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Modeling and Validation of Simulation Results of an Ice Beam in Four-Point Bending Using Smoothed Particle Hydrodynamics

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The goal of this article is to investigate the applicability of smoothed particle hydrodynamics (SPH) to simulate four-point bending failure of an ice beam. The possibility of improving the correlation between SPH and analytical results is explored by conducting a parametric study in both 2-D and 3-D, to determine the required formulation, number of particles, and appropriate values of the parameters affecting accuracy. This study was used to validate the method for simulating elastic bending and was extended to model bending failure of an ice beam. The results were subsequently compared with results from four-point bending experiments available in literature.

INTRODUCTION

Ships operating along the Northern Sea Route have garnered a lot of interest over the years, resulting in increased activity in the Arctic and sub-Arctic regions. The vessels operating in such regions are required to progress through level ice. As the ship advances through level ice, the stem of the vessel comes into contact with it and subsequently local crushing is initiated, which continues until the contact zone is sufficient to produce a flexural failure (Valanto et al., 2001). To come up with effective design of such vessels and to operate competently in such adverse conditions, a thorough knowledge and understanding of the material properties of ice, relevant to crushing and bending, is necessary. This will help in providing better ice resistance simulations and eventually better designs for vessels operating in the Arctic area. Furthermore, the flexural strength of ice sheets is critical, as this has a direct bearing on the performance assessment of a vessel operating in such conditions.

Flexural strength can be determined by conducting cantilever and three- or four-point bending tests. Four-point bending tests are more complex, though they can distinguish between shear and bending failure (Ehlers and Kujala, 2013). Kujala et al. (1990) conducted four-point bending experiments in the Gulf of Finland. However, conducting such tests in the harsh Arctic environment is extremely difficult, and the focus has instead been on developing numerical simulations to predict the failure strength of ice. For an accurate numerical simulation, it is essential that the failure model is able to predict the correct stresses and strains at failure and to show good correspondence with the fracture pattern and location found in experiments (Soa, 2011). The results from the four-point bending experiments conducted by Kujala et al. (1990) are applied in this paper in order to compare with SPH simulations for a similar beam.

BACKGROUND

The finite element method (FEM) has been the most widely used numerical tool to model ice in the marine technology field. Varsta (1983) was one of the pioneers in the investigation of ice failure using FEM. He presented a nonlinear dynamic model to predict the bending failure of an ice wedge using the Tsai–Wu criterion (Tsai and Wu, 1971). However, Varsta's model was not thoroughly compared with experimental investigations. Eventually, the prominent study by Derradji-Aouat (2003) accurately captured the complex mechanisms associated with ship–ice interaction, presenting a multisurface failure model for saline ice. The behavior of ice is affected by temperature, strain rate, and loading direction, which were accounted for in the failure criterion by including two parameters, octahedral shear stress and hydrostatic pressure. This multisurface failure model for ice was later implemented in LS-DYNA by Wang et al. (2009). Similar work on the failure of ice was carried out by Kolari et al. (2009), who developed an anisotropic continuum damage mechanics model to capture the failure of ice. Furthermore, a model update technique was applied in order to update and refine the mesh to predict the continuous failure process. Gürtner (2009) presented a numerical and experimental investigation of ice–structure interaction in which a cohesive element model was applied in order to predict the dynamic fracture of ice. Such a model was based on the cohesive zone approach and requires a knowledge of energy release rate of fracture modes. Since such values were not readily available, the energy release rates were derived heuristically to achieve a good agreement with experimental results. Moreover, for ship–iceberg collisions, Liu et al. (2011) implemented a pressure-dependent material model based on the Tsai–Wu failure surface in LS-DYNA.

Generally speaking, the most commonly used approach for failure analysis has been FEM. Some of the common drawbacks that FEM has, relevant to simulating ice failure, are "hourglassing," mesh tangling, and using erosion to predict failure patterns. Over the past few years, the focus has thus shifted to the application of SPH to model ice, which can successfully avoid the pitfalls associated with FEM simulations. As a matter of fact, at present SPH is considered to be one of the best methods to simulate fracture in brittle solids primarily because of its inherent advantage in offering a natural transition from a continuum to a fragmented state (Monaghan, 2005). Anghileri et al. (2005) compared high-velocity hailstone impacts on aircraft structures using FEM, arbitrary Lagrangian Eulerian (ALE), and SPH methods. Therein, Anghileri et al. (2005) concluded that the FEM model was only able to realistically simulate early stages of the phenomenon when the mesh distortion was not very high. Furthermore, the SPH

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