Modelling of Ice Impacts Using Cohesive Element Method: Influence of Element Shape

O A Makarov¹, A T Bekker²

¹Far Eastern Federal University, International Research and Education Centre “R&D Centre “Arctic”, 8 Sukhanova St., Vladivostok 690091, Russia
²Far Eastern Federal University, Department of Hydraulic Engineering, Theory of Buildings and Structures, 8 Sukhanova St., Vladivostok 690091, Russia

E-mail: bekker.at@dvfu.ru, makarov.oa@dvfu.ru

Abstract. In recent years numerical modelling is widely used for solving ice-structure interaction problems. The most popular numerical method is finite element method. One of the promising approaches for modelling ice destruction is cohesive element method, where ice field is discretized using both bulk and special cohesive elements, which are possible crack paths. The investigation of modelling features and limitations of this method have been performed by several authors but with not appropriate quality. This paper belongs to series of numerical experiments performed to study the cohesive element techniques for ice modelling and includes some considerations and study of influence of finite element shape.

1. Introduction

The numerical experiments on ice-structure interaction problems have been performing since approximately 2008 year. This fact is related to rapid development of digital technologies and increasing of computational power. The most popular numerical methods for solving such problems are discrete element method and finite element method. In terms of first one the following papers can represent some solutions of ice modeling problems: Liu et al. (2016) [1], Richard and McKenna (2013) [2]. Although in some cases results can contribute with field measurements, the picture of interaction in our opinion does not correspond to real conditions. To reproduce ice destruction process during interaction it is better to use finite element method with some special techniques. Among such approaches for destruction modeling the following two are most used: element erosion technique and cohesive element method.

The cohesive element method (CEM) gained a big popularity in the problems of ice numerical modeling after the such papers as Gürtner et al. (2009) [3], Gürtner et al. (2010) [4], Hilding et al. (2011) [5], Hilding et al. (2012) [6]. In this method, the simulated body is discretized using conventional bulk elements, as well as special cohesive elements of zero thickness. Bulk elements are used to model the process of ice deformation, and destruction occurs due to the loss of strength of the cohesive elements. Other words, it is assumed that the cohesive elements are possible paths for the formation and development of cracks. It allows to eliminate very quick change of contact area and also takes into account the hummocking of finite elements up and down from contact area, which also effects on resulting ice load. Thus, this method allows to consider the effect of cracks and spalls of ice field on general picture of interaction with more quality. The obvious disadvantage of this method is
relatively big computing cost, but development of computer technologies and increasing of power of computers makes this disadvantage less important. Earlier several authors performed some investigations of model parameters using this method, but they did not describe mathematical apparatus which connects the deformations and stresses of cohesive elements along its interface.

Along the recent research of ice impacts modeling using CEM the following can be distinguished: Li Liang (2014) [7], Salganik (2014) [8], Wang et al. (2019) [9]. In the last one authors considered the influence of initial damage of ice field on ice load. Results showed that deleting finite elements from initial model contributed to a better convergence of modeling with field data. Also, some studies of mesh influence were performed by Pang et al. (2015) [10]. It should be noted that in all papers described above authors did not pay attention to selection of ice properties and did not consider the temperature gradient in the ice field and respectively the temperature dependence of ice properties.

In this paper we performed the numerical modeling of ice field impact on vertical circular structure using CEM to study the influence of shape of finite elements on the result. This study is important because the finite element analysis as a whole is very strongly influenced by mesh settings. When creating the initial model, the calculation of temperature-dependent properties of sea ice was performed based on several initial conditions. The strength of ice in this paper depends not only on temperature but also on strain rate. It is automatically calculated for every finite element node during calculation process based on current deformation conditions of nodes. The features of model creation process described above provide the scientific novelty of research.

2. Formulation of the problem

2.1. Description of the main method for solving the problem

The numerical modeling will be performed in SIMULIA Abaqus software that is very powerful tool among other finite element analysis software packages. Since the finite element method is used in this paper the solution comes down to solving the main equation of motion, which has the following form:

\[ [M] \ddot{\mathbf{x}} + [C] \dot{\mathbf{x}} + [K] \mathbf{x} = \mathbf{F}, \tag{1} \]

where \([M], [C], [K]\) – global mass, damping and stiffness matrixes respectively;
\(\ddot{\mathbf{x}}, \dot{\mathbf{x}}\) and \(\mathbf{x}\) – nodal acceleration, velocity and displacement vectors respectively;
\(\mathbf{F}\) – applied load vector.

To search for nodal displacements the explicit integration method was used for a more detailed assessment of the behavior of the ice during deformation. Information about the integration method can be found in the help of the software package.

2.2. Loads and boundary conditions

The modeling of actions of level ice on circular structure was performed under the assumption of the infinite ice field conditions. Drift velocity equal to 0.5 m/s is applied to the entire body of the ice field. Shape of ice sheet in plan is rectangular. The dimensions of ice field are 60 x 30 x 1 m and structure diameter is 5 m.

Such horizontal dimensions of ice formation were applied to reduce the influence of boundary conditions. To simulate the conditions of an infinite ice field, all the faces of the body except the frontal one are constrained from movements in the direction orthogonal to the direction of motion (y-axis). The initial velocity is also constant on these faces.

Crushed ice in the process of interaction continues to affect the structure, increases the contact area, and also adds some vertical component acting on the ice field. In this regard, the forces of gravity and buoyance cannot be neglected. Gravity is considered very simply by applying the load to the bulk elements through the interface of the Abaqus software. Buoyancy is modeled by reproducing the water pressure acting on the external faces of bulk elements. Such approach was used by Hilding et al. (2011) [5] and allowed to reduce the computation time in comparison with other approaches. If we assume that the vertical z-axis in the model is directed up, then buoyancy pressure \(p\), Pa, in the node of submerged finite element can be calculated as follows:
\[ p = \rho_w g (z_0 - z), \]  

where \( \rho_w \) – density of sea water, kg/m\(^3\);  
\( g \) – gravitational acceleration, m/s\(^2\); \( g \approx 9.81 \) m/s\(^2\);  
\( z_0 \) – coordinate of water surface in vertical direction (z-axis), m;  
\( z \) – coordinate of node in vertical direction, m;

In the toolkit of the Abaqus software package, there is no way to add a pressure depending on the distance, the value of which will be updated every time increment. To add such pressure, load the subroutine \texttt{VDLOAD} was created in the Fortran programming language, which was then initialized at the beginning of each calculation time increment.

2.3. Constitutive behavior of ice

Physicomechanical properties of ice used in this research are presented in table 1. The constitutive response for bulk and cohesive elements is not equal. It is accepted that bulk elements represent the deformation of ice during interaction and have elastic and plastic properties. The linear Drucker-Prager plasticity model is used to consider the plastic properties of ice with changing yield stress depend on temperature, strain rate and pressure. The yield surface is presented in figure 1 (a). The advantages of this model in ice modeling problems are described in [11]. The yield criterion of this model can be written as follows:

\[ F = t - p \tan \varphi - c = 0, \]

where \( t \) – material parameter that controls the dependence of the yield surface on the value of the intermediate principal stress;  
\( p \) – pressure stress;  
\( \varphi \) – the friction angle of the material determined using approach described in [11];  
\( c \) – cohesion of material equal to shear strength of ice.

The cohesive elements are used to model the ice destruction and have the pure elastic behavior prior to damage initiation. The elastic behavior is written in terms of an elastic constitutive matrix that relates the nominal stresses to the nominal strains across the interface. In this paper simplified formulation was used in which the behavior of the cohesive elements in the normal and tangent directions is uncoupled. In this case each traction component \( t_i \) depends only on its conjugate nominal strain \( \varepsilon_i \):

\[
t = \begin{pmatrix} t_n \\ t_s \\ t_t \end{pmatrix} = \begin{bmatrix} E_{nn} & 0 & 0 \\ 0 & E_{ss} & 0 \\ 0 & 0 & E_{tt} \end{bmatrix} \begin{pmatrix} \varepsilon_n \\ \varepsilon_s \\ \varepsilon_t \end{pmatrix}
\]

where \( t_n, t_s, t_t \) – normal and two shear components of nominal traction stress vector;  
\( E_{nn}, E_{ss}, E_{tt} \) – normal and two shear moduli of ice respectively;  
\( \varepsilon_n, \varepsilon_s, \varepsilon_t \) – normal and two shear components of strain vector respectively.

The damage of cohesive elements is not instantaneous. Material damage occurs according to a damage evolution law (figure 1 (b)), as soon as following damage initiation criterion is met:

\[
\max \left( \frac{\langle t_n \rangle}{t_n^0}, \frac{t_s}{t_s^0}, \frac{t_t}{t_t^0} \right) = 1,
\]

where \( t_n^0, t_s^0 \) and \( t_t^0 \) – maximum values of corresponding tractions.
Figure 1. Constitutive behavior of ice: (a) yield surface of linear Drucker-Prager criterion for bulk elements; (b) typical traction-separation response of cohesive elements.

Table 1. Physicomechanical properties of ice.

| Parameter                                    | Units   | Values                  |
|----------------------------------------------|---------|-------------------------|
| Density                                      | kg/m³   | 924.8–932.2             |
| Angle of internal friction                   | degree  | 64.1–66.4               |
| Elastic modulus                              | MPa     | 5.173–9.337             |
| Poisson’s ratio                              | MPa     | 0.319–0.339             |
| Compressive strength (yield strength of bulk elements) | MPa     | 0.426–6.527             |
| Tensile strength (cohesive elements)         | MPa     | 0.584                   |
| Shear strength (cohesive elements)           | MPa     | 0.612                   |
| Fracture energy (cohesive elements)          | J/m²    | 67.16–302.96            |

Despite all advantages of CEM it is necessary to take into account all features of general finite element method to get an appropriate result. Since the mesh of simulated bodies can significantly affect on results the investigation of its influence should be done. Thus, the main goal of this study is to study the effect of different finite element shapes on modeling result.

3. Study of mesh pattern influence
On the first stage the effect of the finite element mesh pattern on the modeling results was studied. Four mesh patterns were compared: unstructured tetrahedral mesh, unstructured prism mesh, structured hex mesh, unstructured hex mesh. Finite element models for all 4 cases are presented in figure 2. Minimum and maximum element sizes are the same for all cases and equal to 0.25 m and 1.5 m, respectively.

Figure 2. Finite element models with different mesh patterns: (a) tetrahedral mesh; (b) prism mesh; (c) structured hex mesh; (d) unstructured hex mesh.
The time of simulation is assumed to be 5 seconds, so that the structure crashes into the ice field to full width. As an evaluation criterion, the general picture of ice destruction, as well as the history of ice load during the simulation, are used. General modeling information is presented in table 2. Ice load history in the direction parallel (x-axis) is presented in figure 3.

Table 2. General modeling information.

| Case                  | Number of finite elements (bulk / cohesive) | Total calculation time, hours | Peak total ice force along direction of motion, MN |
|-----------------------|--------------------------------------------|------------------------------|-----------------------------------------------|
| Tetrahedral mesh      | 124 261 / 236 075                         | 48.63 (4.01 s out of 5)      | –                                             |
| Prism mesh            | 46 272 / 103 672                          | 12.61                        | 7.358                                         |
| Unstructured hex mesh | 26 312 / 71 918                           | 4.88                         | 9.785                                         |
| Structured hex mesh   | 29 808 / 81 264                           | 2.25                         | 6.224                                         |

As we can see mesh patterns showed quite different results. First, let’s consider the structured hex mesh case. In our opinion this type of mesh showed the worst result. The fracture pattern of ice sheet at the end of the calculation is presented in figure 4 (b). The vertical cohesive elements destroyed along several parallel faces of the central finite elements. To understand the reason, it is necessary to consider the beginning of the interaction. Figure 4 (c) shows that, at first, the two closest finite elements to the structure begin to interact with it. Then, shear stresses $\tau_{xz}$ arise on the lateral faces of these elements. Since the mesh is structured, the propagation of stresses passes deep into the field in a straight line without any bulk elements in the pass. The cause of the unrealistic destruction of vertical cohesive elements are the rapid propagation of shear stresses $\tau_{xz}$, while cohesive elements orthogonal to them are not deforming. This is clearly seen when looking at the fracture pattern presented in figure 4 (b). We assume that such a fracture can be associated with the choice of a uncoupled elastic matrix of cohesive elements.

Figure 3. Load history with different mesh patterns (along x-axis).

Figure 4. Ice crushing during impact of ice field in case of structured hex mesh: (a) general view; (b) fracture pattern at time 5 s; (c) shear stress propagation at the beginning of interaction.
The second type of mesh to consider is unstructured hex mesh. The result of the calculation at the last second of the interaction is presented in figure 4. As for the general picture of the interaction it is obvious that the asymmetric destruction occurs with the breaking away of large parts of the ice field. Although the presence of an unstructured mesh made it possible to avoid the propagation of shear stresses over the entire width of the modeled field, there are still small regions consisting of “direct” parallel faces of elements which are the cause of incorrect destruction of ice.

Given all the above, we can conclude that despite the efficiency of computing, the use of a hexagonal mesh does not give acceptable result when modeling the impact of ice on structures with uncoupled elastic matrix of cohesive elements.

Next, consider the prism mesh case. The result of the calculation at the last second of the interaction is presented in the figure 5. This case shows more realistic picture. Spalls and slight hummocking are present. An interesting fact is the periodic formation of “wing” fracture surfaces in an ice field. For example, as can be seen in figure 5 (b), at the beginning of the interaction, the mean (hydrostatic) stresses have increased values in the region of future cracks. With further interaction, the ice fails mainly on these surfaces, then the process repeats figure 5 (c).

Modeling of ice with a prismatic mesh requires significantly longer calculation time than in the case of a hexagonal mesh, but such a mesh allows to take into account the uneven development of cracks in the vertical plane to a good extent.

The last case to consider is a tetrahedral mesh. This case is considered the most expensive in terms of computation cost. This is due to the much larger number of finite elements needed to discretize the model with the same size settings. The calculation was not completed until the end, since at a time point of 4.01 s in the simulation, the time increment became very small, possibly due to strongly deformed elements. As a result, to calculate a model with the same initial conditions using the tetra mesh, almost 6 times more time is required than in the case of prism mesh. The simulation result for time in model equal to 4.01 s is shown in figure 6.

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**Figure 5.** Ice crushing during impact of ice field in case of unstructured hex mesh: a) general view; b) top view; c) side view.

**Figure 6.** Ice crushing during impact of ice field in case of prism mesh: (a) formation of “wing” failure surfaces at time 0.2 s; (b) at time 5 s.
The destruction pattern in this case is quite different from the previous ones. In this case, there are no large chipped pieces as well as cracks propagation deep into the ice field. Figure 7, c shows a hummocking process, which has a much greater degree than in previous cases. This picture clearly corresponds to the real case of destruction, when a gradual and uniform destruction of ice at the contact is realized. The reason for the strong difference between the tetrahedral mesh and the prismatic one can be seen if we analyze the central vertical section of ice field at the beginning of the interaction.

![Figure 7. Ice crushing during impact of ice field in case of tetrahedral mesh: (a) general view; (b) top view; (c) side view.](image)

The qualitative picture of fracture can be estimated by considering the interaction in the central section of the model. This section is presented in figure 7. With the current drift velocity and the diameter of the structure, the type of interaction should correspond to crushing failure mode of the ice field at the contact. Bekker’s monograph [12] describes the process of field destruction in thickness for this mode. In nature, in the upper and lower layers of ice spalls are formed along inclined surfaces, contributing to the concentration of stresses in the central part of the ice field. In case of tetrahedral elements, the pattern of destruction is more consistent with the process described in [12]. At the beginning of interaction (figure 7 (a)) the central part of the ice field has the highest stress values since spalls have occurred in the upper and lower parts. Uneven destruction of the ice field in thickness is clearly visible in the figure 7 (b). The lower part of the ice field is destroyed to a greater extent due to high ice temperatures and, accordingly, low ice strength. Thus, the fracture process in this case is periodic in nature with the formation of inclined fracture surfaces.

![Figure 8. Central vertical section of model during interaction: (a) at 0.05 s; (b) at 0.25 s.](image)

4. Conclusion
In the end of performed investigation the following conclusions can be done:

1. The influence of the shape of finite elements significantly affects the result. The use of hexagonal element shapes showed the worst result. This may be due to the choice of uncoupled matrix of elasticity of finite elements. Since mutually orthogonal deformations are not interconnected with each other, shear fracture occurs in a structured mesh along parallel faces during interaction. The same problem occurs in a hexagonal unstructured mesh in some places. Thus, to use uncoupled elastic
matrix of cohesive elements in such problems, it is necessary that volumetric elements with spatial deformation behavior are on the path of crack growth.

2. The presence of large values of ice load at the beginning of interaction in our opinion is not correct. This may be due to many factors, such as improper contact stiffness in the model, small contact area, or the incorrect principle of a mesh creation in the contact zone. Therefore, additional studies are needed. In the case of a tetrahedral mesh, this pattern is the only one considered that has relatively small load values at the beginning of the interaction.

3. A logical disadvantage of the choice of tetrahedral elements is an increase in the size of the model and, accordingly, the calculation time. However, this shape of finite elements showed the best result from the side of the ice destruction pattern. This case is the only one in which the destruction of the ice field occurs unevenly in thickness along inclined surfaces, which is consistent with experimental observations.

4. The considered method of modeling buoyancy showed mixed results. On the one hand, it requires less computing power, which has a positive effect on the calculation time. On the other hand, due to the lack of viscosity of the environment, there is a not entirely realistic movement of fragments up and down from the theoretical surface of the water.

In future the following studies can be performed:
- the study of mesh size influence;
- comparison of coupled and uncoupled elastic matrices of cohesive elements;
- the use of another method of simulating buoyancy (for example, using the Coupled Eulerian-Lagrangian (CEL) method).
- use of orthotropic plasticity model for volumetric elements and various properties for cohesive elements in tetrahedral mesh in order to model the orthotropy of ice cover;
- selection of energy parameters of the damage evolution law in cohesive elements;
- generation of inhomogeneous ice properties in plan using subroutines to take into account the spatial inhomogeneity of the ice field.

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