ASYMPTOTIC ANALYSIS OF BOUNDARY EFFECTS ON FRACTURE PROPERTIES OF QUASI-BRITTLE MATERIALS

Kai Duan[1], Xiaozhi Hu[1] and Folker H. Wittmann[2]

[1]School of Mechanical Engineering, University of Western Australia
35 Stirling Highway, Crawley, WA 6009, Australia

[2]Qingdao Institute of Architecture and Engineering, Centre for Durability, Maintenance, and Repair
Qingdao, P.R. China

Composite materials such as concrete and ceramics with coarse material microstructures exhibit size-dependent fracture properties when the size of damage zone or fracture process zone (FPZ) around a crack tip is comparable to the structural or specimen size. These materials do not comply with the linear elastic fracture mechanics (LEFM), and therefore, are referred to as quasi-brittle materials. This size-dependence of fracture behaviour has been attributed to the interactions between the crack tip, fracture process zone and specimen boundaries [1,2]. It was pointed out recently that when a crack tip is close to a free boundary or a bimaterial interface, the stress/strain fields around the crack tip and associated damage zone will interact with the boundary, and the fracture behaviour of the structure is changed [1-5]. Therefore, the size effect in fracture of quasi-brittle materials is in fact, due to the influence of specimen boundaries and/or bimaterial interfaces. This means that the size effect is a boundary effect in reality.

In our previous studies, two boundary effect models have been developed to characterise the interactions between an advancing crack, the associated FPZ and specimen boundaries. Firstly, an asymptotic approach was proposed to approximate the strength behaviour of a large plate with an edge crack [1,2]. The asymptotic solution includes a reference crack length a^*_∞ to account for the influence of the front boundary on fracture strength. The asymptotic solution has later been further developed to describe the fracture properties of specimens with limited sizes, where both the front and back boundaries of a specimen influence the fracture properties [3]. The second approach is based on the local fracture energy concept [6,7] and uses a bilinear function to approximate the local fracture energy distribution along the ligament [4]. In the bilinear function, a transition ligament a_l^* is introduced to characterise the effects of specimen back boundary on the fracture energy. The bilinear model was also extended to characterise the thickness dependence of the fracture energy of concrete materials [8].

It is noted that a key difference between the boundary effect and the size effect concepts is that the former uses the distance of the crack tip to a specimen boundary to determine the fracture behaviour whilst the latter emphasises the role of specimen physical sizes. An important conclusion of the boundary effect analysis is that the size effect can be observed on very large specimens if the crack tip is close to a free boundary, e.g. a short crack or a short ligament.

This paper aims at the further development of the asymptotic boundary effect model. Firstly, the asymptotic solutions for characterising the fracture properties of a finite-width plate with an edge crack are re-derived. Like the previous work [1-3], the derivation starts from these two strength criteria for brittle materials, i.e. the maximum tensile stress and linear elastic fracture mechanics (LEFM) criteria. By considering the similarities between the strength criteria for the large plate case [1,2] and those for a finite width plate with an edge crack, the same equations as given in ref. [3] are derived, but here presented is a more concise derivation operation. More importantly, the physical meanings of the parameters in the asymptotic equations are clarified.

The asymptotic solutions are then used to analyse the fracture behaviour of a few popular fracture mechanics geometries including 3- and 4-point bending beams and compact tension (CT) or wedge splitting specimens. The analysis shows that when a crack tip approaches either front or back free boundary (short crack or ligament), the observed fracture strength increases dramatically while the measured fracture toughness does exactly the opposite. This size-dependence of fracture strength and fracture toughness can be attributed to the effect of free boundaries because a free boundary will ease the stress/strain fields in the vicinity of a crack tip and lead to a decreased FPZ. The boundary effect intensifies with a decreasing specimen size, and for a small specimen, the boundary effect becomes unavoidable because the crack tip is always close to a free boundary.

The asymptotic equations include a term $B(\alpha)\cdot a$ (a is crack length), which represents the distance of the crack tip to the front free boundary when the crack-length-to-specimen-size (α) ratio is close to zero, and the crack-tip-to-back-boundary distance when the α-ratio is close to unity. Therefore, this term can be used as a measurement of the boundary effect on fracture properties.

A number of experimental observations from the literature are analysed using this model. It is shown that the predictions from the model agree well with these experimental observations. As a result, an experimental procedure can be established to measure the fracture properties of the quasi-brittle materials using "small" laboratory specimens.

1. Hu, X.Z., Size Effects in Toughness Induced by Crack Close to Free Edge, in *Fracture Mechanics of Concrete Structures*, Proceedings of FRAMCOS-3, Gigu, Japan, Oct. 12-16, 1998, Ed. H. Mihashi and K. Rokugo (Aedificatio Publishers, Freiburg, 1998) 2011-2020.
2. Hu, X.Z. and Wittmann, F. H., 2000, Size Effect on Toughness Induced by Crack Close to Free Surface, *Eng. Fract. Mech.*, Vol.65, 209-211.
3. Duan, K., Hu, X. Z. and Wittmann, F. H., 2003, Size Effect on Fracture Resistance and Fracture Energy of Concrete, *Materials and Structures, RILEM* (in press).
4. Duan, K., Hu, X.Z. and Wittmann, F. H., 2003, Boundary Effect on Concrete Fracture and Non-Constant Fracture Energy Distribution, *Engineering Fracture Mechanics*, (in press).
5. Duan, K., Hu, X.Z. and Mai, Y.-W., 2003, Boundary Effect on Fracture Energy of Polymeric Adhesives, submitted to *MM2003, 11-13, June 2003, HKUST, Clear Water Bay, Hong Kong*.
6. Hu, X.Z., 'Fracture Process Zone and Strain Softening in Cementitious Materials', ETH Building Materials Reports No.1, ETH Switzerland, 1990 (Aedificatio Publishers, Freiburg, 1995).
7. Hu, X. Z. and Wittmann, F.H., 1992, Fracture Energy and Fracture Process Zone, *Materials and Structures*, Vol.25, 319-326.
8. Duan, K., Hu, X. Z. and Wittmann, F. H., 2003, Thickness Effect on Fracture Energy of Cementitious Materials, *Cement and Concrete Research*, (in press).