Numerical Simulation of Dynamic Ice Forces on Offshore Structures

Jason Blackerby
College of Engineering
University of Florida
PO Box 142304
Gainesville, FL 32614-2304
blaja82@ufl.edu

Mentor: Dr. Wenhua Wu
Dalian University of Technology
Dalian, China 116024

Abstract

In recent decades China’s growth has produced a need for greater oil supplies. Offshore drilling in the Bohai Sea has developed in response to this need. However, this region is subject to annual winter sea ice which can damage offshore structures. Therefore, a numerical simulation was developed using the finite element method to assist in selecting an optimal cone to be fitted to the legs of these structures to alleviate the dynamic forces produced by the moving ice. Simulations were performed examining the relationship between stress on the ice sheet at different contact widths with the cone, at different velocities, and at different cone angles. These simulations were performed using the ANSYS and LS-DYNA software packages. Relationships were then drawn between the stress on the ice sheet and these different parameters.

Introduction

There has been much research conducted in recent decades on the effect of adding cones to the legs of offshore structures to mitigate ice forces. Wessels and Kato provided a review of the state of the art at that time (Wessels 1988). Yue et al. conducted full scale tests which led to the formulation of a simplified ice load function for conical structures (Yue 1998). This work was then followed up with a more complex random ice load function for conical structures (Yue 2003). Määttänen reviewed dynamic ice action and methods to predict dynamic ice loads by numerical simulation (Määttänen 2001). However, none of these projects have addressed the need to determine an optimal cone angle for mitigating ice forces.

In-situ tests of all possible cone sizes and angles under controlled conditions are not possible. Laboratory trials are also not desirable in this instance as they are economically infeasible. Therefore a numerical simulation has been determined to be the favored method by which to determine an optimal cone for mitigating dynamic ice forces on offshore structures.
The Bohai Sea

Located in China’s northeast, the Bohai Sea is the southernmost sea in the northern hemisphere to annually freeze each winter. During a typical winter, ice sheets formed in this region will travel at speeds up to 1m/s. These ice sheets vary in thickness from 10cm to 100cm with the 20cm being the most frequently observed thickness. As this is relatively thin ice, structures in this region are lighter and less rigid than those in Polar Regions. Figure 1 shows a map of the region discussed.

Figure 1. A Map of the Bohai

JZ20-2 Oil Field

The JZ20-2 Oil Field is the site of the four-legged jacket platforms, MUQ and MNW. Originally these platforms were designed to be cylindrical jacket structures. However, after field ice force measurements showed serious vibrations occurring at low ice speed, upward and downward ice-breaking cones, of 60° and 45° respectively, were added to the legs (Yue 1998). The natural period of these structures is approximately one second and at high ice speeds displacement is amplified (Yue 2003). Figure 2 shows a diagram of these platforms and indicates the locations of instruments used to gather field data. Figure 3 is a blown up view of a cone attached to the legs of these platforms along with the load panels that were attached to record ice load data.
Ice Failure Process

Ice forces on a conical structure are less than those on a vertical structure as the failure mode for ice is changed from crushing to bending. Figures 4 and 5 demonstrate this difference. This is due to the flexural strength of ice being lower than the crushing strength. That is, the tension strength and compression strength of ice are not the same. In this paper only tension failure will be considered. A field example of the ice failure by bending is shown in Figure 6. Here the just formed circumferential crack is clearly visible. Figure 7 is a diagram of the ice failure process against a cone showing both radial and circumferential cracks.

Previously, it had been suggested that in the bending failure mode radial cracks appeared first followed by circumferential cracks signaling the peak ice force (Yue 1998). After this, the
broken ice wedges climb and clear the cone. During this time the force reduces nearly to zero until the next contact with the intact ice sheet. However, as will be shown shortly, circumferential cracks may not always form due to insufficient circumferential stress.

Figure 4. Crushing Process of Ice Failure against a Cylinder

Figure 5. Bending Process of Ice Failure against a Cone

Figure 6. Image From Video Footage of Full Scale Field Tests Showing Circumferential Cracking of Ice Against a Cone
Figure 7. Ice Failure Process against a Cone

Model Setup

In order to perform the numerical simulation discussed herein, a standard finite element method software package was employed, ANSYS. LS-DYNA was subsequently used to perform the simulations on the models developed in ANSYS. This combination has been shown to be very successful in the past (Derradj 2005).

The model in question is a simplified version of a single leg of the MUQ platform. In this model only the upper cone is represented. This cone is modeled as a rigid body shell constrained in all degrees of freedom. The bottom and top radii remain constant at 2m and 0.835m respectively though the angle and thus the height vary through the different simulations as will be explained shortly. The ice sheet is modeled as a 20x20x0.3m linear isotropic elastic solid loaded with a $9.8m/s^2$ acceleration in the z direction to simulate gravity. Finally, water was simulated as a 23x22x1m rigid body solid below the ice. The water was constrained in all degrees of freedom at its base. Material properties for these three components can be found in Table 1. Figure 8 shows the simulation pipeline using ANSYS and LS-DYNA. In this model simulation preprocessing began with the selection of the SOLID164 and SHELL163 element types. The ice sheet was discretized to a 100x100x3 element mesh effectively making the element sizes 0.2x0.2x0.1m. Contacts were defined between the ice sheet and the water as well as between the ice sheet and the cone. Simulations were run for 0.1 seconds each with data output every 0.002 seconds. Figure 9 shows a sample of the model set up.

Figures 10 through 13 provide views of the radial and circumferential stresses on both the top and the bottom of the model ice sheet. As the stresses are localized in all four instances it can be assumed the ice sheet used was sufficiently large enough to correctly model a sheet of sea ice. From the negative maximum circumferential force on the top of the ice sheet shown in Figure 12 it can be inferred that the circumferential crack is initiated on the bottom of the ice sheet.
Table 1. Material Properties for Model Components

<table>
<thead>
<tr>
<th></th>
<th>Cone</th>
<th>Ice</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m³)</td>
<td>7850</td>
<td>960</td>
<td>1006</td>
</tr>
<tr>
<td>Young’s Modulus (Pa)</td>
<td>2E11</td>
<td>1E9</td>
<td>2E11</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>0.3</td>
<td>0.27</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Figure 8. The Simulation Process
Figure 9. The Model Setup

Figure 10. Contours of Radial Stress on the Top of the Ice Sheet

Figure 11. Contours of Radial Stress on the Bottom of the Ice Sheet

Figure 12. Contours of Circumferential Stress on the Top of the Ice Sheet

Figure 13. Contours of Circumferential Stress on the Bottom of the Ice Sheet
During trials leading up to the formulation of this model it was determined that there is a lack of good constitutive models for a sea ice material in both ANSYS and LS-DYNA. Therefore, during simulations cracks do not form, but rather must be assumed to have formed when the proper stress values overcome the yield stress. Figure 14 and 15 demonstrate this idea for both radial and circumferential cracks respectively.

![Diagram](image1)

**Figure 14. How a Radial Crack Should Form Once Stress in the Y-Plane Overcomes the Yield Stress of the Ice Sheet**

![Diagram](image2)

**Figure 15. How a Circumferential Crack Should Form Once Stress in the X-Plane Overcomes the Yield Stress of the Ice Sheet**

**Test Cases**

Three series of tests were performed. The first test involved varying the height from the base of the cone at which the ice sheet would strike. In this line of testing the cone angle was held constant at 60 degrees and the initial velocity of the ice sheet was constant at 1m/s for each simulation. Trial simulations were performed at heights of 0.2m, 0.6m, 1.0m, and 1.4m. This test was performed in order to determine whether the contact width between the cone and the ice sheet had a significant effect on ice-cone interaction. Specifically, it was desired to see whether the contact width significantly influenced stress formation in the ice sheet.

The second series of trials involved varying the initial velocity of the ice sheet. In this set the angle of the cone remain fixed at 60 degrees. The ice sheet contacted the cone at a height 1.0m from the cone base (approximately halfway up the cone). Simulations were run with velocities of 0.4m/s, 0.6m/s, 0.8m/s, 1.0m/s, 1.3m/s, 1.6m/s, and 2.0m/s. These simulations were performed to detect whether a relationship existed between velocity and stress formation in the ice sheet and determine the nature of that relationship.
The third and final set of trials consisted of varying the angle of the cone. Here the height of the ice sheet from the base of the cone was once again held constant at 1.0 m. The ice sheet was set to have an initial velocity of 0.6 m/s. The angle of the cone varied from 50° to 70° in increments of 5° for a total of 5 runs. Again, these simulations were performed to establish the effect of cone angle on stress formation in the ice sheet.

**Results and Analysis**

From the data collected during the series of simulations in which only height was varied it can be seen that stress formation in the ice sheet is not sensitive to the contact width with the conical structure. The near horizontal regression lines for both circumferential and radial stresses in Figure 16 demonstrate this. The regression lines for the circumferential and radial stresses are respectively,

\[ y = -7.5025E04 \times x + 1.0563E06 \] (1)

and

\[ y = -1.0000E03 \times x + 1.3258E06 \] (2)

where \( y \) is stress and \( x \) is the height of the ice sheet from the cone base. Data points for this test can be found in Table 2.

![Figure 16. Graph of the Data Points and Accompanying Regression Lines for the Varying Heights Series of Simulations](image)

Figure 16. Graph of the Data Points and Accompanying Regression Lines for the Varying Heights Series of Simulations
The information produced during the varying velocities trials suggests a proportional relationship between the circumferential and radial stresses and the velocity. The data for these simulations can be found in Table 3. The cubic polynomial fits for circumferential stress and the radial stress are respectively,

\begin{equation}
    y = -2.6613E04 \times x^3 - 2.7365E04 \times x^2 + 1.0343E06 \times x + 3.3584E04
\end{equation}

(3) and

\begin{equation}
    y = 1.5741E05 \times x^3 - 7.9207E05 \times x^2 + 1.6938E06 \times x + 1.5982E05
\end{equation}

(4)

where y is stress and x is the velocity of the ice sheet. This data is charted in Figure 17. From this chart it can be seen that the radial stress varies more gradually than does the circumferential stress. As well, it can be seen that for some low velocities the necessary circumferential stress to produce a circumferential crack is not achieved and thus only radial cracks will be observed.

### Table 2. Data Set for the Varying Heights Series of Simulations

<table>
<thead>
<tr>
<th>Height (m)</th>
<th>0.2</th>
<th>0.6</th>
<th>1.0</th>
<th>1.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Circumferential Stress (Pa)</td>
<td>1.033E+06</td>
<td>1.006E+06</td>
<td>1.017E+06</td>
<td>9.293E+05</td>
</tr>
<tr>
<td>Max Radial Stress (Pa)</td>
<td>1.332E+06</td>
<td>1.337E+06</td>
<td>1.282E+06</td>
<td>1.349E+06</td>
</tr>
</tbody>
</table>

Figure 17. Graph of the Data Points and Accompanying Regression Lines for the Varying Velocities Series of Simulations
Table 3. Data Set for the Varying Velocities Series of Simulations

<table>
<thead>
<tr>
<th>Velocity (m/s)</th>
<th>Max Circumferential Stress (Pa)</th>
<th>Max Radial Stress (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>4.451E+05</td>
<td>7.246E+05</td>
</tr>
<tr>
<td>0.6</td>
<td>6.324E+05</td>
<td>9.306E+05</td>
</tr>
<tr>
<td>0.8</td>
<td>8.277E+05</td>
<td>1.072E+06</td>
</tr>
<tr>
<td>1.0</td>
<td>1.016E+06</td>
<td>1.221E+06</td>
</tr>
<tr>
<td>1.3</td>
<td>1.283E+06</td>
<td>1.405E+06</td>
</tr>
<tr>
<td>1.6</td>
<td>1.500E+06</td>
<td>1.465E+06</td>
</tr>
<tr>
<td>2.0</td>
<td>1.782E+06</td>
<td>1.649E+06</td>
</tr>
</tbody>
</table>

In the final series of simulations, the angle of the cone was increased from 50° to 70° in increments of 5°. Data for this series of tests can be found in Table 4. This data along with the cubic polynomial fits can be found in Figure 18. The cubic polynomial fits for circumferential and radial stresses are, respectively, as follows:

\[ y = 3.49676E02 x^3 + 6.2163E04 x^2 - 3.6003E06 x + 6.8444E07 \]  \hspace{1cm} (5)

and

\[ y = 2.1767E02 x^3 - 4.1243E04 x^2 + 2.6333E06 x - 5.5587E07 \]  \hspace{1cm} (6)

where \( y \) is stress and \( x \) is the cone angle. From Figure 18 it can be seen that the circumferential and radial stress both vary proportionally with the increasing angle size up to a point. However, this data would suggest that a critical angle possibly exists around 65° above which the proportionality of the circumferential stress with the increasing angle levels off. As it stands, the data would suggest a cone of angle 65° would be optimal as this angle provides circumferential and radial stresses which are above the yield stress and near enough to one another to ensure both radial and circumferential cracks will be produced.

Table 4. Data Set for the Varying Angles Series of Simulations

<table>
<thead>
<tr>
<th>Angle (°)</th>
<th>50</th>
<th>55</th>
<th>60</th>
<th>65</th>
<th>70</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Circumferential Stress (Pa)</td>
<td>1.215E+05</td>
<td>3.350E+05</td>
<td>6.324E+05</td>
<td>1.077E+06</td>
<td>1.081E+06</td>
</tr>
<tr>
<td>Max Radial Stress (Pa)</td>
<td>1.739E+05</td>
<td>7.097E+05</td>
<td>9.306E+05</td>
<td>1.113E+06</td>
<td>1.307E+06</td>
</tr>
</tbody>
</table>
Future Work

In order to more accurately reflect real world conditions in the simulations a good constitutive model for sea ice must be developed. Finally, a more extensive battery of trials should be run against the model to ensure these results are not isolated incidents.

Conclusions

From the results obtained during the different trials, the following preliminary conclusions may be drawn:

- contact width does not have a significant influence on circumferential or radial stresses
- circumferential and radial stresses increase proportionally with increased velocity
- with increasing velocity, radial stress increases more gradually than circumferential stress
- at low velocities only radial cracks may form
- a 65° cone angle is optimal as radial and circumferential cracks are near equally likely to form as the circumferential and radial stresses are similar at this angle
Acknowledgements

The author would like to thank Professor Yue Qianjin and Professor Wu Wenhua of Dalian University of Technology for their guidance and assistance during this project. Special thanks are given to Mr. Wang Gang for his generous support during this project. Thanks are also expressed to Professor Hung Tao Shen of Clarkson University for arranging of this program. This material is based on work supported by the National Science Foundation under Grant No. OISE-0229657. Any opinions, findings, and conclusions expressed in this material are those of the author and do not necessarily reflect the views of the National Science Foundation.

References


