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Size effect on fracture toughness of snow

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Abstract

Depending on the scale of observation, many engineered and natural materials show different mechanical behaviour. Thus, size effect theories, based on a multiscale approach, analyse the intrinsic (due to microstructural constraints, e.g., grain size) and extrinsic effects (caused by dimensional constraints), in order to improve the knowledge in materials science and applied mechanics. Nevertheless, several problems regarding Solid Mechanics and Materials Science cannot be solved by conventional approaches, because of the complexity and uncertainty of materials proprieties, especially at different scales.
For this reason, a simple model, capable of predicting a fracture toughness at different scale, has been developed and presented in this paper. This model is based on the Golden Ratio, which was firstly defined by Euclide as: "A straight line is said to have been cut in extreme and mean ratio when, as the whole line is to the greater segment, so is the greater to the less". Intimately interconnected with the Fibonacci sequence (1, 2, 3, 5, 8, 13, …), this number controls growth in Nature and recurs in many disciplines, such as art, architecture, design, medicine, etc.., and for man-made and natural brittle materials, the Golden Ratio permits to define the relationship between the average crack spacing and the thickness of quasi-brittle materials. In these cases, the theoretical results provided by the Golden Ratio, used to calibrate a size-effect law of fracture toughness, are in accordance with the experimental measurements taken in several test campaigns carried on different materials (i.e., rocks, ice, and concrete).
This paper presents the case of fracture toughness of snow, in which the irrational number 1.61803 recurs when the geometrical dimensions vary. This aspect is confirmed by the results of experimental campaigns performed on snow samples. Thus, we reveals the existence of the size-effect law of fracture toughness of snow and we argue that the centrality of the Golden Ratio in the fracture properties of quasi-brittle materials. Consequently, by means of the proposed model, the K_{IC} of large samples can be simply and rapidly predicted, without knowing the material performances but by testing prototypes of the lower dimensions.

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Keywords: Snow Properties; Fracture Toughness; Size Effect; Golden Scaling Law.

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1. Introduction

For most man-made materials, like concrete and metals, it is well known that failure originates from microscale damage and propagates to larger scales (Chiaia and Frigo, 2009). This is true also for natural materials like snow, since the imperfections in the snowpack play a leading role in snow avalanche release. The avalanche formation was analyzed by several and different approaches, i.e.,: stability index (Föhn, 1987); failure criteria (stress (McClung, 1979) and coupled stress-energy ones (Chiaia et al., 2008)); strain-rate (Bader and Salm, 1990) and fracture mechanics approaches (McClung, 1981); collapse theories (Heieli and Zaiser, 2008), and damage mechanics ones (Chiaia and Frigo, 2009). It is the clear evidence that fracturing is the most fundamental mechanisms on the release processes of avalanche formation: from damage process in the snowpack to the failure at the interface of two different snow layers (MODE II), to the following crown fracture in tension (MODE I), leading to dry snow slab avalanche.

Accordingly, much of the focus in Snow Mechanics and Snow Engineering, it is now to improve the knowledge on the fracture properties of snow, in which the referring mechanical property has always individuated in the fracture toughness or the stress intensity factor (McClung, 1981). But, the measurement of fracture proprieties presents many complications due to complexity of both the behavior of the snow - material (difficulties in the repeatability of the material and to maintain constant its properties during the tests) and to perform tests in laboratory and full-scale (for logistical, instrumental and extreme weather conditions reasons). Due to this, only a few data on fracture toughness of snow are still available (Kirchner et al., 2000; Kirchner et al., 2002a,b; Faillettaz et al., 2002; and Schweizer et al., 2004). In all previous studies, cantilever beam tests were used to determine fracture toughness applying the linear elastic fracture mechanics (LEFM) theory, varying the snow type and density. In 2004, arguing that the standard size requirements for LEFM were not fulfilled for the used snow specimens, Schweizer introduced the discussion on size effect pointing out the application of the test results to snow slope models (Schweizer et al., 2004). Related to avalanche release process, always in the framework of LEFM, Bažant et al. (2003) formulated a size effect law of fracture toughness in shear. These authors highlight how this propriety is strongly variable with the scale, showing an increase of the stress intensity factor of snow with increasing sample size. However, this behavior is in contradiction with most of the scaling laws, which identify a decreasing trend of the observed characteristic with an increase of the observation scale. A well-known example is the behavior of the ultimate tensile strength of concrete. Its decrease that increases with the size of the structure has been confirmed by experimental measurements.

Anyhow, it is known that the variation of the nominal values of some quantities does not follow the decreasing performance rules of a solid with respect to the considered scale. An intuitive example is the size effect of the embrittlement increasing of the structural response with increasing sample size, already highlighted by Galileo Galilei in the "Discorsi e dimostrazioni matematiche a due nuove scienze attenenti alla mecanica & i movimenti locali" (1638).

The contrast is present just on Mechanics of Materials, considering the fracturing phenomenon where a variation of nominal values of some quantities follows the growth rule of performance with the considered scale.

Restricting the analysis to the materials with a brittle and quasi-brittle behavior (e.g., the snow), a significant examples are the fracture toughness and the fracture energy of ice (Frigo et al, submitted), rocks and concrete (Chiaia et al., 2013; Fantilli et al., 2014) that show this "contradictory" behavior.

Following the evidence in concrete (Fantilli and Chiaia, 2013), Fantilli et al. (2015 and 2016) analyze the crack pattern of brittle and quasi-brittle man-made composites (e.g., basic, reinforced and fiber-reinforced concrete elements), compared to natural ones (e.g., rocks). In both cases, the cracking phenomenon of brittle layers depends on the scale of observation and it is driven by a unique size-effect relationship ruled by the Golden Section number. Herein, a Golden Scaling Law is introduced and used to predict the crack pattern (i.e. the crack spacing) of concrete and rock structures at different scales referred to a reference scale.

The observation that crack pattern phenomena are basically driving by two mechanical proprieties, the fracture energy and the friction, leads to authors to investigate and demonstrate the relevance of the Golden Scaling Law also for the fracture properties of concrete, rock and ice subjected to a scaling effects (Chiaia et al., 2013; Fantilli et al., 2014, Frigo et al., submitted).

This paper reports the evidence of the Golden Scaling Law also in the framework of snow mechanics in accordance with the experimental measurements taken in several laboratory campaigns (Sigrist et al., 2005) carried on different scale.