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Monitoring and evaluating the failure behavior of ice structure using the acoustic emission technique

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ABSTRACT

In this study, damage properties of ice structures were analyzed using acoustic emission (AE) signals. Furthermore, AE characteristic parameters were obtained under uniaxial compression and three-point bending tests of ice specimens. Characteristic AE parameters including b-value and correlogram with RA-AF analysis were carried out. Parametric correlation analysis was used for illustrate the feasibility of using AE technique to monitor ice structure. The damage process and failure mechanism were discussed based on the AE signal characteristics that were measured during ice deformation process. Fracture modes can be differentiated by the relationship between the ratio of the rise time to the waveform amplitude and average frequency analysis under compression and bending failure. The proposed approach was capable of identifying an initial yielding and critical information of ice failure mechanism.

1. Introduction

Acoustic emission (AE) is an established technique for nondestructive and real-time monitoring of damage processes occurring within many materials. The AE system can detect released elastic waves via a transducer that is attached to the surface of the structure (Yuyama et al., 2007; Ding et al., 2010). AE, as a dynamic, real-time, and nondestructive passive monitoring technology, can accurately reflect internal changes and display the damage state of materials or components (Philippidis and Assimakopoulou, 2008). Given its unique advantages, AE technology has been widely used in many engineering fields, such as aerospace engineering, materials engineering, civil engineering, and mechanical equipment fault diagnosis (Couturier and Mba, 2008; Ziehl, 2008; Wu et al., 2007).

In high latitudes or cold areas, ice has been widely used as an effective and economical construction material. In 1983, the world's longest "Ice Highway" was built in Canada, which was used to transport materials to many mines in Northern Canada (Masterson, 2009). China used a "Reinforced Ice Bridge" in the Fuyuan Delta Emergency Project in Heilongjiang Province (Xie et al., 2011). However, similar to concrete, rock, and other brittle materials, ice is strong in compression but weak in tension, and ice strength is highly affected by temperature; when overloaded or temperature rises, ice is prone to brittle failure (Masterson, 2009). Therefore, when using an ice structure, imperative practices include fully recognizing the potential risks of ice structure and taking effective measures to continuously monitor the damage state as well as establish a good early warning mechanism. Roy, Sinha and Zhou (Roy et al., 1998; Sinha et al., 2012; Zhou et al., 2010) studied the real-time monitoring for ice structures or components. However, the layout of these monitoring methods was complicated, especially when it was used to dynamically monitor the ice structure damage mechanism and failure modes. Developing a new method to monitor the damage process in ice structures is necessary.

As a dynamic and non-destructive testing method, AE has been widely used in structural monitoring of concrete materials (Mainali et al., 2015; Wang et al., 2012). Weiss and Grasso (1997) studied the creep deformation of single crystals ice under compression and torsion creep using AE measurements and concluded that the creep of ice single crystals is in a marginally stable state rather than in a steady-stable state. Cole and Dempsey (2004) conducted in situ experiments to investigate the fracture behavior of edge-notched, square plate ice specimens under different cyclic-loading frequency using AE technique. Duca et al. (2014) studied the feasibility of ice segregation location by AE detection. Reiweger et al. (2015) studied damage detection and location in snow.

In this paper, the ice structures were detected under uniaxial compression and three-point bending tests using AE technique. Some

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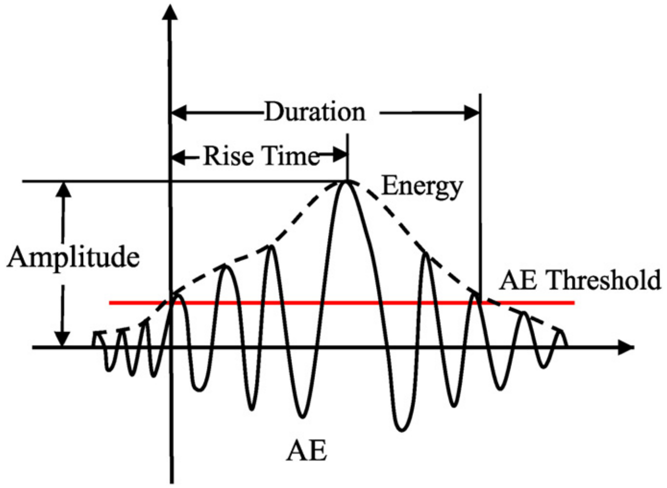

Fig. 1. Typical AE signal.

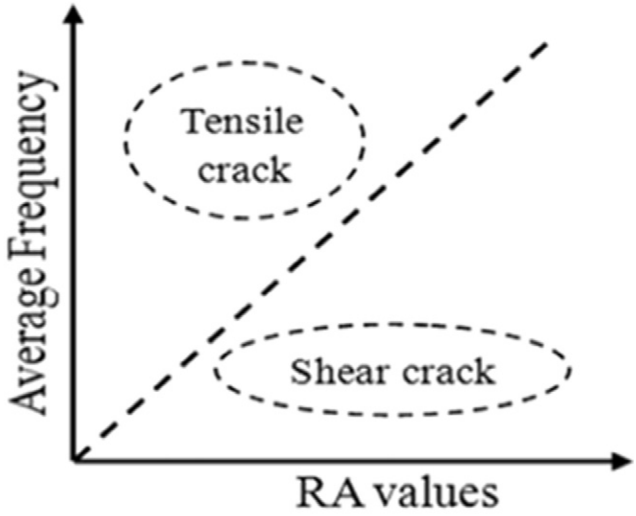

Fig. 2. Crack classification.

representative characteristic parameter, such as accumulated energy, peak frequency, RA and AF values, and b-value, were extracted to verify the feasibility of using AE technique to monitor ice structure, explain the fracture mode and failure mechanism of ice structure.

2. AE signal analysis method

The micro-motion of tip crack excites elastic waves that are acquired by sensors attached to the surface of materials or components. The number of recorded signals during the loading process is proportional to the number of active sources within the material. Additionally, AE signals depend on their sources, specifically the intensity and the mode of fracture. Therefore, AE characteristic parameters can be extracted to analyze failure mechanisms of materials or components (Carpinteri et al., 2013).

Fig. 1 provides the profile of a typical AE signal. Typical AE characteristic parameters included amplitude, rise time, duration, ring counts, energy, and frequency. Ridge and Ziehl (2006) thoroughly described these parameters. For AE evaluation, the physical significance of using various AE parameters can be easily interpreted. The cumulative AE event is connected to the density of cracks, and AE energy is quantified by the intensity of cracks. AE amplitude, duration, and rise time can be used for describe the AE activeness and carry certain information about the crack mode. AE frequency distribution is commonly used for discriminate different damage types in concrete and composite structure.

To evaluate the ice structure failure progression, amplitude distribution of the AE events was analyzed. The b-value is obtained by frequency–magnitude distribution data via the Gutenberg–Richter relationship; this relationship is generally used in seismic waves generated by earthquakes (Farhidzadeh et al., 2013). Material brittle fracture generates an elastic wave, which is similar to seismic waves. Hence, b-values can be widely used in AE detection. Furthermore, Datt et al. (2015) introduced the temporal variation of b-value to estimate the damage degree of snow, and showed that maximum likelihood estimate (MLE) could be a robust approach to obtain an accurate b-value. The b-value for AE technique can be modified as follows:

$$b = \frac{20 * \log_{10} e}{\langle A \rangle - A_{\min}} \tag{1}$$

where $\langle A \rangle$ is the arithmetic mean amplitude and A_{min} is the threshold magnitude.

Early research (Soulioti et al., 2009a) indicated that a relationship exist between the fracture and variation trend of b-value. By contrast, the b-value increases as microcracks begin to form. When macrocracks develop, the b-value decreases. Numerous scientists had used this relationship to monitor the progressive failure of geologic materials, such as rock, concrete, and fiberglass (Hirata et al., 1987; Rao and Lakshmi, 2005).

In addition, based on the Japanese building code (Federation of Construction Materials Industries, 2003), RA and AF has been widely used for identify the type of crack based on their relationship (Aggelis, 2011; Shahidan et al., 2013; Soulioti et al., 2009b). Definition of the two parameters was presented in the following equations:

$$\mathrm{RA} = \text{rise time}/\text{amplitude} \tag{2}$$

$$\mathrm{AF} = \text{counts}/\text{duration} \tag{3}$$

When fracture propagation occurs, some possible failure modes (tensile crack, shear crack, and mixed crack) appear. A tensile cracking incident excites longitudinal waves that carry enormous energy; therefore, most of the energy arrives in the initial part of the acquired waveform because longitudinal waves are the fastest type; they also induce

Table 1
Comparison of both compression test and bending test results.

Compression specimens	Channel number	Load/kN	AE events	Bending specimens	Channel number	Load/kN	AE events
C1	1	48.5	595	B1	1	2.3	282
	2		622		2		270
C2	1	52.5	553	B2	1	2.6	263
	2		532		2		254
C3	1	47.0	638	B3	1	2.4	285
	2		652		2		303