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Experimental study of high-velocity impact and fracture of ice

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ABSTRACT

This paper presents a series of experiments on high-velocity fracture of ice. Two types of experimental results are examined: standard material characterization under compression, and fracture modes observed under high-velocity impact. These fragmentation modes were observed during impact on rigid supports as well as deformable plates. The dynamic fracture phenomena were analyzed using a Cordin ultrafast imaging system. Two types of ice were tested: equiaxed and monocrystalline ice. The results give valuable information both for the understanding of high-velocity ice fracture mechanisms and for the validation of the computation tools.

1. Introduction

Ice impact on structures is a phenomenon which can be encountered in various domains, such as civil engineering (e.g. dams in cold regions), the offshore industry, naval applications or aerospace applications. The first three cases are usually associated with moderate impact velocities and natural ice. Aerospace applications are associated with high strain rates and accretion-type ice. This paper focuses on the study of high-velocity ice impact. In order to do that, one must carry out high-strain-rate characterization of stresses, strains and fracture along with representative impact experiments. The literature on ice behavior in the context of geological and environmental studies is abundant (Jordaan, 2001). An interesting synthesis can be found in Schulson and Duval (2009). In these works, the characterization is associated with very low strain rates. Conversely, the literature concerning high strain rates is scarce. Very interesting results on stress–strain behavior can be found in the works of Schulson et al. (2005), Schulson and Iliescu (2005), Shazly et al. (2006, 2009), Jones (1997), Dutta et al. (2004) and Fasanella et al. (2006). These tests were performed on ice specimens of very different geometries and on equiaxed or columnar monocrystalline ice using dynamic jacks or Hopkinson's bar loading systems. This paper attempts to provide some new information on dynamic compressive stress failure using an ultrafast camera which enables one to observe the ice failure modes during the fracture experiments. It also presents a series of results concerning high-velocity impact on ice or plates and can be compared to the results of Kim and Kedward (2000), Kim et al. (2003) and Kato et al. (1995). These tests are useful for the validation of ice models (Sain and Narasimhan, 2011) as well as numerical tools used for impact simulations (Chuzel et al., 2010). The paper considers two types of natural ice, equiaxed and monocrystalline columnar ice, which can be compared to other results in the literature. This paper is organized as follows:

- Ice types and their fabrication methods.
- Fast compression experiments.
- Impact experiments.

2. Ice types and their fabrication methods

Two types of ice were tested: monocrystalline and polycrystalline ice. Natural ice is generally of the second type and consists of an assembly of monocrystalline grains whose size is usually between 1 and 50 mm. Two main types of polycrystalline ice can be found: equiaxed ice, which is isotropic because of the random orientation of the grains, and columnar ice, whose grains have a preferential orientation. Two other types of ice play an important role in impact on aircraft structures: accretion ice and hail (Fig. 1). Up to now, these are too difficult to produce to make large enough specimens. This is the reason why they will not be considered in this paper.

The specimens were fabricated in five steps.

- Fabrication of rough specimens. Two different processes were used to produce the two types of ice. In both cases, demineralized and deoxygenated water was used. Equiaxed ice was obtained by freezing a mixture of water and crushed ice at

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