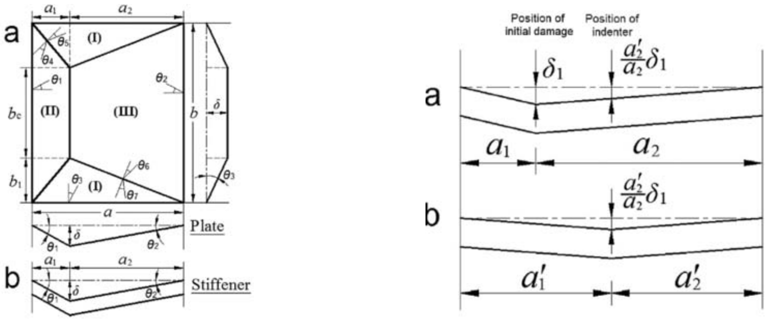
Dynamic responses of a ship structure under the collision accidental scenario are related to many nonlinear effects, including load nonlinearity, geometry deformation nonlinearity and material nonlinearity et al. Modelling these nonlinear characteristics with proper methodology and analysis tool has been a challenge facing scholars and ship designers. In addition, the accuracy of response evaluation of ship structure under collision accidental scenario has to be relied on the qualities of analysis modelling details. Currently, analytical methodology, numerical simulation methodology and model testing methodology are the three tools used most frequently. The latest research outcomes of these three methodologies are summarized in this part.

4.2.1 Analytical methodology on response evaluation

Analytical method has always been granted as one of the most conveniently used methods to predict structural dynamic responses during ship collision and grounding scenarios, when interest is limited to energy absorbing capacity and failure initiation. The structural dynamic responses, including deformation resistance and energy dissipation, though much complicated due to their nonlinear characteristics, can be approximately estimated by analytical formulae within a short time. And the high efficiency and low cost on human labour and calculation time make analytical method much welcomed by ship designers. The analytical expressions for nonlinear structural deformation and responses are established based on internal elastic-plastic mechanisms, and external kinetic dynamics.

The prediction with analytical method for dynamic responses of ship shell, deck, girder and web-frame are mostly developed. The analytical method can be used separately to predict structural response of single structural component, and can also be integrated to predict global structural response of ship side or ship bottom during the ship collision and grounding scenarios.

Stretching of shell plating is playing a dominant role under ship collision scenario. Liu and Soares (2015a) proposed simplified evaluation methods to assess the energy dissipation for stiffened side shell plating under minor rigid bow striking scenario, and further (Liu, et al., 2015b) built a set of analytical methods to predict structural resistance and energy dissipation of stiffened-shell plate and that of damaged shell plate, under the striking of wedge-shape indenter during a quasi-static collision process. The initial minor collision damage is involved to evaluate the total damage of shell plating. The shell deformation mode they used is shown in Figure 4. Similarly, Sun and Hu (2015) investigated the structural deformation resistance of side shell plate under raked bow collision scenario. The deformation of stiffeners attached on the side shell is taken into consideration, and an analytical method for the instant structural resistance of side shell under raked bow striking is proposed.



(a) Deformation mode of intact shell plating (b) Deformation mode of damaged shell plating

Figure 4: Deformation mode of shell plate under minor collision scenario

The in-plane deformation mode of the ship girders and webs is the one of the essentials to predict resistances and energy dissipations of these structures under collision scenario. Deformation models of girder and web have been proposed, including Gao and Hu (2014), and Liu and Soares (2015). Liu and Soares (2016a) further developed analytical method for estimating the crushing behaviour of web girder with stiffeners under collision scenario. Most of these models can be used to predict the deformation resistances with acceptable accuracy. Furthermore, the recent proposed analytical formulae are compared with those proposed in the past researches in Table 1.

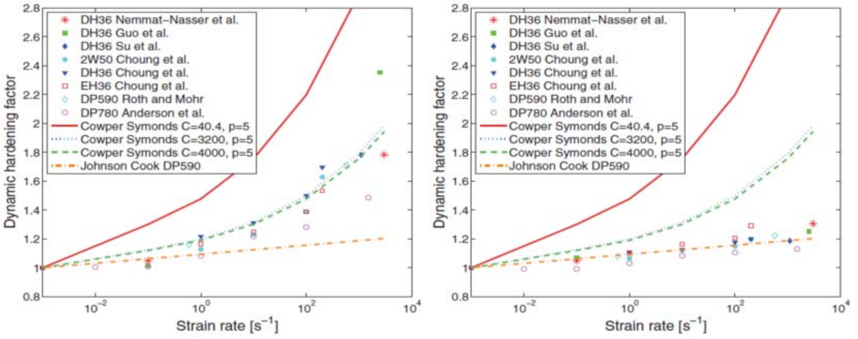
Table 1 A summary of some existing simplified analytical methods for predicting the crushing resistance of web girders

Method	H	λ	F_m	F(δ)
Wang （1995）	$H = 0.811b^{2/3}t^{1/3}$	0.67	$\frac{F_m}{M_0} = \frac{11.68}{\lambda}\left(\frac{b}{t}\right)^{1/3}$	-
Simonsen （1997）	$H = 0.671b^{2/3}t^{1/3}$	1	$\frac{F_m}{M_0} = \frac{14.76}{\lambda}\left(\frac{b}{t}\right)^{1/3}$	$\frac{F(\delta)}{M_0} = \frac{4b}{H\sqrt{1-(1-\frac{\delta}{2H})^2}} + \frac{12H}{bt}\delta$
Zhang （1999）	$H = 0.838b^{2/3}t^{1/3}$	0.75	$\frac{F_m}{M_0} = \frac{11.26}{\lambda}\left(\frac{b}{t}\right)^{1/3}$	$\frac{F(\delta)}{M_0} = 4.37t^{-1/6}b^{2/3}\delta^{-1/2} + 4.47b^{-1/3}t^{-2/3}\delta$
Simonsen and Ocakli （1999）	$H = 0.377b^{2/3}t^{1/3}$	1	$\frac{F_m}{M_0} = \frac{18.72}{\lambda}\left(\frac{b}{t}\right)^{1/3}$	$\frac{F(\delta)}{M_0} = \frac{3b}{H\sqrt{1-(1-\frac{\delta}{4H})^2}} + \frac{22H}{bt}\delta$
Hong and Amdahl （2008）	$H = 0.395b^{2/3}t^{1/3}$	-	$\frac{F_m}{M_0} = \frac{17.0}{\lambda}\left(\frac{b}{t}\right)^{1/3}$	$\frac{F(\delta)}{M_0} = \frac{1.2b}{H\sqrt{1-(1-0.3\frac{\delta}{H})^2}}\left(2+\frac{1-0.3\frac{\delta}{H}}{3+(1-0.3\frac{\delta}{H})^2}\right) + \frac{22.24H}{bt}\delta$
Liu and Soares （2015）	$H = \left(\frac{\pi}{36}b_1b_2t\right)^{\frac{1}{3}} = 0$	-	$F_m = \frac{E}{3H} = \frac{\pi}{6}\sigma_0 t^2 (b_1$	$F(\delta) = \frac{\dot{E}}{\dot{\delta}} = \sigma_0 t^2 \frac{(b_1+b_2)}{3H\sqrt{1-\left(1-\frac{\delta}{3H}\right)^2}} + 2\sigma_0 tH\delta\left(\frac{1}{b_1}+\frac{1}{b_2}\right.$
Gao and Hu （2014）	$H = 0.193(b_1b_2t)^{1/3}$	-	$F_m = \frac{0.75\pi M_0 b}{H} + \frac{40}{}$	$F(\delta) = \frac{1.5M_0 b}{H\sqrt{1-(1-\frac{\delta}{8H})^2}} + \frac{10.2N_0 H\delta}{b}$

4.2.2 Numerical simulation methodology

Numerical simulation with nonlinear finite element method is one of the most powerful methodologies to estimate and evaluate structural responses during ship collision and grounding scenario and allows for the inclusion of progressive failure. These analyses can then be used in combined analyses including e.g. oil outflow or time to capsize. However, many uncertainties and challenges have not been overcome. And these are still obstructing the credibility of numerical simulation results to a further step. Many efforts have been made recently, gaining further insight in numerical simulation methodology. Among these challenges, the definition of structural failure criteria is of crucial importance. Proper definitions of element failure criteria will bring accurate simulation and analytical analysis results. Presently, there are several structural failure criterion existing that have been used and evaluated frequently. These structural failure criterions include equivalent strain criteria, FLD, BWH, RTCL et al.

Storheim and Amdahl (2017) carried out research on the sensitivity to work hardening and strain-rate effects in nonlinear FEM analysis of ship collisions. They investigate the effect of various features of the complete stress-strain curve on the predicted outcome of a collision simulation. The slope of stress-strain curve is strongly dependent on the yield ratio, yield plateau and the elongation to fracture. In addition, Martin Storheim et al. (2015) also presented a fast and reliable method for failure prediction of coarsely meshed shell structures. That method is especially relevant when investigating the impact performance of offshore structures and typically stiffened panel structures. The failure model was based on stress-based BWH local instability criterion and a coupled damage model, and the failure model was incorporated into LS-DYNA code.



(a) (b)

Figure 5: Comparison by Storheim (2017) on dynamic hardening factors for initial yield stress and average flow stress at different strain rates. (a) Yield-stress ratio. (b) Flow-stress ratio.

Yoshikawa et al. (2016) analysed the fracture considering the effect of stress tri-axiality, and they anticipated that the accuracy of fracture analysis can be improved by taking account of the tri-axial effect on fracture strain, due to the reason that the equivalent plastic strain at the ductile crack initiation will decrease with an increase of stress tri-axiality. A. Gilioli et al. (2015) made an analysis of plasticity and fracture test of different type of helicopter tail rotor transmission shaft specimens, to calibrate the phenomenological Modified Mohr-Coulomb model and the empirical Bao-Wierzbicki fracture models, through numerical simulations. A. Shaw et al. (2015) investigated the behaviour of cantilever beams subjected to projectile impact at its tip, through a kind of free-mesh method. A study on modelling of rate-dependent material behaviour in simulation of collision damage has been carried out by Burak Can Cerik (2016), and it is observed that Cowper-Symonds constitutive modelling with parameters based on lower yield stress does not always yield conservative results.

During recent years, Arctic sailing route has made the research on the collision between LNG ship and iceberg more popular than ever, but the challenge on simulation methodology for LNG ship structure in cold region has not been resolved. The influence of brittle fracture criteria on the crashworthiness of ships and offshore structures in arctic conditions is investigated by Woongshik Nam and Jørgen Amdahl (2016). The brittle property of steel exposed to low temperature and in range of ductile brittle transition temperature (DBTT) was considered, and RKR model was used for brittle fracture prediction in numerical simulation. It was concluded that failure criterion for building material used on LNG CCS (cargo containment system) might be quite different from those of normal steel material. The anti-collision capability of LNG carrier and FLNG depends much on the failure limit of the material used in LNG CCS system. Myung-Sung Kim et al. (2016) proposed a failure criteria for the primary barrier of a Mark III-type liquefied natural gas CCS, and the criteria was established based on the instability, ductility and shear failure. Chun-sik Shim et al. (2016) also carried out a study on material used in LNG carrier CCS system.

4.3 Present application and recent development in current standards

For accidental scenarios, the most important standards can be listed as ISO 19900 series, NORSOK standards, DNV-GL standards (DNVGL-RP-C204, 2010; DNVGL-RP-C208, 2016), API Recommended Practice, ABS standard and Lloyd's Register guidance notes on ALS. A more detailed overview of the standards can be found in Czujko et al. (2015).

In the design standards, an overview of approaches is presented that can be used to identify and assess the effects of accidental structural loads arising from accidental actions. It is required that damage from accidental actions with reasonable likelihood of occurrence shall not lead to complete loss of integrity of the structure, and the load-bearing function of the structures must be maintained. The design must be dimensioned such that critical parts for the overall strength are strong enough to withstand an accidental action, or alternatively, can be dimensioned in order to minimize the consequences with a certain redundancy without causing failure. There are different levels of complexity in the approaches ranging from simplified methods with explicit formulas using hand calculations to advanced state-of-the-art numerical methods (FEM, CFD, etc.). Since the computer resources are increasing continuously it is more and more common to use numerical simulations.

The design standards are continuously updated in order to be more accurate and suited for today's practice using numerical simulations. In the most recent version of DNVGL-RP-C208, more examples with details have been included in order to give guidance on how to perform non-linear FE analysis, since experienced users is usually required to obtain reliable results. These examples give a relatively detailed description on FE modelling (material, mesh, boundary conditions, calibration, etc.), analysis procedure and post-processing of the results. In addition, a detailed procedure on how to calibrate non-linear FE analysis against a known solution is included.

The most recent DNVGL-RP-C208 contains also a library with FE models to be used in collision analysis. These are FE models of the bow, side and the stern corner of offshore supply vessels (OSV) and the models are prepared both in Abaqus and LS-Dyna formats that can be downloaded. The library with the FE models will bring more consistency on how finite element analysis are performed. Moreover, this makes it easier with 3rd party verification of non-linear FE analysis.

The main reason for including FE models for collision analysis was because the previous acceptance criteria and analysis methodologies are specified in design standards written decades ago, and based on offshore supply vessel (OSV) design with raked bow and 5000 tons displacement. Today, the modern OSVs are larger and often designed with bulbous bow. Consequently, higher impact energy must be absorbed in the event of a collision, and the Petroleum

Safety Authority Norway recommended to increase the ship impact design energies (Kvitrud, 2013). Increased energy levels for collision scenarios are now implemented into todays practice in DNVGL-SI-0166, 2016 and NORSOK N-003, 2017.

4.4 Material models to be used in FEM

4.4.1 Metallic Shipbuilding Materials

The dynamic behaviour of steel, aluminum, and titanium at high strains reaching near the point of fracture are well described by classical plasticity theory with adjustments for high strain-rate and anisotropic behaviour. The combination of von Mises plasticity with Johnson-Cook (Johnson and Cook, 1983) or other similar hardening rules have proven to be the mainstay of dynamic analysis. For materials such as aluminum, the yield functions of Hill (1948), Hosford (1972) have shown to produce highly accurate results e.g. Yield surfaces for anisotropic materials are well established and have been used for decades in a wide variety of relevant applications.

The determination of fracture proves to be more difficult to capture since the process of ductile fracture is driven by the growth and coalescence of voids on a micron length scale. Although the capability of highly resolved 3D calculations of fracture specimens to provide a predictive capability is evident, such computations require a resolution that is entirely impractical for structural analyses. This can be observed by reviewing the results of the Sandia Fracture Challenge, a recently completed round-robin blind ductile fracture prediction study.

Thus, within the context of ALS analyses of large marine structures, fracture can only be included in a phenomenological manner by "encoding" the material description with a reasonably description of fracture in the relevant length scale of the element, usually as a failure strain that is a function of the stress state and loading rate. The simplest approach to achieving this has been to select a single uniform strain value at which the local element fails. Although this approach does not capture failure in a physically accurate manner, it is simple to use and implement and can be easily calibrated to experiments. An improved approach is to use a strain to failure value that is a function of the stress triaxiality (ratio of mean to effective stress) and J3, the third invariant of the stress deviator tensor. For shell elements, it was shown by [Wiez, AHSS] that due to the assumption of plane stress, J3 itself is not an independent function of the stress triaxiality thus greatly simplifying the problem. On that basis, one recent failure criteria includes the combined effect of mesh size and stress triaxiality on the failure strain, see (Kõrgesaar and Romanoff, 2014; Walters, 2014). The reasoning behind such scaling framework is that mesh size dependency of the FE solution depends on the amount of strain localization, which varies depending on the stress state (Kõrgesaar, et al., 2014). Kõrgesaar and Kujala (2016) showed that such an approach can reliably reproduce, based on comparison with available experimental data, the force-displacement curves of smaller panels as well as large-scale collision experiments. The drawbacks of the approach are that the set-up of the framework still requires user defined material modelling capabilities from the analyst and that the approach does not cover the full range of deformation modes, it being calibrated only for multi-axial tension, but excluding shear and bending. The effect of bending on mesh size sensitivity of the analysis is discussed in Storheim et al. (2015), while the solution to the bending problem was proposed recently by Pack and Mohr (2017). In particular, to differentiate necking initiation under membrane and bending loading they consider the damage accumulation in individual thickness integration points separately. Furthermore, it was shown in a simple manner that a direct relation exists between failure in the Forming Limit Diagram (FLD) space. The FLD space is the failure locus in terms of in-plane principal strains, and effective strain to failure-triaxiality space. Thus, a Fracture Forming Limit Diagram (FFLD) can be developed. This is a useful visualization tool that shows the locus of fracture relative to the limit of necking.

In (Marinatos and Samuelides, 2015) the authors investigate the effect of material modelling in simulation of several indentation and drop weight tests. It is claimed that in most of the examined cases triaxialities are above 1/3rd. Also Storheim et. al (2015) conclude in their paper, in which they study the results of FEM analyses of a collision scenario using different failure modes, that strain state dependent models show a better prediction than strain state independent models. Since failure analyses are also done in the design state, they aim to calibrate the material models based on known data at that state, e.g. uniaxial tensile tests. From the models tested it was concluded that the BWH (Bressan-Williams-Hill instability criterion) with damage and RTCL (Rice-Tracey Cockroft-Latham damage criterion) criterion performed best.

Table 2 The failure criteria compared by Storheim et al. (2015)

Name	Description
BWH w. dam	BWH criterion with damage and geometric mesh scaling
BWH no dam	BWH criterion without damage but with geometric mesh scaling
RTCL	RTCL criterion with geometric mesh scaling
GL	GL criterion on ε_1 and ε_{thin}
SHEAR	SHEAR criterion on ε_{eq}
RPC204	RP-C204 criterion on ε_{eq}
Peschmann	Peschmann's criteria on ε_{eq}
Damage	Ductile failure with coupled linear damage evolution

A more recent comparison study is performed by Calle et al. (2017). They performed several experiments using dogbone-shaped sample geometries to evaluate the constitute models for shipbuilding material SAE 1008 carbon sheet steel. They studied four different failure models also concluding that BWH and RTCL performed best. Furthermore, they studied the effect of mesh refinement. In areas of high strain gradients, independent of the used failure models, the coarser meshes show inaccuracies. Therefore, they recommend avoiding meshes with an aspect ratio > 8 for these situations. Below information on both the BWH and the RTCL criterion is given.

The BWH criterion developed in 2008 combines the shear stress criterion of Bressan and Williams with the local necking analysis in plates presented by Hill. The aim of this method is to define the onset of necking in plates. BWH uses a forming limit diagram (FLD) developed in stress space and limits the principal stresses according to the following formula (Eq.3):

$$\sigma_{1f} = \begin{cases} \dfrac{2K}{\sqrt{3}} \left(\dfrac{1+\frac{\beta}{2}}{\sqrt{\beta^2+\beta+1}} \right) \left(\dfrac{\varepsilon_{1c}\left(\frac{t}{L_e}+1\right)}{\sqrt{3}(1+\beta)} \sqrt{\beta^2+\beta+1} \right)^n & \beta \leq 0 \\ \dfrac{2K}{\sqrt{3}} \dfrac{\left(\frac{1}{\sqrt{3}} \varepsilon_{1c} \left(\frac{t}{L_e}+1 \right) \right)^n}{\sqrt{1-\left(\frac{\beta}{2+\beta}\right)^2}} & \beta > 0 \end{cases} . \quad (3)$$

In this formula, β is defined as the relation between the minor and the major strain rates in the plane principal directions and can be approximated as $\beta = \dot{\varepsilon}_2 / \dot{\varepsilon}_1$. K and n are the strength coefficient and strain hardening exponent of the power law respectively and the ε_{1c} is a material constant.

The RTCL criterion developed in 2003 combines Crockroft-Latham model and Rice-Tracy model that are respectively based on ductile shear fracture (low triaxilities range) and void growth (high triaxiliaties). The damage development is determined by Eq.4

$$\mathrm{D} = \int_0^{\overline{\varepsilon_f}} f(\eta)_{RTCL} d\bar{\varepsilon} \tag{4}$$

Where

$$f(\eta)_{RTCL} = \begin{cases} 0 & \eta \le -\frac{1}{3} \\ \dfrac{2 + 2\eta\sqrt{12 - 27\eta^2}}{3\eta + \sqrt{12 - 27\eta^2}} & -\frac{1}{3} < \eta < \frac{1}{3} . \\ e^{\left(-\frac{1}{2}\right)} e^{\left(\frac{3}{2}\eta\right)} & \eta \ge \frac{1}{3} \end{cases}$$

An analytical approach applicable for shells exposed to multiaxial states of stress, including in-plane shear, is studied in (Walters, et al., 2017). This paper develops an analytical framework that enables the modeling of material wrinkle from their formation until material failure, accounting for triaxial stress effects. The analytical method results reasonably agree with finite element analysis especially for the folding behaviour of thin and moderately thick shells that have a single or a double curvature.

Usually the engineering stress-strain curve is not available at the design stage to determine the strain hardening of the material, and thus analytical expressions are required to estimate the flow stress curve. In (Liu et al., 2017) a new analytical expression is introduced to estimate the failure strain of coarse meshed ship structures struck by an indenter with hemispherical shape. This expression is derived by using finite element simulations of plate punching tests.

4.4.2 Composites

Composite material applications in the maritime field are mainly limited to novel navy ships, sport and leisure yachts and more recently energy harvesting and wind energy offshore structures. Composite materials are also used in the concept of sandwich plate (Notaro et al., 2013) to increase the collision resistance of ships and structures, such as polyurethane. Niklas and Kozak (2016) presented a concept of semi-elastic Steel–Concrete–Polymer structure which can absorb extra energy and protect water tightness of a compartment. Notaro et al. (2013) evaluated the rendering capabilities of a sandwich overlay consisting of a layer of elastomer. Kumar and Surendran (2013) used different kinds of fillers to develop cost-effective composites. Kim et al. (2003) and Rhymer et al. (2012) conducted experiments of carbon/epoxy composite laminates impacting with ice. Tiberkak et al. (2008) studied the fiber-reinforced composite plates subjected to low velocity. Mocanu et al. (2012), Gaiotti and Rizzo (2012) also performed investigations of fiberglass reinforced composite laminates.

Oterkus et al. (2015) reviewed the fracture modes, damage tolerances and fatigue mitigation in marine composites. And the techniques used in finite element modelling to determine the failure progress are listed: virtual crack closure technique; cohesive zone model (CZM); extended finite element (XFEM).

A recently developed continuum mechanics formulation called peridynamics is a tool for failure prediction based on mathematical formulations (Oterkus et al., 2015). Hu et al. (2017) studied the application of peridynamics to predict damage initiation and growth for composites under cyclic loading. Another recently proposed failure theory (Daniel, 2016) is Northwestern (NU-Daniel) theory which predicts the yielding and failure of multi-directional laminates under static and dynamic loadings. Daniel compares the other commonly used failure theories for carbon/epoxy composite under matrix dominated states of stress with transverse compression, transverse tension and in-plane shear. The results of NU-Daniel model, as shown in Figure 6, are in good agreement with the experimental results.

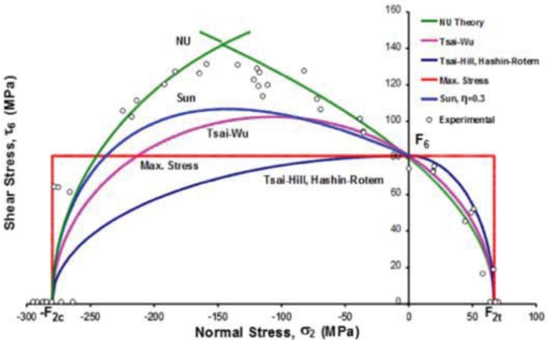


Figure 6: Comparison of failure theories and experimental results (Daniel, 2016)

Finite element modelling of nonlinear behaviour of composite structures at dynamic loading conditions are usually performed with Abaqus or LS-DYNA software. In 2017, Hassoon et al. (2017) showed the behaviour of two glass reinforced composite panels at different impact velocities. The model was developed in Abaqus and user defined VUMAT with Hashin criteria was applied for the 3D interlaminar damage model definition. Modelling of thick composites usually requires ply-by-ply simulation, which results in computationally expensive models. One alternative method is multi scale modelling approach. In 2016, Jia et al. (2016) studied the intra-laminar delamination failure of composites based on multi scale approach.

LS-DYNA has several material models available for composite structure modelling. The complete list of the material keywords that can be used for composite structures in LS-DYNA are provided in the LSTC website (LSTC) and have been summarized in the ANNEX, (Tables A1, A3).

4.4.3 Foam

Foam materials are often used within composite sandwich structures. The compressive behaviour of foam usually exhibit three regions; linear elastic, plateau and the final densification. Also for foam modelling, LS-DYNA has several keywords (see ANNEX, TableA2). Some of these models are mainly for compressive loading, others are capable of including strain rate dependent behaviour of foams. The strain rate dependent behaviour can be expressed as in Eq.5

$$\sigma(\varepsilon) = \sigma_o(\varepsilon)\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon_o}}\right)^{n(\varepsilon)} \tag{5}$$

$$n(\varepsilon) = a + b\varepsilon \quad \text{for} \quad 10^{-3} \le \dot{\varepsilon} \le 10^{2} \tag{5a}$$

where σ_0 and $\dot{\varepsilon}_0$ are the quasi static values of stress and the strain rate, a and b are material constants that can be experimentally obtained.

One common issue with modelling foam under large deformations is the negative volumes of the elements which occur due to excessive distortion. In Ls Dyna, a negative volume calculation will cause the calculation to terminate unless ERODE in *control_timestep is set to 1 and DTMIN in *control_termination is set to any nonzero value in which case the element is deleted and the calculation continues (LSTC). Other recommendations to overcome the negative volume issue are listed here

- Stress vs strain curve can be stiffened up at large strains
- Tailor initial mesh
- Reduce timestep scale factor
- Avoid fully integrated solids which are usually less stable
- Increase DAMP parameter to 0.5 (LSTC)

In 2015, Chen et al. (2015) investigated the blast performance of insulated sandwich panels that consisted of extended polystyrene foam (EPS) and steel skin. They performed simulations using LS-Dyna and the *MAT_CRUSHABLE_FOAM. They compared the experimental results to the numerical ones and pointed out that the results were reasonably accurate. More detail on the comparison study can be found in their previous publication (Chen and Hao, 2014).

Perhaps one of the most comprehensive study on the foam modelling is done by Srivastava et al. (2014). On the performance of LS-DYNA for accurate modelling of foams, they mention that there is no model that can incorporate the different processing parameters, models usually capture limited loading types and usually unloading behaviour is not incorporated. They highlight that Mat 57 in LS-DYNA (Low Density Foam) is suitable for static loading, while Mat 83 (Fu Chang Foam) is suitable for rate sensitive dynamic loading. In ABAQUS, hyperfoam and Crushable Foam Plasticity Model are mentioned. Their review results highlighted that the researchers usually perform investigation using ABAQUS however, industry mostly prefers LS-DYNA, Pam-Crash or Radios. They report that in LS-DYNA, selection of Mat 57 and Mat 83 for modelling EPS resulted in ~28% difference in energy absorption values. Different theoretical models that were proposed throughout the years were schematically shown in the same paper (Srivastava and Srivastava, 2014) . This paper is certainly recommended to get a quick review of foam models.

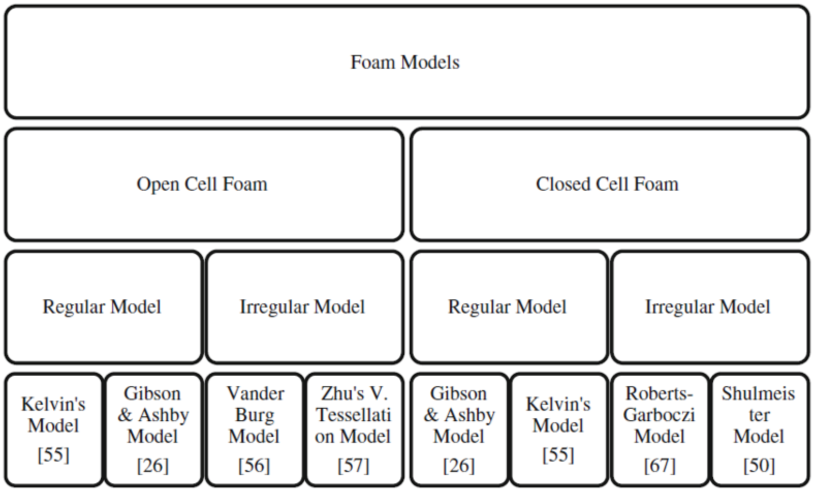


Figure 7: Theoretical models for foams (for the cited references see Jia et al., 2016)

Fang et al. (2015) developed a 3D mesoscopic model for closed-cell foams based on the behaviour of the entrapped air in the cells and the surrounding cell walls. They first randomly create a 3D model grid, then couple this with LS-DYNA. The ALE analysis is used to take into account the Fluid Structure Interaction (FSI). They compare the numerical results to experimental ones to validate the model. They use hydrocode in LS Dyna with ALE algorithm to model the static and dynamic behaviour of aluminum foam. The FSI is activated by using CONSTRAINED LAGRANGE IN SOLID card in LS-DYNA. Cell walls were modelled with Lagrangian elements (with SECTION SOLID keyword) and the air in cells with ALE elements (SECTION SOLID ALE). The material model is composed of two parts; the first part controls the yield strength and the second part is the equation of state the determine the hydrostatic pressure. In the model developed by Fang et al. PLASTIC KINEMATIC model, material type 3 was used for the cell walls without the strain rate effects. The maximum strain failure criterion was adopted in the Mat Add Erosion card; when the maximum tensile strain of cell-wall is larger than 0.37, the cell walls fail. Air in the cells were modelled with Mat Null (Mat type 9) card with the ideal gas state equation. Figure 8 shows the model, loading and the static compression results. In this model, CONTACT AUTOMATIC SURFACE TO SURFACE in LS-DYNA, was used to model the contact between the panels and the specimen and between all the cell-walls in the specimen. Similarly, dynamic simulations were also performed and compared to the experimental results. In the dynamic results, the entrapped air within the cells has greater effect at large deformations.

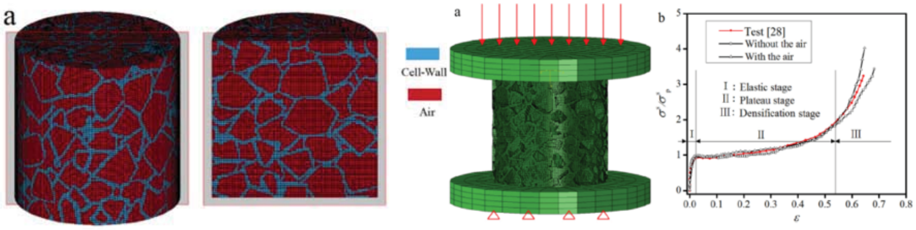


Figure 8: 3D mesoscopic model for closed-cell foams (LSTC).

4.4.4 *Rubber*

Xiao et al. (2015) published a comparative study on honeycomb rubber coatings that can be used as an energy absorber when applied on a ship structure. They considered three different cell geometry, and studied their behaviour and energy absorbing capacity in the event of underwater explosion. They first performed experiments, then numerical analysis of honeycomb coatings using ABAQUS. They modelled the geometry using CPE4R elements which are 4 node bilinear plane strain quadrilateral, reduced integration, hourglass control elements. The structure was compressed with a constant loading rate at the speed of 1, 10 and 30 m/s. Nonlinear stress vs strain behaviour of rubber was modelled with hyperelastic constitutive model based on assumption of isotropic behaviour. They compared five different models to the actual test data on the selected material, and decided to continue the analysis with the Arruda-Boyce model which captured the behaviour of neoprene, the rubber used in their study.

Rate dependency and hysteresis of neoprene rubber is also considered taking into account the viscoelastic model based on Prony series with the damping effect of the material. They conclude that the simulation results suggest that the compression speed and cell topology have a strong influence on the coating's dynamic compression performance.

4.4.5 *Ice*

Gao et al. (2015) simulated the impact of a ship with an iceberg. In their paper they proposed an isotropic elastic- perfectly plastic material model to represent ice and incorporated the material model in LS-DYNA via a user subroutine. The failure model depends on the effective plastic strain and hydrostatic pressure. The properties assumed for the iceberg are given in the Table 3 below:

Table 3 (Gao et al., 2015).

Ice material parameters			
Element type	Solid	Density [kg/m^3]	900
Number of element nodes	8	Poisson's ratio	0.3
Number of element integration points	1	Young's modulus [MPa]	9500
Element length [mm]	50	Cut-off pressure; tension strength [MPa]	2
Strain rate	>10^{-3}	Strain hardening function	none
Limit of the elastic strain	10^{-3}	Limit of elastic stress [MPa]	9.5

Similarly, Kim (2014) has developed a user defined material model for ice to be incorporated in Ls Dyna. The material characteristics were taken from experiments. She assumed two different failure criteria; a generalized strain based and a triaxiality dependent criterion which produced similar results for ice crushing loads for scenario where ice impacts a steel panel at 2 m/s velocity. More recently, Shi et al. (2017) simulated a similar scenario where a spherical iceberg impacts a steel plate at 1 m/s velocity. The ice material model had two types of yield surface functions; Tsai-Wu and n-type. The failure criterion was based on the effective plastic strain and hydrostatic pressure. The implementation of this model is similar to the one performed by Gao et al. (2015). In contrast, Ince et al. (2016) presented a cohesive zone based ice material model that was validated with drop tests. The measured and simulated response showed good correspondence. However, it must be stressed that response includes the combined effect of ice (dropped cone) and steel response from deforming structure meaning that discrepancies between simulation and experiment cannot be explicitly singled out and assigned to the steel material model or the ice material model.

In Ferrari (2015) a material model describing the mechanical properties of ice is implemented in FORTRAN, for use during finite element analyses of the impact (performed using the software Abaqus CAE). The parameters affecting granular ice behaviour are reviewed in the paper, then, following (Liu et al. 2011) a numerical model describing the ice behaviour is formulated, based on a yield function and a failure criterion. The yield surface selected for the study was proposed by Liu et al. (2011), corresponding to the Tsai-Wu surface formulated for isotropic materials. In particular the considered case corresponds to a temperature of -11ºC, for which the surface parameters were derived empirically by Derradji-Aouat (2000). A failure criterion with a parabolic dependence on pressure was implemented following again Liu et al. (2011). The ice model is applied in a first case to a specific situation considering a spherical iceberg of given radius impacting the side of a specific ship (Ferrari et al. 2015). The problem is decoupled, following the NORSOK method, into the analysis of a deformable iceberg impacting a rigid ship side and the analysis of the 'mirror' situation (rigid iceberg against a deformable ship). For the latter case, reference is made to previous results (Addario et al. 2014). Outputs from the two analyses are coupled, assuming that the results, separately derived, can be jointly applied to the real case of an impact between two deformable bodies. The results obtained in this first application confirm that a significant part of the impact energy is actually dissipated by ice deformation, but they are still valid under the simplifying hypothesis of neglecting the contact interactions between the two deformable bodies. The implemented material model can be integrated in the FEM analysis to study the coupled problem.

4.4.6 Soil

Wang et al. (2017) performed a numerical study using a 2D LS-DYNA model to develop a simple and quick assessment of the ground deformation of granular soils due to dynamic compaction which can successfully be implemented to moist and dry granular soils. The assuming loading was a drop of a 40 tons tamper from a height of 15 m. The developed model takes into account the physical phenomena in a compaction process with the dynamic equation of soil and the nonlinear material behaviour of soil as well as the soil-temper interaction. For the soil model they assumed a cap model which is the yield surface due to compression.

5. COLLISION

Collision is a major hazard to the safety of ships and other offshore installations and may result in severe economic loss, environmental pollution and fatalities. Scholars and researchers have strived for establishing a broadly acknowledged methodology, which can be used conveniently and with affordable cost and time to predict and evaluate the responses of the struck items and the striking ships. However, there are still many problems to be resolved before such a methodology can be accepted by the naval architecture and offshore engineering field. During the past years, many efforts have been made right in this direction. A summary of the latest research outputs according to the different ship collision categories is presented in this chapter. Then, the most critical and relevant conditions, including the analysis and design approaches and model test investigations are described. Finally, acceptance criteria for evaluation and corresponding consequences are discussed.

5.1 Ship collision categories

Nowadays, ship collision accidents can be approximately divided into four categories, which are: ship-ship, ship-offshore structure, ship-bridge and ship-iceberg collisions.

5.1.1 Ship-ship collision

Recent researches on ship-ship collision mainly focus on collision-avoidance and quantification of consequences after an accident. Collision-avoidance researches aim at proposing methods for safe manoeuvring. You and Rheeba (2016) made a prior study aimed at solving the intrinsic problem of the critical collision condition, including slower ship's dilemma by considering the manoeuvrability of the own ship and the International Regulations for Preventing Collisions at Sea (COLREGs). They developed a collision ratio that can be used to determine the time at which to begin the collision avoidance manoeuvre. Szlapczynski and Szlapczynska (2016) developed analytic formulas for domain-based collision risk parameters: degree of domain violation (DDV) and time to domain violation (TDV), with the purpose of overcoming the drawback of DCPA and TCPA, which lack efficient analytical solutions in real-time system where computational time is essential. Zhang et al. (2016) proposed a novel method detecting possible near miss ship–ship collisions from AIS data and then discussed how the near miss data can be used to gain further insight in safety of maritime transportation. Zhang et al. (2015) studied a multi-ship anti-collision decision support formulation in a distributed and real time way. It was proved that the formulation can avoid collisions when all ships have complied with COLREGs as well as when some of them do not take actions.

Researches on internal and external mechanism provide understanding of the responses under ship collision scenarios. Zhang et al. (2017) further analysed the validity and robustness of the closed-form analytical methods they proposed in 1998 and further improved the accuracy of some parameters, with 60 experimental results. A simple way of accounting for the effective mass of liquids with free surface carried on board of a ship was also introduced, and it was proved that the analytical procedure can be expanded to take into account the effect of ship roll on the energy released for crushing. By using the nonlinear finite element code LS-DYNA, Yu and Amdahl (2016a) firstly proposed a new coupled approach for a simultaneous calculation of the structural damage and of the 6DOF ship motions in ship collisions. The proposed method is particularly useful for design purposes because a detailed ship hull shape is not needed. The innovative procedure is shown in Figure 9. In addition, Yu et al. (2016b) upgraded the approach taking into consideration the hydrodynamic loads, based on linear potential-flow theory in the LS-DYNA code. Thus, fully coupled six degrees of freedom (6DOF) dynamic simulation of ship collision and grounding accidents can be carried out, while ship motions and hydrodynamic loads have always been neglected in previous investigations.

B. Liu et al. (2015b) proposed a simplified analytical method to examine the energy absorbing mechanisms of small-scale stiffened plate specimens, quasi-statically punched at the midspan by a rigid indenter with a knife or a flat edge shape. Both experiments and numerical simulations were carried out to validate the analytical method. Calle (2017) summarised a series of experiments including scaled collision tests of a T cross-section beam, head-on collision of an oil tanker against a rigid wall, ship grounding and collision between two oil tankers, to validate their finite element analysis. They indicated that the mechanical properties of materials, slight misalignments in test arrangements, failure criteria, weld joints and sloshing effect of ship cargo all influence differences between numerical and experimental results.

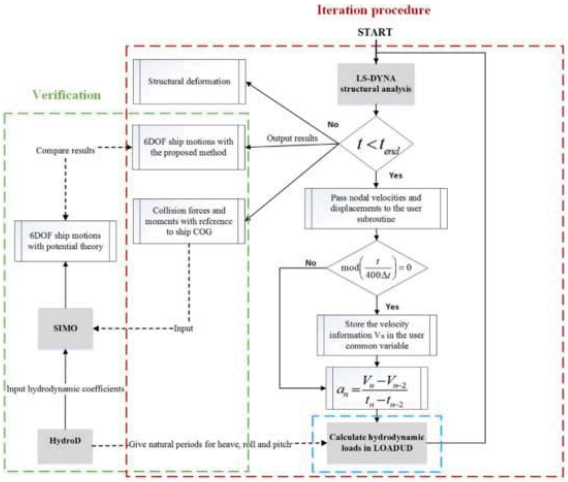


Figure 9: Illustration of the coupling algorithm

5.1.2 Ship-offshore collision

The public concern on ship collisions with offshore structures mainly focus on the consequences. Because the repairing cost for the offshore structure is higher than that of the striking ship, many researches are concentrated on the method to increase the crashworthiness of offshore structure during accidental collision scenarios. Furthermore, with the increasing number of offshore wind turbines along the coastlines, collisions between sailing ships and offshore wind turbines may become more frequent.

Zhang and Terndrup Pedersen (2015) conducted an analysis on collision energy and structural damage in ship - offshore platform collisions for various scenarios. They considered ship collision with offshore installations as one of the key concerns in the design and assessment of the performances and safety of platforms. An example of an ice-strengthened supply vessel colliding against a jack-up rig was analysed and the crushing resistance of the involved thin-walled structures was evaluated. Travanca and Hao (2015) analysed the energy dissipation in high-energy ship-offshore jacket collisions, with the aim of providing a clearer understanding on the strain-energy dissipation phenomenon, particularly as regards the ship-structure interaction. Vinnem et al. (2015) discussed the need for online decision support for FPSO–shuttle tanker collision risk reduction.

One of the most effective way to improve the crashworthiness of jacket platform is to analyse the anti-collision capability of the beam members. Pham and Hao (2017) investigated the plastic hinges and inertia forces in RC beams under impact loads. Cerik et al. (2016) analysed the resistance of ring-stiffened steel cylinders subjected to low velocity mass impact. Furthermore, they also made a comparative study on the damage of tubular members subjected to mass impact. They studied the influence of the geometrical parameters and the interaction between the local shell denting and the global beam deformation modes. Zhang et al. (2016) carried out a theoretical study of low-velocity impact of geometrically asymmetric sandwich beams. Liu and Guedes Soares (2017) carried out model testing and numerical simulations on the influence of impact location on the plastic response and failure of rectangular cross section tubes struck transversely by a hemispherical indenter. Z.Wang et al. (2016) analysed the structural dynamic responses of T- joint of jack-up platform laterally punched by a knife edge indenter, through experimental and numerical simulation methods.

Although serious collision accidents between ships and offshore wind turbines have seldom been reported, the concern for this kind of accident has brought quite a number of related researches. Bela et al. (2017) carried out an analysis on ship collision with the monopile foundation for offshore wind turbines. They concluded that a slight variation of the impact velocity can lead to consequences ranging from minor damage of the OWT to total collapse. Hao and Liu (2017) made an evaluation and comparison for the impact-resistance performances of three typical types of foundations for offshore wind turbines: monopile, tripod and jacket. They found that the jacket solution features the minimum collision force, damage area and nacelle acceleration as well as a medium value of bending moment and steel consumption among the three types of foundations. In addition, C. Liu et al. (2015) proposed a crashworthy device for the monopile offshore wind turbine against ship impact, and completed the optimisation and application analysis.

5.1.3 Ship-bridge collision

Bridge structures across navigable waterways are vulnerable to barge collisions, and bridge pier can be struck by ships frequently. Bridge damage might lead to catastrophic consequences to life and economy. A few innovative bridges, such as the Norwegian floating bridge and tunnel concepts for the project “Ferry free coastal route E39” are also making a critical concern on the ship collision load. It is therefore of great importance to protect bridge structures, especially bridge piers, against impacts from vessels. As a typical engineering practice example, Sha and Amdahl (2017) analysed as case study the collision of a ship against the Bjørnafjorden floating bridge. The global response under ship collision loads was simulated, including the first vibration modes of the bridge. Sha and Hao (2013, 2014a, 2014b) conducted a series of investigations on the ship-bridge collision scenarios, through an analytical method, numerical simulations and model testing methodologies. Sha and Hao (2014a) also proposed a simplified approach for predicting bridge pier responses subjected to barge impact loading, considering material nonlinearity and structural damage. In addition, Sha and Hao, (2013) used numerical simulations to investigate the dynamic responses of continuous girder bridge and bridge damage detection after barge impact accidents. Bridge vibration responses before and after vessel impact were computed. Furthermore, laboratory tests (Sha and Hao, 2014b) and numerical simulations of CFRP strengthened RC pier were also carried out for analysing the dynamic responses due to barge impact load accidental scenario.

Further studies have been carried out on ship-bridge collision with different analysing methods. Fan and Yuan (2014) studied the failure modes and the dynamic interaction process of the pile-supported structures subjected to ship collisions. Their numerical simulations indicate that the platform and the connection of the protective system should be carefully designed to prevent brittle failure in addition to provide piles with enough ductility. Getter et al. (2015) pointed out that for numerical simulations of ship-bridge collision, constitutive relationships assigned to steel components in the vessel model must be capable of accounting for strain rate sensitivities and large-scale plastic deformations. Kang et al. (2017) proposed an effective method to evaluate the cumulative response of steel bridge under earthquake and large drifting object impact due to tsunami flow, and an innovation on the ship-impact effect due to earthquake-induced tsunami directly into ductility demands, a phenomenon which was not previously studied. The impact force history during multicolumn barge flotilla collisions against bridge piers has been determined by Luperi and Pinto (2013). In order to evaluate the engineering standards employed in the United States on designing concrete waterway control structures for barge impact loading, Walters et al. (2017) used analytical techniques and numerical simulations to quantify barge impact loads over a wide range of conditions typically used in experimental testing. Their key finding is that flotilla impact loads are strongly correlated to the momentum of only the barges in the lead row of a flotilla, rather than the total momentum of the entire flotilla. Wang and Wang (2015) proposed a model to evaluate vessel-bridge collision probability. A general mathematical model for navigation channels was suggested for straight and meandering channels, and the effect of waterway obstacles and water levels were both taken into account in their model. The influence of ship-bridge collision on the running safety of moving rail train was investigated by W.Zhang et al. (2014) through numerical simulations. Cheng (2014) also analysed the integrity of the towers of the SuTong Bridge, a cable-stayed bridge in China, under ship impact scenario.

5.1.4 Ship-ice collision

Ship-ice interaction has attracted much more attention since it became possible for ships to sail across the Arctic Ocean. The main methods used for investigations on the interactions between ice and marine structures and on accidental scenarios including ship-iceberg collisions, can be divided into three categories: empirical methods, collision testing methods and numerical methods. With the improvement of computing capability and testing facility, the latter two methods are becoming more popular. These type of investigations are covered in the following.

Experimental methods have been used by researchers for a long time to investigate the fundamental properties of ice during the ice-marine structure interactions and collisions. Von bock and Ehlers (2014) made a qualitative assessment on selected topics to assess the differences between model-scale ice and sea ice and the influence of related experiments on determined mechanical properties is assessed. They concluded that the internal mechanics of Aalto model-scale ice and sea ice differ significantly. Kim et al. (2016) used an experimental method and nonlinear numerical simulations to examine the nonlinear impact response of steel-plated structures in an Arctic environment, and the effectiveness of nonlinear numerical simulation method was proved. The structural crashworthiness of steel-plated structures subject to low temperatures typical of the Arctic environment was investigated by crushing testing by Park et al. (2015b), and the testing results were compared with those from LS-DYNA computation. It was found that low temperatures have a significant effect on the crashworthiness of steel-plate structures in collision scenario in Arctic region.

Compared with collision testing method, numerical simulations can lower the research cost to a large extent, and make it possible for scholars from many countries far from Arctic Ocean to contribute to the research on interaction between ice-marine structures. Discrete Element Method and Finite Element Method are the two methodologies that have been most used world-wide.

Discrete Element Method has an outstanding ability in simulating brittle crush behaviour of ice. DEM can describe the meso-scale structure of ice and simulate the process from intact state to fractured state during ice-structure interaction. Ji, Di and Liu, (2015) investigated the interaction between ice cover and conical offshore structures and discrete element method (DEM) was introduced to determine the dynamic ice loads under different structure parameters and ice conditions. Robb, Gaskin and Marongiu, (2016) used a SPH-DEM model to simulate free-surface flows containing solids applied to river ice jams.

Finite element method (FEM) is a commonly used numerical method with a solid theoretical foundation and easy to implement. Developing effective ice constitutive models is crucial for FEM applications. Shi et al. (2017) proposed a temperature-gradient-dependent elastic-plastic material model of ice for a numerical study of the influence of temperature-gradient on impact force in ship-iceberg collisions. In addition, Shi et al. (2016) proposed a nonlinear viscoelastic iceberg material model and realised it within the LS-DYNA code. The strain-rate effect of ice material has been taken into consideration, too. Ortiz et al. (2015) took into account the well-known Mazars damage model, to simulate the dynamic behaviour of ice. The difference between the behaviour of ice in tension and compression and the influence of the strain-rate on the fragile ice material response were described. Delay effects were used to prevent numerical mesh sensitivity. The constant added mass (CAM) method and the fluid-structure interaction (FSI) method within LS-DYNA were used to simulate ship-ice collisions by Song et al. (2016). It was found that the FSI method yields better results for the motion of the floater, and CAM method was faster but predicted a higher peak contact force and more dissipated energy in the ice mass than in the FSI method. Addario et al. (2014) simulated a collision between the side of a double hull LNG carrier and an iceberg modelled as rigid by adopting ABAQUS, to investigate the influence of mass and shape of the iceberg on the damage of the structure. Based on the study above, Ferrari et al. (2015) adopted a complex material model (see § 4.4.3) to simulate the behaviour of ice. The collision between a spherical ice feature and the double hull of an LNG carrier was simulated to get an evaluation of the share of deformation energy between ice and structure.

Zhou et al. (2016) introduced a solution to the ship-ice interaction problem in the time domain by a combined method involving numerical simulations and semi-empirical formula. The breaking process of level ice is predicted by a 2D numerical method, and the simulation of ship manoeuvring in level ice is carried out by a 3-degree-of-freedom model. Kim et al. (2017) carried out laboratory experiments on shared-energy collisions between freshwater ice blocks and a floating steel structure, to study the physics of this event. A series of laboratory –scale impact tests of freshwater granular ice blocks against stiffened steel panels are described. Myland and Ehlers (2016) evaluated the contribution of the ice breaking force to the motion resistance in ice methodically for different bow shapes, through model tests method. Breaking patterns and geometric bow parameters were specially investigated, and the findings were compared with the selected-empirical method of Lindqvist. The frequency of ice loads of varying lengths and the occurrence probability of their magnitudes were studied in full-scale testing carried out on the Polar Supply and Research Vessel S.A. Agulhas II, by Suominen, Kujala, Romanoff et al. (2017). This statistical study showed that a Weibull distribution gives the best fit to the measured loads on a frame. Overload response of ship structures frames to ice loads were assessed by Daley et al. (2017) and Kõrgesaar et al. (2018).

5.2 Most critical/relevant condition and design/analysis methods

Researches on collision-related-design have not been as many as those on other fundamental aspects or as studies from engineering practices. ALS criteria are however introduced to limit the corresponding residual risk associated with accidental actions, i.e. to prevent progressive collapse failure of the whole structure. Moan (2017) summarized that to stop the escalation of an accident, one of the three following approaches should be taken (ISO, 2015; Moan et al., 2016)

- Designing the structure locally to sustain accidental actions and other relevant simultaneously occurring actions.
- Designing the structure by "accepting" local damage but requiring that the damaged structure survives the relevant accidental actions.
- Designing the structure to meet robustness requirements through (prescribed) minimum levels of ductility, continuity and tying.

Park et al. (2015a) carried out an accidental limit state-based ship collision analysis to identify the operability of aged non-ice class ships in the Arctic Ocean. An innovative relevant condition is that various Arctic ambient conditions, with temperatures down to -80˚C, were applied to the ambient exposed plating of the struck ship. Paboeuf et al. (2016) using a super-element method presented a work performed for the evaluation of an alternative construction within the scope of A.D.N. regulation, a European Agreement concerning the International Carriage of Dangerous Goods. A Bureau Veritas tool, SHARP, based on analytical formulations, permits to perform several quick ship collision analysis. In addition, Akhtar et al. (2016) discussed the methods for choosing collision scenarios and ship collision loads for bridge design. The design concept in DNV-RP-C204 (2010) was applied, as well as the concepts of ductile, strength and shared-energy design, applicable in bridge design, too.

Risk assessment method is a useful tool to evaluate crashworthiness and safety of ships and offshore structures under accidental limit state scenarios. Moan et al. (2017) made a review on the assessment of ship impact risk for offshore structures and pointed out that the new NORSOK N-003 guidelines for Norwegian Continental Shelf specify that ship impact actions and action effects should be determined by risk assessment.

Experiments in model scale have always played an important role in investigating the quasi-static and dynamic structural responses for steel and other materials used in building of ships and offshore structures. Test data have also always been used to validate analytical formulae and for comparison with numerical simulation results. Liu and Guedes Soares (2016b) carried out experiments and finite element simulations of small-scale stiffened web girders subjected to local in-plane loads, in order to examine their crushing deformations and energy absorbing mechanisms. Korgesaar and Kujala (2016) validated the failure criterion for large complex shell structures, through comparison with experimental results. The comparative simulations are performed with the GL failure criterion based on critical through thickness strain.

Model testing can also be used to analyse the resistance capacity of ship structures. J. Liu et al. (2016) conducted an experimental study on the resistance of hat-type stiffened plates struck by a bulbous bow indenter. Different X-core and Y-core sandwich plates were included in the test, and it was shown that significant improvement on energy dissipation capability can be achieved by hat-type stiffened plates, compared to those of conventional stiffened plates. Repeated mass impact model tests were conducted by Truong et.al (2016) at Ulsan University, to investigate the plastic response of steel grillages struck by a knife-edge striker. Holmen et al. (2015) carried out an experimental program investigating the behaviour of monolithic and multi-layered configurations of 0.8 mm and 1.8 mm medium-strength steel plates.

The influence of critical parameters relevant to ship collision can be analysed by model testing results. Antoine and Batra (2015) analysed the sensitivity to material parameters, layer thickness and impact speed of the plate deflection, the contact force between the impactor and the plate, the maximum length of a crack, and the energy dissipated during a low velocity impact at normal incidence of a clamped rectangular laminate by a rigid hemispherical-nosed cylinder. Xia et al. (2015) used various machines in material testing program covering quasi-static, intermediate and high strain-rates, which is referred to as a multiple-machine Program.

5.3 Acceptance criteria/consequence evaluation

Structural damage due to ship collision accidents can lead to serious consequences. For example, the reduction of ship longitudinal strength may induce global hull collapse. This makes the assessment of global strength after collision damage a necessary step in design. Furthermore, some other consequences, such as oil spill, flooding related salvage, and riser collision consequence have all attracted much attention by the scholars.

Global strength has always been a key concern for the damaged ship after collision accidents. Obisesan et al. (2016) proposed a framework for reliability assessment of ship hull damage under ship bow impact. They used reliability computations to show that the probability of hull fracture increases as the hull deformation progresses, with maximum value occurring at the onset of outer hull fracture. Youssef, Faisal et al. (2016) proposed a method for assessing the risk of ship hull collapse following a collision. They used a probabilistic approach to establish the relationship between the exceedance probability of collision and the residual ultimate longitudinal strength index. Begovic (2017) carried out an experimental study on hull girder loads on an intact and damaged naval ship DTMB 5415 at zero speed. It was found that the moorings influence the hull girder loads at some wave frequencies. The global responses of struck ships in collision were investigated by Jia and Moan (2015), with emphasis on hydrodynamic effects. It was found that the equivalent added mass for sway motions depends not only on the duration of collision impact and on the impact force, but also on the collision position. Comparatively, the equivalent added mass for yaw motion could be assumed to be independent of collision position.

Flooding in damaged ships has also been a matter of concern. Lee (2015) proposed new models for vented compartments of damaged ships and an accumulator model, which can adjust the inner pressure in the calculation automatically. The dynamic–orifice equation was investigated in case of large openings. Manderbacka and Ruponen (2016) carried out research on the impact of inflow momentum on the transient roll response of a damaged ship. It was found that when the flooded compartment does not have significant obstructions, it is important to account for the inflooding moment flow. Acanfora and De Luca (2016) carried out an experimental investigation on the influence of the damage opening on ship response. The experimental results indicated that the roll behaviour of a damaged ship is affected not only by its size, but also by the position of damage opening. Rodrigues and Guedes Soares (2017) carried out a study on the transient still water vertical load during the flooding process for a damaged shuttle tanker in full load condition. The flooding progression is simulated by a quasi-static version of a generalized adaptive mesh pressure integration technique for progressive flooding of damage vessel. Total resistance of an intact and damaged tanker was predicted with flooded tanks in calm water scenario, by Basic et al. (2017). RANS equations with VOF technique were employed to solve the flow around the damaged ship in calm water. It was found that the total resistance due to the altered flow around the hole increased with 27%.

Furthermore, oil spills are one of the most crucial topics for investigation, due to the increasing public concern about the environmental protection. Afenyo et al. (2016) made a state-of-the-art review on the fate and transport of oil spills in open and ice-covered water. The review identifies the current knowledge gaps and future research directions. Kollo and Tabri (2017) proposed hydraulic models for one- and two-layer flows combined in different oil spill scenarios for tanker accidents. The discharge coefficients were determined from an experimental verification of the hydraulic models, and the head losses of a stratified flow through the double-hull tank hole was determined by an optimization algorithm.

Further, riser collision in offshore engineering is one of the accidents that generate a larger concern. Fu et al. (2017) carried out a reliability analysis for riser collision and presented an effective way for predicting the failure probability by considering various uncertain loads in the nature environment. They also studied the parameters which may result in riser collision.

6. GROUNDING

6.1 Introduction

Assessment of ship grounding is in many elements similar to that of collision assessment. In grounding, ship motions are mainly in the vertical plane (surge, heave and pitch), while in collision the focus in is on the motions in the horizontal plane (surge, sway and yaw). Similar to the collision assessment, one of the simplifications done in for the grounding assessment is to divide the analysis into external dynamics and internal mechanics. The external dynamics evaluates the ship motions, resulting in the energy to be absorbed by structural deformations and the inner mechanics evaluates the deformations that the structures undergo while absorbing that energy. In addition to decoupled models, several coupled models have been developed, which successfully combine these two fields.

Any model development is related to simplifications and thus uncertainties with respect to the reality. The grounding process is a complex nonlinear process where highly coupled effects, such as large contact forces, large structural deformations and hydrodynamic loads, are coupled. The complexity of a grounding problem depends on whether the ship predominantly moves horizontally, vertically or is a combination of them with respect to the seabed obstruction. If a ship grounds over a sharp rock, then the grounding is termed as “bottom raking” and if over blunt “shoal”-type seabed, then the term of “bottom sliding” is used, see Figure 10: .

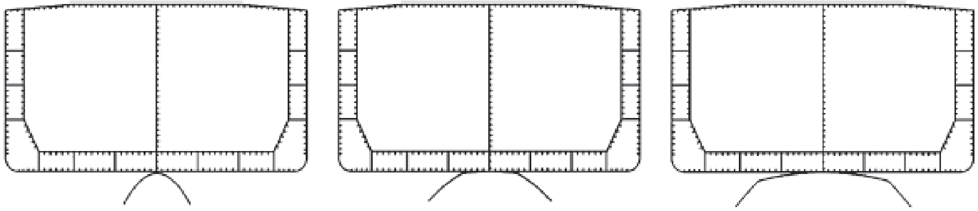


Figure 10: Sea-bed types (Alsos and Amdahl, 2007).

Furthermore, “hard” grounding refers to a grounding with undeformable seabed such as rocks, while the “soft” grounding takes place on deformable seabed. In between these two are the groundings on the reef-type rock. These different classifications correspond to different structural behaviours of a ship bottom, which yield to different failure models.

6.2 Most critical/relevant condition

Grounding assessment is required in sea regions, where the shipping lines are in the vicinity of shallow water or rocky areas. For example, the Gulf of Finland has a dense maritime transportation and it was shown by Brunila and Storgård (2012) that in the past two decades the oil transportation has quadrupled in the region. Due to shallow water areas, there are several grounding accidents and incidents in every year (Kujala et. al., 2009). The effectiveness of preventive measures in the region is obvious, since the number of accidents has not increased with the same rate as the amount of traffic. However, as the traffic continues to increase, it is necessary to further improve various measures to increase the safety at seas.

The definition of a relevant scenario, a crucial element in the development of the measures, is a demanding task. The scenario definition includes the quantification of the probability of occurrence of an accident and the definition of parameters such as the characteristics of the ship and the bottom topology.

Many methods have been applied for risk analysis the past few years, including Hazard and Operability Studies (HAZOP), Failure Mode and Effects Analysis (FMEA), Fault Tree Analysis (FTA), Event Tree Analysis (ETA) and Bayesian Network (BBN). Mazaheri, et al. (2014) reviewed existing risk models available in the literature for ship grounding events and proposed a methodological framework suitable for knowledge based risk modeling, in line with the recommendations issued by the IMO in the formulation of the Formal Safety Assessment procedures. The paper also highlights the models that are more appropriate for risk management and decision making. Amongst other investigation procedures, BBNs became more and more popular for maritime risk modeling during the last decade. They may use experts’ knowledge to integrate scarce historical data and are particularly suited to model the causal relationship of shipping accidents which involve human and organizational factors.

Comprehensive literature review of using BBN models to model grounding accidents is provided by (Zhang and Liu, 2017). A detailed analysis of the benefits and challenges about Bayesian Networks for the study of prevention measures against maritime accident can be found in (Hänninen, 2014). Mazaheri (2017) proposed a BBN based framework for studying grounding scenarios. Traffic data from AIS combined with expert knowledge, ship grounding incident and accident reports are used in input. A region-specific semi-quantitative index, the Waterway Complexity Index is defined to take into account the dependency of ship grounding events on the navigational difficulty of a waterway. New versions of Human Factors Analysis and Classification System and new positive taxonomy as Safety Factors are also introduced. While experts' opinion still plays an important role in providing data for BBN models, data-driven BBNs are considered more objective since they work on objective data (Zhang and Liu, 2017).

Large efforts are therefore devoted to carry out statistical analyses of the available data. (Goerlandt et al., 2017) studied the accidents occurred during wintertime navigation in the Northern Baltic Sea in the period 2007–2013. The analysis is based on an integration of various data sources, aiming at reconstructing the accident conditions based on the best available data sources. Apart from basic accident information from the original accident databases, data from the Automatic Identification System is used to obtain insight in the operations during which the accident occurred, as well as into other dynamic aspects of the accident scenario. Finally, metocean and sea ice data are also integrated in the scenario description. Sormunen et al. (2016a) presented an overview of ship traffic volume and accidents in the Baltic Sea with a special focus on the Gulf of Finland. The annual number of accidents in the Baltic Sea reported to HELCOM varied in the range 34–54 for collisions and 30–60 for groundings. By analyzing two separate accident databases, an estimate for accident underreporting was also calculated. Different statistical methods yielded an underreporting rate in the range of 40–50%. The true number of accidents was estimated, based on the estimated underreporting percentage for the Baltic Sea. Eleftheria et al. (2016) presented a systematic analysis of ship accidents in the last decade as a way to evaluate the current level of safety for the majority of ship subtypes present in the world merchant fleet. The presented analysis also included a deeper investigation about possible relationships between accident rates and ship's age. The outcome of the present study indicated that in the last decade although the frequencies of ship accidents generally increased, the safety level of various ship types did not significantly change, as the consequences of accidents remained in average at about the same level.

Grounding consequences depend on the ship itself as well as on the bottom topology. (Sormunen et al., 2016b) investigated the relevancy of mathematical models to describe rock shape in grounding response analysis. Four different bottom topologies were studied, each described with four mathematical models and with one model following the real shape of the rock see Figure 11. Grounding response in terms of dissipated energy was evaluated for all the models. It was confirmed that the mathematical representation of the bottom topology is of great importance in the grounding response. The results showed that the ship damaged material volume is strongly linearly dependent on the rock area- and volume metrics. A similar linear dependency exists between the damaged volume and the energy dissipated in grounding, see Figure 12. Thus, one should be able to understand the bottom topology in the area under investigation.

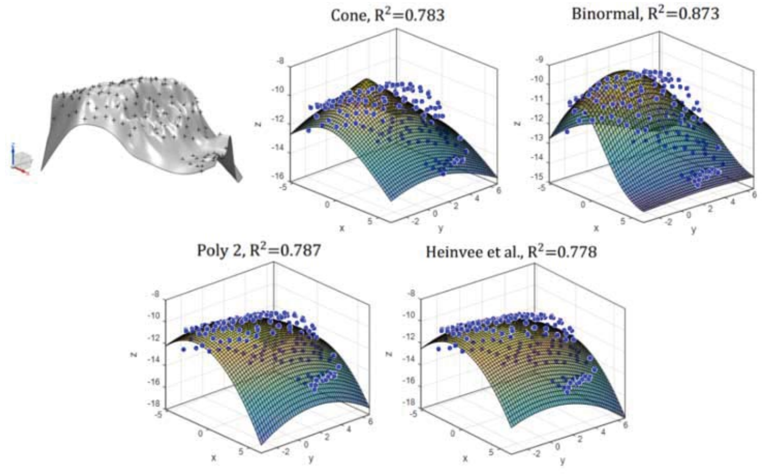


Figure 11: Approximated real rock surface and four fitted models (Sormunen *et al.*, 2016b).

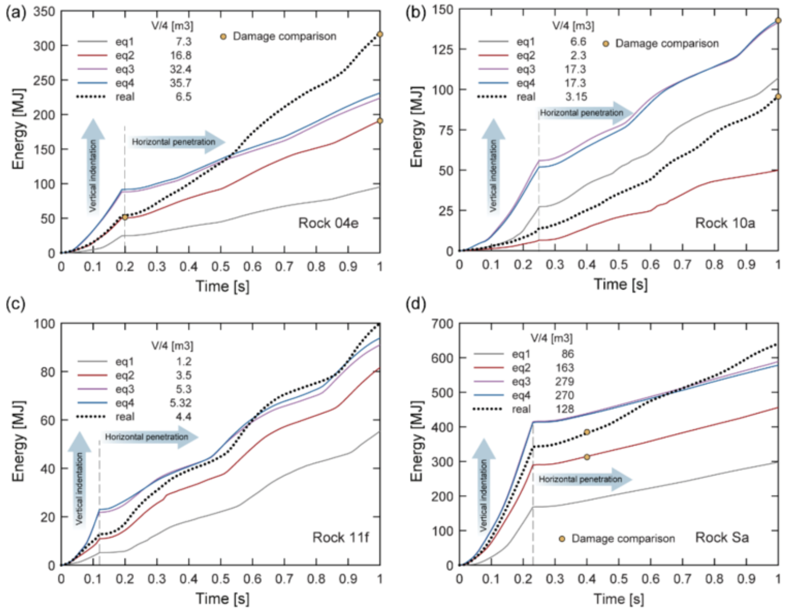


Figure 12: Deformation energy absorbed during grounding using different rock models (Sormunen *et al.*, 2016b).

6.3 Analysis methods

Once the accidental grounding scenario is defined, ship's response to grounding and the consequent damage is to be assessed. Assessment of ship grounding consequences has been the subject for a large number of research studies. Study methods include experimental, statistical, numerical simulations, empirical and regression models or simplified expressions for ship structural elements.

6.3.1 Experiments

Experiments are the most straightforward method to understand structural failure mechanisms. In the mid-1990s several large-scale grounding experiments with a scale of 1/4 were conducted, as reported by Rodd and Sikora (1995) and Vredeveldt and Wevers (1995). In both tests, double bottom structures for tanker models and cone shaped models for intruding rocks were used to provoke the tearing failure modes. However, large scale experiments are expensive and rare. Accordingly, tests in smaller scales are carried out to observe the structural behaviour during the impact and to validate results of FE analysis. In Calle et al. (2017) miniature ship substructures (in particular bulbous bows and ship's mid-sections) were used for ships collision and grounding experiments. Structural resistance was measured and compared to the numerical simulations. Their study showed that it is possible to recognise the same structural behaviour as in case of structures of larger scale. Comparisons between FE simulations and experiments allowed to track and control the key aspects of FE modelling. On the side of the geometrical description, it was observed that slight misalignments could cause noticeable differences in the crushing modes, in the crushing force and in its peaks. As regards the material characterisation, results showed that appropriate failure criteria for base material should include a calibration of both crack initiation and propagation parameters. Liu and Guedes Soares (2016b) carried out experiments and finite element simulations of small-scale stiffened web girders subjected to local in-plane loads, in order to quantify crushing deformations and energy absorbing mechanisms. Three small-scale specimens were designed, one unstiffened web girder and two vertically stiffened web girders, in order to compare the influence of the vertical stiffeners on the structural deformation and response of stiffened web girders. The investigation provides practical information to study scenarios with local penetration of the ship bottom.

6.3.2 Statistical models

A practical framework for input data in risk analyses was adopted by the International Maritime Organization in IMO (1995) and, in revised a version, in IMO (2003). These guidelines present a probabilistic model for the damage extent of an oil tanker design in collision and grounding. The probability density distributions for the damage extent contained in the document were derived from the actual damage data of 63 grounding and 52 collision accidents of oil tankers, chemical tankers and Ore/Bulk/Oil carriers. The damage extent is given in non-dimensional form, as percentage of the length, beam and depth of the ship. It has been argued, see e.g. Sirkar et. al., (1997), Rawson et al. (1998), Pedersen and Zhang (2000) that the damage extension so identified does not reflect the actual dependency on the different structural arrangements and on ship size.

6.3.3 Numerical models

Due to the rapid evolution of computer capability, the numerical simulations of grounding and collision events are regarded as an investigation tool allowing an even better insight in the phenomena under study than the physical experiments. Information about the stress strain and damage spatial distributions are actually available everywhere in the simulated material domain, while transducers in experiments provide local information in a discrete number of locations. Main challenges of these simulations are however a proper representation of structural configuration and of material properties including constitutive equations and failure surface The selection of the size of elements is also important (see §4). Various publications present applications of nonlinear finite element (NLFE) techniques for grounding simulations: see among others Kitamura (2002), Naar et. al. (2002), Alsos and Amdahl (2007), Samuelides et. al (2007). AbuBakar & Dow (2013) focussed on the numerical prediction of the structural damage of ship's double bottom structure. Tests of stiffened panels penetration and double bottom damage, both carried out experimentally by Alsos et al. (2009a, 2009b) and Rodd (1996) were numerically simulated. Liu and Guedes Soares, (2016a) studied the behaviour of stiffened web girders subjected to local in-plane loads characteristic of grounding.

Liu et al (2017) carried out numerical stranding simulations of double hull tanker, studying the influence of different impact locations and failure criteria on the structural response of structural members. Locations showed a smaller impact than failure criteria on results in terms of resistance forces and deformation energies in the structural members. Marinatos and

Samuelides, (2015) carried out a systematic investigation on the main parameters of numerical simulations for the case of indentation of thin walled structures, deriving recommendations for the selection of parameters in ship collisions and groundings. Yu and Amdahl (2016a) presented full six degrees of freedom dynamic simulation of ship collision and grounding accidents, solving the coupled problem i.e. evaluating simultaneously external motions and structural response.

6.3.4 Empirical and regression models

Methods that combine numerical simulations or accidental data or experiments with the regression analysis allow developing formulas that consider main dependencies between the grounding response and the relevant parameters. One of the first empirical models in the field was created by Minorsky (1959) who studied actual collision accidents and found that the energy absorbed by ship structures is in linear correlation with the deformed steel volume. It was shown by Vaughan (1977) that a similar linear dependence is also valid for ship groundings. To determine the damage extent, both models require rather detailed information for ship scantlings. Simonsen et al. (2009) followed the same principles and developed an empirical damage prediction formula, based on a combination of full-scale testing and extensive non-linear finite element analyses. Curves expressing horizontal force as a function of the damage extent were obtained from 12 grounding FE simulations and then tuned to give a best possible fit (Figure 13). The formulation is intended only for grounding events over sharp rocks (raking) where the plate tearing is the dominant failure mode. The model in addition provides the damage size, which is not the same as the damage opening.

$$F_{\mathrm{H}} = 0.77\sigma_0\varepsilon_{\mathrm{f}}^{0.71}(t_{\mathrm{eq}})^{1.17}(B_{\mathrm{d}})^{0.83}$$

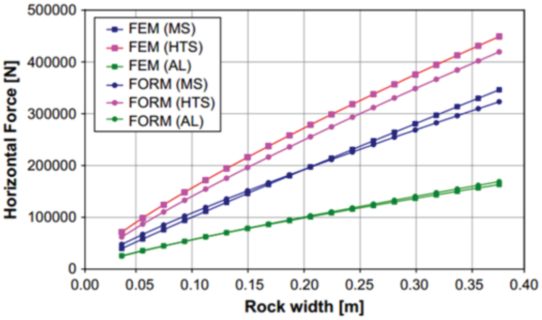


Figure 13: Simplified damage prediction formula and results compared with FEM dots: formula, squares: FEM, (Simonsen et. al. 2009).

However, it is often desired to predict also the size of the damage opening that can be used for flooding and oil spill simulations. Heinvee et al. (2013) presented a model for a rapid prediction of ship grounding damage. This regression model is developed based on a large number of numerical simulation with double-bottom tankers. The damage length and the opening width in outer and inner bottom of a double hull tanker are provided on the basis of a small number of input parameters describing ship size, the rock shape and size and penetration depth. Due to its simple structure and easy computation, the formulation can be effectively adopted when the consequences of a large number of grounding scenarios need to be evaluated. In Heinvee and Tabri (2015) the resistance formula was improved by introducing the ship structural resistance coefficient as a function of ship length. In Heinvee et al. (2016) the influence of transverse and longitudinal bulkheads on the grounding resistance was studied.

6.3.5 Analytical models

One alternative to the NLFEA grounding simulations is adoption of simplified analytical models where the total response of bottom structure is obtained through the summation of the responses of separate structural members. In grounding, the primary deformation modes for individual structural members are sliding deformation of longitudinal girders, denting and crushing of transverse members and indentation of plating. Simplified models for web girder crushing are proposed, for example, by Hong and Amdahl (2008), Yu et. al. (2015) and Gao and Hu (2015). Liu and Soares (2016) investigated the local (subjected local-static or dynamic load) crushing behaviour of transversally stiffened (large stiffeners) deep girders and derived analytical formulae able to estimate the relation between the crushing force and the indentation during the entire folding. This simplified method is only valid before the initiation of material rupture in the structure. Liu and Soares (2015) presented a new simplified analytical method to predict the crushing resistance of longitudinally stiffened deep web girders subjected to local load. The comparison among previously reported simplified methods demonstrates that the new approach can evaluate better the crushing behaviour of web girders during the entire deformation process. The present simplified approach can be combined with other simplified methods of stiffened plates to assess the resistance of the double- hull structures subjected to a wedge-shaped indenter. Yu et. al. (2015) presented a theoretical model for the calculation of grounding response of longitudinally stiffened girders. The model is formulated for shoal groundings. Yu claims that the resistance contribution of girders (longitudinal stiffeners) is underestimated. Therefore, a new girder model is proposed with an additional contribution from stiffeners. Sun et al. (2017) presented a simplified analytical method for predicting the resistance of ship bottom structures when a ship runs aground over rock-type seabed obstructions (raking grounding). The method shares similarities to the models reported earlier (Wang et al. (1997), Wang et al. (2000), Friis-Hansen & Simonsen (2002), where the total grounding resistance is expressed as the sum of resistances of individual structural members. The authors note that in case of powered groundings the contribution from bottom transverse floors to the grounding resistance is frequently underestimated and they claim that the novelty of the new simplified analytical model stands in the capability of accounting for the contribution of transverse floors in preliminary evaluations of the double bottom performances. The stiffeners attached to the plating are accounted through smeared thickness. This is justified with the small contact surface between the rock and the ship bottom.

6.4 Acceptance criteria/consequence evaluation

To evaluate the consequences of grounding, the focus is on the assessment of structural damage and following consequences such as flooding or, in the case of tankers, oil spill. Sergejeva et al. (2013) and Kollo et al. (2017) presented hydraulic models for one- and two-layer flows for different oil spill scenarios for tanker accidents. Five test cases were verified by comparison to the laboratory results of Tavakoli et al. (2011). The model provides the spill amount and duration. In (Sergejeva et al., 2017) the model was extended to account for wintertime conditions by taking into account the effects of emulsification and heat exchange occurring at the interface of fluids at different temperatures.

Tabri et al. (2015) combined the damage assessment model of Heinvee and Tabri (2015) and the oil spill model of (Sergejeva et al. 2013) with an oil spill propagation model (SMHI, 2012) and the environmental consequence models (Aps et al., 2009; Aps et al., 2014). Combining all these aspects together, the consequences can be evaluated not only in terms of structural damage or of amount of oil spill, but (using also meteorological info) as length of impacted shoreline.

7. FIRE AND EXPLOSION

7.1 Introduction

Fires and explosions account for 30% of ship losses records (Chen et al., 2017; Silva et al., 2015; Vairo et al., 2015). Most of the fires initiate in engine rooms. However, on board cruise vessels also fires initiating in cabins, restaurants or entertainment areas are to be taken into consideration, as well as fires starting in car decks on Ro-Ro vessel. A risk of fire or gas explosion accidents always exists in oil and gas facilities which are containing and processing flammable hydrocarbon mixtures. This is especially critical regarding the re-cent increase of LNG (Liquefied Natural Gas) shipping. LNG carriers, LNG-fuelled ships or LNG FSRUs (Floating Storage and Regasification Units) having gas processing units (re-liquefaction systems, fuel gas supply systems, re-gasification systems, etc.) have much more likelihood for fire and explosion accidents compared with the conventional gas carriers having just storage tanks for transportation. Potential accidents can result in serious impact on personnel, environmental or property. Therefore, the safety assessment against fire and explosion accidents should be performed during design phase to prevent loss of lives or catastrophic failure of structures. For offshore oil and gas industry, the design and operation procedures against fire and explosion accidents are well established with performance and risk based approach (Czujko et al. 2015).

Other ships having fire or explosion hazards are naval ships, passenger ships or electric powered vessels with battery systems, etc. Naval ships can be exposed to weapon explosions from above and below water that can affect the survivability of naval vessels, and one of the ISSC Committee has continuously reviewed the design of naval ship including weapon explosion (Ashe, G. et al., 2006; Dow, R. S. et al., 2015). Fire safety for passenger ships usually follows the FSS code (IMO, 2017a), FTP code (IMO, 2010) or SRtP (Safe Return to Port) regulations and Evacuation guidelines of SOLAS (IMO, 2017b). Alternative to these prescriptive requirements, the per-formance-based fire safety design was also suggested by MSC/Circ.1002 (IMO, 2001). Alt-hough the use of battery systems onboard ships is rather new area compared with land-based plants, guidelines have been already prepared (see e.g. DNVGL, 2014; LR, 2015).

7.2 Prescriptive vs performance based codes

With the ratification of IMO's resolution MSC.99 (73) on 1st July 2002, fire ship codes are shifted from prescriptive formats (rules in SOLAS) to performance-based (as long as an adequate level of safety is maintained) for technical, economic and social reasons. In prescriptive codes, most requirements indicate solutions without explicitly stating their aim. In performance-based codes, on the contrary, the desired objectives are presented and designers are given the possibility of choosing their solution, provided it meets the objectives. Generally, prescriptive codes are used as primary means to enforce fire safety in the ship design. They are based mainly on past experience (accidents or near-accidents history). As such, they may result to be either conservative (as a result of an over-reaction to a specific accident) or non-conservative (because they do not cover an accidental scenario not yet present in records). Moreover, the level of safety enforced is implicit and cannot be compared to requirements expressed in explicit levels. It is possible to synthesize the main advantages and disadvantages for the prescriptive and performance-based approaches.

Prescriptive codes:

- Advantages: simply evaluation of compliance with established requirements; no need for high level expertise.
- Disadvantages: requirements specified without a clearly statement of objectives; no promotion of cost-effective designs; very little flexibility for innovation.

Performance codes:

- Advantages: establishment of clear safety goals and leaving the means of achieving; permitting innovative design solutions that meet the performance requirements during first stages of application; facilitating use of new knowledge when available; allowance for cost- effectiveness and flexibility in design.
- Disadvantages: difficult to define quantitative levels of safety performance with those goals to the designer criteria; need for education because of lack of understanding especially; difficult to evaluate compliance with established requirements; need for validation of the tools used for quantification.

Areas where the application of performance codes is particularly promising are:

- large passengers (cruise) and ferry ships' passive fire protection (walls and ceilings) can be moved in order to create larger connected areas;
- in large ships higher passive resistance can substitute fixed installed fire suppression measure;
- in naval ships the expected extent of damage can be reduced through improved fire measures.

7.3 Fire and explosion analysis: General

Fire is a major threat to human life mainly due to toxic smoke. The important time dependent and location dependent factors to be determined during modelling are temperature, heat release rate, carbon monoxide, CO^2, and visibility. Two types of models are used to study the case: zone models and field models. Zone models divide the problem into a small number of zones, e.g. upper layer and lower layer. This kind of modelling is fast and a lot of different cases can be calculated in short time. Therefore, it is often used during design stage. More than 50 different zone models are available. Scenarios for the analyses are defined considering geometrical aspects, fire scenario, people, etc. Then the conversation laws for mass, energy, species (fuel, O^2, etc.) are applied.

The field models estimate the evolution of the fire in a space by mean of numerical tools, resolving the basic equations of mass, energy conservation, etc. The action characteristics of hydrocarbon fires can be modelled using the CFD method, which is recognized as one of the most powerful approaches and which makes it possible to model the fire phenomenon using first principles via solving the basic conservation equations of mass, energy and momentum (Paik et al., 2015; Novozhilov, 2001). In contrast, the action effects of fire on structures are characterized by the nonlinear finite element method (NLFEM) that can be solved with NLFEM codes such as LS-DYNA (LS-DYNA, 2013) or USFOS (USFOS, 2013).

The aim of fire CFD simulation is to characterize gas cloud dispersion, gas cloud temperatures and heat fluxes which are time- and space-dependent after the fire. Fire loads are elevated temperatures and heat fluxes in the ambient or gas cloud obtained by the fire CFD simulations. Radiation and convection associated with fire are key elements to characterize fire loads. One of the tools for fire CFD simulations well adopted for the offshore industry practices is KFX code (2013) which is a 3D transient finite volume CFD program. KFX is a cartesian, incompressible, three-dimensional transient finite volume CFD code that solves the discretized conservation equations for mass, energy and momentum adopting an iterative implicit pressure-correction method. Heat fluxes due to fire are transferred into structures with time, increasing the steel temperature which depends on the temperature of gas cloud, the area of steel exposed to the fire, and the characteristics of fire protection applied, among others. It is obvious that the gas cloud temperatures are not identical to the steel temperatures with time, and thus the heat transfer analysis should be performed to define the steel temperature with time. For practical purposes, the fire can be represented by temperature curve obtained from rules or from CFD simulations. Another FE based simulation environment called VistaFire is provided as part of the VistaMat Suite. VistaFire is a thermomechanical analysis module for predicting fire effect on structures.

The explosion accident is a complex phenomenon derived by a number of random variables (e.g., leakage rate and direction; wind speed and direction; locations of ignition; gas clouds size, location and concentration, etc.), which have many uncertainties. The easiest way to get the explosion loads is to bring the prescriptive loads by referring to the relevant rules, standards or industrial guidance (API, 2006; DNV-OS-A101, 2014). However, it is often a conservative value and used in the early project phase. In the case of simplified calculation models for explosion loads, there are some empirical models such as TNT method for the high explosive and Multi-energy methods (Lees, 1996) or B-S-T model (Tang and Baker, 1999) for vapour cloud explosion. These are based on correlations with experimental data, and usually used to predict far field blast effects. However, these simplified models are gradually substituted by the numerical simulation. The numerical simulation model for explosion requires consideration of likely sources and magnitudes of leaks, ignition and consequent explosion development. These are presently well addressed by CFD which is the most fundamentally based method and has the best potential for accurate prediction of gas explosion phenomenon. These tools solve the conservation equations of mass, momentum and energy including turbulence and combustion. For instance, FLACS software is widely used for gas explosion simulations in oil and gas industries (Czujko et al. 2015).

7.4 The Risk of Fire and Explosion accidents

7.4.1 Action effects and modelling

The main parts of quantitative risk analysis are consequence calculation and probability estimation of selected design scenarios. Pitblado and Woodward (2011) performed comprehensive historical review on LNG risk, especially focused on the consequence route and modeling of LNG accidents, that is, discharge, evaporation, pool and jet fire, vapor cloud explosion, rollover, Rapid Phase Transitions (RPT), Boiling Liquid Evaporating Vapor Explosion (BLEVE). In (Woodward and Pitblado, 2010), predictions are compared of various LNG pool spread and pool fire models, and the possibility is discussed of a change in burning mechanism with large pool fires, fire engulfment of an LNG carrier causing cascading failures, the circumstances for a possible LNG BLEVE, and accelerated evaporation by LNG penetration into water.

LNG is highly flammable and explosive substance with ignition point of 650℃, rapid flame propagation, large mass burning rate about 2 times more than gasoline, high flame temperature, so the burning is of strong radiant heat, easy to form large area of fire. The LNG carrying ships have been designed, constructed and equipped to carry cryogenic liquefied natural gas stored at a temperature of -163℃. Breakage in the working piping or loading and unloading system, rupture in liquid hold, collision and other factors may lead to leakage of liquefied gas and create a liquid pool, which will result in fire accidents. Also, liquid cargo of ultra-low (cryogenic) temperature contacting with general hull, because local cooling produces excessive thermal stress, will make the hull brittle fractures spontaneously, and loses ductility, thereby endangering the entire ship's structure (Moon et al., 2009; Li and Huang, 2012).

The boiling point of LNG (taking methane into account) is 162℃, easy to be gasified. If LNG leaks or spills, initial flash vaporization of the leaking LNG occurs in the air, generating lots of steam instantaneously, mixing with surrounding air and forming cold steam fog and white smoke after condensation in the air, then diluted and heated to form flammable gas cloud with air (gas/air mixture), and reaching explosive concentrations (5 ~ 15 vol%), which will lead to Vapor Cloud Explosion (VCE) when encountering ignition sources.

When liquefied natural gas tanks on the ship are heated or exposed to external flame for a long time, the structural integrity of tanks will gradually decreases. When the structural capacity decreases to a certain extent, the tank will suddenly burst, resulting pressure suddenly reduces, and liquefied natural gas vaporizes and burn rapidly, resulting in Boiling Liquid Expanding Vapor Explosion (BLEVE) accidents. Sudden burst of tanks can release tremendous energy and produce shock waves and throw container pieces to the distant. Also, intense burning of liquefied petroleum gas can release enormous heat, resulting in a huge fireball and strong thermal radiation. Unlike the on-land LNG tank facilities, LNG marine shipping hazard studies have discounted BLEVE hazards associated with LNG vessels. Marine LNG vessels have differently designed tanks and it is demonstrated that the combination of physical barriers makes direct thermal input to the LNG inner tank more limited, but if it occurs these tanks cannot rise to a pressure sufficient to cause a large flash of liquid and consequent BLEVE event of a scale hypothesized in the literature (Pitblado, 2007).

7.4.2 Accidental scenario and probability

To establish accidental design scenarios used in risk assessment, not only the consequence models of the accidental scenarios, but also the possible accidental events and corresponding probabilities must be identified. The incident that follows a loss of containment event (such as the collapse of a tank, a hole in a pipe, etc.) can follow different sequences depending on the specific circumstances, which include the properties and condition of the released material, the presence of one or more safety barriers, and other factors. Each sequence will lead to a final accident scenario, the severity of which will range between "no outcome" (no consequences or negligible consequences for people and property) and a "major accident" such as an explosion or a large fire. As shown in Figure 14, Vílchez et al. (2011) presented a set of generic event tree analysis for the most common scenarios involving different types of hazardous materials and the corresponding intermediate probabilities based on the literature (BEVI, 2009).

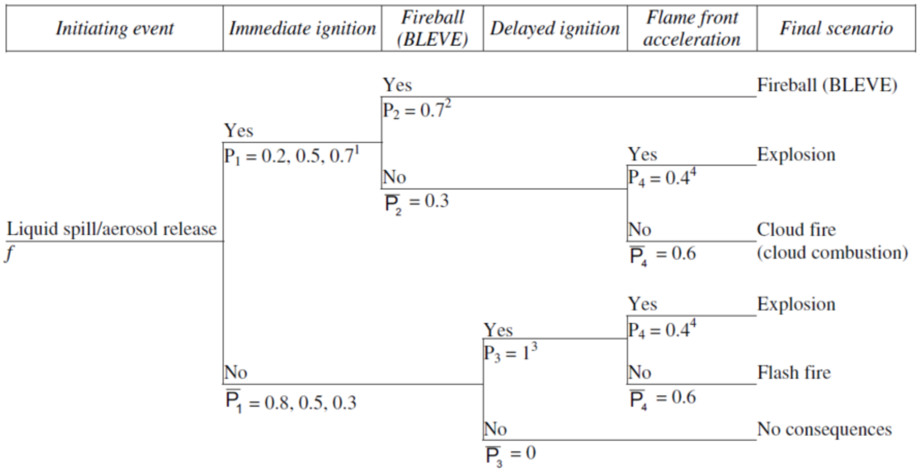


Figure 14: An example of Event Tree for instantaneous releases of extremely flammable pressurized liquefied gases (Vílchez, J. A. et al., 2011)

The probability is typically assessed by evaluation of historical data. Beside the statistical evaluation, Bayes networks are used to model the probability of fire for different locations. Independent variables and their conditional dependencies are used to determine probabilities.

Where conditional dependencies are unknown machine learning is considered. This dynamic Bayesian networks are gaining more popularity, especially in modelling fire risk modelling.

7.5 Design Requirements of Fire and Explosion Accidents for LNG Ships

7.5.1 Fire and explosion design for LNG carriers and FSRU

FSRU (Floating Storage and Regasification Unit) is a LNG Ship with large vaporizers to supply natural gas directly to clients and therefore ensuring that supply match demand at the right time and with the right supply conditions. It can be disconnected from the client at the location and is built under the traditional rules for ships as opposed to floating offshore installation. The uncontrolled leakage of the LNG from process equipment or cargo tanks during operation could result in fire or explosion accidents due to evaporation and dispersion of the product and, in some cases, could cause brittle fracture of the ship's hull due to low-temperature (cryogenic) exposure. Therefore, technical safety assurance, especially on regasification design integrity and operation in a whole ship, is required. International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk or IGC code (IMO, 2016) is to provide design rules for the safe carriage by sea in bulk of liquefied gases. The revised IGC code, entered into force in 2016, indicates as potential risks for a ship equipped with a re-gasification system: fire and explosion; evacuation; extension of hazardous areas; pressurized gas discharge to shore; high-pressure gas venting; process upset conditions; storage and handling of flammable refrigerants; continuous presence of liquid and vapor cargo outside the cargo containment system; tank over-pressure and under-pressure; ship-to-ship transfer of liquid cargo; and collision risk during berthing maneuvers.

Compared with previous IGC code, the revised code suggests new requirements for the concept of re-gas vessels and possibility to use risk analyses to base design requirements. The risk assessment for fire and explosions specifically addresses areas or spaces containing piping, machinery, equipment and components. For example, cargo containment and handling space design refer to SOLAS for the purpose of fire protection and prevention of potential explosion. Furthermore, those areas shall be designed to retain their structural integrity in case of explosion or fire and this capability is to be substantiated on the basis of a risk analysis with due consideration of the characteristics of the safety measures like fire detection, suppression or pressure relieving devices. To address the collision risk and protect cargo tanks, the distance of cargo tanks from side shell has been increased as a function of the individual protected tank volume. Classification Societies have issued guidelines based on the IGC code (DNVGL, 2016 and 2017a; BV, 2017; LR, 2014). Fire and explosion safety assessment of FSRU, however, benefit from the experience gained in the similar field of offshore operation, where practices including the selection of design scenario or load from risk analyses and structural safety assessment are also widely used. For a detailed guidance on fire and explosion design for offshore structures see Czujko et al. (2015).

7.5.2 Fire and explosion design for Gas fuelled ships

The introduction of stricter local, national and international environmental legislations demands new fuel solutions within the maritime industry. One possible approach to meet the emission requirements is to use natural gas as fuel for propulsion. The typical systems for gas fuelled ships are containment and process systems. Even though the containment systems which store LNG on board ships follow the design principles known from gas carriers, LNG as a ship fuel has initiated new design concepts for containment systems. To use LNG as fuel it is necessary to extract it from the tank with pumps or pressure, and condition it by vaporization, pressurization and warming. Also, the natural gas has to be routed to the engine's gas valve unit and into the engine itself. All these steps in the process must be accomplished without any gas leakage into the ship which can lead to fire or explosion accidents.

Until recently, there was a lack of international safety requirements for gas as fuel for non-LNG tankers, that is, ships other than gas tankers. However, the IGF Code (International Code of Safety for Ships using Gases or other Low-Flashpoint Fuels IGF code; IMO, 2017c) entered into force in 2017. The goal of the IGF Code is to provide an international standard for ships with natural gas-fuelled engine installations. Therefore, this code provides mandatory provisions for the arrangement and installation of low-flashpoint fuelled machinery. Similar to IGC code, IGF code also requires that risks affecting persons on board, the environment, the structural strength or the integrity of the ships are addressed by conducting risk assessments for the inherent hazards. The analysis shall ensure that risks are eliminated wherever possible. Risks which cannot be eliminated shall be mitigated as necessary. Especially, the code requires that explosion consequences shall not:

- cause damage to or disrupt the proper functioning of equipment/systems located in any space other than that in which the incident occurs;
- damage the ship in such a way that flooding of water below the main deck or any progressive flooding occur;
- damage work areas or accommodation in such a way that persons who stay in such areas under normal operating conditions are injured;
- disrupt the proper functioning of control stations and switchboard rooms necessary for power distribution;
- damage life-saving equipment or associated launching arrangements;
- disrupt the proper functioning of firefighting equipment located outside the explosion-damaged space;
- affect other areas of the ship in such a way that chain reactions involving, inter alia, cargo, gas and bunker oil may arise;
- prevent persons access to life-saving appliances or impede escape routes.

However, as this code also doesn't provide clear or prescriptive criteria of risk assessment or accidental limit state design for fire and explosion accidents, offshore practices of fire and explosion design (Czujko et al. 2015) are also widely used, together with classification society's rules and guidelines (DNVGL, 2017b; LR, 2016).

7.6 Fire and explosion analyses for LNG ships

7.6.1 Fire and explosion analyses for LNG carriers and FSRUs

Although in LNG shipping there has rarely been an event of cargo loss from accident, a relevant potential cause of leaks from LNG storage tanks is represented by collision or grounding accidents (Pitblado and Woodward, 2011). Therefore, the safety assessment of LNG carriers has been mainly focused on collision/grounding accidents and on following leakage events like dispersion or evaporation of LNG and heat radiation by pool fire. Luketa-Hanlin and Hightower (2008) have defined three categories of postulated LNG spills from carriers as shown in Fig. 15. The categories are basically Type I. above the water level; Type II. at the water level; Type III. below the water level. For each category, Pitblado and Woodward (2011) reviewed recent developments for collision/grounding calculation including leakage hole size and location, LNG pool size prediction, penetrations and hull pressure effects, etc. The theoretical models of dispersion, evaporation, pool fire and BLEVE from LNG spills are also reviewed.

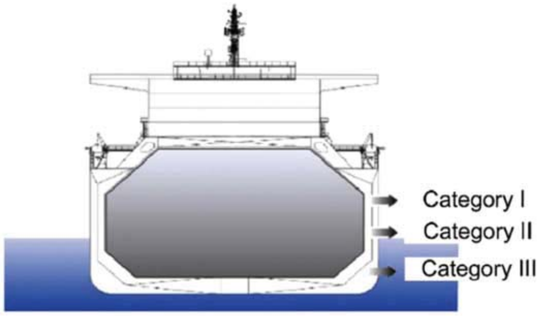
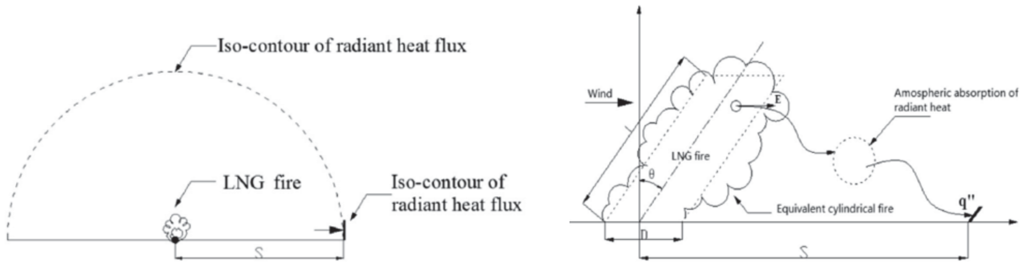


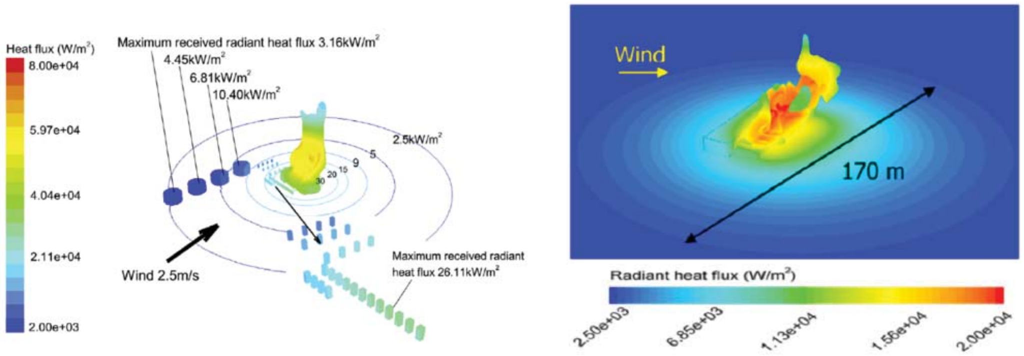
Figure. 15: Types of LNG leak location (Luketa-Hanlin and Hightower, 2008)

Fay (2003, 2007) proposed a comprehensive model for predicting the dynamics of spills from LNG tankers based on fluid mechanics principles and empirical properties of LNG spills on water, and Ray (2007) reviewed the integral and semi-empirical models (point source and solid flame) for LNG pool and vapor fire including thermal radiation hazard modelling. Recently, numerical simulations with CFD for LNG pool fire are widely used. Sun and Pareek (2015) analyzed the fire hazard and mitigation measures around an existing on-land LNG station using a computational fluid dynamics (CFD) model, and the results of CFD simulations were compared with the phenomenological models (Fig. 16). They also showed the CFD pool fire simulation of LNG spill on water for ship-to-ship bunkering between a LNG carrier and an FSRU as shown in Fig. 16(d). The significant hazards associated with LNG ship-to-ship bunkering could involve LNG vapor dispersion and LNG pool fires. The boil-off LNG vapor initially behaves as a denser-than-air vapor due to its cryogenic temperature and then is dissipated, as the vapor cloud heated up by surrounding environment. LNG pool fires occur due to either the source ignites immediately or a flash fire burns back to the source. It could cause thermal radiation damage to the surrounding properties or people. Due to different LNG discharge locations, three possibilities of lumped LNG vapor source planes (i.e. below waterline, at waterline and above waterline) were compared to investigate the vapor dispersion behaviour and fire radiation hazards in the different cases. in the study, thermal radiant heat flux and temperature were utilized to analyze the material effectiveness on both the LNG bunker and the cargo vessel. The water curtain, which is commonly used to prevent material stress cracking in case of LNG leakage, was also considered appropriately to mitigate the radiation hazard. Water curtain is often used as a physical barrier in the chemical and petrochemical industries which holds back the gas cloud and reduces the safety distance to a lower flammability limit (LFL) range. Detailed engineering criteria for designing an effective water curtain system are available from continuous research works in Mary Kay O'Connor Process Safety Center (Olewski et al., 2011, Kim et al., 2013).



(a) Point source model

(b) Solid Flame model



(c) CFD model on land tanks (d) CFD model of bunkering on sea water

Figure. 16: Radiant flux models (Sun and Pareek, 2015, 2017)

Martins et al. (2016) presented a complete quantitative risk analysis of undesired events (pool fire, jet fire, explosion, etc.) that may occur during the loading and unloading of LNG between a typical LNG carrier and an offshore terminal (FSRU). Initially, the potential hazardous events are categorized in some possible scenarios; the frequencies of occurrence of the undesired events are estimated; the weakness of each scenario is identified in the consequence analysis of a specified case; which is evaluated by providing the data to estimate the total risk of the installation. The risk was evaluated in terms of social and individual risk. Lastly, possible control measures able to reduce the frequency of occurrence, or mitigate the impacts associated with the analyzed scenarios, were proposed and new risks levels are estimated by considering those control measures.

Onboard ships, the most probable location of the fire is a machinery or engine room. Su and Wang (2013) used a CFD code to predict the developing processes of the fire in the design of engine room with multilayer structures, and Moon et al. (2009), CFD simulation for the arrangement of compressor room in LNG carriers. Kang (2017) also presented CFD simulations for the fire safety design of machinery room. In particular, he suggested a framework for using computational fire simulations during the early phases of ship design. This work is focused on how to arrange fire control options with minimal changes of existing design procedures. Currently, computational simulation tools are used to predict and mitigate fire propagation during the ship design process within the performance-based alternative design requirement.

Ignition of natural gas is generally not considered to pose explosion hazards in unconfined and low or medium congested areas. However, as the degrees of confinement and/or congestion increase, a potential exists for the ignition of a methane cloud to result in damaging overpressures. An area of potential interest for VCEs is the dock, while an LNG carrier is being offloaded: the vessel hull provides one degree of confinement and the shoreline may provide another; some degree of congestion is provided by the dock and associated equipment. Gavelli, et al. (2011), evaluated the consequences of the ignition of a flammable vapor cloud from an LNG spill during the LNG carrier offloading process. The CFD simulations show different approaches that can be followed to evaluate a vapor cloud explosion scenario in a partially confined and partially congested geometry

In addition to fire or explosions, another major safety concerns in LNG-related facilities is the reliability of a LNG Cargo containment system (CCS) for LNG carriers. Cryogenic LNG leakage due to CCS damage or failure can have dangerous effects on the ship structure. Lee et al. (2015) studied the LNG evaporation and heat diffusion through a membrane CCS with CFD simulations which considers liquid-to-gas phase changes and reactions in the porous insulation media and the accompanied rates of heat transfer. Choi et al. (2006) investigated, further to LNG leakage, the consequent temperature change of the hull steel plate in a CCS. They used experimentally determined ductile-to-brittle transition temperature (DBTT) as the index of critical temperature for the hull plate, and a numerical simulation was performed to estimate the behaviour of cryogenic liquid in a porous structure in an LNG CCS and the resulting temperature change of the hull's plate due to LNG leakage. According to the study, the critical leakage hole size where temperature of hull plate did not reach a DBTT lies between 2 mm and 5 mm under the leakage conditions.

7.6.2 Fire and explosion analyses for LNG fuelled ships

For the use of natural gas as a fuel which should be stored in a liquefied form, a dedicated system, called the LNG fuel gas supply system (FGSS), should be installed on board. The system also needs subsystems for the storage and handling of pressurized LNG that surely present LNG-related risks. When the LNG-FGSS is above the deck, the fire risk is more detrimental than the explosion risk. An explosion in open space is unlikely to occur, and the overpressure even in the case of explosion is not considerable. In contrast, a fire due to cryogenic LNG and high-pressure natural gas after evaporation may lead to catastrophic consequences and should be addressed appropriately. A dedicated fire risk analysis was carried out by Chu and Chang (2017) with a structured procedure of quantitative risk analysis for fire accidents in FGSS. They performed primary tasks to estimate and manage the fire risks: the selection of representative scenarios, the estimation of frequency, the analysis of consequences and risk estimation for personnel. Lee et al. (2015) also conducted fire risk analysis for FGSS especially with CFD fire consequence analysis and estimation of design fire loads. A CFD explosion consequence analysis for LNG fuelled ships was carried out by Fu et al. (2016).

8. MARITIME SAFETY AND RESCUE SERVICES

Maritime Search and Rescue (SAR) services exist to assist people in distress or danger at sea, and involve activities such as assisting ships and vessels in difficulty, accident prevention, search and rescue, medical consultations and patient transport. An efficient response to maritime incidents and accidents is thus of vital importance. Apart from highlighting the need for research on and operational improvements for preventing accidents, the need for efficient response to maritime incidents and accidents is well acknowledged.

In (Nordström et al., 2016), a method is proposed for enhancing the communication between the SAR response operators and the crew of the distressed vessel. It aims at assessing and communicating whether a vessel can provide a safe environment for the people onboard. This method, named Vessel TRIAGE, borrowed the idea from the well-established working methods in emergency medicine, and it attempts to establish a shared understanding of the nature of the distress situation using a set of threat factors and a four-level ship safety categorization.

Especially in the Artic regions, due to the severe environmental conditions, there is a great concern about possible accidents, and their consequences for life and nature. Accordingly, a high level of preparedness for emergency cases is required. In Marchenko,et al. (2016) the rescue system resources of three northern regions of the Arctic are analyzed and compared, focusing on the need of international collaboration for safety on the sea in the border area.

Shipping accidents in northern Baltic sea areas are studied by (Goerlandt et al., 2017), providing insights in the operational types and environmental conditions under which the accidents occurred. According to the authors, the outcomes of their research could be useful for developing realistic training scenarios for oil spill response operations, although the results were primarily intended for improving risk analyses focusing on oil spill risks in winter conditions.

In Vettor & Guedes Soares (2015) the main features of the SAR intervention are described focusing on the existing components for an integrated information system in the Portuguese coasts. The subjects covered include the computation of the environmental conditions and the adoption of dedicated graphical interface that provides all the necessary information to support and planning fast and efficient operations.

8.1 Emergency Response Services - ERS

On the 1st January of 2007 the Revised Annex I of MARPOL 73/78 entered into force. Regulation 37.4 of this Annex (IMO, 2004b) specifies that all oil tankers of 5000 tons deadweight or more shall have prompt access to computerized, shore-based damage stability and residual structural strength calculation programs. The same requirement was issued later in 2011 for passenger vessels (IMO, 2011). At a first sight, the specified Regulation regulates only nominating of the coastal organization which can assist vessel's crew in calculations, having provided carrying out emergency calculations for situations that are out of the crew's qualification. Emergency situations, however, set more stringent requirements. The vessel will not only need auxiliary calculations, but often a guide for carrying out fight for survivability or emergency salvage.

Purpose of the survivability or emergency salvage actions is the rescue action of emergency vessel by consecutive effective task prioritization on people rescue, preventing environmental pollution and eliminating the loss of property (vessel and/or cargo). Certainly, while specific experience and intuition is a necessary condition for successful res-cue operation, a key condition is the existence of operative and qualified forecast of conditions of the vessel in distress, and also the possibility to estimate the residual strength of the damaged hull as well as trim and stability changes with help of computation methods.

The corresponding problem includes a high degree of uncertainty and transient emergency situations. In combination with responsibility for people's life, survivability of a vessel and safety of cargo, this problem puts very rigid boundaries on the person in charge of decisions. This circumstance forced USA legislators first, and then IMO to create shore support for the vessel's Master in the form of ERS centres..

8.2 ERS Functionality

The adoption of the specified MARPOL Regulation initiated the creation of ERS centres. In the first place, ERS centres were organized Classification Societies, e.g. ABS (ABS, 2010), DNV (DNV-GL, 2016), BV. In addition, a number of other organizations claim to provide ERS for the marine industry, but the capability of the service provider is not addressed in the legislation. This has led to a situation where operators may even elect to provide this service internally without the assistance of external service providers. It is noted in OCIMF (2013) report that ERSs are rarely used, and accordingly may not attract appropriate priority by vessel management. Merely having a service agreement in place does not ensure that, when needed, the quality of service provided meets the need. Therefore, OCIMF (2013) report highlights a list of recommended minimum items for a prompt and reliable service.

The primary requirement of the ERS is to provide shore based damaged stability calculations. Further, it requires residual structural strength calculations as well as estimation of oil spill after groundings, collisions, breakage of construction, fires, explosions, etc. Regarding structural strength, an initial assessment should include a rapid assessment of the damage condition. This assessment should help to check that the vessel is in a condition to remain safely afloat and define the immediate corrective actions recommended to ensure the safety of the crew. There are two tiers in strength assessment, depending on the extent of the damage. First tier stipulates immediate (within 2h) longitudinal strength assessment in the damaged conditions. Second tier involves post initial response analysis either with 3D beam or FE analysis.

Such analyses require accurate calculation models on stable, pre-tested software. For instance, a ship stability calculation model should be prepared in advance and ready for use. This aspect should be part of the design approach, covering the entire lifecycle of the ship. As pointed out by Design Methods committee (ISSC, 2015a), this data sharing is certainly in the realms of present capabilities, but has some practical limitations such as intellectual property protection of the data within the systems. Shipyards are rightly concerned about exposing detailed production information to all downstream users.

According to the results of the calculation work by shore ERS centre, guidelines for the master are worked out. Guidelines include recommendations due to survivability fighting and decreasing of possible loss. Recommendations also include suggestions for emergency towing if needed.

The tasks set for ERS centres are quite similar for different organizations and can be derived by example from the Rapid Response Damage Assessment (RRDA) of ABS:

- development of a database of pertinent aspects of the vessel's structure, materials, machinery, and equipment;
- development of a computer model of the vessel that will allow for damage stability and residual strength analysis;
- evaluation of salvor's or owner's plans for off-loading, ballasting or cargo transfer sequences to improve residual stability and reduce hull girder loads and ground force reaction;
- calculation of bending and shear stresses caused by ground force;
- calculation of the residual hull girder strength based on the reported extent of damage;
- calculation of residual stability when the vessel's compartments are breached;
- calculation of hull girder strength in damaged condition with wave loading;
- calculation of hull girder ultimate strength;
- calculation of local strength in the damaged area;
- calculation of local buckling and ultimate strength;
- other calculations as appropriate for the vessel's condition.

ERS should be available round-the-clock without rest-days, but it is stressed that the success of the action is based on the predefined numerical models for the vessels managed by the centre.

8.3 Basis for decisions making

The general scheme for actions at the beginning of the emergency is given e.g. in Egorov et al. (2015). The actual formulation of rescue actions on board the vessel in distress starts after taking decisions about the object of rescue (people and/or vessel and/or cargo).

As pointed out by Egorov (1990), while preparing a plan for action one should take into consideration requirements about buoyancy, stability, maximum heeling angle, post damage global and local strength and restrictions in the capacity of compartments. While fixing limit values for trim and stability is quite straightforward, strength limits are not so obvious. In Egorov (2006), specific still water permissible bending moments are defined taking into consideration the missing part of the hull longitudinal members and a non axial bending load.

One of the most significant dangers is represented by water on deck that can imply a catastrophic decrease of vessel's stability leading in turn to capsize. Returning the vessel into the right floating position is a key for keeping it afloat. Therefore, an important phase of rescue actions is the righting of the vessel (Egorov et al. 2015), which means taking operational measures to control heel and trim after the accident.

9. BENCHMARK STUDY

9.1 Introduction

The objective of the benchmark study is to simulate a grounding scenario with finite element software and compare results with experimental tests. The ability to assess the strength of a ship against such incidents is crucial in the evaluation of this type of scenarios.

The following committee members have contributed to the benchmark study:

Table 4 Committee members contributed to the benchmark

Participation	Affiliation	Analysis software
L. Brubak	DNV GL, Norway	ABAQUS
Z. Hu	China	LS-DYNA
M. Kõrgesaar	Finland	ABAQUS
I. Schipperen	TNO, Netherland	LS-DYNA
K. Tabri	MEC, Estonia	LS-DYNA

A detailed FE model of one of the double bottom models tested in Rodd 1996 was created. The one chosen for the study was the conventional model most resembling the double bottom of a traditional tanker.

9.2 Experiment

The grounding model was created from the dimensions given in (Rodd, 1996) and (Simonsen, 1997), and shown here in Figure 17. The model includes the double bottom, the front, centre and aft bulkheads and the two sides. The double bottom features inner and outer plating with a thickness of 3mm, 7 transverse webs with a thickness of 1.9 mm between each bulkhead and one continuous longitudinal web in the centre of the model with a thickness of 2.28 mm. In addition to that, the inner and outer bottom is stiffened by folded plate continuous stiffeners and the transverse webs contain two manholes, one on each side of the longitudinal web. The manholes are reinforced by circumferential stiffeners along their edges. The bulkheads are vertically stiffened by L-stiffeners.

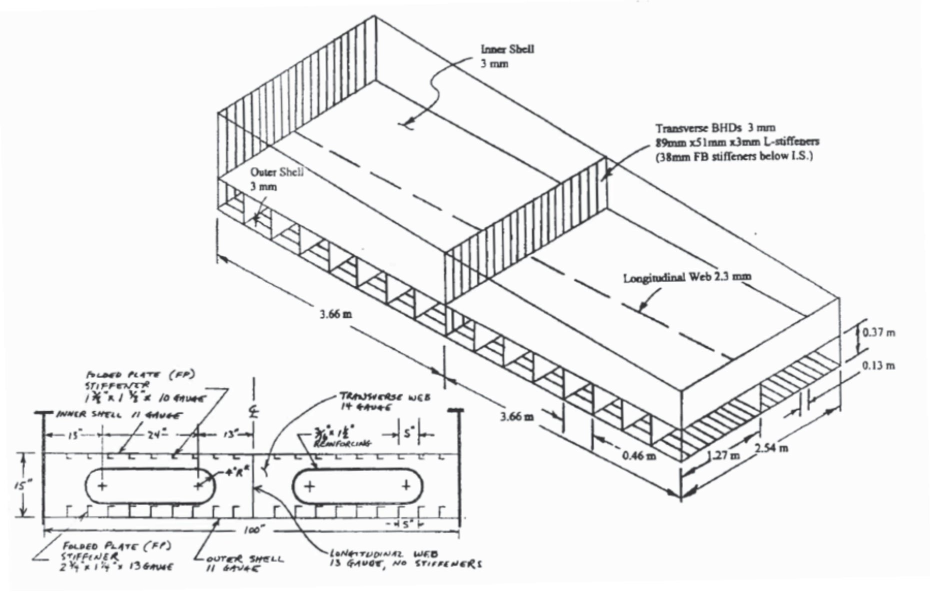


Figure 17 Model dimensions (Rodd 1996, Simonsen 1997).

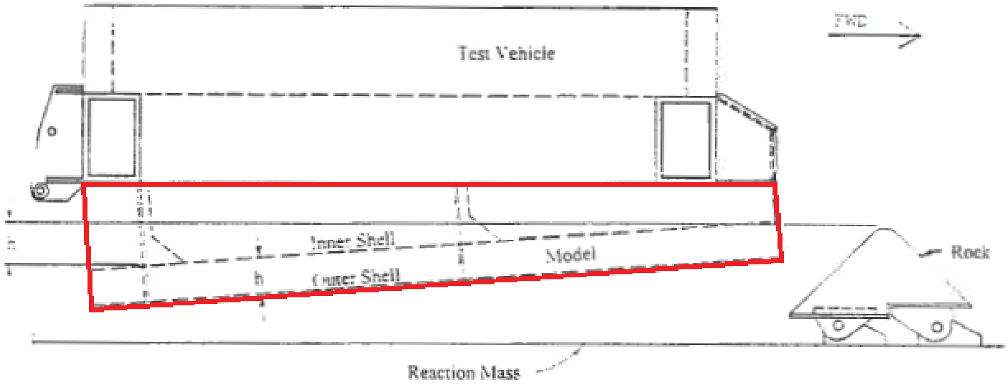


Figure 18 The grounding model mounted beneath the sled at an angle.

The grounding model is a 1:5 scale model of a ship double bottom and is meant to represent a conventional double bottom of a tanker in the 30,000-40,000 tones range. It was one of a total of four types of double bottom grounding models that were tested in the mid-1990s at the Naval Surface Warfare Centre in Virginia, USA. The methodology adopted for these tests and results obtained are presented in detail in (Rodd, 1996) and (Simonsen, 1997).

In the test, the scale model was fixed to a sled consisting of two railway bogies and dragged up an inclined slope to accumulate potential energy. The total mass of the grounding model and the sled was 223tons. At the end of the slope and centered between the two railway tracks was an artificial "rock" made of a steel cone with a semi-apex angle of 45° and a rounded tip with a radius of 0.17m. Details of the rock are shown in Figure 19.

The cone was fixed to a reinforced concrete pad with a mass of 1200tons. The test setup is shown in 18 reporting a cut view of the mounted model in way of the rock. The model was mounted with a longitudinal inclination (trim) angle so that when the model hits the tip of the rock, the tip is at the same level as the inner bottom plate. As the model moves over the rock, the rock tip is forced further up through the model and if the barge eventually clears the rock completely, the rock tip will be at a penetration height equal to twice the double bottom height. According to Simonsen (1997), this will ensure that the inner bottom is ruptured at some point during the test.

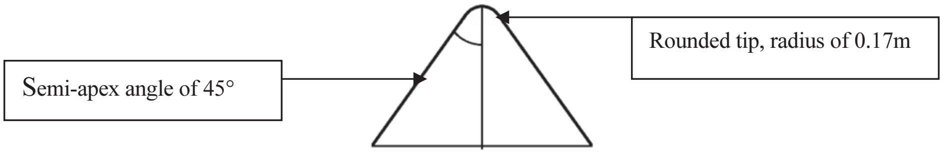


Figure 19 Artificial rock

9.3 Input data

The same geometry of the barge and the rock was used by all the contributors, with a friction coefficient equal to 0.35 (except in the sensitivity study reported in section 9.5). The material was ASTM A569 steel. Material characteristics are taken from the experiment description given in Simonsen (1997) and summarized in Table 5.

Other parameters relevant for the study (such as mesh size, failure strain, etc.) were assumed by each of the contributors. A summary is provided in Table 6.

Table 5 Material properties of ASTM A569

Material parameter	Value
Young's modulus	206 GPa
Poisson's ratio	0.3
Yield strength, σ_y	283 MPa
Ultimate strength, σ_u	345 MPa
Material flow stress, $\sigma_0=(\sigma_y+\sigma_u)/2$	314 MPa

Table 6 Assumptions in FE modelling by each contributor

parameter	Brubak	Hu	Kõrgesaar	Schipperen	Tabri
Strain hardening, n	0.22	0.22	0.2	n.a.	Full stress-strain curve
Mesh size	10 mm (3.3 times plate thickn.)	30mm	30 mm	30 mm	45 mm
Critical strain	Triaxiality depended; 22% for uniax. tension	0.17	Element thickness/ length/ triaxiality dep.	Element thickness/ length dependent	Through thickn. strain 0.087(3.4mm)/ 0.093 (3 mm)
Failure criterion	Damage evolution in Abaqus	plastic_ kinematic	Kõrgesaar & Romanoff (2014)	GL criterion, ADN-2015	Lehmann, et al. (2001)

9.4 *Results*

The results from the analyses are shown in Figure 20, where the energy and force curves are plotted against the horizontal position (grounding distance) of the barge. It can be seen that the agreement between experimental results and numerical simulations is relatively good.

From the force curve, several smaller spikes and two large spikes are observed, corresponding to the structure resisting deformations as the rock passes through the several smaller transverse frames and the two cargo hold bulkheads placed at mid-length and in the aft end. An overall increase in force is recorded, due to the trim angle. The absorbed energy can be found by integrating the reaction force over the grounding distance. Following the pattern of the force curve, the energy plot shows a slightly higher absorption rate (energy absorption per meter) around the two bulkheads than in the rest of the cargo hold.

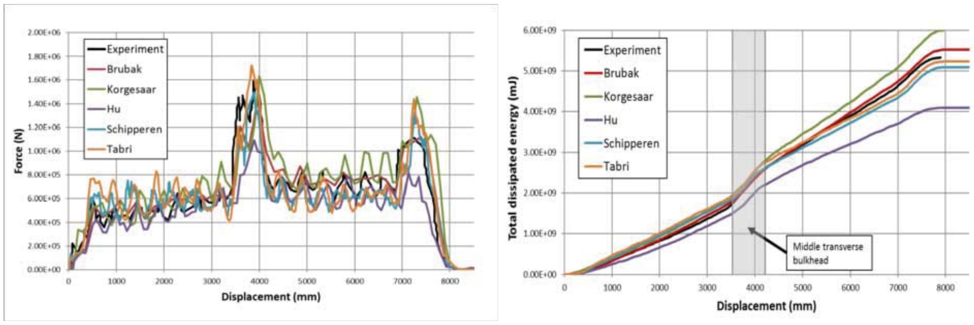


Figure 20 Results in terms of reaction force (left) and energy (right) versus grounding distance –base case, comparison among contributors.

The total dissipated energy can be broken down into several components such as friction, plastic deformation, elastic strain and energy gone into tearing elements apart. In the analyses that were run it is seen that most of the energy is dissipated by plastic deformation and friction while the other aforementioned contributions are relatively small. The ratio between the energy going into friction and plastic deformation varies depending on the coefficient of friction. A sensitivity study of the influence of the friction coefficient is presented in section 9.5.

Damages are shown in Figure 21, where deformations show to be very large. From what can be read from the pictures of the experimental test, the damages are very similar to what was found in the present finite element analysis. This illustrates that non-linear finite element computations can be used to estimate the damage extent with reasonable accuracy.

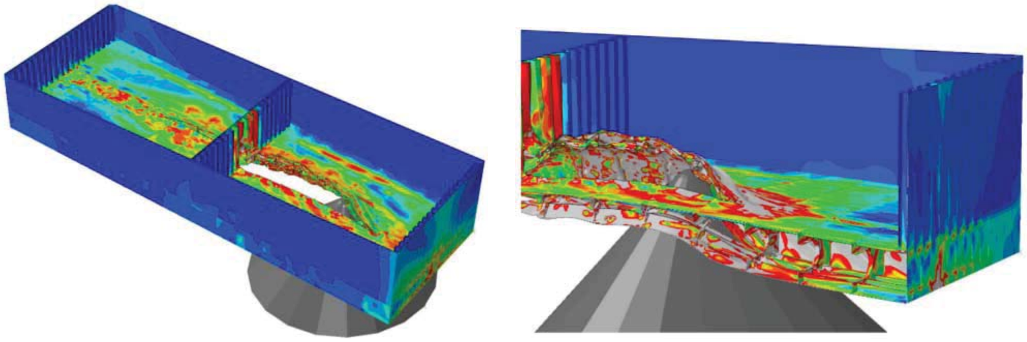


Figure 21 Damage extent of the barge (left) and close-up view of the damages (right).

9.5 *Sensitivity studies*

The results of the analyses are rather sensitive to different input parameters: a sensitivity study has been carried out to investigate to effect of: friction coefficients, failure strain values and mesh refinements. In order to isolate the effect of the different parameters, only one parameter per time is changed in respect to the model described in section 9.4.

9.5.1 *Sensitivity for friction coefficients*

The effect of the friction coefficient is studied for three different values: 0.3, 0.35 and 0.4. The other parameters are the same as in section 9.4. The average of results between the contributors is plotted in terms of force (left) and energy (right) in Figure 22

It can be noted that the failure mode may change slightly for different values of friction. This is the reason why the average result at the aft wall (about 8000 mm of displacement is higher for a friction coefficient equal to 0.35 compared to 0.4, since a higher friction caused a vertical rupture of the entire wall in the simulation by one of the contributors.

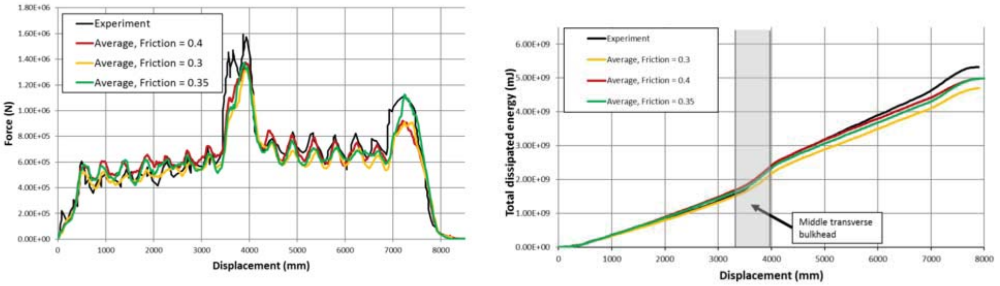


Figure 22 Sensitivity for friction coefficients (average values among contributors)
Results in terms of force (left) and energy (right).

9.5.2 Sensitivity to failure strain values

The effect of different failure strain values is studied in the same manner as for the friction, by varying failure strain values and keeping all other parameters at the same value as in section 9.4. In total three different values of failure strain are used: the one from Table 6 and two more, corresponding to variations of +/- 20% (Figure 23). In the same manner as for friction, the failure mode may change for different values of failure strain.

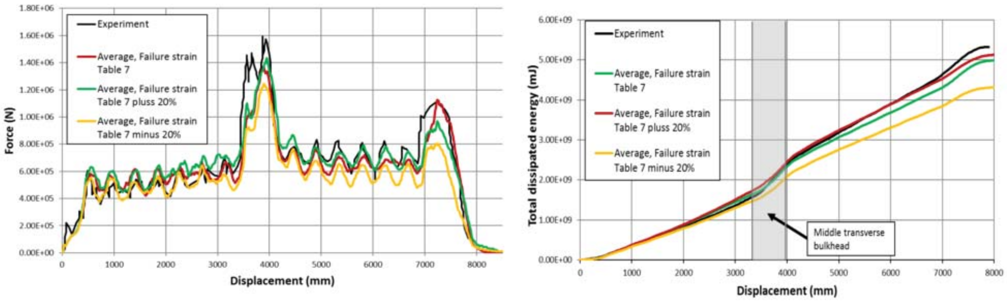


Figure 23: Sensitivity to failure strain (average values among contributors)
Results in terms of force (left) and energy (right)

9.5.3 Sensitivity to mesh refinement

The effect of mesh refinement is investigated with a fine and a coarse mesh by the various contributors. The size adopted as fine mesh is in the 10-15 mm range (i.e. 3-4 times the thickness of the outer plate) while for the coarse mesh is around 30 mm (about 10 times the outer plate thickness).

Mesh resolution has a relationship with material failure strain. The material models from each contributor are tuned for either a fine mesh (i.e. 3-5 times the thickness) or for a coarser mesh. In this section, the same material models are used for different mesh size in order to isolate the effect of mesh refinement. The effect of mesh refinement of using a coarser and a finer mesh is shown in Figure 24.

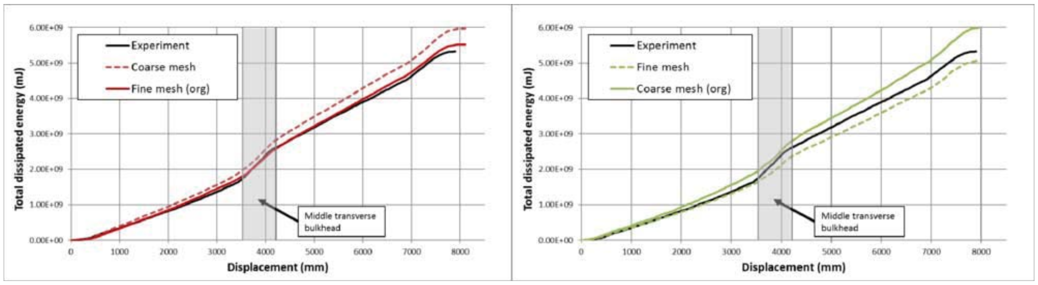


Figure 24 Sensitity study to mesh dimensions. Left: coarser right: finer

9.6 Summary

A benchmark study with five contributors has been performed with nonlinear finite element analyses of a grounding scenario and comparison with available results from an experimental test. The same geometry of the barge and the rock was used by all the contributors, and the adopted friction coefficient was equal to 0.35. The other input for the construction of the FEM models (such as mesh size, failure strain, etc.) were assumed freely by each of the contributors. The differences among the results reflect therefore the different choices made by the analysts. If this set of analyses is considered as representative of the typical dispersion in prediction results by experts in the field, the average value of predictions can be adopted to evaluate the bias between numerical results and experiments, while the standard deviation of numerical results can be assumed as an indication of the uncertainty in predictions. Figure 26 reports for force and energy the average curve and the confidence interval corresponding to +/- a standard deviation. The corrected standard deviation is used which gives an unbiased estimate of the variation and is more representative for small data sets. The figures show a small underestimation of force and energy in comparison to experiments. Most of the experimental values fall within the confidence interval corresponding to standard deviation for a given displacement. The standard deviation among the predicted forces and energies, expressed as percentage of the corresponding average value, features a mean value (computed on the whole test i.e. averaged over the barge length) of 16% and 11%, respectively. The maximum value of the same quantity is 28% for the force (at 7.2 meter displacement in Figure 25 left) and 13% for the energy (at 8 meter displacement in Figure 25 right).

In Figure 26, the ratio between the computed average value and the experimental result is plotted versus the displacements for energy and force. It can be seen that the average computed force deviates more from the corresponding experimental value (variations of the order of +/-40%) than the average energy (+/-10% in respect to experiments). This is expected, since the energy is an integral value of force. If the same ratios are averaged over the whole test, a value of 96% is obtained both for the force and the energy (same number since the energy is an integrated value of the force). This means that computed forces and energies are on the average 4% lower than the experimental results (this number quantifies the above mentioned underestimation).

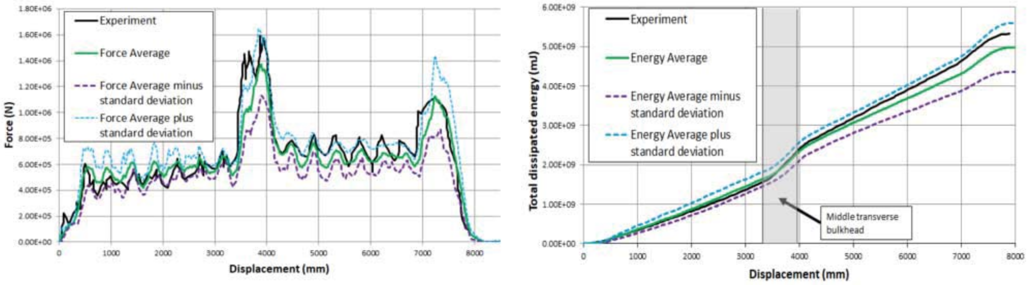


Figure 25 Average and standard deviation of results for base case in section 9.4.
On the left: force, on the right: energy

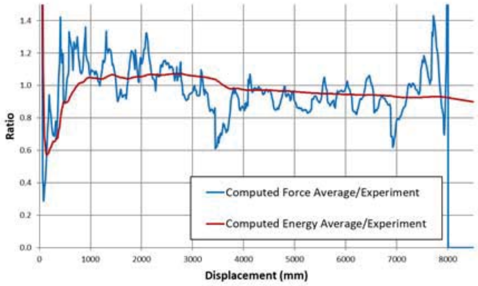


Figure 26 Ratio between average of computed values and experimental result for the energy

It is to be noted that the benchmark was not 'blind' (i.e. participants knew the experimental results) and this is always considered to improve the quality of predictions. However, it can be concluded that the fairly good agreement between experimental values and numerical predictions coming from this exercise demonstrates that a complex grounding scenario can be effectively simulated with nonlinear finite element analysis.

REFERENCES

ABS (2010) Guide for rapid response damage assessment, American Bureau of Shipping.

AbuBakar, A. & Dow, R. S. (2013) 'Simulation of ship grounding damage using the finite element method', International Journal of Solids and Structures. Elsevier Ltd, 50(5), pp. 623–636.

Acanfora, M. and De Luca, F. (2016) 'An experimental investigation into the influence of the damage openings on ship response', Applied Ocean Research, 58, pp. 62–70.

Addario, N., Rizzuto, E. and Prestileo, A. (2014)'Ship side damage due to collision with icebergs', Proceed. IMAM 2013, 15th Congress of the International Maritime Association of the Mediterranean, La Coruna ES.

Afenyo, M., Veitch, B. and Khan, F. (2016) 'A state-of-the-art review of fate and transport of oil spills in open and ice-covered water', Ocean Engineering, 119, pp. 233–248.

Akhtar, M. J. et al. (2016) 'The choice of multiple design ships for calculation of bridge collision design loads', Proceedings of 7th International Conference Collision and Grounding of Ships and Offshore Structures, Ulsan, Korea.

Alsos, H. S. and Amdahl, J. (2007) 'On the resistance of tanker bottom structures during stranding', Marine Structures, 20(4), pp. 218–237.

Alsos, H. S. and Amdahl, J. (2009a) 'On the resistance to penetration of stiffened plates, Part I - Experiments', International Journal of Impact Engineering, 36(6), pp. 799–807.

Alsos, H. S., Amdahl, J. and Hopperstad, O. S. (2009b) 'On the resistance to penetration of stiffened plates, Part II: Numerical analysis', International Journal of Impact Engineering, 36(7), pp. 875–887.

Antoine, G. O. and Batra, R. C. (2015) 'Sensitivity analysis of low-velocity impact response of laminated plates', International Journal of Impact Engineering, 78, pp. 64–80.

API, R., 2FB, Recommended Practice for the Design of Offshore Facilities against Fire and Blast Loading. 2006. Washington, DC: API.

Aps, R. et al. (2009) 'Bayesian inference for predicting potential oil spill related ecological risk', in WIT Transactions on the Built Environment, pp. 149–159.

Aps, R. et al. (2014) 'Incorporating dynamics factor to the Environmental Sensitivity Index (ESI) shoreline classification – Estonian and Spanish example', Journal of Coastal Research, 70, pp. 372–377.

Ashe G, et al. (2006) 'Committee V.5 Naval Vessel Design', Proceedings of the 16th Int. Ship and Offshore Structures Congress, Vol.2. August 2006. Southampton, UK.

Bašić, J., Degiuli, N. and Dejhalla, R. (2017) 'Total resistance prediction of an intact and damaged tanker with flooded tanks in calm water', Ocean Engineering, 130, pp. 83–91.

Begovic, E., Day, A. H. and Incecik, A. (2017) 'An experimental study of hull girder loads on an intact and damaged naval ship', Ocean Engineering, 133, pp. 47–65.

Bela, A. et al. (2017) 'Ship collision analysis on offshore wind turbine monopile foundations', Marine Structures, 51, pp. 220–241.

BEVI (2009) 'Reference Manual Bevi Risk Assessments', Ver.3.2, National Institute of Public Health and the Environment (RIVM), Netherlands.

Bitner-Gregersen E.M. and Gramstad O. (2016) 'Rogue Waves: Impact on ships and offshore structures' DNV-GL Position Paper 05–2015.

Bitner-Gregersen E.M. et al. (2012) 'Reply to discussers of the report of ISSC 2012 Committee I.1 Environment', Proceedings of the ISSC 2012, September 2012 Rostock, Germany.

Bitner-Gregersen, E.M., et al. (2015) 'Report of Committee I.1 Environment', Proceedings of the ISSC 2015, September 2015, Cascais, Portugal.

Brunila, O. P. and Storgård, J. (2012) 'Oil Transportation in the Gulf of Finland in 2020 and 2030', Publications from the Centre for Maritime Studies. Turku.

BV (2017) ' Rules for the Classification of Floating Storage Regasification Units', NR 645 DT R00 E, Bureau Veritas.

Calle, M. A. G., Oshiro, R. E. and Alves, M. (2017) 'Benchmark study of failure criteria for ship collision modeling using purpose-designed tensile specimen geometries', Marine Structures, 53, pp. 68–85.

Calle, M. A. G., Verleysen, P. and Alves, M. (2017) 'Ship collision and grounding: Scaled experiments and numerical analysis', International Journal of Impact Engineering, 103, pp. 195–210.

Cerik, B. C. (2016) 'A study on modelling of rate-dependent material behaviour in simulation of collision damage', Proceedings of 7th International Conference Collision and Grounding of Ships and Offshore Structures, Ulsan, Korea.

Cerik, B. C., Shin, H. K. and Cho, S. R. (2016) 'A comparative study on damage assessment of tubular members subjected to mass impact', Marine Structures, 46, pp. 1–29.

Chen, Q., Qi, X. and Sun, Q. (2017), 'Analysis of Causes of Maritime Accidents', 3rd International Conference on Applied Mechanics and Mechanical Automation (AMMA 2017).

Chen, W. and Hao, H. (2014) 'Experimental and numerical study of composite lightweight structural insulated panel with expanded polystyrene core against windborne debris impacts', Materials and Design, 60, pp. 409–423.

Chen, W. et al. (2015) 'Performance of composite structural insulated panel with metal skin subjected to blast loading', Materials & Design, 84, pp. 194–203.

Cheng, J. (2014) 'Reliability analysis of the Sutong Bridge Tower under ship impact loading', Structure and Infrastructure Engineering. Taylor & Francis, 10(10), pp. 1320–1329.

Chu, B., & Chang, D. (2017) 'Effect of full-bore natural gas release on fire and individual risks: A case study for an LNG-Fuelled ship', Journal of Natural Gas Science and Engineering, 37, 234–247.

Czujko, J. et al. (2012) 'Report of Committee V.1 Damage assessment following accidents', Proceedings of the ISSC 2012, September 2012 Rostock, Germany.

Czujko, J. et al. (2015) 'Committee V.1 Accidental limit states', Proceedings of 19th International ship and offshore structures congress, Sep. 2015, Cascais, Portugal.

D3view, 'Best Practices for Modeling Recoverable Low Density Foams – By Example', 12 10 2006. [Online]. Available: http://www.d3view.com/best-practices-for-modeling-recoverable-low-density-foams-by-example/. [Accessed 10 3 2017].

Daley, C. G. et al. (2017). 'Overload response of flatbar frames to ice loads', Ships and Offshore Structures, 12(sup1), pp. S68-S81.

Daniel, I. M. (2016) 'Yield and failure criteria for composite materials under static and dynamic loading', Progress in Aerospace Sciences, pp. 18–25.

Derradji-Aouat, A. (2000) 'A unified failure envelope for isotropic fresh water ice and iceberg ice', Proceeding of the ETCE/OMAE-2000 Joint Conference, Energy for the New Millennium, New Orleans, USA,

DNV GL (2014) 'Guideline for Large Maritime Battery Systems', No.2013-1632, Rev.1.0, Det Norske Veritas, Norway.

DNV GL (2016) 'Rules for Classification Ships – Part 5 Ship types – Chap. 7 Liquefied gas tankers', Det Norske Veritas, Norway.

DNV GL (2017a) 'Rules for Classification Ships – Part 6 Additional class notations – Chap. 2 Propulsion, power generation and auxiliary systems – Sec. 5 Gas fuelled ship installations – Gas Fuelled', Det Norske Veritas, Norway.

DNV GL (2017b) ‘Rules for Classification Ships – Part 6 Additional class notations – Chap. 4 Cargo operations – Sec. 8 Regasification plant - REGAS’, Det Norske Veritas, Norway.

DNV GL-RP-C204 (2010) ‘Design against accidental loads’, Recommended Practice C204, Det Norske Veritas Oct. 2010, Norway, pp.7-52.

DNV GL-RP-C208 (2016) ‘Determination of structural capacity by non-linear FE analysis methods’, Recommended Practice C208, Sep. 2010, Norway.

DNV-OS-A101 (2014) ‘Safety Principles and Arrangements’, Det Norske Veritas Apr. 2014, Norway.

Dow, R. S. et al. (2015) ‘Committee V.5 Naval Vessel Design’, Proceedings of the 19th Int. Ship and Offshore Structures Congress, Sep. 2015, Cascais, Portugal.

Egorov, G. V. (1990) ‘Automated calculation of damaged vessel straightening with help of onboard personal computer // Present-day problems of shipbuilding and ship-repairing’, Transactions of OIIMF. M., V/O “Mortekhinformreklama”, pp. 26-30.

Egorov, G. V. (2006) ‘Hull’s residual strength in the damage stability calculations and providing of survivability fighting’, Criteria and examples // Visnyk ONMU. Odessa: ONMU, Vol. 19. pp. 49-63.

Egorov, G. V., Vorona O.A. & Chernii V.A. (2015) ‘"Grigoriy Bugrov" tanker salvage operation execution with integrated approach to damage control with account of strength requirements’ // Proc. of the 29th Asian Technical Exchange and Advisory Meeting on Marine Structures (TEAM'2015). – Vladivostok, Russia, pp. 35-42.

Eleftheria, E., Apostolos, P. and Markos, V. (2016) ‘Statistical analysis of ship accidents and review of safety level’, Safety Science. Elsevier Ltd, 85, pp. 282–292.

Fan, W. and Yuan, W. C. (2014) ‘Numerical simulation and analytical modeling of pile-supported structures subjected to ship collisions including soil-structure interaction’, Ocean Engineering, 91, pp. 11–27.

Fang, Q. et al. (2015) ‘A 3D mesoscopic model for the closed-cell metallic foams subjected to static and dynamic loadings’, International Journal of Impact Engineering, 82, pp. 103–112.

Fay, J. A. (2003) ‘Model of spills and fires from LNG and oil tankers’, Journal of Hazardous Materials, 96(2), pp. 171–188.

Fay, J. A. (2007) ‘Spread of large LNG pools on the sea’, Journal of Hazardous Materials, 140(3), pp. 541–551.

Ferrari, N., Rizzuto, E. and Prestileo, A. (2015) ‘Modelling ice characteristics in iceberg-ship collision analyses’, in 16th International Congress of the International Maritime Association of the Mediterranean, IMAM 2015, pp. 305–316..

Friis-Hansen, P. and Simonsen, B. C. (2002) ‘GRACAT: Software for grounding and collision risk analysis’, Marine Structures, 15(4–5), pp. 383–401.

Fu P., Leira B.J. & Myrhaug, D. (2016). ‘Parametric Study Related to the Collision Probability Between Two Risers’, In ASME 2016 35th International Conference on Ocean, Offshore and Arctic Engineering, American Society of Mechanical Engineers. Pusan, Korea.

Fu, P., Leira, B. J. and Myrhaug, D. (2017) ‘Reliability analysis of wake-induced collision of flexible risers’, Applied Ocean Research. Elsevier B.V., 62, pp. 49–56.

Fu, S. et al. (2016) Framework for the quantitative assessment of the risk of leakage from LNG-fuelled vessels by an event tree-CFD, Journ.of Loss Prevention in the Process Industries, 43, pp. 42–52.

Gaiotti M. and Rizzo C. M. (2012) ‘An analytical/numerical study on buckling behaviour of typical composite top hat stiffened panels’, Ships and Offshore Structures. Taylor & Francis, 7(2), pp. 151–164.

Gao, Y. et al. (2015) ‘An elastic-plastic ice material model for ship-iceberg collision simulations’, Ocean Engineering, 102, pp. 27–39.

Gao, Z., Yang, S. and Hu, Z. (2014) ‘The resistance of ship web girders in collision and grounding’, Mathematical Problems in Engineering, 2014.

Gao, Z. and Hu, Z. (2015) ‘Structural response of ship bottom floor plating during shoal grounding’, pp. 685–692.

Gavelli, F. et al. (2011) ‘Evaluating the potential for overpressures from the ignition of an LNG vapour cloud during offloading’, Journal of Loss Prevention in the Process Industries. Elsevier Ltd, 24(6), pp. 908–915.

Getter, D. J. et al. (2015) ‘Strain rate sensitive steel constitutive models for finite element analysis of vessel-structure impacts’, Marine Structures, 44, pp. 171–202.

Gilioli, A. et al. (2015) ‘Predicting ballistic impact failure of aluminium 6061-T6 with the rate-independent Bao-Wierzbicki fracture model’, International Journal of Impact Engineering, 76, pp. 207–220.

Goerlandt, F. et al. (2017) ‘An analysis of wintertime navigational accidents in the Northern Baltic Sea’, Safety Science, 92, pp. 66–84.

Hänninen, M. (2014) ‘Bayesian networks for maritime traffic accident prevention: Benefits and challenges’, Accident Analysis and Prevention. Elsevier Ltd, 73, pp. 305–312.

Hao, E. and Liu, C. (2017) ‘Evaluation and comparison of anti-impact performance to offshore wind turbine foundations: Monopile, tripod, and jacket’, Ocean Engineering, 130, pp. 218–227.

Hassoon, O. H., Tarfaoui, M. and El Moumen, A. (2017) ‘Progressive damage modeling in laminate composites under slamming impact water for naval applications’, Composite Structures, 167, pp. 178–190.

Heinvee, M. (2016) ‘The Rapid Prediction of Grounding Behaviour of Double Bottom Tankers’, Doctoral thesis, Tallinn University of Technology.

Heinvee, M. and Tabri, K. (2015) ‘A simplified method to predict grounding damage of double bottom tankers’, Marine Structures, 43, pp. 22–43.

Heinvee, M. et al. (2013) ‘A simplified approach to predict the bottom damage in tanker grounding’, in Collision and Grounding of Ships and Offshore Structures - Proceedings of the 6th International Conference on Collision and Grounding of Ships and Offshore Structures, ICCGS 2013.

Heinvee, M. et al. (2016) ‘Influence of longitudinal and transverse bulkheads on ship grounding resistance and damage size’, Proceedings of 7th International Conference Collision and Grounding of Ships and Offshore Structures, Ulsan, Korea.

Hill, R. (1948) ‘A Theory of the Yielding and Plastic Flow of Anisotropic Metals’, Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences, 193(1033), pp. 281–297.

Holmen, J. K., Hopperstad, O. S. and Børvik, T. (2015) ‘Low-velocity impact on multi-layered dual-phase steel plates’, International Journal of Impact Engineering, 78, pp. 161–177.

Hong, L. and Amdahl, J. (2008) ‘Crushing resistance of web girders in ship collision and grounding’, Marine Structures, 21(4), pp. 374–401.

Hosford, W. F. (1972) ‘A Generalized Isotropic Yield Criterion’, Journal of Applied Mechanics, p. 607.

IACS (2017) ‘Common Structural Rules for Bulk Carriers and Oil Tankers’, Part 1 Chapter 4 Section 2- Dynamic load cases.

IMO (1995) Interim guidelines for approval of alternative methods of design and construction of oil tankers under regulation 13F(5) of Annex I of MARPOL 73/78, Resolution MEPC 66(37).

IMO (2001) ‘Guidelines on Alternative Design and Arrangements for Fire Safety’, MSC/Circ.1002, International Maritime Organization (IMO).

IMO (2003) Revised Interim Guidelines for the Approval of Alternative Methods of Design and Construction of Oil Tankers under Regulation 13F(5) of Annex I of MARPOL 3/78, Resolution MEPC 110(49).

IMO (2004a). Revised Annex I of MARPOL 73/78. Resolution MEPC.117(52).

IMO (2004b) ‘Explanatory notes on matters related to the accidental oil outflow performance under regulation 23 of the revised MARPOL Annex I’, RESOLUCIÓN MEPC.122(52), MEPC/52/24/Add.1

IMO (2010) ‘The International Code Application of Fire Test Procedures (FTP Code)’, International Maritime Organization (IMO).

IMO (2011) ‘Guidelines on operational information for masters of passenger ships for safe return to port by own power or under tow’, IMO, MSC.1/Circ.1400.

IMO (2016) ‘International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code)’, International Maritime Organization (IMO).

IMO (2017a) ‘The International Code for Fire Safety Systems (FSS Code)’, International Maritime Organization (IMO).

IMO (2017b) ‘International Convention for the Safety of Life at Sea (SOLAS)’, International Maritime Organization (IMO).

IMO (2017c) ‘International Code of Safety for Ships using Gases or other Low-Flashpoint Fuels (IGF code)’, International Maritime Organization (IMO).

Ince, S. T. et al. (2016) ‘An advanced technology for structural crashworthiness analysis of a ship colliding with an ice-ridge: Numerical modelling and experiments’, International Journal of Impact Engineering.

ISO (2007) ‘Fixed steel offshore structures’, Standard ISO-19902 International Organization for Standardization.

ISO (2015) ‘General principles on reliability for structures’, International Organization for Standardization, London.

Ji, S., Di, S. and Liu, S. (2015) ‘Analysis of ice load on conical structure with discrete element method’, Engineering Computations, 32(4), pp. 1121–1134.

Jia, H. and Moan, T. (2015) ‘Global Responses of Struck Ships in Collision With Emphasis on Hydrodynamic Effects’, Journal of Offshore Mechanics and Arctic Engineering, 137(4), p. 41601.

Jia, L. et al. (2016) ‘Combined modelling and experimental studies of failure in thick laminates under out-of-plane shear’, Composites Part B: Engineering, 105, pp. 8–22.

Johnson, G. R. and Cook, W. H. (1983) ‘A constitutive model and data for metals subjected to large strains, high strain rates and high temperatures’, 7th International Symposium on Ballistics, pp. 541–547.

Kang, H. J. et al. (2017) ‘A framework for using computational fire simulations in the early phases of ship design’, Ocean Engineering, 129(September 2016), pp. 335–342.

Kang, L. et al. (2017) ‘Accumulative response of large offshore steel bridge under severe earthquake and ship impact due to earthquake-induced tsunami flow’, Engineering Structures, 134, pp. 190–204.

KFX (2013) ‘User’s manual for Kameleon FireEx’, Computational Industry Technologies AS, Stavanger, Norway.

Kim, B. K. et al. (2013) ‘Key parametric analysis on designing an effective forced mitigation system for LNG spill emergency’, Journal of Loss Prevention in the Process Industries, 26(6), pp. 1670–1678.

Kim, E. (2014) ‘Experimental and numerical studies related to the coupled behaviour ofice mass and steel structures during accidental collisions’. Skipnes kommunikasjon as.

Kim, E. et al. (2017) ‘Laboratory experiments on shared-energy collisions between freshwater ice blocks and a floating steel structure’, Ships and Offshore Structures. Taylor & Francis, 12(4), pp. 530–544.

Kim, H., Welch, D. A. and Kedward, K. T. (2003) ‘Experimental investigation of high velocity ice impacts on woven carbon/epoxy composite panels’, Composites Part A: applied science and manufacturing. Elsevier, 34(1), pp. 25–41.

Kim, K. J. et al. (2016) 'An experimental and numerical study on nonlinear impact responses of steel-plated structures in an Arctic environment', International Journal of Impact Engineering, 93, pp. 99–115.

Kim, M. et al. (2016) 'Dynamic failure analysis of mark III type LNG CCS primary barrier using instability, ductile and shear failure criteria', Proceedings of 7th International Conference Collision and Grounding of Ships and Offshore Structures, Ulsan, Korea

Kitamura, O. (2002) 'FEM approach to the simulation of collision and grounding damage', Marine Structures, 15, pp. 403–428.

Kollo, M., Laanearu, J. and Tabri, K. (2017) 'Hydraulic modelling of oil spill through submerged orifices in damaged ship hulls', Ocean Engineering. Elsevier, 130(December 2016), pp. 385–397.

Kõrgesaar, M. and Kujala, P. (2016) 'Experimental validation of failure criterion for large complex shell structures', in Proceedings of the International Conference on Collision and Grounding of Ships and Offshore Structures, pp. 47–53.

Kõrgesaar, M. and Romanoff, J. (2014) 'Influence of mesh size, stress triaxiality and damage induced softening on ductile fracture of large-scale shell structures', Marine Structures, 38, pp. 1–17.

Kõrgesaar, M., Kujala, P. & Romanoff, J. (2018). Load carrying capacity of ice-strengthened frames under idealized ice load and boundary conditions. Marine Structures, 58, pp.18-30.

Kõrgesaar, M., Remes, H. and Romanoff, J. (2014) 'Size dependent response of large shell elements under in-plane tensile loading', International Journal of Solids and Structures, 51(21–22), pp. 3752–3761.

Kujala, P. et al. (2009) 'Analysis of the marine traffic safety in the Gulf of Finland', Reliability Engineering & System Safety, 94(8), pp. 1349–1357.

Kumar, K. and Surendran, S. (2013) 'Design and analysis of composite panel for impact loads in marine environment', Ships and Offshore Structures, 8(5), pp. 597–606.

Lee, G. J. (2015) 'Dynamic orifice flow model and compartment models for flooding simulation of a damaged ship', Ocean Engineering, 109, pp. 635–653.

Lee, S., Seo, S., & Chang, D. (2015) 'Fire risk comparison of fuel gas supply systems for LNG fuelled ships', Journal of Natural Gas Science and Engineering, 27, pp. 1788–1795.

Lees, F. P. (1996) 'Loss prevention in the process industries', Butterworth Heinemann.

Li, J. and Huang, Z. (2012) 'Fire and explosion risk analysis and evaluation for LNG ships', Procedia Engineering, 45(Supplement C), pp. 70–76.

Liu, B. and Guedes Soares, C. (2015) 'Simplified analytical method for evaluating web girder crushing during ship collision and grounding', Marine Structures. Elsevier Ltd, 42, pp. 71–94.

Liu, B. and Guedes Soares, C. (2016a) 'Analytical method to determine the crushing behaviour of girders with stiffened web', International Journal of Impact Engineering, 93, pp. 49–61.

Liu, B. and Guedes Soares, C. (2016b) 'Experimental and numerical analysis of the crushing behaviour of stiffened web girders', International Journal of Impact Engineering, 88, pp. 22–38.

Liu, B. and Guedes Soares, C. (2017) 'Influence of Impact Location on the Plastic Response and Failure of Rectangular Cross Section Tubes Struck Transversely by a Hemispherical Indenter1', Journal of Offshore Mechanics and Arctic Engineering. ASME, 139(2), pp. 21603–21612.

Liu, B. et al. (2017) 'A simple criterion to evaluate the rupture of materials in ship collision simulations', Marine Structures, 54, pp. 92–111.

Liu, B., Villavicencio, R. and Guedes Soares, C. (2015a) 'Simplified method for quasi-static collision assessment of a damaged tanker side panel', Marine Structures, 40, pp. 267–288.

Liu, B., Villavicencio, R. and Guedes Soares, C. (2015b) 'Simplified analytical method to evaluate tanker side panels during minor collision incidents', International Journal of Impact Engineering, 78, pp. 20–33.

Liu, B., Zhu, L. and Chen, L. (2017) 'Numerical assessment of the resistance of ship double-hull structures in stranding', Proceeding of 6th International Conference on Marine Structures, pp. 469–475. May, Lisbon, Portugal.

Liu, C., Hao, E. and Zhang, S. (2015) 'Optimization and application of a crashworthy device for the monopile offshore wind turbine against ship impact', Applied Ocean Research, 51, pp. 129–137.

Liu, J., Cui, M., Zhang M. (2016) 'An experimental study on the resistance to penetration of hat-type stiffened plates', Proceedings of 7th International Conference Collision and Grounding of Ships and Offshore Structures, Ulsan, Korea.

Liu, Z. et al. (2011) 'Plasticity based material modelling of ice and its application to ship-iceberg impacts', Cold Regions Science and Technology, 65(3), pp. 326–334.

LR (2014) 'Provisional Rules for LNG Ships and Barges Equipped with Regasification Systems', Lloyd's Register.

LR (2015) 'Large Battery Installations – a Lloyd's Register Guidance Note', Lloyd's Register.

LR (2016) 'Rules and Regulations for the Classification of Natural Gas Fuelled Ships', Lloyd's Register.

LS-DYNA (2013) 'User's manual', version 14.0, ANSYS Inc., USA.

LSTC (2014) LS-DYNA Keyword User's Manual Volume II R7.1, Materials & Design.

LSTC, [Online]. Available: http://ftp.lstc.com/anonymous/outgoing/support/FAQ/composite.models. [Accessed 10 3 2017].

LSTC, [Online]. Available: http://ftp.lstc.com/anonymous/outgoing/support/FAQ/negative_volume_in_brick_element.tips. [Accessed 10 3 2017].

LSTC, [Online]. Available: http://www.lstc.com/dynamat/. [Accessed 10 3 2017].

Luketa-Hanlin, A., and Hightower, H. (2008) 'On the evaluation of models for hazard prediction for liquefied natural gas (LNG) spills on water', Sandia National Laboratories.

Luperi, F. J., & Pinto, F. (2013). 'Determination of Impact Force History during Multicolumn Barge Flotilla Collisions against Bridge Piers', Journal of Bridge Engineering, 19(3), p. 04013011.

Manderbacka, T. and Ruponen, P. (2016) 'The impact of the inflow momentum on the transient roll response of a damaged ship', Ocean Engineering, 120, pp. 346–352.

Marchenko, N. A. et al. (2016) 'Maritime safety in the high north - Risk and preparedness', Proceedings of the International Offshore and Polar Engineering Conference, 2016, Janua, p. 880653.

Marinatos, J. N. and Samuelides, M. S. (2015) 'Towards a unified methodology for the simulation of rupture in collision and grounding of ships', Marine Structures. Elsevier Ltd, 42, pp. 1–32.

Mazaheri, A. (2017) A framework for evidence - based risk modeling of ship grounding. Aalto University.

Mazaheri, A., Montewka, J. and Kujala, P. (2014) 'Modeling the risk of ship grounding—a literature review from a risk management perspective', WMU Journal of Maritime Affairs, 13(2), pp. 269–297.

Minorsky, V. U. (1959) 'An Analysis of Ship Collisions with Reference to Protection of Nuclear Power Plants', Journal of Ship Research, pp. 1–4.

Moan, T. (2016) 'Damage tolerance requirements to structures', Proceeding of 3rd offshore structural reliability conference, Stavanger, p.14

Moan, T., Amdahl, J. and Ersdal, G. (2017) 'Assessment of ship impact risk to offshore structures - New NORSOK N-003 guidelines', Marine Structures.

Mocanu, C. I., Tocu, F., Dobrot, O. M., & Teodor, F. (2012), 'The impact behaviour of plane and curved composite material plates with or without reinforcements', in

12th International Multidisciplinary Scientific GeoConference: SGEM: Surveying Geology & mining Ecology Management, 3, pp. 245-252.

Moon, K. et al. (2009) ‘Fire risk assessment of gas turbine propulsion system for LNG carriers’, Journal of Loss Prevention in the Process Industries, 22(6), pp. 908–914.

Myland, D. and Ehlers, S. (2016) ‘Influence of bow design on ice breaking resistance’, Ocean Engineering, 119, pp. 217–232.

Naar, H. et al. (2002) ‘Comparison of the crashworthiness of various bottom and side structures’, Marine Structures, 15, pp. 443–460.

Nam, W., Amdahl, J., Hopperstad, O. S. (2016) ‘Influence of brittle fracture on the crashworthiness of ship and offshore structures in arctic conditions’, Proceedings of 7th International Conference Collision and Grounding of Ships and Offshore Structures, Ulsan, Korea.

Niklas, K. and Kozak, J. (2016) ‘Experimental investigation of Steel-Concrete-Polymer composite barrier for the ship internal tank construction’, Ocean Engineering, 111, pp. 449–460.

Nordström, J. et al. (2016) ‘Vessel TRIAGE: A method for assessing and communicating the safety status of vessels in maritime distress situations’, Safety Science, 85, pp. 117–129.

NORSOK (2007) ‘Action and action effects’, Standard N-003, Norway Sept. 2007.

NORSOK (2017) ‘Action and action effects’, Standard N-003, Norway Jan. 2017.

Notaro, G. et al. (2013) ‘Evaluation of the fendering capabilities of the sps for an offshore application’, in 6th International Conference on Collision and Grounding of Ships and Offshore Structures, ICCGS, pp. 85–92.

Novozhilov, V. (2001) ‘Computational fluid dynamics modeling of compartment fires’, Progress in Energy and Combustion Science, Vol. 27, pp. 611–666

Obisesan, A., Sriramula, S. and Harrigan, J. (2016) ‘A framework for reliability assessment of ship hull damage under ship bow impact’, Ships and Offshore Structures. Taylor & Francis, 11(7), pp. 700–719.

OCIMF (2013). Oil Companies International Marine Forum (OCIMF). Guidelines on Capabilities of Emergency Response Services. Available in http://www.intertanko.com/Global/admin_WeeklyNews/Guidelines%20on%20Capabilities%20of%20Emergency%20Response%20Services%20.pdf

Ohtsubo, H. and Wang, G. (1995) ‘An upper-bound solution to the problem of plate tearing’, Journal of Marine Science and Technology, 1(1), pp. 46–51.

Olewski, T. et al. (2011) ‘Medium scale LNG-related experiments and CFD simulation of water curtain’, Journal of Loss Prevention in the Process Industries, 24(6), pp. 798–804.

Ortiz, R., Deletombe, E. and Chuzel-Marmot, Y. (2015) ‘Assessment of damage model and strain rate effects on the fragile stress/strain response of ice material’, International Journal of Impact Engineering, 76, pp. 126–138.

Oterkus, E. et al. (2015) ‘Fracture modes, damage tolerance and failure mitigation in marine composites’, in Marine Applications of Advanced Fibre-Reinforced Composites, pp. 79–102.

Paboeuf, S. et al. (2016) ‘Crashworthiness of an alternative construction within the scope of A.D.N. regulations using super-elements method’, Proceedings of 7th International Conference Collision and Grounding of Ships and Offshore Structures, Ulsan, Korea.

Pack, K. and Mohr, D. (2017) Combined Necking & Fracture Model to Predict Ductile Failure with Shell Finite Elements, Engineering Fracture Mechanics.

Paik, J. K. et al. (2015) ‘A new procedure for the nonlinear structural response analysis of offshore installations in fires’. Transactions - Society of Naval Architects and Marine Engineers. 121, pp. 224-250.

Park, D. K. et al. (2015a) ‘Operability of non-ice class aged ships in the Arctic Ocean-part II: Accidental limit state approach’, Ocean Engineering. Elsevier, 102, pp. 206–215.

Park, D. K. et al. (2015b) ‘On the Crashworthiness of Steel-Plated Structures in an Arctic Environment: An Experimental and Numerical Study’, Journal of Offshore Mechanics and Arctic Engineering, 137(5), p. 51501.

Pedersen, P. T. and Zhang, S. (2000) ‘Effect of ship structure and size on grounding and collision damage distributions’, Ocean Engineering, 27, pp. 1161–1179.

Pham, T. M. and Hao, H. (2017) ‘Plastic hinges and inertia forces in RC beams under impact loads’, International Journal of Impact Engineering, 103, pp. 1–11.

Pitblado, R. (2007) ‘Potential for BLEVE associated with marine LNG vessel fires’, Journal of Hazardous Materials, 140(3), pp. 527–534.

Pitblado, R. M. and Woodward, J. L. (2011) ‘Highlights of LNG risk technology’, Journal of Loss Prevention in the Process Industries, 24(6), pp. 827–836.

Prestileo, A. et al. (2013) ‘Bottom damage scenarios for the hull girder structural assessment’, Marine Structures, 33, pp. 33–55.

Rawson, C., Crake, K. and Brown, A. (1998) Assessing the Environmental Performance of Tankers in Accidental Grounding and Collision, SNAME Transactions.

Rhymer, J., Kim, H. and Roach, D. (2012) ‘The damage resistance of quasi-isotropic carbon/epoxy composite tape laminates impacted by high velocity ice’, Composites Part A: Applied Science and Manufacturing. Elsevier, 43(7), pp. 1134–1144.

Rizzuto, E., Teixeira, A. and Soares, C. G. (2010) ‘Reliability assessment of a tanker in grounding conditions’, 11th International Symposium on Practical Design of Ships and Other Floating Structures, PRADS 2010, 2, pp. 1446–1458.

Robb, D. M., Gaskin, S. J. and Marongiu, J.-C. (2016) ‘SPH-DEM model for free-surface flows containing solids applied to river ice jams’, Journal of Hydraulic Research, 54(1), pp. 27–40.

Rodd, J. L. (1996) ‘Observations on conventional and advanced double hull grounding experiments’, in Int. Conf. on Designs and Methodologies for Collision and Grounding Protection of Ships, pp. 11–13.

Rodd, J. L. and Sikora, J. P. (1995) ‘Double Hull Grounding Experiments’, in Proceedings of the Fifth (1995) International Offshore and Polar Engineering Conference. The Hague, pp. 446–456.

Rodrigues, J. M. and Guedes Soares, C. (2017) ‘Still water vertical loads during transient flooding of a tanker in full load condition with a probabilistic damage distribution’, Ocean Engineering, 129, pp. 480–494.

Samuelides, M. (2015) ‘Recent advances and future trends in structural crashworthiness of ship structures subjected to impact loads’, Ships and Offshore Structures. Taylor & Francis, 10(5), pp. 1–10.

Samuelides, M. et al. (2007) ‘Simulation of the behaviour of double bottoms subjected to grounding actions’, in 4th International Conference on Collision and Grounding of Ships. Hamburg, pp. 93–102.

Sergejeva, M., Laanearu, J. and Tabri, K. (2013) ‘Hydraulic modelling of submerged oil spill including tanker hydrostatic overpressure’, in Analysis and Design of Marine Structures - Proceedings of the 4th International Conference on Marine Structures, MARSTRUCT 2013.

Sergejeva, M., Laanearu, J. and Tabri, K. (2017) ‘On parameterization of emulsification and heat exchange in the hydraulic modelling of oil spill from a damaged tanker in winter conditions’, pp. 43–50.

Sha, Y. and Hao, H. (2013) ‘Numerical Simulation of Barge Impact on a Continuous Girder Bridge and Bridge Damage Detection’, International Journal of Protective Structures, 4(1), pp. 79–96.

Sha, Y. and Hao, H. (2014a) ‘A Simplified Approach for Predicting Bridge Pier Responses Subjected to Barge Impact Loading’, Advances in Structural Engineering, 17(1), pp. 11–23.

Sha, Y. and Hao, H. (2014b) 'Laboratory Tests and Numerical Simulations of CFRP Strengthened RC Pier Subjected to Barge Impact Load', International Journal of Structural Stability and Dynamics. World Scientific Publishing Co., 15(2), p. 1450037.

Sha, Y., Amdahl, J. (2017) 'Ship collision analysis of a floating bridge in ferry-free E39 project', OMAE 2017-62720 Proceedings of 36th International Conference on Ocean, Offshore and Arctic Engineering. Trondheim, Norway.

Shaw, A. et al. (2015) 'Beyond classical dynamic structural plasticity using mesh-free modelling techniques', International Journal of Impact Engineering, 75, pp. 268–278.

Shi, C. et al. (2016) 'A nonlinear viscoelastic iceberg material model and its numerical validation', Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment. SAGE Publications, 231(2), pp. 675–689.

Shi, C. et al. (2017) 'Validation of a temperature-gradient-dependent elastic-plastic material model of ice with finite element simulations', Cold Regions Science and Technology, 133, pp. 15–25.

Shim, C. et al. (2016) 'A study on materials used in LNGC cargo containment system', Proceedings of 7th International Conference Collision and Grounding of Ships and Offshore Structures, Ulsan, Korea.

Silva, F. and Raquel. S (2015), 'Analysis of Maritime Fire and Explosion Accidents', Universidade de Lisboa, Instituto Superior Técnico, Portugal.

Simonsen, B. C. (1997) 'Ship grounding on rock - I. Theory', Marine Structures, 10, pp. 519–562.

Simonsen, B. C. et al. (2009) 'A simplified grounding damage prediction method and its application in modern damage stability requirements', Marine Structures, 22, pp. 62–83.

Simonsen, B. C., & Ocakli, H. (1999). Experiments and theory on deck and girder crushing. Thin-walled structures, 34(3), 195-216.

Sirkar, J. et al. (1997) A Framework for Assessing the Environmental Performance of Tankers in Accidental Groundings and Collisions, SNAME Transactions.

SMHI (2012) 'SMHI. (2012). Manual Seatrack Web — a user-friendly system for forecasts and backtracking of drift and spreading of oil, chemicals and substances in water. https://stw-helcom.smhi.se/.', p. 2012.

Song M., Kim E., Amdahl J., Ma J. & Huang Y. (2016) 'A comparative analysis of the fluid-structure interaction method and the constant added mass method for ice-structure collisions', Marine Structures, 49, pp. 58–75.

Sormunen, O. V. E. et al. (2016a) 'Marine traffic, accidents, and underreporting in the Baltic Sea', Scientific Journals of the Maritime University of Szczecin, 46(118), pp. 163–177.

Sormunen, O. V. E. et al. (2016b) 'Comparing rock shape models in grounding damage modelling', Marine Structures, 50, pp. 205–223.

Srivastava, V. and Srivastava, R. (2014) 'On the polymeric foams: modeling and properties', Journal of Materials Science, 49(7), pp. 2681–2692.

Storheim, M. and Amdahl, J. (2017) 'On the sensitivity to work hardening and strain-rate effects in nonlinear FEM analysis of ship collisions', Ships and Offshore Structures. Taylor & Francis, 12(1), pp. 100–115.

Storheim, M. et al. (2015) 'A damage-based failure model for coarsely meshed shell structures', International Journal of Impact Engineering, 83, pp. 59–75.

Storheim, M., Amdahl, J. and Martens, I. (2015) 'On the accuracy of fracture estimation in collision analysis of ship and offshore structures', Marine Structures. Elsevier Ltd, 44, pp. 254–287.

Su, S., & Wang, L. (2013) 'Three dimensional reconstruction of the fire in a ship engine room with multilayer structures', Ocean Engineering, 70, pp. 201–207.

Sun, B., Guo, K., & Pareek, V. K. (2015) 'Dynamic simulation of hazard analysis of radiations from LNG pool fire', Journal of Loss Prevention in the Process Industries, 35, pp. 200–210.

Sun, B., Guo, K., & Pareek, V. K. (2017) 'Hazardous consequence dynamic simulation of LNG spill on water for ship-to-ship bunkering', Process Safety and Environmental Protection, 107, pp. 402–413.

Sun, B., Hu, Z. and Wang, G. (2015) 'An analytical method for predicting the ship side structure response in raked bow collisions', Marine Structures, 41, pp. 288–311.

Sun, B., Hu, Z. and Wang, J. (2017) 'Bottom structural response prediction for ship-powered grounding over rock-type seabed obstructions', Marine Structures, 54, pp. 127–143.

Suominen, M. et al. (2017) 'Influence of load length on short-term ice load statistics in full-scale', Marine Structures, 52, pp. 153–172.

Szlapczynski, R. and Szlapczynska, J. (2016) 'An analysis of domain-based ship collision risk parameters', Ocean Engineering, 126, pp. 47–56.

Tabri, K. et al. (2015) 'Modelling of structural damage and environmental consequences of tanker grounding', in Analysis and Design of Marine Structures - Proceedings of the 5th International Conference on Marine Structures V, pp. 703-710.

Tang, M. J. & Baker, Q. A. (1999), 'A new set of blast curves from vapor cloud explosion', Process Safety Progress, 18, pp. 235-240.

Tavakoli, M. T., Amdahl, J. and Leira, B. J. (2011) 'Experimental investigation of oil leakage from damaged ships due to collision and grounding', Ocean Engineering. Elsevier, 38(17–18), pp. 1894–1907.

Tiberkak, R. et al. (2008) 'Damage prediction in composite plates subjected to low velocity impact', Composite Structures, 83(1), pp. 73–82.

Travanca, J. and Hao, H. (2015) 'Energy dissipation in high-energy ship-offshore jacket platform collisions', Marine Structures, 40, pp. 1–37.

Truong, D. D. et al. (2016) 'Plastic response of steel grillages subjected to repeated mass impacts', Proceedings of 7th International Conference Collision and Grounding of Ships and Offshore Structures, Ulsan, Korea.

USFOS (2013) 'User's manual for USFOS', version 86a, USFOS A/S, Sandsli, Norway.

Vairo, T. et al. (2015), 'An Approach to Risk Evaluation in Connection with Fire Scenarios from a Cruise Ship', Chemical Engineering Transactions, 43, pp. 1939-1944.

Vaughan, H. (1977) Vaughan H. Damage to ships due to collision and grounding. DnV Technical Report No. 77-345. Oslo.

Vettor, R. and Soares, C. G. (2015) 'Computational System for Planning Search and Rescue Operations at Sea', Procedia Computer Science, 51, pp. 2848–2853.

Vílchez, J. A. et al. (2011) 'Generic event trees and probabilities for the release of different types of hazardous materials', Journal of Loss Prevention in the Process Industries. 24(3), pp. 281–287.

Vinnem, J. E., Utne, I. B. and Schjølberg, I. (2015) 'On the need for online decision support in FPSO-shuttle tanker collision risk reduction', Ocean Engineering, 101, pp. 109–117.

von Bock und Polach, R. and Ehlers, S. (2014, June). On the Scalability of Model-Scale Ice Experiments. In ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering (pp. V010T07A010-V010T07A010). American Society of Mechanical Engineers.

Vredeveldt, A.W & Wevers, L, T. (1995) 'Full scale grounding experiments', in Conference on Prediction Methodology of Tanker Structural Failure &: Consequential Oil Spill. Tokyo.

Walters, C. L. (2014) 'Framework for adjusting for both stress triaxiality and mesh size effect for failure of metals in shell structures', International Journal of Crashworthiness, 19(1), pp. 1–12.

Walters, R. A. et al. (2017) 'Characterization of multi-barge flotilla impact forces on wall structures', Marine Structures, 51, pp. 21–39.

Wang, G. (1995) ‘Structural analysis of ships' collision and grounding’, Ph.D. dissertation, Department of Naval Architecture and Ocean Engineering, University of Tokyo.

Wang, G., Arita, K. and Liu, D. (2000) ‘Behaviour of a double hull in a variety of stranding or collision scenarios’, Marine Structures, 13, pp. 147–187.

Wang, G., Ohtsubo, H. and Liu, D. (1997) ‘A Simple Method for Predicting the Grounding Strength of Ships’, 41(3), pp. 241–247.

Wang, J. and Wang, W. (2015) ‘Estimation of Vessel-Bridge Collision Probability for Complex Navigation Channels’, Journal of Bridge Engineering, 20(7), p. 4014091.

Wang, W., Chen, J. J. and Wang, J. H. (2017) ‘Estimation method for ground deformation of granular soils caused by dynamic compaction’, Soil Dynamics and Earthquake Engineering, 92, pp. 266–278.

Wang, Z. et al. (2016) ‘Experimental and numerical investigations on the T joint of jack-up platform laterally punched by a knife edge indenter’, Ocean Engineering, 127, pp. 212–225.

Woodward, J. L., Pitblado, R. M. (2010) ‘LNG risk-based safety; modeling and consequence analysis’, John Wiley and Sons, Inc.

Xia, Y., Zhu, J. and Zhou, Q. (2015) ‘Verification of a multiple-machine program for material testing from quasi-static to high strain-rate’, International Journal of Impact Engineering, 86, pp. 284–294.

Xiao, F. et al. (2015) ‘Experimental and numerical investigation on the shock resistance of honeycomb rubber coatings subjected to underwater explosion’, Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment, 229(1), pp. 77–94.

Yoshikawa, T. et al. (2016) ‘Fracture analysis considering the effect of stress tri-axiality’, Proceedings of 7th International Conference Collision and Grounding of Ships and Offshore Structures, Ulsan, Korea.

You, Y. and Rhee, K. (2016) ‘Development of the collision ratio to infer the time at which to begin a collision avoidance of a ship’, Applied Ocean Research, 60, pp. 164–175.

Youssef, S. A. M. et al. (2016) ‘Assessing the risk of ship hull collapse due to collision’, Ships and Offshore Structures. Taylor & Francis, 11(4), pp. 335–350.

Yu, Z. and Amdahl, J. (2016a) ‘Full six degrees of freedom coupled dynamic simulation of ship collision and grounding accidents’, Marine Structures, 47, pp. 1–22.

Yu, Z. and Amdahl, J. (2016b) ‘Influence of 6DOF ship motions in the damage prediction of ship collision and grounding accidents’, 7th International Conference on Collision and Grounding of Ships and Offshore StructuresShips and Offshore Structures, (2010), pp. 199–205.

Yu, Z. et al. (2016) ‘Implementation of Linear Potential-Flow Theory in the 6DOF Coupled Simulation of Ship Collision and Grounding Accidents’, Journal of Ship Research, 60(3).

Yu, Z., Hu, Z. and Wang, G. (2015) ‘Plastic mechanism analysis of structural performances for stiffeners on bottom longitudinal web girders during a shoal grounding accident’, Marine Structures. Elsevier Ltd, 40, pp. 134–158.

Zhang, J. et al. (2015) ‘A distributed anti-collision decision support formulation in multi-ship encounter situations under COLREGs’, Ocean Engineering, 105, pp. 336–348.

Zhang, J. et al. (2016) ‘A theoretical study of low-velocity impact of geometrically asymmetric sandwich beams’, International Journal of Impact Engineering, 96, pp. 35–49.

Zhang, M. and Liu, J. X. (2017) ‘Experimental and numerical analysis of tanker double-hull structures punched by a wedge indenter’, (2009), pp. 549–556.

Zhang, S. (2002) ‘Plate tearing and bottom damage in ship grounding’, Marine Structures, 15, pp. 101–117.

Zhang, S. and Pedersen, P. T. (2016) ‘A method for ship collision damage and energy absorption analysis and its validation’, Ships and Offshore Structures. Taylor & Francis, 5302(May), pp. 1–10.

Zhang, S. et al. (2017) 'Impact mechanics of ship collisions and validations with experimental results', Marine Structures, 52, pp. 69–81.
Zhang, S., Pedersen, P. T. and Ocakli, H. (2015) 'Collisions damage assessment of ships and jack-up rigs', Ships and Offshore Structures. Taylor & Francis, 10(5), pp. 1–9.
Zhang, W. et al. (2016) 'A method for detecting possible near-miss ship collision from AIS data', Ocean Engineering, 107, pp. 60–69.
Zhang, W., Jin, X. and Wang, J. (2014) 'Numerical analysis of ship–bridge collision's influences on the running safety of moving rail train', Ships and Offshore Structures. Taylor & Francis, 9(5), pp. 498–513.
Zhou, Q., Peng, H. and Qiu, W. (2016) 'Numerical investigations of ship-ice interaction and maneuvering performance in level ice', Cold Regions Science and Technology, 122, pp. 36–49.

ANNEX

As described in Chapter 4, LS_DYNA provides several material models for composite structure modelling. Out of the complete set, the following material models are provided in the following tables with additional notes on their use.

Table A-1 Composite material model in LS_DYNA

	Material keywords	**Additional notes**
22	*MAT_COMPOSITE_DAMAGE	An orthotropic material with optional brittle failure for composites can be defined. Lamination theory is supported.
32	*MAT_LAMINATED_GLASS	A layered glass including polymeric layers can be modeled.
54/55	*MAT_ENHANCED_COMPOSITE_DAMAGE	Enhanced versions of the composite model material type 22. Arbitrary orthotropic materials can be defined.
58	*MAT_LAMINATED_COMPOSITE_FABRIC	This model may be used to model composite materials with unidirectional layers, complete laminates, and woven fabrics. Only for shell elements.
59	*MAT_COMPOSITE_FAILURE_OPTION_MODEL	For shell, solid and SPH.
114	*MAT_LAYERED_LINEAR_PLASTICITY	This model defined a layered elastoplastic material with an arbitrary stress versus strain curve and an arbitrary strain rate dependency.
116	*MAT_COMPOSITE_LAYUP	For the modelling of elastic responses of composite layups that have an arbitrary number of layers through the shell thickness. No stresses calculated. This model does not use laminated shell theory, which is not good for foam core/sandwich composites.
117/118	*MAT_COMPOSITE_MATRIX/DIRECT	This material is used for modeling the elastic responses of composites. No stresses calculated.
158	*MAT_RATE_SENSITIVE_COMPOSITE_FABRIC	Like 58 but with rate effects via viscoelastic stress term.