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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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1. OFFICIAL DISCUSSION

1.1 Official Discussion by Jørgen Amdahl

1.1.1 Introduction

It is a great pleasure and honour to serve as the Official Discusser of the report by Committee V.1. Most of my professional career I have been involved in methods to determine the response to accidental actions so this is a subject of great interest to me. My review is based on the version received 14th of February 2018.

The committee has many new members, but four members remains from the previous period. This should ensure some degree of continuity, but the large change of members must have represented a challenge..

The report is approximately 70 pages long and it refers to more than 250 publications. Thus, there is no doubt that the committee has done a substantial effort in preparing the report and it shall be complimented for that. The question is whether the volume of the report as well as the number of references is justified. I must admit that I am not fully convinced of that. In my view the mandate of the committee is to conduct a critical review of the published papers, to evaluate new knowledge and contribution to the state of the and on this basis propose guidance and recommendations for quantitative assessment of accidental loads. In these respect parts of the report is just description of work carried out various researchers/institution without a proper evaluation of the value of the work. It is somewhat difficult to find clear recommendations and guidance for quantitative assessment and management of accidental risks

1.1.2 Content

I must confess that I am quite surprised that the report contains quite extensive discussions of general analysis and design principles for other limit states (SLS, FLS and ULS) than accidental limit states. I question whether this should rather be within the scope of other ISSC Committees. This part of the report is much in the format of a textbook and contains almost no references. Several pages of the report are further devoted to definition of wave loads for both ULS and ALS. For ULS this seems superfluous, but I do also question whether this committee and not Committee I.2 Loads shall cover the wave-in-deck condition and slamming loads. When it comes to the response to abnormal waves and hydro-elasto-plastic interaction with waves this is, of course, within the scope of this committee. However, no reviewed papers are found except for one paper on composite structures

In Section 3.2 it is stated that STATOIL has increased the air gap by 10% due to climate changes. The actual reason for this increase is not climate change, but the adverse effect of considering area extremes instead of conventional point extremes.

Concern for dropped objects is given in the mandate. It therefore is somewhat surprising that the report contains no section on dropped objects. Is this because papers of value have not been found? It is my view that challenges still remain, e.g. how to take into account response interaction between the dropped object and the hit structure.

1.1.3 Design standards

Design standards relevant for Accidental Limit States are discussed in several sections of the report. The committee correctly points out that explicit design against accidental and abnormal actions have reached a much larger implementation for offshore structures than for bridges. For ship structures this has not yet been widely adopted and prescriptive rules are commonly used, influenced by industry conservatism and unknown operational conditions. However, there are deviations, which could have been mentioned in the report. I had also appreciated that the actual energy levels be specifically listed. e.g. in the DNV GL(2015) rules for compressed natural gas carriers require minimum energy dissipation for penetration of inner hull based on an assessment of collision frequencies and collision energies for specific trades. The energy requirement depends on the ship length and is effectively in the range of 50–100 MJ for vessels in the range of 50,000–100,000 tons. This is a relatively moderate energy dissipation and is much too small to stop a large ship with high speed (kinetic energy 1,000–10,000 MJ) before the cargo tank is penetrated. The striking ship can be assumed to have a raked bow (i.e., no bulb). This is definitely non-conservative as most ships are fitted with bubs that have a much larger damage potential than the forecastle.

According to the European Agreement concerning the International Carriage of Dangerous Goods by Inland Water- ways (UNECE, 2011), alternative vessel design is accepted provided that the strain energy for rupture of cargo tank is shown to be at least 22 MJ.

As a consequence of severe collision events on the Norwegian continental shelf the standard energy criterion for bow impact with offshore structures according to NORSOK N-003 was increased from 11 MJ to 50 MJ. For stern (22 MJ) and side collision (28 MJ) the standard design kinetic energy was doubled because the standard supply vessel size has increased from 5,000 to 10,000 tons displacement. As discussed later will push the design of offshore structures in the direction of the strength design domain.

The requirement to resistance against direct accidental action goes along with requirement to residual strength in damaged condition. This is mentioned several places in the report, but various methods could have been discussed in more detail. Assessment of ultimate strength of ships in intact and damaged condition has been investigated quite extensively in the last decades and IACS (2014) requires residual strength to be checked.

1.1.4 External and Internal mechanics

For most of the accident scenarios I miss a proper classification of methods to be used for damage assessment; what is the state of the art and what are the present challenges.

Generally, the assessment of accidental and abnormal loads deals with local damage and global response/integrity and possible interaction. For collision and grounding the damage assessment can be conducted by fully integrated analysis aiming at simulating "all" governing physical effects simultaneously or, e.g. by splitting it up into external mechanics, that determined the demand for energy dissipation based on rigid body motions, and internal mechanics, that determines the local structural damage at the contact point. The split into external and internal mechanics is discussed somewhat briefly in in Section 6 dealing with ship grounding, but is as relevant for ship collisions and ice impacts. It is briefly mentioned in Section 5.1.1 Ship-ship collision (Erroneously as external mechanisms) and probably also in Section 4.2.1.Analytical methodology on response evaluation; it is not clear what is meant by internal elastic-plastic mechanisms and external kinetic dynamics. If this is external and internal mechanics the terminology should be consistent.

In essence, I think external and internal mechanics should have been discussed more lengthy and on a general basis in Section 4 Methods and procedures for the analysis of ALS.

The separation of internal mechanics and external mechanics is very often the basis for the use of analytic methods to determine the local damage, but it is also useful for assessment by nonlinear finite element analysis, which then can be carried out up to a pre-determined deformation level using constant deformation rate without considering the real deformation rate. This is often considered acceptable provided that strain rate effect and local inertia effects are not important. It could be interesting to have the committees views on if or when this is justified.

In fact, the split into external mechanics and internal mechanics is more challenging for powered grounding events than ship collisions and ice impacts, because the grounding duration may be long and not impulsive. A significant part of the ship bottom may be subjected to deformations that in turn depend on the global motions. Hence, the split is not so straightforward. Methods for simplified analysis have been proposed, but this is not discussed in the report.

For many dynamic structures the interaction between local response and global response becomes important, e.g. jack-ups with large eigenperiods or ultra-long bridges. The dynamic global response of the structure will influence the temporal variation of the impact force and is not know a priori. A way to account for this is to model local deformation properties of the bridge and ship with nonlinear springs from local analysis (assessment of internal mechanics) that connects a mass point representing the ship and the hit structure, refer e.g. Amdahl and Holmås (2016) and Sha and Amdahl (2017). A discussion and critical evaluation of this approach is being missed.

1.1.5 Design principles for collision

The principles for designing against accidental actions can be categorized as ductile -, shared-energy or strength design. This is described in detail in DNVGL RPC204. They are mentioned briefly in Section 5.2 but are not explained, which I think they deserve. A significant part of the research on collisions is based on the assumption of a rigid ship (bow, side, stern, which is a valid as long as the hit structure is weaker than the ship, corresponding to ductile design. A rigid ship can, however, lead to biased - or even completely impractical and unrealistic results if the resistance of the hit structure becomes on par with the crushing force of the impacting ship, i.e. the shared-energy - or strength design domain. Therefore, I believe that the mutual interaction between the colliding bodies should be taken into account to a much larger extent than what is done today. To comply e.g. with the new standard collision energy criteria in NORSOK N-003 (50 MJ for bow) collisions with offshore platforms, it is often not possible to obtain sufficient energy dissipation is a single member (brace); it may be necessary to move towards strength design. The library of supply vessel structures made available through DNVGL-RP-C208 will allow improved possibilities of taking this structural interaction into account, in addition to bringing more consistency on how finite element analysis is performed, as correctly pointed out by the Committee.

1.1.6 Hydrodynamic effects

Hydrodynamic effects are important, notably in conjunction with collisions and grounding. Added mass is e.g. often taken into account by means of a constant, equivalent value. Thus, I do not believe that the statement in Section 5.1.1 Ship–collision that “ship motions and hydrodynamic loads have been neglected in previous investigations” is entirely correct. Indeed, the added mass is frequency dependent, but procedures to take this into account exist. The coupled approach hydrodynamics-structural response estimation could have been discussed more in detail when the various approaches are evaluated.

1.1.7 Analytical methods

Analytical expressions are discussed in section 4.2.1. I do agree with the committee that analytic methods can be very useful to obtain quick estimate of energy dissipation. I further believe that simplified methods are crucial to check the results of advanced nonlinear finite elemetn analysis. It is not clear what is meant by ‘methods for dynamic response assessment for ship shell, deck, girder and web frames are mostly developed’, is it ‘most developed’ or ‘mostly well developed’? Seven formulations are listed in Table 7 for web girder crushing. Which is better? It would be interesting to have the Committee’s view on that. In my view Table 1 as it stands now, does not provide useful information and could be omitted.

My personal view is further that there is still room for improvement, e.g. how to take stiffeners into account in several simplified mechanism and how to calculate rolling type of deformation of the ship bottom plating and girders during grounding.

1.1.8 Material modelling of steel

The report contains interesting information about material modelling and failure. I do agree with the Committee in section 4.2.2 that the definition of structural failure criteria for steel is of crucial importance. Material failure is discussed in both section 4.2.2. and 4.4.1. It is not clear why this is split into two sections rather than one section. Two failure criteria, BWH and RTCL are presented in detail with relevant formulas, but I do not see a good reason for this. Actually the BWH and RTCL criteria are presented in detail later in the report (Section 4.4.1) and not the first time they are discussed. The review of the various approaches are otherwise satisfactory, but I do miss a more fundamental discussion of the challenges related to the failure criteria e.g. stress tri-axiality (there could be more criteria than those mentioned) and what the different criteria aim to take into account.

Figure 3 can be informative, but needs more explanation. It is not referred to in the text.

1.1.9 Ice material and ship-ice collision

Ice-structure interaction and accidental damage is indeed increasingly important as the oil and gas and ship traffic move towards the artic. Collisions with ice features are not specifically given in the mandate for this committee and could as well be within the scope of Committee V.6 Arctic Technology? I presume that this has been coordinated with Committee V.6 and include some comments.

Material modelling of ice is dealt within Section 4.4.5 Ice, but also in section 5.1.4 Ship-ice collision. Preferably, this should have been carried out in a single section (4.4.5), only. The discussion in Section 4.4.5 Ice gives the reader the misleading impression that several models have been developed, while in reality almost all material models are just small variations of Tsai-Wu yield surface and associated failure criterion, that was first adopted for ship-ice interaction analysis by Liu et. al. (2011). This should have been better pointed out in the discussion. Some ice material properties are given in Table 3, but there is no discussion related to the values that are used, so this information is of little value. A reference is made to a material model based on cohesive zone, but there is little discussion of pros and cons. It could be interesting to know how the Committee evaluates this model compared to e.g. Tsai-Wu model.

Paper by Ferrari et. al is discussed at some length in Section 4.4.5 and this is somehow repeated in Section 5.1.4. In my view most of the material belongs to Section 5.1.4.

Section 5.1.4 Ship-ice collision contains a lot of references, but the material could be better structured. It is not easy to grasp what is the purpose of the various studies, e.g.: How well can the demand for energy dissipation be assessed on the basis of external mechanics and constant added mass, versus ice-fluid-structure interaction analysis of ice impacts?

I miss a discussion of what are the major challenges related to ice action. Ships have a long history of sailing in ice-infested waters and ship classification societies have rules for designing against ice action. These are typically based on pressure–area (p-A) relationships. In my view these rules are basically ULS rules. ALS ice actions cannot be based on p–A curves because the structure may deform and influence the ice pressure by e.g. increasing confinement or by just dictating the interface pressures if the structural response is in the ductile regime.

1.1.10 Ship collision

The coupled approach to hydrodynamics- structural response estimation could have been discussed more in detail when the various methods are discussed.

Simplified methods for small-scale stiffened plate are discussed, while this could have been included in Section 4.1. I miss also a discussion of what are new with these methods compared to previous approaches.

Experimental studies have been carried out on ship collisions. Normally the models have been in a scale range of 1:10 to 1:5, allowing only part of the structure to be modelled. A rather new approach is to model the ship structure with miniature specimens, at a scale of 1: 100, obeying basic scaling laws. The committee has reviewed a few of these papers, and described the findings results. I would appreciate the committee's assessment of the approach. Are the miniature specimens representative of the structural configurations, and are the deformation modes and failure modes representative? Of course, costs may be saved by use of miniature specimens, but can we just scale the results to full scale un a manner that we do for hydrodynamic tests?

1.1.11 Ship- offshore structures collision

Analysis and direct design against ship collision have probably reached the highest level of sophistication and application for offshore structures. The type of methods spans from simplified analytical methods to explicit time domain analysis with detailed shell finite element models of the structure and the ship. Quite extensive procedures have been proposed, e.g in the DNV GL RPC204 for design against accidental loads. It is therefore somewhat disappointing that the section is relatively short and the discussion is not well structured. It would be interesting to if the committee had discussed challenges related to interaction between colliding ship and hit platform, challenges related to energy dissipation in jackets, column stabilized floating structures and jack-up rigs. The impact response of RC beams is erroneously discussed in the context of crashworthiness of jacket platforms.

1.1.12 Ship-bridge collisions

Quite a few papers are reviewed regarding ship-bridge collisions. The review could have been more informative. It is difficult to grasp what the new methods contribute to further development of analysis procedures. I miss a discussion of present standard method for design of bridges against collision. Obviously, there is a local damage and global integrity aspect and possible interaction. For long bridges the response can be very dynamic and limited information exists on how to combine local crushing characteristics with global analysis.

1.1.13 Fire and explosion

The report contains an extensive section on fires and explosions. I agree with the committee that design and operation procedures against fire and explosions are well (actually better) established for offshore structures, but I think that there is still challenges and further development in this area. I am therefore surprised that the section almost exclusively deals with ship issues, which are generally quite prescriptive. Part of the material is very descriptive with limited information regarding new knowledge and new methods and could be reduced.

1.1.14 Benchmark study

The committee has conducted a benchmark study. This is generally welcomed because it shows the ability to carry out nonlinear finite element analysis. However, the objectives of the study are not well formulated. It cannot be simply "to simulate a grounding scenario and compare the results with experimental tests". In the discussion it is somewhat better stated that a major objective has been to assess the uncertainty in the prediction implied by the choices made by the differed analysts. Unfortunately, the benchmark test was not blindfold, thus inevitably an "adjustment" to the experimental results have been made and make this objective harder to achieve.

In fact, all analysts get results in reasonable agreement with the tests and, probably, much better than what they would do than if it were blindfold. This reduces the value of the study.

Unfortunately, the information regarding input data is limited. It is understood (but no explicitly stated) that the power-law is widely used for material modelling, whereas some analyst has used the full-stress-strain curve. It would have been interesting to see uni-axial stress-strain curve associated with the chosen modelling, further the prediction of failure strain for the different criteria.

The numerical behaviour in nonlinear finite element analysis depends on finite element formulation, reduced or full integration, whether warping and drilling stiffness is included, and solution with single or double precision, solver type etc. Beneficially, this information could have been given for the various analysts. E.g. in ABAQUS drilling stiffness is included by default while this has to be specified specifically in LS-DYNA. Figures 1 and 2 illustrate how the choice of drilling stiffness affects the crushing response for a bulbous bow using fully integrated and reduced integration elements.

In addition, the mesh size, friction coefficient, failure criterion and modeling as such may have a great impact. The question is how much that should have been decided before embarking on the study. The difference may have a noteworthy impact on the damage distribution for the ship and the hit structure.

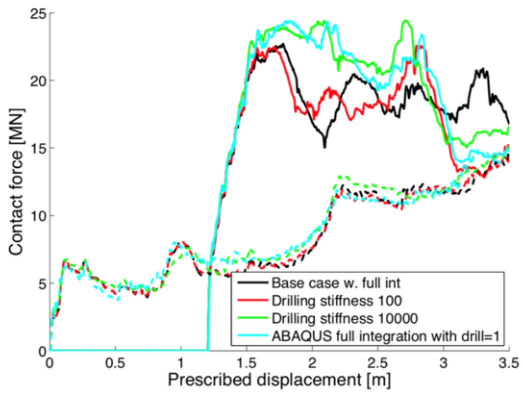
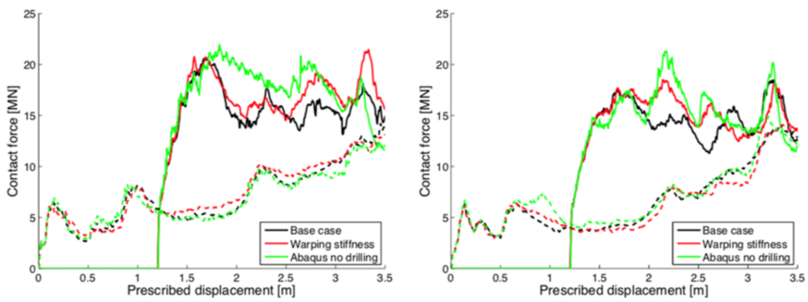


Figure 1: LS-DYNA vs. ABAQUS with full integration elments and drilling stiffness included. Solid lines for bulb, dashed lines for forecatsle. Storheim (2015)



(a) Coarse mesh **(b)** Refined mesh

Figure 2: LS-DYNA vs. ABAQUS for reduced integration elements without drilling stiffness. Solid lines for bulb, dashed lines for forecastle. Storheim (2015)

1.2 Reply of the Committee to the Official Discusser

It is an honour to have as Official Discusser of our report Prof. Jørgen Amdahl, who is among world's leading experts on the analysis of accidental scenarios in the context of ships and offshore structures. The committee is grateful for the time he devoted to analyse and comment the report. The OD shows about the report quite a high degree of criticism, which regards the content as well as the form. In the following the reply of the committee, which is not necessarily meant to deny the presence of weak points, but sometimes aims at clarifying the statements contained in the report and sometimes supports different positions on the various subjects.

1.2.1 Introduction-general comments

1.2.1.1 Composition of the committee

The OD points out that a large turnover has occurred in the committee composition. The number of new members in the committee is relevant, but a considerable disruption in the activity, actually, was created by the withdrawal of some expert members during the term, when part of the activities were already set.

1.2.1.2 Length and style of the report

The OD remarks on the length of the report and the number of references, suggesting that a deeper and more critical analysis should have been carried out on the literature.

The paper is actually slightly oversized and probably a better synthesis could have been achieved. As regards the claim for a more critical review of the literature, it is not always possible to formulate recommendations and guidance for a selection among the procedures presented by the various authors. In any case, the depth of the analysis unavoidably depends on the specific expertise of the committee members.

1.2.2 Content

1.2.2.1 Other limit states

The OD remarks that a large space at the beginning of the report is devoted to other limit states (in particular SLS, FLS and ULS). The reason for this part of the text was to introduce in what checks on accidental states differ from the traditional ones based on an intact state of the structures and why accidental states analysis was more recently introduced into the design process. A recall of these basic concepts was deemed useful to interpret the present degree of development in the analysis of accidental states and their implementation in design.

1.2.2.2 Wave loads

The OD points out that the subject of wave loads is extensively treated in the report. The reason for that is the attempt to understand to what extent extreme environmental events within accidental scenarios are actually included in the design process of off-shore structures and why they are not considered for ships. To understand this, reasons and procedures for introducing extreme wave events in offshore verifications were analysed in details. In particular, it was deemed interesting to investigate in what accidental situations with 'abnormal' waves should differ from the similar category of scenarios adopted for ULS checks and based on 'extreme' waves. In this context, the identification of criteria for defining accidental scenarios based on waves was deemed to be in line with the scope of our report, while methods for studying such scenarios were considered as covered by Committee 1.1 (for waves) and I.2 (for wave loads).

1.2.2.3 Requirement on air gap

The internal STATOIL requirement cited in the report about a 10% increase in the reference wave height for air gap design was mentioned in the official discussion of the ISSC 2012 report of committee I.1 by Dr Sverre Haver and later recalled in the report of the next term of the same committee [Bitner-Gregersen et al. (2015)]. The context in both cases was the climate change and the frequency of occurrence of freak waves, even though the motivations for the increase in the wave height was related also to other (not specified) sources of uncertainties. Later, in the NORSOK (2017), as mentioned in our report, two increments were foreseen for design wave heights: +10% because of local free surface effects (run up on the legs of platforms) and +4 % for climate changes effects.

1.2.2.4 *Dropped objects*

The OD correctly points out that scenarios regarding dropping objects are not covered in the report, while contained in the mandate. As suggested by the same OD, the reason is due to the fact that no significant references were found on the subject.

1.2.3 *Design standards*

The OD remarks that, while the general attitude in the shipbuilding world towards the design against accidental and abnormal actions is based on prescriptive requirements, various examples indicate an approach based on direct design.

The committee did mention examples of deviations from a purely prescriptive approach in ship structural design, but it is acknowledged that the further cases indicated by the OD of performance based goals for the structural design against collisions should have been mentioned. This should have been stated explicitly.

1.2.4 *External and Internal mechanics*

1.2.4.1 *Definitions and relationships between the two aspects*

The Committee agrees with the comment that the basic definitions of external and internal mechanics could have been recalled in general terms, as they apply to different types of collisions.

As regards the subject of the relation between internal and external dynamics in ship collision scenarios, a few recent studies discuss the relevance of a coupling of the external and internal mechanics in that context (Tabri, 2012; Liu et al., 2017). Both papers reached the similar conclusion that the accuracy of the decoupled approach reduces in oblique collision scenarios and when both ships have forward velocity. According to Tabri (2012) in a decoupled approach the energy might be even well predicted, but the penetration path, and thus also the damage shape, are not well modelled. The effect of this should be evaluated in the context of a holistic approach where damage evaluation is followed by ship survivability assessment. Such approach was presented e.g. in Hogström and Ringsberg (2012), but despite the consideration of different collision angles, only a decoupled approach was used for damage assessment. This knowledge gap related to damage shape and consequence analysis should be further investigated in the future.

1.2.4.2 *Influence of the strain rate*

As regards the influence of strain rate on the results of FE simulations, the opinion of the Committee is that it is acceptable to neglect effects related to strain rate and inertia effects for most applications. In ship collisions, in particular, these effects are in general locally concentrated near the contact area and the contribution to total energy is small.

1.2.4.3 *Duration of the impact*

The Committee agrees on the importance of the duration of the collision event in assessing the dependency between global and local response. The references recalled by the OD about the analysis of ship-bridge collisions are very interesting.

1.2.5 *Design principles for collision*

The concepts of ductile, shared-energy or strength design are basic schemes for modelling colliding structures. The description of the concept had been covered in previous reports and it was not repeated in details in the present one.

The committee agrees that the final goal of a realistic simulation is a proper evaluation of the interaction between the crushing structures during the collision and, accordingly, of the share of energy absorption between the two. This can be sought in general through a proper model of the structures in terms of geometry, of stress-strain curves and failure limit of the material and of energy absorption phenomena. The library of supply vessel structures available in DNVGL-RP-C208, represents a most valuable source of data for accounting for the interaction between colliding structures.

1.2.6 Hydrodynamic effects

It is acknowledged that hydrodynamic effects play a role in determining the global motions of the structure and therefore in affecting the structural behaviour of the colliding bodies. Also in this case, however, a key point is the comparison between the time constants of the various types of responses.

1.2.7 Analytical methods

It is mentioned by the OD that it would be useful to have the committees view on the ranking of the analytical procedure mentioned in table 1. To give a proper response to that, all those methods would have to be checked against the same experimental results or non-linear FE methods and this possibly for several typical structural designs. As the methods are taken by single works in which each formulation is validated against different single cases, it is hard to establish an objective ranking.

1.2.8 Material modelling of steel

1.2.8.1 Organisation of the chapter

As Pointed out by the OD, material failure is treated in both section 4.2.2 and 4.4.1. The reason for this split is that 4.2.2 gives a more general overview of developments in material modelling, for example the need for the inclusion of the effect of strain rate, stress tri-axiality, the need for other models due to arctic and LNG developments etc., while section 4.4.1 zooms into the models themselves. Although the latter section gives examples of recent developments in user defined material modelling, taking into account aspects that might be placed in section 4.2.2, the section also discusses some models that are currently available in most FE packages and the performances of these models.

1.2.8.2 Failure criteria

As briefly mentioned in the report, it was seen from comparisons made that among the currently available models for material failure criteria the BWH (Bressan-Williams-Hill) criterion and the RTCL (Rice-Tracey Cockroft-Latham) damage criterion performed best. This, together with the fact that they both in some fashion include dependence on strain combinations, was the reason to describe them only in more details.

Further, the committee fully agrees with the OD that there are still main challenges in the definition of failure criteria especially in respect to stress tri-axiality. The determination of parameters for failure at different tri-axial stress states is normally cumbersome without an elaborate test program. On the other hand, research has been carried out into the formulation of failure criteria for FE simulation based on just a mono axial test characterisation (Voormeren et al 2014). In this approach the Modified Mohr-Coulomb (MMC) failure criterion is applied.

Most analyses on ship structures are carried out on shell structures with a plane stress assumption: the issue of necking, when the plane stress assumption is no longer valid, is also an area of current interest (Walters and Voormeeren 2014). Not taking into account this aspect might result in an overestimation of the failure strain.

1.2.8.3 Length scales (Figure 3)

Figure 3 shows the different length scales present in extreme events on ship structures (ranging up to tens of meters or more). As indicated in the figure, however, small scale material phenomena, too, needs to be incorporated in some way in the analysis. Material scale phenomena need solid descriptions for allowing a proper capture of their behaviour. However, a translation or incorporation of this information in the shell model, feasible in principle, may result to be still difficult in a structure in full scale.

1.2.9 Ice material and ship-ice collisions

1.2.9.1 Scope and organisation of the sections

Accidental collisions with ice features are deemed to be included in the scope of the report, as well those with other floating or not floating bodies. Other types of ice-structure interaction like those occurring 'normally' when a ship sails in ice covered or infested waters are part of different situations.

The split of the subject of ice-structure interaction into different paragraphs was based on the criterion of a description of models for ice material in general (4.4.5) and of the more specific aspect of ship-ice collision (5.1.4). Links between the two sections are present in the text, as in the case of the reference mentioned by the OD, which is cited as regards the model of ice and also for the application to ice-ship collision.

1.2.9.2 Classification and ranking among ice models

The values in table 3 of section 4.4.5 refer to a specific study. Those ice properties are reported just to provide the reader with some reference values. Ice properties on the other hand depend in actual world very much on how the ice was created and its age, while in the theoretical characterisation of the ice behaviour type and values of material parameters depend on the model adopted for the description. The section tried to review the models detected, without a classification or a ranking. Similarly, the studies on ship-ice collision are reported in Section 5.1.4, without a classification.

1.2.9.3 Share of energy

The efforts dedicated to modelling the ice material by the various procedures aim definitely at assessing the portion of energy dissipated in the ice, which, according to the reported investigations, is significant as compared with the energy dissipated in the structure. Other terms of the energy balance may include hydrodynamic terms coming from the global dynamics of the floating bodies.

1.2.9.4 Challenges related to modelling ice action.

To answer to the question raised by the OD about the major challenges related to ice action in the context of accidental scenarios, a key aspect from the Committee viewpoint is represented by current experimental research. It is felt, in general, that relevant experiments are missing able to mimic the conditions in the field. It is recalled in the report that Ince et al. (2017) performed drop tests between steel panels and ice cones to study the structural crashworthiness of a ship colliding with an ice-ridge. Similar experiments have been recently performed also at the Memorial University of Newfoundland, see Kim (2014) [this reference is actually missing from the report]. It is not clear if in both cases results are able to reproduce the actual low temperature scenario and its potential effects on the ice-structure interaction phenomenon. Another aspect that future studies could address is how to generate large enough ice loads in a controlled experimental environment that can actually rupture the steel structure. To the best of the committee knowledge, such experimental studies are currently not available.

1.2.10 Ship collision

1.2.10.1 Share of contents between chapt 4 and 5

In principle the general aspects of the response models of structures should be included in chapter4, while aspects regarding the specific scenario should be in the dedicated chapter. The border is admittedly not well defined and may have generated some confusion.

1.2.10.2 Miniature experiments

A specific question is raised by the OD about the experimental approach based on miniature specimens, examples of which are recalled in the report. The advantage of using very large scale factors is evident, but the scaling procedures adopted to interpret the results of this class of experiments need further investigations and validations. Deformation and failure modes in particular may be affected sensibly.

1.2.11 Ship- offshore structure and ship-bridge collisions

The OD comments about the chapters on ship-offshore and ship-bridge collisions call, in one case, for a wider overview of the procedures proposed and, in the other one, for a deeper analysis of the papers available in literature and presented in the report. The degree of detail of the chapters, however, reflects the expertise of the committee members.

The committee anyway agrees that major challenges in the analysis of these classes of collisions are represented by a proper model of the global interaction between the colliding bodies, influencing the share of energy absorption. The aspects of global mechanics involved are clearly much dependent on the type of body involved in the collision (floating or not)

1.2.12 Fire and explosion

As regards the section on fire and explosion, the OD points out that it focuses on ships only, instead of revising also procedures and methods for off-shore structures. The decision of concentrating on ships (right or wrong it may be) was a 'strategic' one, in the sense that the previous report was dealing with off-shore and not with ships and in this term the opposite trend was followed.

1.2.13 Benchmark study

The major objective of the benchmark carried out by some of the Committee members, as stated in the report, is to investigate the uncertainties obtained by use of fully non-linear finite element calculations, in addition to demonstrating the ability of these methods to model complex stress-strain states in ship structures. The committees agrees that it would have been interesting to carry out the study in a blindfold mode to get a picture of the overall dispersion in results. This would have been representative of all effects, including the various subjective choices of computation parameters made by the different participants. In fact, all analysts got results in reasonable agreement with the tests and this achievement was probably much better than what would have been obtained if the study had been blindfold.

On the other hand, the study provided some systematic insight on the influence of various single parameters in the computation. This was obtained by a sensitivity analysis carried out on selected items. It could be stated that instead of a single overall uncertainty, the specific influence of a few key parameter (considered separately from each other's) was studied.

The investigated computational parameters were: friction coefficient, failure strain and mesh refinement. The OD points out that many other could have been added, among which the value of drilling stiffness for the elements. The Committee agrees that drilling stiffness can, in principle, affect the results of this type of computations, but this depends much on the failure mode. For the specific case, the influence of drilling stiffness was actually tested in Abaqus with the fine meshed model (must be done manually in input files), and it was concluded that the effect was rather small for this application/model [this discussion, however, was not included in the report]. In general, the drilling stiffness is of greater importance in folding/buckling than in other deformation modes as also discussed in the paper by Storheim et al 2015. Such modes are not the governing ones in the examined case.

The Committee agrees with the OD when he says that it would be useful to include more details about computations in particular as regards the material models adopted by the analysts. This, however, is a common problem in most of the results published in literature, due to limited space.

2. FLOOR AND WRITTEN DISCUSSIONS

In the following Q stands for question, A for answer, W for written

2.1 Discusser 1: Bruce Quinton

Q: It would be advantageous to know why and which type of finite element analysis, either explicit or implicit, was used for the accidental limit states simulation.

A: Most if not all analysts are using explicit analysis. For grounding and collision analysis with failure and element deletion, it would be very difficult, and maybe impossible, to find a solution with an implicit solver, since it is extremely difficult numerically and convergence problems are likely to occur.

2.2 Discusser 2: Jonas Ringsberg

Q: How would the committee recommend to handle corrosion when it comes to modelling fracture strain, both globally and locally, in these types of numerical simulations?

A: Corrosion is not discussed in the report, but it is definitely something that should be included in the analysis. The characterisation of the corrosion of the structure should be one of the features of the initial state of each scenario. Corrosion, however, is not specific for accidental scenarios: it is a general problem encountered in all type of scenarios covered in design.

In general, corrosion may be accounted for in the simulation input in two ways: through material characteristics and/or geometry: e.g. the effect may be reflected in the stress-strain curve of the material and in the thickness of structural elements.

2.3 Discusser 3: Zhaolong Yu

Q1: In some recent research, it was common to simplify stiffener indentation by treating the bodies and the flanges of the stiffener differently. Is this also done in the accidental limit state simulation?

A: It is typical for simplified analytical model to describe the energy absorbing mechanisms separately for different structural elements. Mutual interaction is somehow accounted for and the energies of the different components are summed to derive the total energy absorption.

It has been shown that such models work well in the loading scenarios they are developed for. However, as the scenario changes, (e.g. the collision impact angle varies), the deformation mechanism and the interaction between the elements might change to a mode that is not included in the initial energy absorption formulation and thus, the accuracy of such simplified model might decrease.

When carrying out full numerical simulations such simplification is obviously not necessary.

Q2: Regarding the scale of the experiment, recently there was an experiment with a scale of 1:100. What is the committee's opinion on this?

A: The answer to a similar question is given in the written reply to the official discusser. Very large scales may be used, which is convenient from a practical point of view. Failure modes and failure description, however, can be affected by scale effects, which leads to doubt about the effectiveness of the experiment.

Q3: Concerning the external dynamic models. The model is based on a lot of assumptions, like the colliding structures are rigid bodies, whereas in reality they are not so: they may get stuck and all the kinetic energy will be dissipated. This may make the model fail so the users of the model should be aware of this assumption and its consequences.

A: It cannot be said that all the external dynamic models assume rigid bodies. F.i. there have been model scale ship collision tests conducted in Aalto University, in which models were not assumed as rigid. In these tests, the structure was able to get stuck and it was also allowed to slide.

The external dynamic model does not have to be wrong even though it might include the assumption of rigid bodies. The influence of rigid bodies (assuming that we are not talking about the dynamic vibratory response of the ship hull, but about rigidity in the contact area) is defined via the coupling of the inner mechanics (contact force) and external dynamics (ship motions). This coupling defines whether we account for infinite stiffness correctly. So it is not necessary that the external dynamics model is wrong but it's really how do the external and internal dynamics models interact. In the end, it is up to the user to use the models properly in order to get the contact force to the external dynamics model.

2.4 Discusser 4: Ekaterina Kim

Q: In the context of ship-ice collisions you have made the distinction between discrete and finite element analysis. Can you give an example of when discrete element methods have been used in the context of accidental limit states for ship-ice collisions?

A: Both discrete element methods and finite element method can be used in principle in the numerical simulation of ice-structure collisions. From the viewpoint of ice properties, finite element method is more suitable to simulate ship-iceberg collision, because the huge mass and volume of iceberg generates large high-pressure contact zones, which prevent a discrete mode of failure in the contact area and imply a continuum mode. For simulations on interactions between ships and e.g. level ice, the adoption of the discrete element method would be more suitable, because level ice is more prone to fail in a discrete mode.

A reference on this topic is present in the report (Ji, Di and Liu, 2015), even though it does not cover specifically a ship-ice collision scenario.

2.5 Discusser 5: Herve Le Sourne

Q: Is there a recommendation of classification societies about the different use of parameters like ship velocities, collision on-go and different points of the ship in order to simplify the simulations so that it becomes feasible for companies to do the research using non-linear finite element methods within a reasonable amount of time?

A: A practical way is just to take the most conservative case, for instance a head on collision and look at different impact areas. In other words, to look at worst case scenarios.

Q: But it is not always the case that perpendicular collision is the worst case, sometimes for example a 120 degrees collision can be worse.

A: For puncturing the inner side of a ship or offshore installation, a head-on collision is normally the most conservative scenario, but if the margins are small it may be necessary to extend the scope and investigate other impact angles, etc. Other scenarios such as hitting a flare tower or damage piping equipment may also be relevant, and this will vary from case to case. The key point is to consider the whole risk associated to the situation to be assessed. This can be more or less concentrated in a comparatively small number of scenarios (or can be spread over a large number).

When analysing a ship collision according to a classification society, one has to comply with their regulations, that indicate which scenarios should be accounted for.

WA: An example of a detailed regulation covering a collision situation for inland vessels carrying hazardous cargo is given in UNECE (2015). The referenced chapter includes criteria for the alternative design of vessels fitted with tanks with larger length and volume than normally admitted. A level of safety is to be demonstrated for the alternative design equivalent to a reference (standard) design. The procedure includes the assessment of a number of cases identified in terms of type of struck vessel, type of striking bow, vertical and longitudinal position of the impact area, collision speed (% of the design value) and angle. For the various situations, collision energy absorbing capacities are to be evaluated, in order to derive a conditional probability of exceedance (i.e. of tank rupture). The latter is unconditioned over the probability of occurrence of the situation and multiplied by the consequences of rupture in order to assess the risk of the unconventional design and compare it to the one of the standard design.

2.6 Discusser 6: Gaetano de Luca

Q: My question is about the computational effort for the benchmark. Grounding is quite a long duration phenomenon compared to, for example, a car crash. For an explicit calculation a small time step may be needed. On a large ship with a long collision duration, it can be hard to carry out a complete computational simulation.

A: The benchmark case was relatively simple because the speed was quite high and the length of the specimen itself was quite small, so the benchmark calculation lasted about five to six hours. If the grounding of a large ship is to be calculated, which really starts to slow down, it would be necessary to simulate a time duration of the order of twenty seconds of real life grounding. Then two to three weeks with a very powerful desktop computer are needed: grounding simulations are actually demanding, if done properly.

Q: In your simulation, did the model slow down? How did you control the speed?

A: In the numerical analysis a constant speed was modelled. A grounding scenario like this can be considered as quasi-static. One advantage of using constant speed is that the energy levels, forces, etc. are computed for all indentations without stopping after a target energy is reached, and consequently the margins up to higher energy levels can be computed.

2.7 Discusser 7: Carey Walters

WQ: The committee performed benchmark simulations of an experiment which was reported back in 1996. Since then, we have learned a lot about material failure, but, of course, we can't retrospectively look at material tests. I was wondering if, based on your experience, you could recommend additional material tests, in case such an experiment was performed again in the future.

A1: In the specific case of the benchmark, not very large tria-xialities are detected in the hull plates and in the stiffeners, but this is not always the case in this class of problems. Other crashing simulations showed that especially stiffening members tend to fail under shear and in such a situation, fracture criteria based on tension tests are not suited. In general is now recognized that the critical fracture strain obtained from tensile tests should not be directly applied for non-linear finite element analysis. Accordingly, knowledge of material properties at different stress states can greatly help in improving predictions in all analyses. Additional material tests, providing information on the behaviour at different stress tri-axialities are therefore definitely beneficial.

A2: It should also be noted that, while it is quite well known that fracture strain is mesh-size sensitive, it can be observed also that the stress tri-axiality depends on mesh-size. With a very coarse mesh, very different tri-axialities can be observed compared to using a fine mesh. The issue cannot just be solved by fine tuning failure criteria, but it should also be kept under control the range for the elements size allowed in particular structural member.

WQ: Were all of the benchmark simulations performed with element erosion? Does the committee believe that the correlation with experiments would have been improved with a more advanced failure modelling technique, such as XFEM? Or would you suggest to keep on with the element deletion?

A1: The analyses by all the contributors were carried out using element erosion. Not sure if it would be beneficial to carry them out in a more detailed modelling technique, since it may be very computationally costly. However, more advanced techniques can probably be used to calibrate failure and element erosion for “simplified” models.

A2: The use of XFEM techniques is indeed computationally quite costly. Furthermore, the implementation of XFEM in commercial FE codes is still not widespread. Abaqus has a fairly good implementation, but tests done with XFEM in LS-DYNA were not successful: a very limited implementation, with only a limited number of failure criteria to pick from. Furthermore, most of the XFEM implementations, to our knowledge, have crack growth over a complete element. So crack growth is still somehow mesh dependent, and, therefore, it does not seem able to solve all the mesh dependency issues related to element erosion.

In our opinion, at the moment, the chosen element erosion technique is the best combination of computational efficiency and required accuracy at the scale of full ship or compartment analyses. XFEM can be a powerful tool in the future for crack analyses and perhaps, at present, for a more detailed calibration of simplified models, as mentioned earlier.

2.8 Discusser 8: Yasuhira Yamada

Q: You used different mesh size for each participant and fracture criteria. How about using the same mesh for all participants instead of using different mesh, since it may be difficult to distinguish effect of fracture criteria and effect of mesh on benchmark results?

A1: The mesh size is related to the failure criteria for element deletion, and for instance in one analysis the guideline DNVGL-RP-C208, the new guideline for non-linear FE analysis was followed. There it is stated that the mesh size should be 3-5 times the plate thickness. Then failure strain is given in a calibration case. According to the guideline, no other element sizes should be used.

A2: About the relation between failure criteria and mesh size, once a simple benchmark was carried out, in which a stiffened panel was modelled with different mesh sizes. The failure strain was fitted in order to get similar results in the analyses. For element sizes over 5 times the shell thickness failure strains were fairly independent, below they needed to increase rapidly, especially when going to element sizes of 2 times the element thickness or less. Then it becomes very mesh dependent what to take.

Q: When selecting the mesh size, did you perform a convergence study to choose the best size?

A: We did some tests on the mesh size but not very systematic. Basically, everybody modelled according to her/his best practices and then results were compared. Results are shown in the report where we tried to analyse the various choices made by the analysts identifying trends in the results. This was done also decoupling the effect of mesh size from that of failure criteria. We are planning to publish more extensive results and there will probably be a systematic study of how different parameters affect the outcome.

Comment: According to my experience, a convergence test is very helpful to determine the best mesh size

2.9 Discusser 9: Lennart Josefson

Comment: Fracture strain is normally mesh size dependent. XFEM could help to get rid of this mesh size dependence.

A: To best of our knowledge, as above already mentioned, XFEM does not remove completely the problem of sensitivity to the mesh size. It is an extended FEM, but it has still the same background of traditional FEM in the sense that the solution is interpolated in nodes over the element. If this distance increases, the solution changes. Additionally, for XFEM to work as intended for crack propagation, quite a fine mesh is still needed, which is prohibitive in these large structures we are dealing with. For the accuracy we are aiming at, in future the trend could be rather to use an adaptive mesh refinement, where the size is refined during the calculation according to the damage in the element.

2.10 Discusser 10: Tetsuo Okada

Q: The strain-rate effect might be very small in a collision, if the fracture is very local, but what is your opinion about that strain-rate effect if the fracture is wide-ranged? Does the committee have any quantitative results with regard to what percentage the effect will be in case of different fracture localizations?

A: We do not have specific results on this effect in the benchmark case. A good reference on the subject is however available by Storheim & Amdahl (2017). Their conclusion about the inclusion in the analysis of ship collisions of dependence on strain-rate is that it should be done with care in order not to alter results beyond the real effect and that it is not simple to obtain a proper material characterisation.

REFERENCES

OD references

Amdahl, J., Holmås, T. (2016) ISUM for offshore frame structures, OMAE2016-55053. Proceedings of 35th International Conference on Ocean, Offshore and Arctic Engineering. Busan, Korea

DNV GL (2015) 'Rules for Classification Ships – Part 5 Ship types – Chap. 8 Compressed natural gas tankers', Det Norske Veritas, Norway

IACS (2014) 'Common Structural Rules for Bulk Carriers and Oil Tankers', Part 1 Chapter 5 Hull Girder Strength

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

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

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

Committee references

Bin Liu, Villavicencio, R., Zhang, S., Soares, C.G., (2017). Assessment of external dynamics and internal mechanics in ship collisions 1–11. doi:10.1016/j.oceaneng.2017.06.053

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.

Hogström, P., Ringsberg, J.W., (2012). An extensive study of a ship's survivability after collision - A parameter study of material characteristics, non-linear FEA and damage stability analyses. Mar. Struct. 27, 1–28. doi:10.1016/j.marstruc.2012.03.001

Ince, S.T., Kumar, A., Park, D.K., Paik, J.K., 2017. An advanced technology for structural crashworthiness analysis of a ship colliding with an ice-ridge: Numerical modelling and experiments 1–11. doi:10.1016/j.ijimpeng.2017.02.014

Kim, H., (2014) An experimental study of the design and overload capacity of structural grillages subjected to ice loads. Master thesis. Memorial University of Newfoundland.

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

Storheim M. & Amdahl J. (2017) On the sensitivity to work hardening and strain-rate effects in nonlinear FEM analysis of ship collisions, Ships and Offshore Structures, 12:1, 100-115, doi: 10.1080/17445302.2015.1115181

Tabri, K., (2012), 'Influence of coupling in the prediction of ship collision damage' Ships and Offshore Structures 7, 47–54. doi:10.1080/17445302.2011.553812

UNECE (2015) European Agreement concerning the International Carriage of Dangerous Goods by Inland Waterways ADN 2015 vol 1 section 9.3.4 Alternative Constructions United Nations Economic Commission for Europe

Voormeren, L.O., Walters C.L., Tang L., Vredeveldt A.W.(2014) 'Estimation of failure parameters for finite element simulations based on a single state of stress and arbitrary stress-strain relation', Proceed. of the 33rd Int Conf on Ocean, Offshore and Arctic Engineering OMAE 2014

Walters C.L. and Voormeren L.O. (2014) 'Consequences of using the plane stress assumption for damage calculations in crash analyses', Proceed. of the 33rd Int Conf on Ocean, Offshore and Arctic Engineering OMAE 2014