MEMBRANE-TYPE LNG CARRIER SIDE COLLISION WITH ICEBERG

EFFECT OF IMPACT CONDITIONS ON STRUCTURAL RESPONSE THROUGH SENSITIVITY ANALYSIS

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ABSTRACT

Collision studies were formerly carried out by equivalent quasi-static analysis. Nowadays, dynamic analysis within explicit hydrocodes is mature to solve such shock phenomena, and can even include fluid-structure interaction capabilities. However, this requires much more carefulness as fast dynamic responses are very sensitive to impact conditions. Consequently, the choice of the initial hypotheses is decisive and should be considered with great care in numerical simulations to avoid unrealistic responses.

Previous works underlined possible high response of cargo containment system of a LNG carrier in case of collision with an iceberg. High stresses were obtained through fast dynamic simulations and were due to the sudden perfectly flat contact between cubic iceberg and ship side hull in void (no sea water). Two factors play a significant role: the contact <u>discontinuity</u> and the <u>large size</u> of the initial contact area. The present paper demonstrates through a sensitivity study that this initial hypothesis of <u>perfectly flat</u> collision <u>in void</u> is not relevant. In particular, it confirms that dynamic response is highly sensitive to small changes of initial conditions and that the sea water between the two bodies prevents any sudden high pressure on the side hull from occurring.

1 INTRODUCTION

Simulations of collisions between an iceberg and a LNG Carrier (LNGC) were previously performed [1] in order to analyze the response of the cargo containment system (CCS) in case of such accidental event. Two cases were studied: bow and side collisions. The last one was found to be worse in terms of CCS response. In this last case, unrealistic conditions were considered: the <u>sea water was not considered</u>, and the impact was <u>perfectly flat</u> type (i.e. the striking flat face of the cubic iceberg remained perfectly parallel to the flat side of the ship up to contact). This resulted in the spontaneous generation of a large shock wave mainly propagating in the transverse direction of the ship and leading to high levels of acceleration and stress in the structure (in some CCS localized areas in particular). Physically, the generation of shock waves is due to discontinuities (there is no shock wave if there is no highly sharp change). In this problem, the discontinuity corresponds to the <u>sudden contact</u> between the two bodies with relative velocity. The second important characteristic is the <u>large surface</u> (approximately 150 m²) involved in this very first contact. This paper illustrates that some impact conditions (geometry of the iceberg striking face and sea water consideration) have a strong effect on the response.

At first, the initial model was improved in terms of contact method and iceberg mesh size. Some ice material characteristics from experimental tests as well as ice failure criterion were also taken into account. In analyses performed in this part (see § 2), the same impact conditions as the ones presented in [1] were considered.

The effect of small changes in the initial contact conditions on the response was assessed. For this purpose, curvature radius and inclination angle of the iceberg striking face were investigated (see § 3).

Both ship and iceberg are surrounded by sea water that has a significant effect on the ship loading (see § 4). Final position and speed of the iceberg with regard to ship hull were studied by flow analysis. The effect of the water layer entrapped between side hull and iceberg on structural response was assessed and compared to the results reported in [1].

These numerical simulations aimed at demonstrating that the impact conditions considered in [1] were really far from realistic and disregarded the important effect of initial hypotheses on the response. In particular, the generation of shock waves induced by contact between bodies is known to be very <u>sensitive to geometrical contact conditions</u>. Furthermore, the water layer entrapped between side hull and iceberg is expected to decrease the iceberg relative velocity and to lead to much more <u>progressive</u> loading on the side hull due to squeezing pressure avoiding any discontinuity (source of potential shock wave in the structure).

2 PRESENTATION AND IMPROVEMENT OF THE INITIAL MODEL

2.1 CONTEXT OF THE STUDY: MODEL, COLLISION SCENARIO AND ANALYSIS

Main characteristics and general arrangement of the target LNGC were reported in [1]. The cargo volume of the vessel was 150,000 cubic meters divided into 4 tanks. The ship loading condition considered was ballast case with cargo tanks empty. The hull ice belt was strengthened in accordance with Baltic Ice Class 1A.

The iceberg was assumed to be cubic (20 m in each dimension) with 2 m height above waterline. It was characterized by the elasto-plastic material shown in Figure 1, as well as by the following properties: density 910 kg/m³, Young's modulus 6.25 GPa, Poisson's ratio 0.28, yield stress 3.5 MPa, tangent modulus 3.125 MPa, and no failure strain.



Figure 1: Iceberg elasto-plastic behaviour law.

The side collision scenario studied in the numerical simulations presented in [1] corresponded to the accidental case of an evasive manoeuvre and sharp turning but unavoidable collision with iceberg at ship side (see Figure 2). The ship forward speed was the full design one (19.5 knots) and a transverse speed by turning was assumed to be 1.95 knots (10% of design speed). The iceberg drifting speed was taken equal to 2 knots.

These numerical simulations [1] were actually carried out considering no initial velocity for the ship, longitudinal initial velocity of 19.5 knots and transverse initial velocity of 3.95 knots for the iceberg in void. There was no difference in global and local analyses responses in void between the former accidental case and the latter actual simulation scenario. The simulation began with the iceberg close to the ship, and only initial velocities were imposed. The collision location was at the middle of No. 2 cargo hold.

The latter iceberg-ship side collision scenario is adopted hereafter as the basic iceberg-ship collision scenario for the simulations in void, i.e. when sea water is not considered. The FE model described in [1] has been specifically optimized in the present side collision study for computational efficiency. It is referred to as initial model.



Figure 2: Initial FE model and collision scenario.

The simulations were carried out in two steps. At first, a global analysis was performed based on the entire ship FE model including one layer of solid bricks (CCS) attached to the inner hull. The structural components of the CCS were assumed to have an equivalent single isotropic elastic material property by linear rule mixture, and averaged density. Then, a local analysis was carried out based on a detailed FE model of the CCS composite structure (see Figure 3) to capture the structural response of the CCS. The same CCS material properties as the ones presented in [1] (see Table 1) were taken into account in this study to be consistent when comparing results.



Figure 3: CCS model (local model).

The location of interest for the detailed FE analysis was selected from the maximum value of acceleration on the inner hull, as acceleration is a good indicator of dynamic effects. A multi-scale technique was applied to transfer time history data from the local segment of the global ship hull FE-model to the local CCS FE model. Two schemes were compared in this study: transfer of boundary nodal velocities of the node set [1] and transfer of displacements and velocities of the segment set [2]. After comparison with the results from the CCS model directly included in the global model, the first scheme was chosen under the current mesh size in the local segment on the inner hull.

The main results presented in this paper come either from global FE model (contact force, acceleration on ship inner hull) or from CCS FE analysis (stress in mastic ropes). The previous multi-scale analysis showed stress peaks in localized parts of mastic ropes. This dynamic response involved local vibration modes excited by the propagation of a large shock wave in the structure.

Physically, the generation of shock waves is due to discontinuities: there is no shock wave if there is no high sharp change. The discontinuity corresponds here to the sudden contact between two bodies with relative velocity. At the very beginning, the energy is concentrated in one direction normal to the contact surface, and the shock wave propagates in this direction. Then, due to shear effects on its outline, the wave front gradually changes into a curved shock wave with radial propagation (see Fig. 8 in [1]). The shock wave propagates, the initial energy is spread on a larger area, and the energy density decreases. However, due to the large initial contact surface in this study (about 150 m²), the curving of the shock wave front is relatively slow; therefore, the energy density remains high when this shock wave reaches CCS. Furthermore, high energy density is combined with very short durations (generally not more than several milliseconds in structures). This is due to the high propagation velocity of shock waves, equal to the acoustic speed for moderate shock waves (about 5000 m/s for mild steel). These short durations explain why shock waves have <u>wide energy density spectra</u>. Thus, they can excite very local vibration modes as energy is available at high frequencies, and locally induce high levels of acceleration and stress.

In sections 2.2 to 2.4, important improvements of the model are presented. The aim is to improve the reliability of this model in the view to perform dynamic simulations presented in the following chapters (§ 3 and § 4). The changes made in the present chapter are not expected to have significant influence on the fast dynamic nature of the response as the impact conditions are still the same as the initial ones. Impact conditions will be discussed in depth in following chapters through sensitivity analyses to physical parameters known to have a major effect on the response.

2.2 INFLUENCE OF THE CONTACT METHOD

The contact is made between shell elements of the hull and solid elements of the iceberg. The initial contact method defined the iceberg as master using segments and the LNGC side structure as slave using nodes. It was compared to another method usually applied for contact between solid and shell elements, defining the LNGC side structure as master using shells and the iceberg as slave using nodes.

The Figure 4 compares the contact force time history with the initial/new contact methods and iceberg meshes. Much more stable global and local responses were obtained using new contact method for the different iceberg meshes studied (see § 2.3). Furthermore, a very strong isolated peak in the initial contact force time history disappeared, and the hourglass energy [3] of the iceberg model became negligible with the new method contrary to the initial one. Thus, the new contact method is more reliable than the initial one. It has been preferred for the further calculations and comparisons.



Figure 4: Contact force for initial/new contact methods and iceberg meshes (initial mesh (a) and new mesh (c) – see Figure 5).

2.3 INFLUENCE OF THE ICEBERG MESH SIZE

The concentric mesh initially used for a bow collision was changed into a mapped mesh more convenient for the side collision problem (see Figure 5). A total of seven different mesh sizes were investigated.

In contact problem, the mesh size of master has in general to be larger than the slave one. Compared to the mesh size (0.87 m \times 0.83 m in fine mesh) of the ship side hull, responses in mesh models (b) and (c) were usually larger than those of mesh model (a). Both global and local responses were sensitive to the mesh size. Larger maximum stresses than the initial ones were observed in the mastic ropes for some meshes. The highest ones were obtained for mesh (c) (see Figure 6).

Whatever these levels, the main point is that the dynamic nature of the response was unchanged because the impact conditions remained the same as initially. The purpose of the next chapters (§ 3 and § 4) is to deal with impact conditions and to confirm the significant effect of relevant physical parameters on the response.





(b) Uniform mesh for striking face (0.5x0.5m) - (c) Uniform mesh (0.5x0.5x0.5m) Progression in normal direction (0.2 to 1 m)

Figure 5: Some iceberg meshes used in the study.



Figure 6: Maximum stress in mastic ropes with the initial/new iceberg mesh.

2.4 INFLUENCE OF THE ICE MATERIAL CHARACTERISTICS

Basically, ice properties depend on natural conditions like temperature, salinity, porosity, grain. Besides differences between tension and compression, the ice also exhibits a variety of types of behaviours ranging from ductile to brittle under compression that are functions of the strain rate [4] [5] [6]. Consequently, not only the natural conditions should be clearly specified when studying ice-structure interaction, but the material model should also be adapted to the problem in terms of strain rate in particular. Experts on ice behaviour strongly advise to implement a model validated in conditions close to those considered. However, the state-of-art provides few characterized models.

The ice contact interface consists of a relatively intact hard zone of ice surrounded by softer pulverized ice during impact and crushing. Several studies and tests on the ice response to collision loads highlight the typical melting effect. This phenomenon can play a significant role in removing ice from the high-pressure zones during impact. Such behaviour was examined in this study.

The characterization of ice failure is one of the greatest challenges for collision problems. The ice behaviour shows very brittle failure modes for high strain rates that may have a strong influence on the response. The effect of failure was also investigated in the study.

2.4.1 <u>Material characteristics from experimental tests</u>

The melting layer can be very thin and therefore difficult to include in a meshed simulation. However, a crushable foam material model can represent the same kind of macroscopic ice behaviour including the melting effect, and so be compatible with meshed simulations. Institute for Ocean Technology (IOT) adopted this material model for collisions with a bergy bit [7] and a growler [8] to represent the observed realistic ice behaviour during laboratory and field tests respectively. The parameters of the material model were assessed from numerical simulations of the previous experimental tests.

This ice model is simplified in that it does not include any spalling (cracking) behaviour and associated dynamics. Nevertheless, it was studied in the scope of this analysis as it is the only one known to be validated from full-scale experiments. According to the author R. E. Gagnon, this model can potentially give reasonable results when

properly implemented for the specific case of collisions with small icebergs that have a well-rounded shape in the area where the collision is to occur. Reasonable agreement between experimental and numerical results was achieved (load and pressure distribution) but neither of both experiments mentioned above went to very strong loads. So it is not a fully validated model with regard to our case. For these reasons, this ice material model was just tested here but it was not considered in the rest of the study.

The crushable foam material model is characterized by the stress-volumetric strain curve shown in Figure 7. It exhibits a non-recoverable deformation composed of two parts: a perfectly-plastic phase representing the melting effect in the soft zone, followed by a slope representing the hard zone behaviour. The volumetric strain qualifying the start of this second phase is denoted by ε_h and is equal to 0.065. The tangent modulus for the hard zone behaviour is equal to 4.7 GPa. The other aspect of the material properties for this ice model in the impact zone is a low value of Poisson's ratio (0.003), to insure a flattening of the ice at the contact zone that is more representative of melting than a flattening that induces bulging of surrounding material such as occurs in an elastic deformation scenario with a classical Poisson's ratio (for example 0.28 for the initial model). The curve ensures furthermore that a relatively small region in the centre of the contact area experiences high pressure (a hard zone) and the surrounding contact material exerts a somewhat lower pressure (soft zone). These features of ice have been observed in various studies, some mentioned in [7] and [8]. Finally, the same Young's modulus as initially was used (6.25 GPa).

In this study, the above crushable foam material model was compared to the initial model. Half peaks for both contact force (see Figure 8) and maximum stress in mastic ropes (see Figure 9) were found. This large discrepancy comes mainly from the much lower yield stress considered for the crushable foam material model (0.1 MPa compared to 3.5 MPa). As a matter of fact, the results showed that the yield stress 0.1 MPa was exceeded on the whole iceberg striking face with the crushable foam material model, whereas it was reached very locally (in the upper corners only) with the initial material model (yield stress 3.5 MPa). The stiffness change at the end of the elastic response stage causes the stop of the shock wave generation, so the difference of levels. Furthermore, ε_h has no effect on the peak. It can be concluded that the melting phenomenon as modelled here has a great influence on the response.



Figure 7: Curve of stress-volumetric strain of crushable foam material model [7] - [8].



Figure 8: Contact force with initial material model / ice material model from experimental tests.



Figure 9: Maximum stress in mastic ropes with the initial material model / ice material model from experimental tests.

2.4.2 Failure

The effect of ice failure was investigated from the initial material model. An eroding approach (deletion of the stiffnesses of elements keeping their masses) was adopted to describe iceberg failure based on ice failure strain. Two failure strain values (0.005 and 0.010) were considered. The most suitable iceberg mesh size corresponding to the refined mesh of the striking face with progression in normal direction (Mesh (b), see Figure 5) was selected for these simulations.

The failure modelling had no influence on global and local responses during the shock wave generation (first 15 ms approximately) and very low influence afterwards (see Figure 10). This result was already expected from the plastic strain field obtained when no failure criterion was taken into account. It was confirmed here and could be explained by the fact that the first element failed at 14 ms, i.e. relatively late, only at the end of the shock wave generation. This element was located at one of the iceberg striking face upper corner. Figure 11 shows the erosion of the contact area at the end of the calculation (0.3 s).

The strong initial discontinuity of the problem has been emphasized previously. This results in very high strain rates in the iceberg contact zone in particular. Now the ice behaviour is very sensitive to the strain rate. For high strain rates the ice behaviour is brittle elastic and the failure stress decreases with increasing strain rate (see Figure 12). This should have a strong influence on the collision force and the structural response. Unfortunately, this effect was fully disregarded in the initial study, and it was not possible to test it in this analysis either due to a lack of suitable data about the relationship between failure stress and strain rate. It would have been relevant to take this effect into account in the next chapter (§ 3) where high strain rates are also involved at the beginning of the contact, which is not the case in the subsequent chapter about the effect of fluid (§ 4) as strain rates are negligible.



Figure 10: Maximum stress in mastic ropes with failure.



Figure 11: Stress on the iceberg striking face (failure strain 0.005).



Figure 12: Compressive failure modes of ice as function of strain rate [4] - [5] - [6].

2.5 CONCLUSION

The aim of this part was to investigate numerical parameters (contact method, mesh size) in order to make the model more reliable, and to study the sensitivity of global and local results to ice physical characteristics (melting, failure).

It was found that a more suitable contact method had to be considered in this problem (contact between shell and volume elements) to ensure the stability of the contact force results for different meshes. Regarding meshes, the iceberg mesh size has more influence on the results than the hull mesh size, however the former had better be smaller than the latter for a more suitable response. Therefore, the iceberg mesh ($0.5m \times 0.5m \times 0.5m$) inducing the highest stress peak was used in the rest of the study. As far as ice behaviour model is concerned, the importance of melting and failure phenomena was underlined.

As the initial impact conditions (perfectly flat impact without water) remained the same as the initial ones, the large shock wave phenomenon and high induced local stress peaks were still obtained as expected. In the following, other impact conditions are analyzed to test the relevance of the collision scenario initially considered.

3 INFLUENCE OF THE GEOMETRICAL PARAMETERS OF THE ICEBERG

Important characteristics of shock waves have been reminded in § 2.1 to justify why high levels of acceleration and stress could locally occur when considering the initial collision scenario. The very short duration that characterizes shock waves also explains why even short time-lags between contact points may prevent the generation of large shock waves. In this case, only local shock waves may be observed as the fast increasing area of the shock wave front causes as fast decrease of the energy density, having finally slight repercussions on the CCS structural response.

Two geometric parameters of the iceberg striking face (curvature radius and inclination angle) were considered. The values selected for these parameters have no scientific background: they were intentionally chosen very close to the ones considered in the initial scenario for demonstration purpose.

3.1 CURVATURE RADIUS

The curvature radius of the iceberg striking face was defined in the horizontal plane. Two values were studied, R = 1000 m and 500 m (see Figure 13).

The first peak of the contact force time history nearly disappeared (see Figure 14). This is because the first contact involved a much smaller area compared to the flat case, with similar contact pressure (fast dynamics theory). Nevertheless, acceleration peaks subsisted and also stress peaks, but they were much smaller than for the initial flat shape (see Figure 15). The maximum stress decreased by 40% due to lower energy density at the mastic ropes location compared to the flat shape.



Figure 13: Configurations of iceberg shape with curvature (top view).



Figure 14: Contact force iceberg for curved shapes.



Figure 15: Maximum stress in mastic ropes for iceberg curved shapes.

3.2 INCLINATION ANGLE

The inclination angle of the iceberg striking face was defined in the vertical plane (see Figure 16). The bottom edge was set back from the initial vertical striking face. Three values were considered: 0.2 deg, 0.4 deg and 0.6 deg.

The first peak of the contact force time history was even lower than for the previous iceberg curved shape (see Figure 17). This is consistent as the areas involved in the very first times of the impact were smaller (from both mesh and geometric points of view). Acceleration and stress peaks were much lower than for iceberg curved shape because of even lower energy density at the mastic ropes location (see Figure 18).

For inclination angles 0.2 deg and 0.4 deg, the maximum stress was not obtained during the first contact between the iceberg striking face and the ship side hull but during the second one occurring at 0.136 s and 0.146 s respectively. As the contact area on the ship side hull was located closer to a stringer than the first one, this second contact led to relatively higher stress peaks in mastic ropes (around 6 MPa and 5 MPa respectively, see Figure 18).

Nevertheless, the maximum stress decreased by 70% compared to flat impact.



Figure 16: Configurations of iceberg shape with inclination angle (side view).



Figure 17: Contact force for iceberg inclined shapes.



Figure 18: Maximum stress in mastic ropes for iceberg inclined shapes.

3.3 CONCLUSION

As soon as the initial contact surface is not perfectly flat, here due to curvature radius or inclination angle of the iceberg striking face (more generally it could be due to an irregular striking face), global and local responses are much less severe. This confirms that even very small changes in such flat impact conditions imply significant changes in the response by noticeably reducing shock wave effects in the structure.

4 INFLUENCE OF THE SEA WATER

Several numerical simulations including the modelling of the sea water were undertaken in order to investigate the effect of the sea water entrapped between the ship side hull and the iceberg.

4.1 INVESTIGATION OF ICEBERG FINAL POSITIONS AND SPEEDS

The preliminary question was: considering the iceberg kinematics relative to the ship, from "far field" to "near field", would a final angle of 0 deg between the ship side hull and the iceberg potential striking face be a common case or an isolated one? This question refers to the stability of such a configuration from flow point of view.

A sensitivity study based on numerical simulations over long duration (up to 24 s) was carried out to investigate the relative kinematics of the iceberg in water for several initial relative angles. As only trends about possible impact conditions were looked for, this fluid-structure coupled problem was solved in 2D for computational efficiency.

The configuration selected for these simulations was the following one: LNGC forward speed of 19.5 knots and transverse speed of 1.95 knots; current of 2 knots opposed to the ship transverse speed; iceberg simply carried by the current (values are given in the reference frame linked to the earth).

The numerical simulations were performed with the explicit FE code LS-DYNA [3], including fluid-structure coupling capabilities. The previous configuration was transposed in the ship frame. This enabled to model the ship contour as inner boundary of the Eulerian fluid model (see Figure 19 and Figure 20). The relative current was imposed on both input/output outer boundaries of the grid. The fluid problem solved amounted to the Reynolds Averaged Navier-Stokes Equations (RANSE) without turbulence model. No viscosity was considered. The iceberg was modelled as a rigid square. The separation between inner and outer fluid domains with respect to the iceberg outline was controlled with two capabilities: fluid-structure coupling based on a penalty method and multi-material modelling based on a volume of fluid (VOF) method. The confined inner fluid mass density corresponded to the mass density of the ice to be consistent with iceberg inertias, and the outer fluid was defined with the characteristics of the sea water. The quality of the previous technique for long simulations lies on the quality of the grid mesh in particular (see Figure 21). A sensitivity analysis on the mesh size led to elements of 0.4 m side all along the iceberg trajectory.

When the iceberg was let free, results showed that collision never occurred. However, it could be said that this result was influenced by amplified hydrodynamic loads against inertia effects in 2D in comparison with 3D. To compensate this, the relative translational motion of the iceberg was finally imposed on most part of the trajectory, and was released just at the end (at a distance between side hull and iceberg of about 6 m). All results underlined that the iceberg turned around its vertical axis. The rotation started once the iceberg was at the perpendicular of the bow shoulder (around 10 s in Figure 22). In this zone, the fluid velocity exceeds the one of the iceberg inducing a relative flow between the iceberg and the ship side hull that leads to lower pressures (Venturi effect) between both structures. This phenomenon is more marked for the corner closer to the hull that initiates the rotation. However, the most significant yaw motion occurred when the iceberg approached the ship side hull. For initial angles lower than 35 deg, the angle in this approach phase was small enough to lead to a water layer entrapped between the side hull and the iceberg. This is illustrated by the flow away effect in Figure 23. The highest squeezing pressures were located in the area where the fluid velocity relative to the iceberg was zero (see the green area between side hull and iceberg in Figure 23). This area was not centred with regard to the iceberg striking face but shifted on the right causing a rapid yaw rotation of the iceberg by lever arm effect and a drop of the iceberg relative transverse velocity. No contact occurred in these cases (see Figure 24). On the contrary, when the angle in the approach phase was too much open, this water layer effect couldn't develop, and an impact finally occurred but with lower velocity compared to the initial simulation in void, and with a reduced contact zone (corner instead of whole iceberg face).

From these simulations it can be concluded that a final relative angle of 0 deg should not be an isolated case. But when it occurs, the relative transverse velocity decreases so much that there may be no impact at all.



Figure 19: Outlines of fluid domain and iceberg, and specification of the relative angle between ship side hull and iceberg face.



Figure 20: FE model of the fluid domain.



Figure 21: VOF field on each side of the iceberg outline when the iceberg is approaching the ship side hull (sea water outside the square and ice inside).



Figure 22: Relative angle time histories.



Figure 23: Fluid velocity field in the ship frame showing the flow away effect between the side hull and the iceberg (the iceberg velocity of about 10 m/s has to be subtracted to visualize this effect).



Figure 24: Final relative angles and impact velocities for cases where contact occurred.

4.2 EFFECT OF THE SEA WATER LAYER ENTRAPPED BETWEEN SIDE HULL AND ICEBERG ON THE LOADING RISE TIME AND STRUCTURAL RESPONSE

The objective of this part was to study the effect of the sea water layer entrapped between the iceberg and the ship side hull in the idealized case of an iceberg moving at a constant speed of 3.95 knots (2.03 m/s) perpendicular to the ship hull. The side hull of the ship and the striking face of the iceberg were kept parallel all the time of the simulation. The geometry of the iceberg and of the ship transverse section was in accordance with the initial one [1]. No ship forward speed was considered. The major difference between this case and the initial one was the modelling of the sea water.

Computations were performed with ICARE solver, which is a RANS with free-surface solver. It is developed by Ecole Centrale Nantes and HydrOcean mainly through French Navy (DGA) support. It has been successfully used for ten years, mainly for naval applications such as ship resistance, propulsion and manoeuvring simulations and damping coefficient computations by free damping or forced motions simulations. Recent developments now allow the simulation of regular or irregular incoming waves.

For this study, a specific mesh deformation procedure was developed in order to simulate the displacement of the iceberg relative to the ship at the expected speed. At each time step, the mesh was obtained by interpolation between the initial mesh, where the iceberg was far away from the hull (Figure 25 on the left), and the final mesh, where the iceberg was close to the hull (Figure 25 on the right). This methodology allowed to impose the velocity of the iceberg, with or without taking into account external current. The simulation was simplified by considering two rigid bodies: the iceberg was 200 m away from the hull and it finished at a distance of 2 mm due to cell size in the boundary layer. The total grid size was around 1 million cells.



Figure 25: Initial and final meshes.



Figure 26: Description of the idealized scenario.

Figure 27 presents the mean pressure on the ship side hull as a function of the distance between the iceberg and the hull. A linear increase of the pressure was observed on the hull up to 5 m due to the propagation of the pressure field generated by the moving iceberg. Below a distance of about 5 m, confinement effects became predominant, and the pressure drastically increased to reach at least 10^7 Pa (mean contact pressure level obtained when considering the initial scenario [1]). The rise times was about 0.30 s from 10^5 to 10^6 Pa, and about 0.15 s from 10^6 to 10^7 Pa (see Figure 28).

This phenomenon would not occur if the iceberg velocity was very slow: the water entrapped between the side hull and the iceberg would have time to flow away with no resistance. The difference here came from the non negligible iceberg velocity forcing the entrapped water to <u>rapidly</u> flow away. The surrounding fluid dynamically resists to this increasing inflow rate, what led to a pressure increase in the sandwiched zone between the side hull and the iceberg (see Figure 29). So the phenomenon was closely linked to the dynamics of the problem.



Figure 27: Mean pressure on the ship hull vs. iceberg/hull distance.



Figure 28: Mean pressure on the ship hull vs. time (full curve and zoom in on last seconds).



Figure 29: Pressure field on free surface.

This flow analysis enabled to investigate the effects of the water layer entrapped between the iceberg and the ship hull. The case was really severe as the iceberg velocity was kept constant, i.e. the dynamic equilibrium of the iceberg, which would necessarily lead to a decreasing velocity, was not represented. Results highlighted that the pressure increase was mainly due to confinement effects, and that the reach of the same pressure level as in void (mean contact pressure of 10^7 Pa [1]) took <u>several ten seconds</u> instead of being instantaneous. This confirmed that the presence of water fully modify the dynamics of the impact. If the impact could be considered as fast dynamic without water, the initial strong discontinuity causing such a response doesn't exist anymore when the presence of water is considered.

Subsequently, a dynamic calculation of the ship global response was performed by applying the previous mean pressure time history on the side hull in the area where contact occurred in void, using model and method presented in § 2. As expected, no shock wave was generated due to the lack of strong discontinuity. The local dynamic analysis of the CCS response confirmed that the stress levels in the mastic ropes remained very small (lower than 0.8 MPa, see Figure 30) compared to the void case.



Figure 30: Maximum stress in mastic ropes.

4.3 COLLISION SCENARIOS WITH CONSIDERATION OF SEA WATER

Finally, two 3D numerical simulations involving the ship and iceberg structural models were carried out taking into account fluid-structure coupling (see Figure 31):

- Configuration A: LNGC forward speed of 19.5 knots and transverse speed of 3.95 knots; no current; iceberg <u>free</u> all the time;
- Configuration B: LNGC forward speed of 10 knots and transverse speed of 3.5 knots; no current; iceberg <u>free</u> all the time.

Both configurations represented the same kind of accidental side collision occurring during an evasive manoeuvre as mentioned in [1]. The only difference between these configurations came from the ship speeds values. Parameters selected for Configuration B corresponded to physical values obtained from manoeuvring tests (turning tests) performed at model basin on a similar LNGC. It can be noticed that these values are significantly different from the values considered in the initial scenario.

Compared to previous cases, the relative velocity of the iceberg was not imposed in these simulations: there was a dynamic equilibrium of the iceberg surrounded by sea water.

The same method as for 2D simulations (see § 4.1) was used for fluid-structure coupling. The differences were that no fluid but void was considered inside the two structures here, and that the fluid was coupled to the hull in addition to the iceberg. The initial distance between the side hull and the iceberg was 3 m, as shown in Figure 32.

Complete global analyses were carried out. For both cases, the simulations showed that <u>no contact</u> occurred (see Figure 33 and Figure 34). Thus, the stresses in mastic ropes were negligible compared to the ones presented in [1].



Figure 31: FE configuration of the iceberg-ship collision simulation using fluid-structure interaction (FSI) technique.



Figure 32: Initial state for configuration A.



Figure 33: Time histories of the distance between the ship side hull and the iceberg.



Figure 34: Time histories of the iceberg relative transverse velocity.

4.4 CONCLUSION

The study of the iceberg relative kinematic in 2D showed that a final configuration with iceberg face parallel to the ship side hull should not be so uncommon. But the main result, confirmed by 3D simulations with different approaches, was that <u>no contact occurs</u> in this case. Even in the very severe case where the iceberg relative transverse velocity is imposed all the time, the hydrodynamic pressure rise time is sufficiently long to avoid any discontinuity, and so any shock wave in the ship structure.

5 GENERAL CONCLUSION

In the scope of this study, the FE model used in [1] was improved based on sensitivity analysis. Nevertheless, the nature of the structural response (strong acceleration and stress peaks due to the propagation of a large shock wave in the structure) was not modified since the same unrealistic impact conditions were considered, i.e. flat impact without prior iceberg relative slow down.

The generation of shock waves caused by impact is very sensitive to initial contact conditions. Small changes of these conditions are often sufficient to avoid fast dynamic response. In this study, the sensitivity of the response to small shape modifications (curvature radius and inclination angle of the iceberg striking face) was investigated. It was confirmed that dynamic response is significantly reduced leading to acceptable stress levels.

Surrounding sea water has a large effect in case of collision between floating bodies, as shown through the wide literature about this subject (see [2] for example).

In this study, 2D simulations of the iceberg kinematic in water relative to the ship were performed for several initial horizontal angles to investigate the possible relative final angles and transverse velocities. In many cases, the final relative horizontal angle is zero (iceberg striking face parallel to ship side hull). Nevertheless, no impact occurs (the iceberg final relative transverse velocity is zero) due to the resistance from the flow away effect of the water entrapped between the hull and the iceberg. For the other cases, this effect is less significant leading to impact between the iceberg vertical edge and the side hull. However, there is no large shock wave within ship structure as the contact area is too small.

In addition, 3D simulations showed that the water layer entrapped between the LNGC and the iceberg would have two main effects. Regarding the iceberg, the hydrodynamic loading slows it down enough (relative to the ship) to prevent any impact. This result is consistent with the conclusion drawn from 2D calculations. On the ship hull, the hydrodynamic loading is much more <u>progressive</u> compared to the sudden contact loading obtained without sea water in [1]. Thus no discontinuity occurs and no shock wave is generated in the structure.

The final conclusion of this study is that perfectly flat impact conditions between the LNGC and the iceberg cannot occur due to the resistance effect of the water layer entrapped between the side hull and the iceberg. Consequently, no shock wave is generated and there is no high dynamic response in the ship structure. Finally, maximum stresses in CCS are far below design criteria eliminating any risk of damage on the basis of the hypotheses investigated in the scope of this study.

APPENDIX: ADDITIONAL INVESTIGATION ON SHOCK WAVE GENERATION DUE TO ICE FAILURE

Ice load is typically characterized by a sequence of relatively slowly rising force, each followed by an abrupt load drop. While the load is rising, the structure responds quasi-statically. The potential transient dynamic effects may occur following the load drops. The drop is caused by a fracture in the ice involving very short durations. The sketch below shows the general nature of ice load time-histories.



Figure 35: Ice-hull interaction – Typical ice load time history.

As ice failures might create shock waves in the structure due to abrupt load drops, it was worth examining this case. The purpose of this analysis was to conduct a transient analysis of the response of the CCS to ice load drop. The focus was in short duration dynamic effects that result in rapid transient accelerations and stresses. The proposed analysis did not reflect detailed ice mechanics, which is much more complicated. Nevertheless, this approach served the purpose of checking possible transient dynamic effects that ice might cause.

The problem here addressed is not the so-called collision between ship and iceberg reported in the rest of this paper but a <u>progressive</u> load of the ship due to ice (pack ice e.g.). Based on the previous model, the following scenario was considered: the displacement of the iceberg was imposed to the iceberg back side towards the hull side. This displacement was applied quasi-statically to the iceberg during the whole simulation, i.e. even after contact occurred between the side hull and the iceberg. The whole side of the ship hull opposite to the iceberg was fixed to ensure equilibrium. Flat contact conditions were kept. The ice failure was modelled in accordance with the erosion method presented in § 2.4.2.

Ice load drops corresponding to fractures in the ice can be shown in the contact force time history (see Figure 36). The main failure occurs around 2 s (see Figure 37). This is corroborated by the peak observed in the acceleration time history of the ship inner hull (see Figure 38). However, the time history of maximum dynamic stress in the mastic ropes (see Figure 39) indicates that this significant load drop has only a very limited effect (maximum value less than 3 MPa) on the response of the CCS.

This simulation confirmed that the ice failures occur at <u>different times</u> during the iceberg progress and affect <u>different</u> <u>locations</u> of the iceberg striking face. Therefore, no large shock wave occurs. Only local ones may be generated that vanish rapidly with no consequence on CCS integrity.



Figure 36: Contact force.



Figure 37: Stress on the iceberg striking face (failure strain 0.005) at t=1.967 s and t=2.149 s.



Figure 38: Acceleration on ship inner hull.



Figure 39: Maximum dynamic stress in mastic ropes.

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