Volume expansion vs cryosuction in frost-driven fracture: a look through numerical modeling

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Abstract

Exposing hydrogels to sufficiently low temperatures can cause the liquid imbued within to freeze into ice crystals. Far from innocuous, the presence of these internally growing solid inclusions compromises the hydrogel's structural integrity, ultimately having the potential to trigger fracture. Traditionally, the volume expansion that water undergoes upon freezing has been assumed to be the main culprit behind frost-driven fracture. This classical line of thought hypothesizes that this volume expansion has to be accommodated by the hydrogel's microstructure, hence causing it to stretch and eventually rupture. However, conclusive experimental evidence has showed that frost-driven fracture can also occur in wet solids imbued in liquids that contract upon freezing for instance, thus ruling out this physical process as the sole cause. Instead, another physical mechanism has recently arisen as a contender for causing frost-driven fracture: cryosuction. This concept stands for the migration of liquid water towards the ice front driven by a reduction of the liquid pressure therein. As such, cryosuction can potentially play a dual role in frost-driven fracture: (i) leading to cracking by desiccation, and (ii) allowing ice to build up within the internal crevices for as long as the supply of supercooled water holds. In this context, the present work leverages numerical models inspired by experimental evidence to weigh the contribution of these two mechanisms to the occurrence of frost-driven fracture in hydrogels. This is done through two different approaches. Firstly, a simplified hyper-elastic numerical model is used to assess the difference between the actual freezing experiments and the hydrogel deformation merely due to the experimentally documented presence of ice, hence providing an indirect quantification of the actual cryosuction-induced hydrogel desiccation around the ice-filled crack tip. Secondly, a hygro-mechanical numerical model of the hydrogel is set up to preliminarily describe the migration of water towards the ice-filled crack as it grows in time at different speeds. As in the previous model, the crack shape is directly extracted from the experimental observations, while the liquid pressure drop at the crack lips is derived from the ice-water thermodynamic equilibrium. This model provides detailed insights into how cryosuction draws water from the bulk as the ice-filled crack grows, and it helps interpret the experimentally observed size-dependency of the desiccation-affected region near the ice-filled cracks.

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