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Breaking Pattern of Semi-infinite Ice Sheets During Bending Failures Against Sloping Structures

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Sloping geometries are often adopted by ice-class vessels or cold region offshore structures at the waterline because of their ability to induce ice sheet bending failures. Therefore, bending failures of semi-infinite ice sheets against sloping structures have been investigated extensively. Recently, interest has grown in real-time simulations of ice–structure interactions because of their application potentials. For such purposes, analytical or semi-analytical models for bending failure events with different ice breaking patterns can be implemented into the real-time simulator for its accuracy and efficiency. Predictions of the ice breaking pattern are thus essential to the accuracy of real-time simulators since different models should be utilized for different breaking patterns. However, most existing theoretical models for semi-infinite ice sheet bending failures against sloping structures focus on the maximum ice load on the structure during the entire loading process, without conclusions on the bending failure processes (i.e., radial-before-circumferential or circumferential-before-radial cracking pattern). In this study, the criterion for breaking pattern determinations is established based on nondimensional formulae. It is found that the breaking pattern transfers from radial-before-circumferential to circumferential-before-radial cracking as the structural waterline width increases and the ice thickness decreases, with the transition point occurring when the structural waterline width is equal to 3.65 times the characteristic length of the ice sheet.

INTRODUCTION

For the design of ice-class vessels or offshore structures in cold regions, sloping and conical geometries are preferred at the waterline because of their ability to induce ice sheet bending failures (Wang et al., 2014). The corresponding ice loads on structures are much lower than those from ice crushing failures against vertical geometries. Sloping geometries are often adopted at the side, stern, and even bow of ice-class vessels (Lu et al., 2014), as well as the waterline of wide offshore structures in cold regions. Thus, extensive investigations on bending failures of semi-infinite ice sheets against sloping structures have been carried out (Croasdale and Cammaert, 1994; Paavilainen et al., 2009; Croasdale et al., 2016; Wang and Poh, 2017).

In recent years, real-time simulations of ice–structure interactions are gaining increasing traction because of their great application potentials in the dynamic positioning of ice-class vessels, designs of offshore structures in cold regions, and crew trainings (Su et al., 2010; Lubbad and Løset, 2011; Berglund, 2012; Daley et al., 2012; Metrikin, 2014). In the process of dynamic positioning of ice-class vessels, ice sheet bending failures against different parts of the vessel (including the stern) occur. Therefore, for the accuracy and efficiency of real-time simulators, analytical or semi-analytical models for the ice sheet bending failures in different loading scenarios with different ice breaking patterns (Fig. 1) can be implemented in the ice breaking module. Additionally, criteria for the determination of ice sheet breaking patterns are thus essential to the accuracy of real-time simulators, since different models should be utilized for different breaking patterns. However, most existing theoretical models for semi-infinite ice sheet bending failures against sloping structures focus on the maximum ice load on the structure during the entire loading process, without conclusions on the bending failure breaking pattern (i.e., radial-before-circumferential or circumferential-before-radial cracking pattern, as shown in Fig. 1). Against this backdrop, this paper focuses on the breaking pattern determination for semi-infinite ice sheet bending failures against sloping structures.

In this paper the criterion for breaking pattern determinations for semi-infinite ice sheet bending failures against sloping structures is established based on nondimensional formulae. The theory of plates on elastic foundations is adopted. For better efficiency, the governing equation is normalized before being solved by the finite element method (FEM). Afterward, the maximum principal stresses, as well as their locations and orientations on the upper and bottom surfaces of the ice sheet, are obtained and compared, facilitating the establishment of the breaking pattern criterion.

PROBLEM DESCRIPTION

In the context of semi-infinite ice sheet bending failures against sloping structures (e.g., the side or stern of ice-class vessels), the complete problem description is given in Fig. 2. Different structural waterline widths W lead to different loading areas, since the width of the loading area is the same as that of the contacting ship part (Figs. 2a and 2b). For a given waterline width of W, the indented length D determines the loading area (Fig. 2c), which can be idealized as being subjected to four force components in the three orthogonal directions. In the loading process, the indented length D increases from zero, meaning no loading, to a certain value inducing the ultimate bending failure of the ice sheet.

As the indented length D increases, the contacting force from local crushing of the ice sheet increases, leading to the evolution of the stress fields on the upper and bottom ice sheet surfaces. On

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