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Validation of a temperature-gradient-dependent elastic-plastic material model of ice with finite element simulations

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ABSTRACT

A temperature-gradient-dependent elastic-plastic material model of ice is proposed for the numerical study of the influence of temperature-gradient on impact force in ship-iceberg collisions. The model is based on the 'Tsai-Wu'-type yield surface, and an empirical failure criterion is adopted. A series of yield surfaces with different sizes but the same shape are obtained from the linear interpolation of test results to represent the continuous temperature range in an iceberg. Temperature dependence is defined as the change in ice properties due to the temperature gradient as a function of depth of the iceberg. Based on field test data, three types of iceberg temperature profiles are assumed. The ice model is implemented as a user-defined subroutine in the commercial explicit finite element code LS-DYNA. Collisions between a rigid plate and different geometric iceberg shapes are simulated to analyse the influence of iceberg geometry and ice model temperature. The calculated contact area-pressure curves are compared with design laws to further calibrate the proposed ice model. Both a sharp temperature profile and low temperature range can increase the local contact pressure and global contact force as the penetration increases. The simulation results show that the ice model can capture and be used to demonstrate the influence of temperature-gradient on contact force in ship-iceberg collisions.

1. Introduction

As the climate changes in the Arctic, ice coverage and thickness continues to decrease during the summer season. Regular transport through the northeastern and northwestern Arctic Sea has become possible. Moreover, it is estimated that approximately 25% of the world's total new oil and gas reserves may be located in the Arctic (Bergan et al., 2010). These changes will lead to a significant increase in marine and offshore activities in the Arctic region in the coming years. The probability of collisions between icebergs and ships or offshore structures might increase, and severe collisions may lead to oil leakage, causing environmental pollution. Therefore, from the viewpoints of environmental protection and economic demand, research on the crashworthiness and safety of marine and offshore structures under the scenario of iceberg impact must be conducted.

Sea ice is a complex material consisting of solid ice, brine, gas and, depending on the temperature, various types of solid salt (Timco and Weeks, 2010). The mechanical properties of sea ice, such as the failure criterion, compressive strength and flexible strength, depend on many factors, e.g., temperature, porosity, salinity, density, microstructure, loading rate and confinement ratio. Temperature, as a basic thermal-mechanical parameter in the growth of sea ice, significantly influences the physical properties of sea ice. For instance, as the temperature decreases, the density of ice crystals increases and the dislocation mobility decreases. The stiffness of ice increases by approximately 25% as the temperature decreases from near the melting point to zero Kelvin (Schulson and Duval, 2009). Therefore, temperature is an important factor in research on the mechanical properties of sea ice and ship-iceberg collisions.

According to the NORSOK N-004 (2004) code (NORSOK N-004, 2004), when a structure is designed according to the accidental limited state format, the collision between the iceberg and a rigid plate belongs to the strength design, which implies that the structure is capable of crushing the ice with moderate structural deformation. In this strategy, the temperature gradient in the iceberg can be completely reflected in the collision process; therefore, temperature may significantly influence the total contact force in ship-iceberg collisions. In this paper, a temperature-gradient-dependent elastic-perfect-plastic ice model is proposed based on the 'Tsai-Wu' yield surfaces presented by Ahmed A. Derradji (Derradji-Aouat, 2000). These surfaces were fitted from triaxial compressive experiments of icebergs conducted by Gagnon and Gammon (Gagnon R. and Gammon, 1995). The influence of temperature on the ice model is reflected by the different sizes of the Tsai-Wu yield surfaces. Linear interpolation is applied to obtain yield surfaces

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Nomenclature

f	function of the yield surface (MPa^2)
σ	Cauchy stress (MPa)
p	hydrostatic pressure (MPa)
J_2	deviatoric stress tensor (MPa^2)
a_0	first material constant in the yield function (MPa^2)
a_1	second material constant in the yield function (MPa)
a_2	third material constant in the yield function
ε_{eq}^{p}	effective plastic strain
ε_f	failure strain
ε_0	initial failure strain
$p_{cut-off}$	cut-off pressure (MPa)
σ_v	von Mises stress (MPa)
σ_i	normal stress (MPa)
τ_{ij}	shear stress (MPa)

at different temperatures. Three iceberg temperature profiles are assumed. The compressive and tensile behaviour of ice are described separately. The effective plastic strain and pressure-driven failure criterion proposed by Gao Y. et al. (Gao et al., 2015) and Liu Z. et al. (Liu et al., 2011) are used to determine the element failure during the simulation. Then, the ice model is applied in the simulation cases to study the influence of the iceberg's temperature range and temperature profile on the collision process. Based on a spherical iceberg-rigid plate collision, the effects of temperature on the high-pressure zone of simulated area-pressure curves are discussed. In the simulation of collisions between different iceberg shapes and a rigid plate, the influence of temperature on the total contact force and the significance of temperature effects for different iceberg shapes are analysed. The simulation is conducted with the commercial code LS-DYNA 971. The ice model is realized by a user-defined subroutine.

The simulation of compressive ice with failure is under development for decades and many aspects are not understood in full to develop a consistent material model for design loads. In this study, we do not try to develop a consistent material model to simulate such complex behaviours of ice in ice-structure interaction. The temperature-gradient-dependent elastic-plastic material model is limited for iceberg under constant range of strain rates. The focus is study the influence of temperature profiles on impact force. Therefore, the details of failure process are ignored. Iceberg properties given to ice elements are from the experimental results conducted at strain rate around $4 \times 10^{-3}\,s^{-1}$, corresponding to ductile-to-brittle transition strain rate in this study (Schulson and Duval, 2009). At transition strain rate, ice has the strongest strength and is most dangerous to vessels (Michel and Toussaint, 1978). At this relatively high strain rate and short impact time, the visco-plastic effect is considered not strong. The irrecoverable strain is approximately considered behave as plastic model. Once again, this model is trying to capture global response of sea ice instead of all details of ice behaviors. If the model is able to simulate are-pressure curve, it is considered to be sufficiently acceptable for the simulation of contact force. Nevertheless, more accurate model, such as viso-elastic, visco-plastic and crack, should be considered in the future. The temperature-gradient model can be incorporated with these models.

2. Temperature characteristics of iceberg

Temperature of icebergs is not constant and changes significantly from the surface to the core of iceberg (Jones, 2007). In field tests of ship-iceberg or structure-iceberg interactions, there is a limited amount of measured data on the temperature profile of iceberg samples compared with their velocity and approximate mass. This lack of data may be because special equipment, such as a temperature probe, is required to measure the iceberg temperature in the field (Ralph et al., 2008). In 1995, impact tests between icebergs and an engineering structure were conducted on Grappling Island (Timco, 2011). The temperature gradient was quite sharp, from −4°C at a depth of 0.05 m into the ice to −12°C at a depth of 0.5 m into the ice. Larger penetrations led to a larger contact force and pressure with the same iceberg (Ralph et al., 2004). Iceberg impact tests with the icebreaker CCGS Terry Fox were conducted in 2001, and the temperature profile of some iceberg samples were measured (Ralph et al., 2008; Johnston et al., 2008).

One of the most comprehensive reviews of field-testing results is that by Jones (Jones, 2007), in which 27 groups of iceberg temperature data are compared and analysed. Part of these data is shown in Fig. 1, in which the temperature decreases with depth because these data were measured in summer or spring, when the air temperature was higher. However, for 6 groups, temperature increases with depth because it was measured in winter, when the atmospheric temperature was low. Temperature typically decreases rapidly from the surface to a depth of 8 m and remains constant at depths deeper than 8 m. Because low temperature leads to firm ice, which has been observed experimentally, the rapid decrease in temperature means that the strength of ice near the surface increases rapidly with increasing depth.

In ship-iceberg collisions, the contact force may increase rapidly as the penetration increases. This phenomenon was observed in a field test by Ralph et al. (Ralph et al., 2004) and was estimated by Timco (Timco, 2011) based on their field test results. Nevertheless, there are few published references about the influence of using temperature-dependent ice material models in the analysis of contact forces in ship-iceberg interactions.

3. Presentation of a material model of ice

3.1. Description of the yield surface and its temperature dependence

In the simulation of ship-iceberg collisions, the ice model is a significant factor influencing the simulation results and typically depends on experimental results. The results of several triaxial compressive experiments with granular sea ice are compared to analyse the effects of temperature on yield surfaces. The advantages and disadvantages of the 'Tsai-Wu' yield surfaces adopted in this paper are discussed.

Tsai-Wu-type yield function (Riska and Frederking (Riska and Frederking, 1987); Liu Z et al. (Liu et al., 2011); Ahmed A. Derradji (Derradji-Aouat, 2003; Derradji-Aouat, 2000)) and n-type yield function (Timco et al. (Timco and Frederking, 1986; Timco and Frederking, 1984; Timco and Weeks, 2010)) are two types of functions have been used to describe the yield surface of ice. Based on the formula derivation in Appendix I, for isotropic ice, these two yield functions can be transited to each other. Therefore, yield surfaces fitted by these two functions can be compared, as shown in Fig. 2, and the influence of temperature on yield surface can be studied in a wider experimental data.

Iceberg ice can be regarded as granular sea ice (Riska and Frederking, 1987; Liu et al., 2011). Therefore, both types of yield functions can be used to represent the mathematical behaviour of icebergs. Few triaxial experiments on iceberg ice have been reported. Triaxial experiments on other types of granular sea ice (e.g., multi-year floe ice, laboratory-prepared granular ice) can be applied to verify the yield surface of an iceberg and study the influence of temperature on the iceberg's yield surface. The results from triaxial compressive experiments conducted at a strain rate of approximately $10^{-3}\,s^{-1}$ have been presented by several researchers. These results, shown in Fig. 2, are described in p-J_2 space to more easily implement in the FE model. The experimental conditions are listed in Table 1.

From the series of experiments by each researcher, the influence of temperature is notable and coincident. Based on the experiments of Sammonds (Sammonds et al., 1998), Y. Mizuno (Mizuno, 1998), Riska (Riska and Frederking, 1987) and Ahmed A. Derradji (Derradji-Aouat, 2000), the second invariant of the deviatoric stress tensor increases