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Out-of-plane failure of an ice floe: Radial-crack-initiation-controlled fracture

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ABSTRACT

Out-of-plane failure of an ice floe has been studied extensively over the past several decades for different application purposes (e.g., an ice cover's bearing capacity for transportation; bending failure of level ice interacting with a sloping structure). Notably, most of the previous studies have idealised the considered ice floe as an infinite or semi-infinite thin plate resting on a Winkler-type elastic foundation. However, a typical ice field in the Arctic is far from continuous. Furthermore, recent Arctic offshore structures have usually been designed with support from ice management; i.e., these sloping structures are most often operating in a broken ice field and are interacting with ice floes of finite sizes. Bearing this loading environment in mind, this paper starts with the question 'What are the physical processes behind the failure of a finite size ice floe interacting with a sloping structure, and what will the failure pattern look like?' Based on an in-depth literature review in relation to out-of-plane failures of infinite and semi-infinite ice floes, depending on the floe sizes, we propose a conservative classification of an ice floe's out-of-plane failures under an edge load, i.e., 1) finite size ice floes that are broken at radial crack initiation and 2) a semi-infinite ice floe that is broken by sequentially forming radial and circumferential cracks. Between these two scenarios, we focused our study on 'radial-crack-initiation-controlled fracture' of a finite size ice floe. Specifically, we are trying to answer the following question: 'how small/large should an ice floe be to be treated as a finite size/semi-infinite ice floe?' Based on a series of assumptions, radial crack initiation and propagation within a square ice floe were theoretically formulated and numerically studied. The respective loads to initiate and propagate a radial crack have been extracted and compared to quantify the required size smaller than which an ice floe would fail at radial crack initiation. For typical ice material properties, it is theoretically illustrated that a nearly square shaped ice floe can fail at crack initiation if its physical size is smaller than approximately $27 \times (\text{ice thickness})^{3/4}$. On the theoretical side, this paper contributes to the derivation of non-dimensional formulae to study radial crack initiation and propagation. Additionally, simplified yet effective numerical models to study radial crack initiation and propagation within an ice floe were proposed and validated. On the practical side, the research methodologies and conclusions presented herein shed light on the possibility of a more economic design for an Arctic offshore structure whose major operating environment is filled with finite size ice floes. In addition, because the 'radial-crack-initiation-controlled fracture' of an ice floe means a much smaller ice load (i.e., compared with continuous circumferential type bending failure within a level ice environment) on a sloping structure, it is recommended, from a mechanically preferred point of view, that floes with sizes smaller than $27 \times (\text{ice thickness})^{3/4}$ should be produced in the downstream of an ice management operation.

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1. Introduction

Out-of-plane failure of an ice floe has been an important research topic for decades. There are two main driving forces/applications behind this research. The first research application focuses on estimating the bearing capacity of ice covers for engineering applications such as transportation on ice roads, landing of air craft on a floating ice cover, and an ice cover serving as a construction platform. (Masterson, 2009). Numerous excellent studies have been conducted within this field. In this research context, the purpose is to use the ice cover and ensure its integrity. An ice cover is usually assumed to be an 'infinite' thin plate on a Winkler-type elastic foundation. Relevant experimental and theoretical studies can be found in early literature reviews (e.g., Ashton, 1986; Kerr, 1976; Langhorne et al., 1999; Michel, 1978; Sodhi, 1995; Squire et al., 1996).

The second research applications are related to the design and operation of sloping structures (e.g., icebreakers, fixed and floating offshore structures) in ice infested waters. This is the main focus of this paper.

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Sloping Arctic offshore structures and the bow of ice breakers are preferred geometric forms in ice-infested waters because such sloping geometries introduce a vertical load component that is exerted on the edge of an ice floe at contact. This vertical load component enables the incoming ice floe to fail in a predominant bending failure mode. Such bending failure mode can be considered a type of out-of-plane failure. Converse to the ice cover's bearing capacity problem, the purpose of the second research application is to understand how much ice load is exerted on the concerned sloping structure, and the purpose is to enable the designed structure to effectively break ice floes.

Comparing the 'ice-sloping structure interaction problem' with the 'ice cover's bearing capacity problem', many similarities regarding the ice floe's failure processes and failure pattern can be observed (Kerr, 1976). In both cases, a two stage fracture of an ice floe was observed and theoretically analysed. The first stage is the so-called radial cracking of the ice floe (i.e., radial cracks emanating from the vertically loaded area); the second stage is the formation of circumferential cracks some distance away from the vertically loaded area. It is generally accepted that the closest circumferential crack's formation corresponds to the maximum ice load on a sloping structure (or to the breakthrough/loss of the bearing capacity of an ice cover). Therefore, it is the circumferential crack's formation that is most studied during ice and sloping structure interactions. As an example, this is also one of the reasons that theories such as a two-dimensional beam on an elastic foundation are widely applied to analyse the failure of an ice sheet interacting with a sloping structure (e.g., Croasdale and Cammaert, 1994; Lu, 2010; Lu et al., 2014; Mayne, 2007; Shkhinek and Uvarova, 2001). Furthermore, for a more advanced three-dimensional theory, in view of the eventual breakthrough of an ice cover involving the formation of circumferential cracks, Nevel (1958, 1961) obtained analytical solutions for the failure of an infinite ice wedge beam on an elastic foundation. The solution then finds application in the calculations of ice breaking loads for various types of sloping structures (Kotras et al., 1983; Lubbad and Løset, 2011; Milano, 1972; Nevel, 1992).

It should be noted that all of the above-mentioned studies assumed that the considered ice floe is either infinite or semi-infinite or in the so-called 'level ice' condition. However, 'level ice' is rather a theoretical simplification. A typical ice field in the Arctic is far from continuous. Furthermore, recent Arctic offshore structures have usually been designed with support from ice management; i.e., these sloping structures are often operating in a broken ice field. Therefore, they are interacting with ice floes with finite size instead of those with infinite boundaries.

What would the failure pattern be like for a finite size ice floe interacting with a sloping structure? Based on previous theoretical studies and experimental observations, this paper attempted to propose a conservative classification of an ice floe's out-of-plane failure pattern depending on its geometric size: 1) finite size ice floes that fail at radial crack initiation and 2) semi-infinite ice floes that fail by sequentially forming radial and circumferential cracks. Focus has been directed towards the theoretical analysis of radial-crack-initiation-controlled fracture of an ice floe with finite size. Although radial-crack-initiation-controlled fracture of an ice floe does not necessarily lead to the critical design load in comparison to continuous failures within a level ice condition, an understanding of such a physical process is of practical importance. For example, 1) pertinent theoretical analysis can help capture a finite size ice floe's correct failure patterns, failure process and failure loads, which is beneficial to achieving a more economic structural design in its dominant operating ice conditions (e.g., if a broken ice field is its most frequently encountered loading environment); and 2) because radial-crack-initiation-controlled failure of an ice floe leads to a largely reduced[1] ice load compared with continuous circumferential cracking, an intuitive suggestion for ice management operation would be to manage the initially large ice floes into smaller sizes such that their prevailing failure patterns (if they fail) are controlled by radial crack initiation.

Driven by the above mentioned potential applications, we idealised the original problem as a finite size ice floe under an edge load.[2] Based on this idealised model, we separately studied radial crack initiation and propagation within an ice floe of varying size. During theoretical studies, the focus has been on deriving non-dimensional formulae such that generalised results can be obtained. Based on the derived formulae, simple but effective numerical models have been established to calculate the corresponding non-dimensional load to initiate and propagate a radial crack. Using the known radial crack initiation and propagation load, we are thus able to set a quantified floe size boundary between those that can be conservatively treated as semi-infinite ice floes and those whose fracture is controlled by radial crack initiation.

By implementing and validating the above briefly described approach, the main objectives of this paper include the following: 1) establishment of a verified methodology to study radial crack initiation and propagation within a finite size ice floe; 2) for typical ice material properties, recommendation of a physical size smaller than which an ice floe would fail at radial crack initiation. In the long term, the developed theories and formulations are to be implemented in a numerical simulator (Lubbad and Løset, 2011) to effectively calculate the global ice load and to test different ice management strategies in an ice field composed of ice floes of varying sizes.

2. Problem description and assumptions

In this paper, we focus on the out-of-plane failure of an ice floe under an edge load. In the context of a sloping structure interacting with an ice floe, the complete problem description is shown in Fig. 1. We consider the initial contact between a sloping structure and an ice floe (Fig. 1❶ and ❷). After isolating the loading area (Fig. 1❸) where a complicated stress state exists, four load components can be expected in three different directions. These are a pair of splitting load components in the Y direction causing the in-plane failure of an ice floe; a load component in the vertical Z direction leading to the out-of-plane failure of an ice floe; and a load component in the X direction increasing the in-plane compressive stress within the ice floe. An ice floe's eventual failure patterns and failure process are jointly affected by all of these load components. However, we neglect the interactions among these load components and study them separately; in other words, we decouple the in-plane and out-of-plane problems. However, it should be cautioned that such a decoupling approach needs further study to quantify its influence. For the current study with this simplified decoupling approach, the ice splitting load F_Y (i.e., the in-plane load pair required to propagate a global splitting crack through an ice floe) has been studied in a separate paper (Lu et al., 2015). In this paper, we focus on the study of F_Z, under which the out-of-plane bending failure of an ice floe is induced. To be more representative of the actual contact between a sloping structure and an ice floe, we assume that this vertical load component is evenly distributed within a half circle, as shown in Fig. 1❹.

In this study, the ice floe is considered to be a thin plate resting on a Winkler-type elastic foundation (Fig. 1❹). As mentioned, out-of-plane bending failure of ice involves two different types of cracks: 1) radial cracks emanating from the loading area and 2) circumferential cracks, which usually correspond to the eventual breakthrough of the ice

[1] For example, for a semi-infinite ice floe, only approximately 60% of the eventual breakthrough load is needed to initiate the first radial crack. Detailed information will be presented in Section 2.1.1 in relation to Eq. (3).

[2] More details of this model will be presented in Sections 2.2 and 3.1.

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