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A large scale simulation of floe-ice fractures and validation against full-scale scenario

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While interacting with a sloping structure, an ice floe may fracture in different patterns. For example, it can be local bending failure or global splitting failure depending on the contact properties, geometry and confinement of the ice floe. Modelling these different fracture patterns as a natural outcome of numerical simulations is rather challenging. This is mainly because the effects of crack propagation, crack branching, multi fracturing modes and eventual fragmentation within a solid material are still questions to be answered by the on-going research in the Computational Mechanic community. In order to simulate the fracturing of ice floes with arbitrary geometries and confinement; and also to simulate the fracturing events at such a large scale yet with sufficient efficiency, we propose a semi-analytical/empirical and semi-numerical approach; but with focus on the global splitting failure mode in this paper. The simulation method is validated against data we collected during the Oden Arctic Technology Research Cruise 2015 (OATRC2015). The data include: 1) camera images based on which we specify the exact geometry of ice floes before and after an impact and fracturing event; 2) IMU data based on which the global dynamic force encountered by the icebreaker is extracted for the impact event. It was found that this method presents reasonably accurate results and realistic fracturing patterns upon given ice floes.

1. Introduction

Fracturing of sea ice is one of the most visually significant events during ice-structure interactions. However, it is rather challenging to numerically simulate all the fracturing events which spans several scales, from local crushing, bending to the global splitting failure. Instead, we can focus on certain types of fractures and give corresponding appropriate treatment. For example, the local crushing has been treated with a plasticity model taking into account its energy dissipative nature without explicitly modelling the cracks (Liu et al., 2011). Modelling the bending failure is not so straightforward in a three-dimensional space. To the authors' knowledge, there exists not a complete set of numerical scheme to model the initiation and propagation of radial cracks; then the formation of circumferential cracks. These two types of cracks are usually studied separately, e.g., Nevel (1965), Lubbad and Løset (2011) proposed analytical solutions towards the radial crack initiation in a semi-infinite plate on a Winkler type foundation; and Lu et al. (2015b) studied the radial crack propagation within a finite square ice plate before circumferential crack's formation. In comparison, more studies were made on the eventual circumferential crack formation since it governs the final bending failure with a priori assumption of existing radial cracks, e.g (Nevel, 1958). In terms of the global splitting failure, it is less treated in literature and engineering practice. However, its importance in nowadays' Arctic marine operation should not be underestimated (Lu et al., 2015a, 2016). In this paper we adopted a numerical scheme based on which the global splitting failure can be modelled taking into account arbitrary geometries and contact scenarios. The basic numerical method is based on the eXtended Finite Element Method (XFEM), which alleviates us from constant re-meshing procedures to capture the near crack tip field variables (e.g., displacement). This allows us to model a stationary/propagating crack with improved

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efficiency and accuracy. The numerical scheme is applied upon one interaction case and is compared against field measurement during the Oden Arctic Technology Research Cruise in the Arctic Ocean during September, 2015 (OATRC2015) (Lubbad et al., 2016). The effectiveness of the adopted numerically scheme to simulate the global splitting failure of an ice floe during ice-structure interaction is demonstrated in this paper.

2. Methods

In the field expedition of OATRC2015, icebreakers Oden and Frej were extensively instrumented with, e.g., camera systems to monitor the ice environment (ice thickness, ice concentration, and floe sizes), an Electro-Magnetic (EM) inductive device to continuously extract ice thickness, and Inertia Motion Units (IMUs) to get the global impact force during ice-structure interactions. These instrumentations provide necessary inputs for numerical setup and outputs for final comparison. Before we dive into the detailed methodology, it is convenient to first setup the floe-ice structure interaction model.

2.1. Interaction model

For floe ice–structure interactions, the assumed basic interaction model is described in Fig. 1. Side views in Fig. 1(a), (b) and (c) described the initial contact between ship hull and the gradually crushing at the ice edge, and eventually the hull-ice contact reached the full ice thickness. During this process, ice fractures at different scales are taking place. Rather small scale fractures are taking place at the crushed zone; relatively larger radial and circumferential cracks are formed due to the dominant vertical force from the sloping structure. Radial cracks are usually formed with relatively small vertical forces and they do not contribute to the final failure of an ice cover (Lu et al., 2015b). As the penetration proceeds to Fig. 1f), the ice cover can either fail continuously in local bending failure (i.e., formation of wedges and cusps) or in a global splitting failure (as depicted in the figure). Once the global splitting failure takes place, it is considered as the final limiting mechanism amongst all the fracture events.

Instead of simulating all these fracture events with one model from the very beginning, we decide to treat them separately with correspondingly appropriate models. For example, the local crushing has been effectively described by plasticity theories (Liu et al., 2011); by an energy based contact model (Daley, 1999); or the specific energy in a crushed volume approach (Kim and Høyland, 2014; Kinnunen et al., 2016). The local bending failure can be treated either with theoretical formulas (Nevel, 1958, 1972) or empirical formulas (Kerr, 1976) (originally from (Panfilov, 1960)). Combining all these approaches, we are thus analysing the floe ice–structure interaction in a semi-analytical/empirical and semi-numerical manner. This paper, however, focuses primarily on the global splitting failure's numerical simulation.

In order to simulate the splitting failure of an ice floe, it is necessary to gain information such as the floe geometry, ice thickness and impact angle as inputs. Afterwards, a numerical scheme based on eXtended Finite Element Method (XFEM) is initiated and output the splitting force history versus splitting crack propagation. In the end, the calculated splitting force is compared with measurements from IMUs. In later sections, the method adopted within each of these steps is described. Particularly, we shall focus on the instrumentations and interaction scenarios on the icebreaker Frej.

2.2. Ice floe geometry extraction

The geometry of an ice floe is extracted from images taken by an 180° camera system that has four lens looking in different directions covering the majority of the area on the port and starboard sides of Frej. Detailed camera system information, installation location and calibration methods onboard Frej can be found in Lu

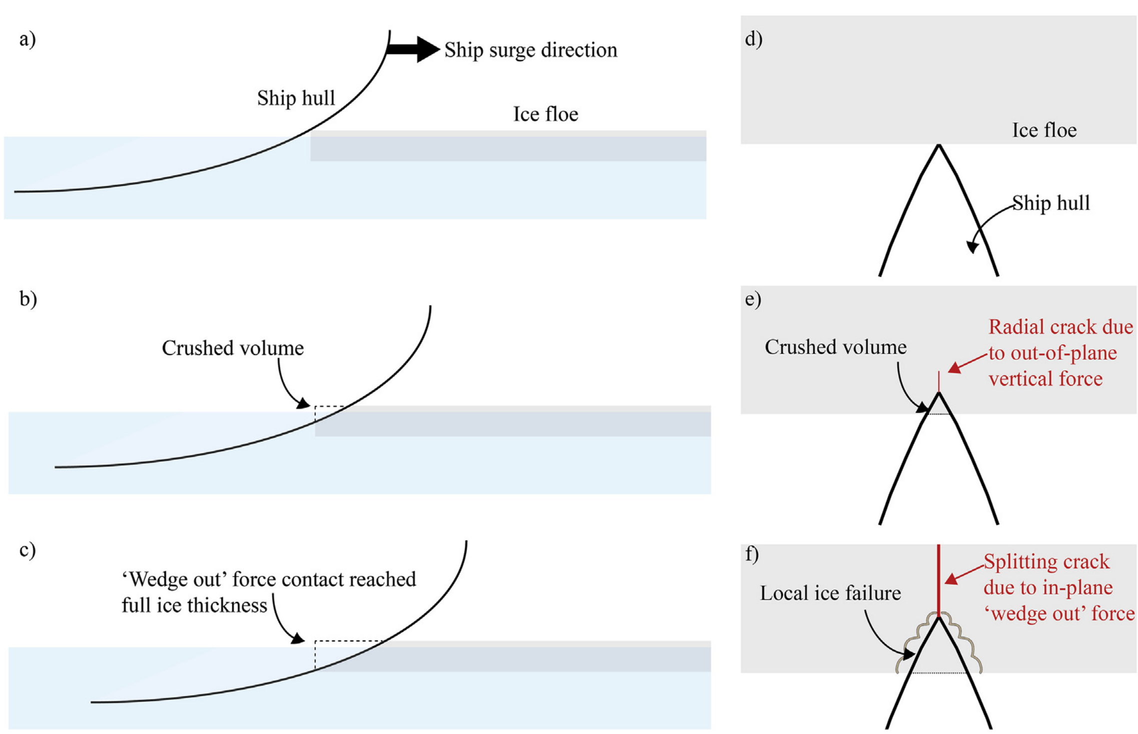

Fig. 1. Floe ice–structure interaction model (left: side view; right: plan view).