Numerical Modeling of the Ice-Conical Structure Interaction Process Using Element Erosion Technique

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Abstract. Nowadays, the Finite Element Analysis method is widely used, including in the field of fracture mechanics, because of the growth of computing power. Numerical modeling of fracture mechanics is a developing method in the Ice-Structure Interaction field. One of the approaches to modeling ice failure is the Finite Element Method with Element Erosion Technique, which is widely used among researchers. However, the question of using a material model that most accurately describes the behavior of ice taking into account its physical and mechanical characteristics remains open. Also, researchers often overlook the question of the strain rate effect on the values of ice load. This article presents the results of numerical modeling of the interaction of level ice with a conical support of offshore structure. The dependencies of the ice load value on the ice velocity are also presented and compared with the results obtained according to regulatory documents.

1. Introduction

The study of the ice-structure interaction using the numerical modeling has become widespread in modern science because of significant increase in power of computers, as well as the evolution of the Finite Element Analysis software systems that allow to reproduce the complex dynamic processes.

One of the main questions in problems of interaction of bodies is a competent mathematical description of fracture mechanism. The Finite Element Method has several basic approaches for modeling materials fracture. The article [1] presents the advantages and disadvantages of the main modeling methods, among which Finite Element Method with Element Erosion Technique (FEM), Discrete Element Method (DEM), Cohesive Element Method (CEM) and Extended Finite Element Method (XFEM) stand out. According to the authors [1], the advantages of the Finite Element Method with Element Erosion Technique are wider use, simplicity in comparison with other methods and also lower requirements in computational power.

The serious work is presented in a study [2] using the standard FEM. In this work, much attention was paid to the choice of constitutive models of the material, which is one of the main issues in solving such problems. However, the dual sets of finite elements that are used in that paper complicate the model and increase the computation time.

An example of using the CEM is a research [3] in which the impact of ice on conical supports was simulated. The results presented in the work showed high convergence with experimental results.

Despite this, the question of a suitable material model that accurately describes the behavior of ice taking into account complex physical and mechanical parameters remains open. The work [4] presents...
a study of the applicability of the material models for modeling the ice failure, but there are no final recommendations on the application of specific model. In addition, there is no comprehensive study of the effect of ice strain rate on ice load values during numerical modeling.

This paper describes the numerical modeling of the interaction of an ice cover field and conical support. The Johnson-Cook plasticity model was used as a constitutive ice model. The study of the ice velocity effect on ice load values is also presented.

2. State of the problem

2.1. Description of the modeling method

In this work numerical simulation was conducted in ANSYS software using the Explicit Dynamic solver, in which the integration uses the method of central differences. In this case acceleration can be expressed as:

\[ a_t = [M] \cdot (F^\text{ext}_t - F^\text{int}_t), \]

where

- \( a_t \) - acceleration vector;
- \([M]\) - the mass matrix;
- \( F^\text{ext}_t \) and \( F^\text{int}_t \), the external resultant force and the internal resultant force, respectively.

Based on the obtained acceleration values \( a_t \), the velocities and displacements are calculated as follows:

\[ \{v_{t+\Delta t/2}\} = \{v_{t-\Delta t/2}\} + \{a_t\} \cdot \Delta t_t, \]

\[ \{u_{t+\Delta t}\} = \{u_{t}\} + \{v_{t+\Delta t/2}\} \cdot \Delta t_t, \]

where \( \Delta t_{t+\Delta t/2} \) and \( \Delta t_{t-\Delta t/2} \) are calculation steps time, which equal to \( 0.5(\Delta t_t + \Delta t_t+\Delta t) \) and \( 0.5(\Delta t_t - \Delta t_t+\Delta t) \) respectively.

There are several methods to describe the material failure. In this article we used the Finite Element Method with Element Erosion Technique, which also was used in leading scientific works [2,5,6] and showed its effectiveness.

2.2. Geometry, loads and boundary conditions

Real ice fields impacting offshore structures can be up to hundreds of thousands of square meters in area, as well as have various shapes that are problematic to reproduce in modeling. The ice field is assumed to be conditionally infinite, and the size of the visible part of the simulated field depends on the characteristic length parameter \( L_c \), m:

\[ L_c = \left(\frac{E \cdot h^3}{12 \rho g (1 - \nu^2)}\right)^{1/4}, \]

where

- \( E \) - the Elastic modulus of ice, which equal to \( 5 \cdot 10^9 \) Pa [7];
- \( h \) - the thickness of ice cover, 1 m;
- \( \rho \) - sea water density, 1025 kg/m\(^3\);
- \( g \) - Earth Gravity acceleration, 9.0866 m/s\(^2\);
- \( \nu \) is the Poisson's ratio, which equal to 0.33 [7].

According Wenjun Lu* et al. [1] the considered area of ice, in which a significant change in the stress-strain state occurs, is limited to a value equal to four characteristic lengths. Based on value of characteristic length \( L_c = 14.97 \) m by formula (4), the depth of the field is taken equal to 60 m, and the length of the field along the front is 120 m. The dimensions of simulated ice field and the conical support are presented in the figure 1.
For the correct determination of model behavior, the following boundary conditions and loads were introduced:
- the ice field is limited by three vertical surfaces from moving along the direction transverse of ice movement (Y-axis), which allows to take into account the conditional infinity of the ice field. Also, a constant speed in the direction of movement along the X-axis, is applied to these surfaces. Thus, it is possible to imagine the inertial component of a conditionally infinite ice field that cannot stop when it interacts with the structure;
- conical support is presented as a rigid body and fixed in space from any movements and rotations;
- initial velocity is applied to the bulk elements of the ice field along the X axis and equal in value to the constant velocity. Thus, it is supposed to consider the inertia of the movement of the finite elements, even if they have lost contact with the rest of the ice;
- to simulate buoyancy, hydrostatic pressure is applied to the lower and lateral faces of the ice field model;
- Standard Earth Gravity is applied to all elements of the model, which equal to 9.0866 m/s².

Boundary conditions and loads are presented in the figure 2.

2.3. Constitutive models of ice
The behavior of the simulated ice depends on the accepted material models available in the ANSYS software library. The Johnson-Cook plasticity model was used to obtained the yield strength and start plastic behavior of ice. A detailed description of the model is presented in article [8]. This model allows considering strains, strain rate, and temperature. These three factors are taken into account by the yield criterion, which can be described as follows:

\[
\bar{\sigma} = \left[ A + B \left( \dot{\varepsilon}^p \right)^n \right] \cdot \left[ 1 + C \ln \left( \frac{\dot{\varepsilon}^p}{\dot{\varepsilon}_0} \right) \right] \cdot \left( 1 - \dot{\theta}^m \right),
\]  

(5)
where \( \varepsilon^{\text{pl}} \) – effective plastic strain; 
\( \dot{\varepsilon}^{\text{pl}} \) and \( \dot{\varepsilon}_0^{\text{pl}} \) – effective and reference plastic strain rate, s\(^{-1}\), respectively; 
\( C \) – strain rate constant, which observed in temperature conditions equal or less then transition temperature of material. This constant was accepted equal to 0.001 according to [4]; 
\( A \) – initial yield stress, MPa; 
\( B \) – hardening constant, MPa; 
\( n \) – hardening exponent; 
\( m \) – thermal softening exponent, which was accepted equal to 1.029 according to [4]; 
\( \theta \) – homologous temperature, which depends on current temperature, melt temperature and transition temperature of material, and determined to the next formula:

\[
\hat{\theta} = \begin{cases} 
(\theta - \theta_{\text{transition}})/(\theta_{\text{melt}} - \theta_{\text{transition}}) & \text{, when } \theta_{\text{transition}} < \theta \leq \theta_{\text{melt}} \\
0 & \text{, when } \theta < \theta_{\text{transition}} \int \\
1 & \text{, when } \theta > \theta_{\text{melt}} 
\end{cases}
\]  

(6)

where \( \theta \) – current temperature of material, °C; 
\( \theta_{\text{transition}} \) – transition temperature, below which there is no dependence of the yield strength on temperature, °C; 
\( \theta_{\text{melt}} \) – melt temperature of material, °C.

The failure of the material occurs when stresses in element nodes reach tensile strength and can be describe as:

\[
P < P_{\text{min}} \cdot (1 - D).
\]  

(7)

where \( P \) – current material pressure (or stress), MPa; 
\( P_{\text{min}} \) – minimal value of material pressure upon reaching which failure occurs, MPa. 
\( D \) – degree of the element failure, which equal to 0 in this work.

In the interaction of level ice fields with conical structures, ice destruction occurs mainly due to the achievement of ultimate tensile stresses in the lower part of the ice. Some authors [6, 7] admit that the ratio of the tensile strength of ice on the compressive strength of ice is equal to 1/3.

The ice field was divided in height into four layers of thickness equal to 0.25 m. For each layer, mechanical characteristics were determined depending on the temperature gradient of ice, which are presented in the table 1.

**Table 1. Mechanical properties of ice.**

| Number of layer, \( i \) | Initial yield stress \( A \), MPa | Hardening constant \( B \), MPa | Thermal softening exponent, \( m \) | Tensile strength, \( P_{\text{min}} \), MPa |
|--------------------------|---------------------------------|-------------------------------|---------------------------------|---------------------------------|
| 1                        | 3.58                            | 0.50                          | 1.000                           | 1.193                           |
| 2                        | 3.16                            | 0.47                          | 1.665                           | 1.053                           |
| 3                        | 2.18                            | 0.34                          | 1.532                           | 0.726                           |
| 4                        | 1.20                            | 0.22                          | 1.913                           | 0.400                           |

3. **Modeling of ice impact on conical support**

Three computational cases were performed for different velocity of the ice field with all other parameters being equal. These cases correspond to 1 m/s, 0.5 m/s and 0.25 m/s. In each case, the simulation time took 6 seconds. The total number of elements and nodes in the model are 29357 and 37497, respectively.

The pattern of the stress-strain state of the model at a velocity of the ice field movement of 1 m/s is shown in the figure 3.

As we can see from the figure 3, the pattern of the failure of the ice field is similar to the real picture of failure observed in real tests. The figure 3 (b) shows the formation of a circular crack at a distance approximately equal to the value of the characteristic length \( L_c \). The propagation of cracks similar in appearance to radial cracks is also visible.
Figure 3. The pattern of the stress-strain state at the 6 second of simulation at 1 m/s ice velocity: (a) general view; (b) bottom view.

However, in the figure 3 (a), an asymmetry of the stress-strain state of ice is observed, which may be a consequence of insufficient optimization of the finite element mesh.

Based on the simulation results, the dependences of ice load on time were obtained for all three design cases. The figure 4 shows a curve of the horizontal and the vertical components of the load at the ice velocity of 1 m/s. The dependences and the obtained values are comparable with the results of the authors [2, 3, 5].

Figure 4. Curves of the horizontal and the vertical components of the load at the ice velocity of 1 m/s.

The maximum ice load values obtained from the simulation were compared with the values determined according to the recommendations of regulatory documents. For comparison, the following were selected: the Russian regulatory document SP 38.13330.2018 [9], the German regulatory document Germanischer Lloyd Oil and Gas GmbH 2005 [10] and the international regulatory document ISO 19906:2010 [11]. The calculations were carried out with the same initial parameters. Comparison of the results obtained is shown in the figure 5 for the horizontal and vertical components of ice load.

The figure 5 shows some of the similarities and differences in the dependences obtained. On the one hand, the load values by the numerical method are quite close to the values of the two regulatory documents SP [9] and GL [10]. On the other hand, the nature of the dependence has a clear difference: the maximum value of the ice load based on the simulation results was obtained at ice velocity equal to 0.5 m/s, but according to regulatory documents, the load increases with increasing ice velocity and has no peak. It is assumed that the obtained dependence can be influenced by some adopted parameters of the mechanical properties of ice, in particular, the strain rate constant $C$ [4].
It should be noted that the results obtained according to ISO [11] do not have a dependence on the ice movement velocity, and give overestimated results, even in comparison with other regulatory documents [9,10], which in this case indicates the incompetence of the method used.

![Figure 5](image.png)

**Figure 5.** Comparison of maximum ice force values obtained by numerical and analytical methods. Solid lines are horizontal force, dotted lines are vertical force.

### 4. Conclusions

According to present results the following conclusions can be drawn:

1. The Johnson-Cook plasticity model used in this work showed the possibility of using it as a constitutive model of ice, however, it requires further study on the expediency of application.

2. The pattern the failure of ice field is similar to that observed in real tests, however, there are some losses associated with the optimization of the finite element mesh. It is assumed that the refinement of mesh in the contact area will change the fracture pattern for the better. Also, a more substantiated approach to accounting for ice buoyancy remains necessary, possibly using the Coupled Eulerian-Lagrangian (CEL) method.

3. Obviously, an increase in the time of interaction of objects is required, at least until ice cutting is observed by the value of the full diameter of the support. But this will inevitably lead to an increase in the calculation time or to the need to increase the computer power.

4. The obtained dependences of the load on time, as well as the maximum values of the ice load, are close to the results of other studies on numerical modeling. Further studies require comparison of the results with experimental data.

5. When comparing the ice load values with the results obtained by the regulatory methods, both similarities and differences were revealed. The range of ice load values is small, but the dependence curves of the ice load on the ice velocity is different. It is assumed that the dependence of the load on the velocity is a special case and may differ when using ice parameters from other sources or experimental data. When solving real engineering problems, it is recommended to carry out additional tests to determine the dependence of the ice load on the movement velocity.

### 5. References

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