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Scaling of quasi-brittle fracture: Boundary and size effect

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Abstract

A boundary effect model recently developed for scaling of quasi-brittle fracture is used to study the common size effect on strength and fracture toughness of finite-sized specimens. An equivalent crack length is adopted following the boundary effect model and used to measure the distance of a crack tip to the front and back specimen boundaries. This equivalent crack leads to a simplified asymptotic solution for finite-sized specimens akin to that for a large plate with a small edge crack. The two common failure criteria, the strength and the linear elastic fracture mechanics (LEFM) K_{IC} criteria, are taken as two asymptotic limits. The transition from the strength to toughness criterion is then given by the asymptotic solution. The recent asymptotic model for finite-sized specimens/structures is applied to geometrically similar specimens of a fixed α-ratio, and specimens of identical size, but different α-ratios.

Keywords: Boundary effect; Size effect; Quasi-brittle fracture; Fracture toughness; Strength; Fracture process zone

1. Introduction

It is known that fracture properties of brittle–matrix composites such as concrete, coarse-grained ceramics and fibre-reinforced composites are commonly specimen-size and crack-size dependent. These phenomena exist due to the fact that there is a relatively large crack-tip damage zone or fracture process zone (FPZ) in comparison with the specimen size, which can be measured by the specimen width, thickness and height, or the initial crack length or un-cracked ligament (Dowling, 1999; Hu and Wittmann, 1992, 2000; Hu, 1990, 1997, 1998, 2002; Hu and Duan, 2002; Duan and Hu, 2002, 2004a,b; Duan et al., 2001, 2002, 2003b,c,d, 2004b). It is well understood that the linear elastic fracture mechanics (LEFM) does not apply if the crack-tip FPZ is not small in comparison with the specimen/structure size. However, measurements of non-LEFM properties, or the size-dependent fracture properties of these quasi-brittle materials have very important practical

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implications as most composite designs and their structure sizes are determined by their needs in applications rather than by their compliance with LEFM. Therefore, a good understanding of the size effect is crucial to many composite and structure designs and analyses.

The non-LEFM fracture properties of different materials can exist in various ways. For instance, it has been shown that fracture of concrete is size dependent, fracture of ceramics is grain-size dependent, metals can fracture almost completely elastically or plastically, or experience elastic and plastic failure (Kaplan, 1961; Walsh, 1972; Higgins and Bailey, 1976; Rice, 1977; Nallathambi et al., 1984, 1985; Dowling, 1999). Furthermore, fracture of thin ceramic coatings, and polymer adhesive joints can be thickness dependent (Bascom and Cottingham, 1976; Kinloch and Shaw, 1981; Hunston et al., 1984; Daghyani et al., 1995a,b; Yan et al., 2001a,b; Duan et al., 2003a, 2004a). These apparently different fracture phenomena have already been studied extensively, but unfortunately often separately and with little cross-reference of relevant work in different fields of materials science and engineering. Among these non-LEFM properties, the most well studied and understood phenomenon is the elastic and plastic fracture and large scale yielding of metals, and the most troublesome and well-published phenomenon is probably the size effect of concrete. Therefore, we chose the ''size effect'' of concrete as the main focus of the present paper, and use the elastic/plastic failure analysis of metals as the foundation for the size effect study. It is expected that through the proposed study we will be able to explain why those non-LEFM properties such as size effect and elastic/plastic fracture exist, and why the recently proposed boundary effect model can be used to identify the primary cause for various non-LEFM fracture phenomena.

Experimental data of the size effect on concrete fracture are abundant in the literature. Naturally, various analytical models have been developed to explain those experimental findings and to provide theoretical bases for design applications of fracture mechanics. Among those theoretical models, one of the most commonly known approaches is the size effect law (SEL) proposed by Bažant (1984) and Bažant and Pfeiffer (1987). Like the SEL, most of those size-effect models for concrete fracture deal exclusively with geometrically similar specimens. Other size effect models include the multi-fractal scaling law (MFSL) proposed by Carpinteri and Chiaia (1995, 1996) and Carpinteri et al. (1995), the size-effect model for ''large'' 3-point-bending specimens by Karihaloo (1999) and size-effect models for un-notched specimens by Kim et al. (1989) and Bažant and Li (1996). All the size models are able to characterise effectively the transition of concrete failure from the maximum tensile strength criterion to the LEFM criterion for geometrically similar specimens because each model has at least two experimental parameters that can be adjusted to fit the experimental results. It should also be mentioned that the size effect models emphasise the influence of the physical size of a test sample, and therefore, is confined to geometrically similar specimens. The crack length or ligament dependence of the fracture properties is not emphasised in these models although such behaviour is known to be another form of the size effect for concrete fracture (e.g. Higgins and Bailey, 1976; Nallathambi et al., 1984, 1985; Wittmann et al., 1990; Hu, 1998; Hu and Wittmann, 1992, 2000; Hu and Duan, 2002; Duan and Hu, 2002, 2004a,b; Duan et al., 2001, 2002, 2003b,d, 2004b).

An asymptotic model for fracture of a large plate with an edge crack (Hu, 1998; Hu and Wittmann, 2000; Duan et al., 2003d) and a local fracture energy concept (Hu and Wittmann, 1992; Duan et al., 2001, 2002, 2003b,c, 2004b) have been developed to cover the crack length or ligament dependence of concrete fracture. Different to those aforementioned size-effect models, the models proposed by Hu and his colleagues believe the physical size of a specimen or structure itself is not the most fundamental measurement although the size variation of geometrically similar specimens can indeed lead to the commonly observed ''size effect''. For instance, a large specimen or plate with a crack tip away from all boundaries will follow LEFM and shows no ''size effect'' or crack length or ligament dependence in its fracture behaviour. However, the same large plate will show the crack length or ligament dependence in