Cold Regions Science and Technology 131 (2016) 129–141

Contents lists available at ScienceDirect

Cold Regions Science and Technology

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

Ice-induced vibrations and ice buckling

Hayo Hendrikse *, Andrei Metrikine

Delft University of Technology, P.O. Box 5048, 2600GA Delft, The Netherlands
SAMCoT, Dep. Civil and Transport Engineering, NTNU, NO0-7491 Trondheim, Norway

ARTICLE INFO

Article history:
Received 20 May 2016
Received in revised form 31 August 2016
Accepted 6 September 2016
Available online 9 September 2016

Keywords:
Ice engineering
Ice loads
Ice-induced vibrations
Ice-structure interaction
Ice buckling

ABSTRACT

Ice-induced vibrations can occur when flexible, vertically-sided offshore structures are subject to level ice such that the failure mode of ice is predominantly crushing. When the ice is relatively thin, or when the width of the structure is much larger than the ice thickness, the ice tends to buckle and subsequently fail as soon as the stress caused by the buckling exceeds the bending strength of the ice sheet. This type of failure is referred to in this paper as buckling failure. The buckling failure can limit the global load on the structure but not necessarily prevents the development of ice-induced vibrations. Study of the latter in cases when ice fails by mixed crushing and buckling is of interest for the design of offshore structures as well as for the interpretation of model-scale tests which often show buckling as a consequence of the use of relatively thin ice. In this study a phenomenological approach for ice crushing and a model of a wedge beam on elastic foundation are combined, thereby composing a simplified model which incorporates both crushing and flexural motion of the ice sheet. Typical load signals and a failure mode map generated with the model correspond well with model-scale observations in a qualitative sense. The model predicts that ice-induced vibrations of limited duration can develop as long as the buckling failure does not occur within at least one period of intermittent crushing or frequency lock-in. A specific case is discussed for which buckling failure would be expected to occur, but sustained intermittent crushing is observed instead, illustrating that buckling does not necessarily limit the development and duration of ice-induced vibrations, but even the opposite could happen. The possibility for ice-induced vibrations to develop in the regime of mixed crushing and buckling failure is further discussed focusing on the effects of the boundary conditions, structural shape and structural and ice properties.

1. Introduction

Flexible, vertically-sided offshore structures may experience ice-induced vibrations in level ice conditions for which the ice fails in crushing. Three regimes of ice-induced vibrations are distinguished, defined as intermittent crushing, frequency lock-in, and continuous brittle crushing (ISO19906, 2010). Often, in model-scale as well as full-scale conditions, ice-induced vibrations are limited in duration due to failure of ice in out-of-plane bending (Bjerkås et al., 2013; Ziemer and Evers, 2014). For vertically-sided structures the latter is often a result of buckling of the ice sheet that leads to large out-of-plane deformations. We refer to this type of failure as buckling failure, not to confuse it with bending failure observed when level ice acts on sloping structures or ship hulls.

Combined buckling and crushing of ice against vertically-sided structures occurs when the ice is relatively thin or the aspect ratio, defined as the ratio between structure width and ice thickness, is high (Kärnä and Jochmann, 2003; Timco, 1991). Such conditions may be present during significant part of the lifetime of offshore structures placed in locations where level ice is present. It is therefore of interest to model the scenario in which ice fails by mixed crushing and buckling, and study the possibility for ice-induced vibrations to develop within this scenario.

Existing phenomenological models and approaches for the study of ice-induced vibrations generally consider only crushing to occur (Kärnä et al., 1999; Määttänen, 1999; Sodhi, 1994). As such these models are applicable only to relatively thick ice and small aspect ratios.

In this paper we expand one of the most recent phenomenological models for ice crushing (Hendrikse and Metrikine, 2015) by combining it with a model of a wedge beam on elastic foundation. The resulting model incorporates, in a simplified manner, creep, crushing, and flexural ice behaviour and captures typical trends observed for ice-induced vibrations. The wedge beam approach has been introduced by Kerr (1978) to be a reasonable approximation for the ice buckling problem taking into consideration the radial cracks which form in the ice during its interaction with a structure. Limitations of the wedge beam approach are discussed by Sodhi (1979) in comparison with plate theory. Although the limitations are quite severe, accuracy of the wedge beam model predictions is deemed sufficient for the developed phenomenological model. The

* Corresponding author at: Delft University of Technology, P.O. Box 5048, 2600GA Delft, The Netherlands.
E-mail addresses: H.Hendrikse@tudelft.nl (H. Hendrikse), A.Metrikine@tudelft.nl (A. Metrikine).

http://dx.doi.org/10.1016/j.coldregions.2016.09.009

model introduced in this paper is subsequently applied to study the development of ice-induced vibrations in the regime of mixed crushing and buckling. To the knowledge of the authors, studies on ice-induced vibrations in this regime are not available in the literature.

The paper is structured as follows. Section 2 briefly summarizes observations of and literature on failure modes which can occur when level ice acts on vertically-sided structures; some definitions are also introduced therein. Section 3 presents a description of the developed phenomenological model and the method of definition of input parameters. In Section 4 the model is applied to study action of a sheet of model-ice on a rigid, vertically-sided structure. The obtained results are discussed with reference to model-scale experimental observations. Section 5 presents a study of the development of ice-induced vibrations for a flexible structure in the regime of mixed crushing and buckling. Discussion of the obtained results and main conclusions are collected in Sections 6 and 7.

2. Failure of level ice acting on vertically-sided structures

In this section we present a brief overview of ice failure as observed in model-scale and full-scale and specify some definitions used in this paper. Level ice acting on a vertically-sided structure may fail in multiple ways depending on indentation velocity, aspect ratio, and ice properties (Blanchet et al., 1988; Timco, 1991). In this paper we use the terms creep, crushing failure, and buckling failure as generalized terms each of which combines several deformation and crack formation processes in the ice. In Fig. 1 the different crack formation processes are sketched, indicating which are encompassed by creep, crushing failure, and buckling failure. A failure map indicating the dependence of failure on indentation velocity and aspect ratio based on model-scale data from Timco (1991) is also shown to illustrate the transition between different types of failure. Typical time dependencies of the ice load for the different types of failure can be found in Timco (1987). We now briefly describe creep, crushing failure, buckling failure, and the transition between those.

Creep defines the deformation of ice at low indentation velocities and low aspect ratios, sometimes also referred to as ductile failure. Creep is characterized by full contact between the ice and structure and a uniform pressure at the ice-structure interface. Large creep deformations can develop over long periods of time. In creep the ice load increases gradually over time towards a peak value, after which the load reduces to a steady-state value (Sodhi, 1991). Creep of ice is treated in detail in Ponter et al. (1983) and Schulson and Duval (2009).

Crushing defines the ice deformation and failure at high indentation velocities and low aspect ratios which is characterized by local contacts and quasi-random ice load signals (Jordaan, 2001; Sodhi, 2001). We use the term crushing to define the combined pulverization of ice, formation of spalls and flakes, and formation of radial cracks. Spalls and flakes generally occur for aspect ratios above one, the range of interest for ice-induced vibrations, resulting in a wedge shaped front of the ice when looking from the side. Radial crack formation results in a wedge shaped geometry of the ice in front of the structure when looking from above, but does not necessarily have a measurable effect on the load on the structure (Palmer et al., 1983). Deformation of ice during crushing is mainly elastic at high indentation velocities. At indentation velocities around the transition from creep to crushing 'ductile' deformation, i.e. viscoelastic and/or plastic deformation, contributes to the total deformation, but the ice still fails by fracturing locally.

Buckling is defined as the out-of-plane deformation of the ice sheet resulting in failure as soon as the bending stress caused by the buckling exceeds the bending strength of the ice plate. This mechanism leads to the formation of circumferential cracks in the ice (Michel and Blanchet, 1983) and is referred to in this paper as buckling failure. Buckling failure occurs for high aspect ratios and can develop at both high

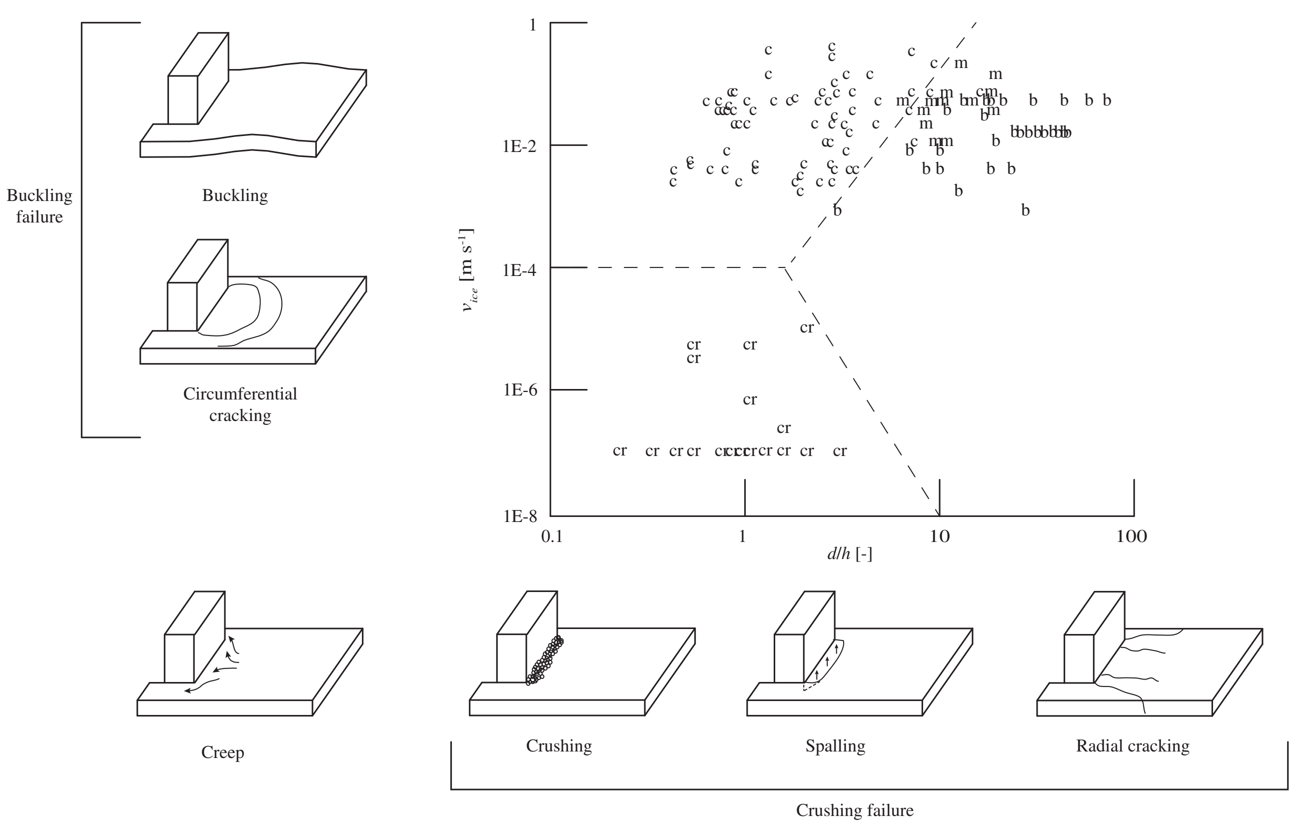

Fig. 1. Failure mode map for model-scale conditions based on the data reported by Timco (1991). Dashed lines indicate transitions between different failure modes. Sketches of distinct types of failure and fracture are shown. Legend: cr – creep, c – crushing failure (crushing, crushing with spalling, and crushing with radial cracking), b – buckling failure, m – mixed crushing and buckling failure.