Numerical Simulation of the Ice-Structure Interaction in LS-DYNA

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Summary

Design of offshore structures in Arctic waters is strongly dependent on local and global ice loads. These loadings are, in general, contact forces transmitted to the structures during interaction with ice floes, ice ridges or icebergs. The prediction of ice forces on structures relies heavily on a thorough understanding of mechanical behavior of sea ice as well as on in-depth knowledge of interaction between ice features and structures.

Sloping, or conical shaped structures are commonly used structures for arctic oil and gas exploration and production due to the fact that these structural shapes induce ice bending failure on the structure slope, so that the horizontal ice loads on the structure can be reduced compared to a crushing type of failure, which occurs when ice floes interacting with vertical structures.

As an ice sheet advances toward a conical or sloping structure, the ice load increases until the drifting ice sheet fails by bending and forms ice blocks. Following the failure of the ice cover, the failed ice blocks are pushed up the sloping structure or forms ice rubble in front of the structure.

Predicting the correct failure modes (crushing, bending, and splitting or combined modes of failure) is desirable as well as the global force on the structure. However, this is not straightforward due to the complexity of the mechanical behavior of ice. It is facing some challenges such as, anisotropy (ice can be considered as a transversally isotropic material), inhomogeneity, and strain rate and pressure dependent response. Some of these key behaviors are considered on this study as a preliminary start for the further investigations as a part of the ColdTech project.

The following major features are modeled and discussed in this paper:

- The bulk material behaves like von Mises material.
- To account for the anisotropic behavior of columnar ice, the planar anisotropic failure strength was accounted for by utilizing cohesive zone elements in two different major directions.
- Fluid-structure interaction (FSI) was employed in order to assess a more realistic boundary condition of drifting ice sheet, i.e. account for the weight of the ice (if the ice blocks being pushed up the sloping structure), or account for the buoyancy forces, (if the ice blocks forms ice rubble in front of the structure). However, as expected, it increases the computational cost considerably.

Keywords

Ice, LS-DYNA, cohesive zone model, fluid-structure interaction

Introduction

The economic activity growing fast in the Arctic region and consequently the need increases for new constructions. The structures must fulfill specific requirements because of the cold winters and ice conditions [1, 2]. The offshore structures may subject to the ice force during the cold period, Figure . There are three main ice action limiting mechanism, limit-stress, limit-energy and limit-force [1]. This paper deals mostly with limit-stress which indicates that the maximum force is governed by the ice failure. Ice may fail in different modes e.g. crushing, bending, buckling, and splitting or under a mixed-mode.

Figure The lighthouse Norströmsgrund is located in the Gulf of Bothnia, about 65 km southeast of Luleå in Sweden [3]. It shows the accumulated ice after crushing.

The failure modes depend upon the mechanical properties of sea ice [4], geometries of ice feature and structure, collision speed and the boundary condition. Sloping or conical shaped structures are commonly used for arctic oil and gas exploration and production due to the fact that these structural shapes induce bending failure of the ice on the structure slope, so that the horizontal ice loads on the structure can be reduced [5]. As an ice sheet advances toward a conical or sloping structure, the ice load increases until the drifting ice sheet fails by bending and forms ice blocks. Following the failure of the ice cover, the failed ice blocks are pushed up the sloping structure or formed ice rubble in front of the structure. This problem was investigated both theoretically [1, 6-9] and numerically [10-14] over the last three decades. Finite element method has become an important tool in order to predict the mechanical response of ice. However, other numerical techniques such as particle-in-cell were used [15] for the large scale simulations. Martonen et al. [14] implemented a multi-surface failure model in ANSYS, a finite element package. Effect of the strain rate, temperature, salinity and porosity was considered in the failure model. Sand [11] has employed an elliptical failure criteria, implemented in ANSYS, to determine the maximum force on the slopping structure. The ice anisotropic effect is considered in the failure criteria. Cohesive zone element was utilized by Gurtner [16] in order to predict the ice failure in LS-DYNA. In this study, ice was modeled with an isotropic bulk which associated by anisotropic cohesive element. A relatively new approach called XFEM (Extended Finite Element Method) was employed by Bergan et al. [12] to model the complex failure behavior of ice. XFEM is a numerical technique that extends the classical finite element method (FEM) approach by enriching the solution space for solutions to differential equations with discontinuous functions.

The aim of this study is to simulate the ice fixed-structure interaction by using the cohesive zone element to model the ice. In order to get the correct boundary condition, fluid-structure interaction was employed to account for the buoyancy forces acting on the floating ice floe.

Numerical model

The model comprises of several aspects, bulk material, cohesive zone elements (CZE), Fluid-structure interaction (FSI) and contact. The bulk material was considered isotropic and it behaves like von-Mises plasticity. MAT_PIECEWISE_LINIEAR_PLASTICITY was assigned to it, see Tabel for more details.

Fluid-structure interaction

The buoyancy force acting on the ice floe is playing important role in the failure mode [11, 16]. The conventional way to consider the buoyancy force is using a Winkler foundation. A linear spring which cannot model the submerged or lifted out ice blocks. When ice failure occurs the failed ice blocks may push up by the drifting ice sheet or accumulate in the front of the structure. In order to get the correct response, the water and air were modeled as an Eulerian mesh. Since the effect of the air can be neglected, it is defined as void. Both water and air are modeled by using the solid element formulation 12 (one point integration with single material void). Material model number 3 (MAT_NULL) [17] and accompanying equation-of-state were assigned to the Eulerian materials. Equation of state must be defined for the null material that prescribes relation between thermodynamic variables e.g. pressure and volume. Grüneisen equation [18] was chosen and calibrated based upon earlier studies [19, 20]. Tabel summarizes the material parameters which is used in that paper.

The hydrostatic pressure was initialized by using LOAD_BODY_Z to create the gravity condition. Beside that it is important to constrain nodes on the free surfaces of the Eulerian mesh. The preliminary simulation shows a periodic oscillation of the pressure. This was examined by simulation a floating object under equilibrium condition. A mass weighted damping was defined in order to reduce the oscillation. It is intended to damp low-frequency structural modes and also rigid body motion [17]. The damping coefficient was determined based on the preliminary simulation, without damping, and estimating by $4 \times piT$. Where, T is the period of oscillations in second. Damping factor was reduced when the hydrostatic pressure correctly settled. It seems that the buoyancy equilibrium condition cannot be achieved without applying the appropriate damping to the system.

The interaction between Lagrangian and Eulerian mesh was defined via *CONSTRAINED_LAGRANGE_IN_SOLID command. LS-DYNA provides two types of coupling, penalty based and constrain based [21]. Both coupling algorithms were evaluated in order to check the performance and results shown that the penalty-based is better choice. Furthermore, the constrain-based coupling does not conserve energy [17]. The number of coupling points which is in connection to the Lagrange-Euler relative mesh resolution set to 3. However, higher value will increase the CPU time considerably. The remained parameters left their default values.

The appropriate hourglass control type should be assigned to the fluid and solid [19]. A viscosity-based hourglass with coefficient 1.0e-6 is recommended for fluid [22]. Therefore, hourglass formulation type 1 (viscosity-based) was employed with a magnitude of 1.0e-6 and type 5 (stiffness-based), while a magnitude of 0.1 were defined for the Eulerian and Lagrangian material, respectively.

Cohesive zone elements

Cohesive zone elements are used to simulate the crack initiation and growth. It is based on the early work of Dugdale [23] and Barenblatt [24]. The cohesive element represents the cohesive force while following the traction-separation curve. A cohesive constitutive law relates the traction, force per unit area, to the separation at the interface via non-linear spring elements. The separation between adjacent element surfaces is derived based on the displacement at Gauss points. The cohesive element can have zero thickness without leading to numerical instability. It is worth mentioning that the order of the nodes is important to define the cohesive upper and lower surfaces. It means the first four nodes (1-4) and the second four nodes (5-8), in an eight-node solid hexahedral element, define the lower and upper cohesive surfaces, respectively, see Figure c.

(c)

L

Modeling the ice failure by using cohesive element was introduced by Gürtner et al. [25]. Element formulations 19 and 20 can be used to model the cohesive element in LS-DYNA. They have defined two different material properties for the horizontal and vertical element. The same approach was used in this paper to model the ice block, see Figure . The cohesive elements can be attached to the bulk either by sharing the nodes or defining tied contact between parts. In this case cohesive and bulk elements share nodes. Since the hexahedral solid element with 3 degree of freedom at each node is assigned to the bulk, element formulation number 19 is assigned to cohesive elements which does not transfer the moments [17].

5

6

7

8

1

2

3

4

U

(b)

(a)

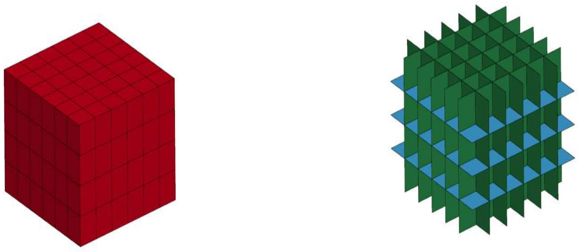

Figure a) Shows bulk elements while the cohesive elements were inserted at inter-element. b) Cohesive elements, two different parts (colors) indicate the transversally isotropic. c) Schematic drawing of cohesive element.

Four material models, MAT_138, MAT_184, MAT_185 and MAT_186 can be used for element formulation 19/20. MAT_186 (MAT_COHESIVE_GENERAL) was chosen due to the flexibility it provides. Tabulated traction-separation can be defined directly for both facture modes I and II.

In order to prevent asymmetric deformation, the number of integration points required for the cohesive element to be deleted set to 1 [17]. This material model was calibrated based on the data presented by Gürtner [16]. Two tri-linear curves were defined to represent the normalized traction-separation behavior. The ultimate mixed-mode displacement is calculated using the following equation.

$$\delta F=1+\beta 2ATSLCTGIcXMU+S.\beta 2GIIcXMU-1XMU \tag{1}$$

Where, β is the ratio between normal and tangential separations. GI c and GII care the fracture

toughness for modes I and II, respectively. A_{TSLC} is the area under the normalized traction-separation curve. T and S are peak tractions in normal and tangential direction.

Contact formulation

Two types of contact were defined which are between ice-sloping structure and ice block-ice block. As mentioned already the ice sheet drifts toward the sloping structure and then fails into the smaller block due to bending failure. The contact between ice and rigid stricture is penalty-based contact with two different 0.0 and 0.1 friction coefficients. The post failure contact should be considered between the failed ice blocks to get the correct behavior. As the cohesive elements will fail and delete therefore an eroding type of contact, CONTACT_ERODING_SINGLE_SURFACE, was assigned to the ice sheet [26] to account the post-failure contact.

Tabel values were used to calibrate the material modes.

	GIC (N/m)	GIIC (N/m)	T (MPa)	S (MPa)	λ_1	λ_1
***MAT_COHESIVE_GENERAL**	6	30	0.065	0.065	0.1	0.8
	Density (kg/m^3)	Elastic modulus (MPa)	Poisson's ratio	Yield stress (MPa)		
***MAT_PIECEWISE_LINIEAR_PLASTICITY**	910	6000	0.3	2		
	Density (kg/m^3)					
***MAT_NULL**	1027					
	C speed of sound (m/s)					
***EOS_ GRUNEISEN**	1500					

Results

An ice floe with 1000 mm length and 20 mm thickness is driven towards a 45 degree inclined-structure. Depending on the geometry, ice mechanical properties and contact condition may ice behaviors differently. In order to evaluate the ability of the methodology to predict the different ice behavior, two different contact situations between ice and the rigid structure were considered, i.e.

friction coefficient equal to 0.1 and a frictionless contact situation. As are shown in Figure 3, it seems that both the applied FSI and CZM formulations works well together and does not lead to numerical instability. The maximum horizontal force between the ice floe and structure has been extracted from the contact reaction force. Those values, for two different contact conditions, are shown by circle in Figure .

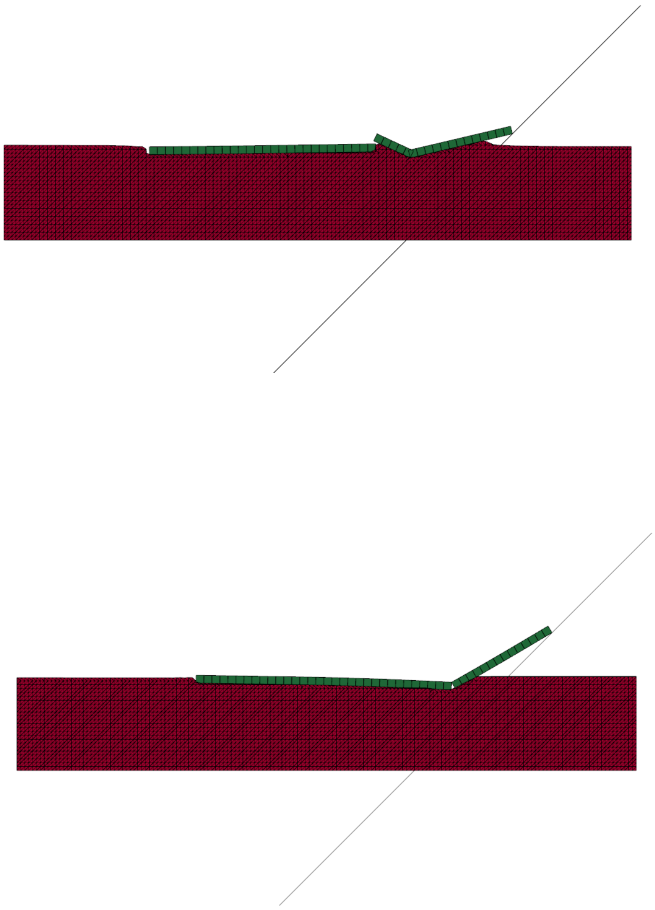

Figure An ice floe (green) is interaction with an inclined-structure (black solid line). Friction coefficient between ice and structure a) set to 0.1 and b) set to 0.0, a frictionless contact.

The maximum horizontal force per unit width was determined based on Eq. (2) [11]. This is a two dimensional analysis of the ice force on the slopping structure. The equation consists of two parts, the force required to break the ice and to lift the ice block on slop.

PHb= σfρwgh5E14C1+zhρicegC2 (2)

$C1=0.68\sin\alpha+\mu\cos\alpha\cos\alpha-\mu\sin\alpha$

(3)$C2=\sin\alpha+\mu\cos\alpha\sin\alpha+\mu\cos\alpha\cos\alpha-\mu\sin\alpha+ \cos a\sin\alpha$

(4)

Where, PH is the horizontal force. b and h are the width and thickness, respectively. σf is the

flexural strength and E the elastic modulus. ρice and ρw are the density of ice and water, respectively.

The z indicates the distance of the ice block that pushed up on the structure. Finally, μ is the ice-

structure friction coefficient and α is the slope angle of the structure. The horizontal force has been

calculated based on the Eq. (2) and values that have been presented in Tabel . The z-factor in the second part of the Eq. (2) set to the value that determined from FE simulation. Ice force on the sloping structure for different friction coefficient and angle are presented in Figure .

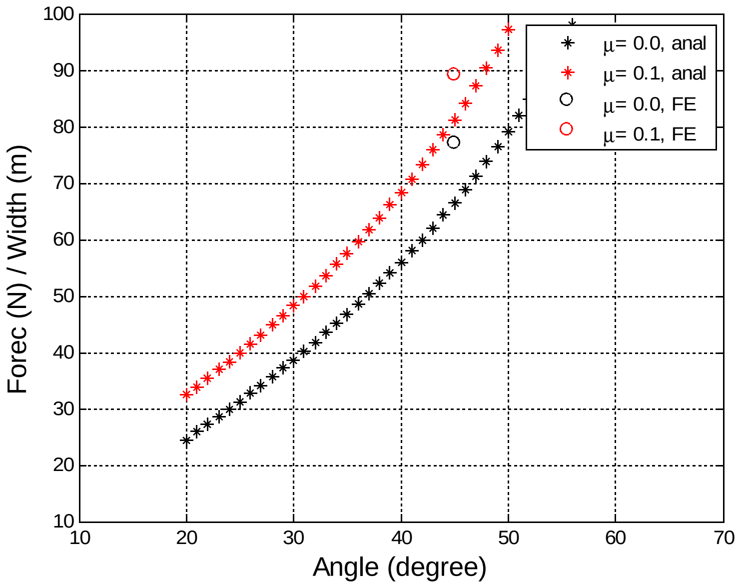

Figure Horizontal ice force on the sloping structure for different friction coefficient (μ) and angle (just for analytical solution). μ vary with line colors (legend).

Discussion and conclusion

A comparison of the horizontal force between FE and analytical solution shows that the FE overpredicts the maximum forces approximately 15%. The differences could be partly governed by assumptions such as elastic foundation for the analytical solution. However, the sensitivity analysis shows that the FE prediction depends on damping, hourglass formulation and the mesh size. This is an important issue when the aim is to extrapolate the verified solutions for the different problem. That means the effect of those parameters should be well understood. Regarding the mesh size, creating the cohesive element can be quit time consuming especially for the complex geometry and needs some manual work.

All in all, it seems that the methodology can be applied to the problems related to ice mechanics. However, still some issues like material model calibration and computational time for the large structure and applying it to the dynamic model should be studied more extensively.

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