Cold Regions Science and Technology 118 (2015) 91–104

Contents lists available at ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

Numerical analysis of the bending strength of model-scale ice

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ARTICLE INFO

Article history:
Received 27 October 2014
Received in revised form 4 June 2015
Accepted 9 June 2015
Available online 25 June 2015

Keywords:
Model-scale ice
Bending strength simulation
Temperature gradient
Strength property distribution

ABSTRACT

Performance simulation tools are of high significance for the design and especially the optimization of ships and offshore structures. However, for ice covered waters such tools are hardly available and are either costly as ice model tests or have a limited range of validity, such as semi-empirical formulas. This arises from the complexity of ice as material and insufficient knowledge on its mechanics. This paper presents a numerical analysis for model-scale ice in which material parameters are developed that can represent: tension, compression and in-situ downward bending. Those parameters are incorporated into a material model following the Lemaitre damage law. The developed material characteristics for model-scale ice are intended to support the design process of ships and offshore structures. The key phenomenon joining the deformation processes in bending together with those in compression and tension, proved to be the through thickness dependency of properties. This analysis and development is a continuation of previously presented parameters for compression and tension and is developed in agreement with experimental evidence.

1. Introduction

The simulation of ice-structure and ice-ship interactions became in the past decade of increasing significance. This development is driven by increasing activities in the high North and increasing computational capacities. Ice model tests are still the state of the art method to validate the performance of designs, but time consuming and of significant costs. Therefore ice model tests are not suitable for design optimization, which however needs to be performed to determine economically suitable designs (see von Bock und Polach et al., 2014). Therefore, this paper is a contribution towards the development of a numerical version of the Aalto model ice basin.

1.1. The significance of ice failure in bending

The bending failure of ice is of high significance for ships in ice due to the inclined contact interfaces with the ice (see e.g. Enkvist, 1972; Lindqvist, 1989 or Valanto, 2001). Fig. 1. illustrates the bending failure of level ice after contact with the Finnish icebreaker *Urho*. This is also the reason, why the so called bending strength is often found in semi-empirical resistance formulations such as those of Lindqvist (1989). Fig. 2 illustrates the state of the art theory on ice failure (see Varsta, 1983), where despite bending as main failure mechanism the initial contact causes local compressive failure (crushing). The more vertical the contact area or structure becomes, the more compressive features are included in the failure process. This underlines the importance to represent the failure in bending and compression with the same model. The work in this paper is a further development of von Bock und Polach and Ehlers (2013). In consequence to model in future ice structure interactions the compliance with cantilever beam bending tests is introduced as criterion, to establish the physical connection between tensile and compressive strength properties for horizontal loading and downward bending.

1.2. Beam bending simulation with state of the art model

The beam bending experiments to be reproduced numerically are conducted in the same ice sheet for which in von Bock und Polach and Ehlers (2013) the compressive and tensile material parameters are determined. The initial stress–strain relationship is governed by the elastic strain modulus, E, until yielding occurs, after which the hardening modulus, H, determines the stress–strain relationship for compression, H_c, and tension, H_t. In the *plastic regime* of H the stresses additionally increase by the evolution of damage according to the material model of Lemaitre and Desmorat (2001). The damage based material model of Lemaitre and Desmorat (2001) proved to represent elasto-plastic behavior including softening in tension and compression well (see von Bock und Polach and Ehlers, 2013) and is in consequence also applied on the bending failure. The damage law represents the increasing damage in the inter-granular junctions, which fail once reaching the critical damage value, dc. Fig. 3 reflects the principle stress–strain diagram, with the hardening moduli of less than 2% of

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http://dx.doi.org/10.1016/j.coldregions.2015.06.003

Fig. 1. Bending failure of ice (marked crack) in front of IB Urho.

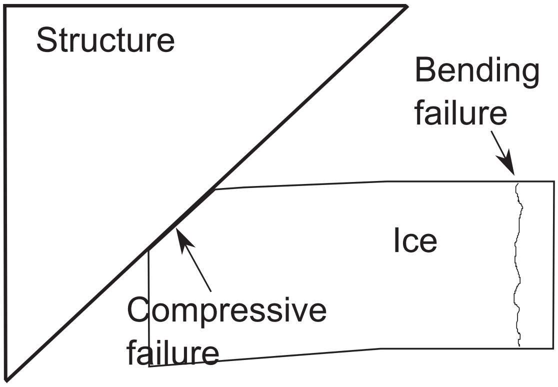

Fig. 2. Inclined structure causing compressive and bending failure of ice.

the elastic-strain modulus. Furthermore, the yield stress is low and not higher than 3% of the ultimate failure stress. More detailed information are found in von Bock und Polach and Ehlers (2013).

The material parameters developed in von Bock und Polach and Ehlers (2013) assume constant material properties throughout the thickness. Furthermore, representative material parameters are determined for each loading case with the help of numerical simulations, with which corresponding force displacement curves are generated. Consequently, those material parameters for tension and compression should suffice to model the beam bending experiment as it was done in Fig. 4. However, the obtained numerical result shows a poor agreement with the experiments with a too weak response stiffness. The result in Fig. 4 shows that the currently available model is not suitable to characterize the mechanical behavior sufficiently.

1.3. Thickness dependency of strength

The hardening modulus, H, is the parameter dominating the stress–strain relationship of the model-scale ice. In the uni-axial horizontal loading cases, as in von Bock und Polach and Ehlers (2013) the through thickness distribution of H cannot be captured, since any distribution satisfying the axial stiffness, S, results in compliance with the experiments. Eq. (1) shows the basic dependency of the stiffness, S, on the cross-sectional area, A, and H as a function of the thickness coordinate z. Fig. 5a illustrates example curves for H, which are all of the same global stiffness and would produce the same force–displacement curve.

$$S = \int H(z)dA \tag{1}$$

Fig. 5b illustrates the principle stress distribution in bending for a constant hardening modulus. The bending stiffness is a function of the *second moment of area* where the distribution of H and the distance of each curve point, H(z), to the neutral axis which is of significance. In consequence, the distributions in Fig. 5a deliver the same axial response, but different bending stiffnesses.

Kerr and Palmer (1972) stated that the through thickness distribution of the elastic strain modulus is of significance for sea ice, which the model of von Bock und Polach and Ehlers (2013) did not account for. Furthermore, based on the suggested property distribution functions of Kerr and Palmer (1972) a four point beam bending experiment of sea ice has successfully been simulated by Ehlers and Kujala (2014). This additionally indicates the significance of the through thickness dependency of the material properties.

The through-thickness dependency of the ice properties is commonly associated with the temperature gradient over thickness. The temperature boundary conditions of the ice are, the ambient air temperature at the top and the basin water temperature at the bottom, which is analogous for sea ice (see Timco and Weeks, 2010).

The exact impact of the temperature gradient on the distribution of the model-ice properties over thickness is not found in literature. Therefore, analogy between model-scale ice and sea ice is assumed. The existence of a property or strength gradient is supported by visual observation in tensile tests, where the upper layers appeared to bear most of the load.

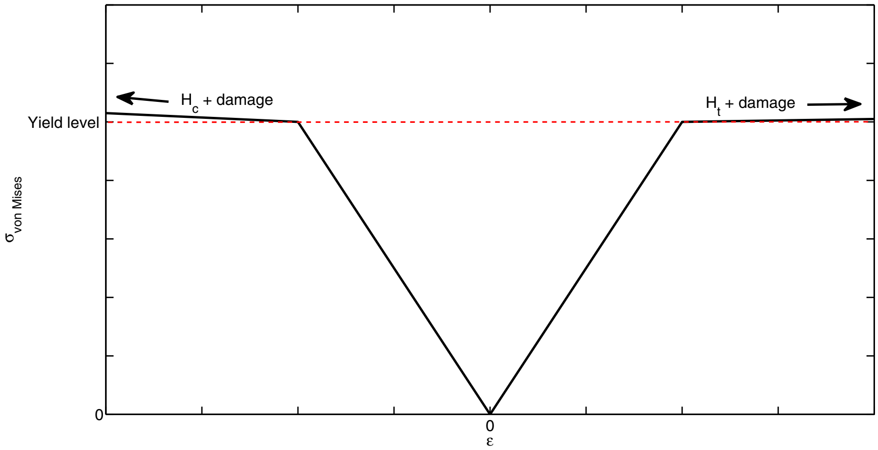

Fig. 3. Principle stress–strain relationship of Aalto model-scale ice defined in von Bock und Polach and Ehlers (2013).