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Influence of inclusion size and strain rate on the interaction between cracking and the matrix–inclusion interface in composites

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ABSTRACT

The critical deflection/penetration behaviour of a crack terminating perpendicular to a circular matrix–inclusion interface under dynamic tensile loadings is simulated numerically. It is found that higher strain-rate loading is necessary for a crack to penetrate through an inclusion with a smaller radius. Moreover, the minimum loading amplitude for penetration increases with the strain-rate, and this strain-rate dependence appears to be independent of the inclusion size and the interfacial strength. Additionally, these results imply that the strain-rate effect of dynamic strength can be induced by the quasi-static structural properties of composites, which is in agreement with the results of previous works.

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1. Introduction

Over the past few decades, a variety of elastic composite and quasi-brittle materials have been increasingly widely applied in various civil facilities and military installations, which has led to significant developments in the impact dynamic mechanics of composites. The failure of composites under high-rate dynamic loadings differs considerably from that of homogeneous elastic materials in that, in addition to matrix damage and fractures, the former has two other failure modes, i.e., interfacial fractures and Second Phase (such as aggregate particles in concrete or inclusions in other granular reinforced composites) Failure (SPF). In general, it is believed that the dynamic strength of composites is dependent on the loading rate (or strain rate), which is usually referred to as the strain rate effect [1–3], and traditionally, this strain rate dependence has been considered to be an intrinsic property of materials, although this belief has been challenged by some authors recently [4–6]. Conversely, as one of the most important failure mechanisms, SPF plays a significant role in the overall dynamic failure behaviour of composites, which usually occurs under dynamic loads with higher loading rates. For example, a recent work by Brara and Klepaczko [6] showed experimentally that all of the aggregate particles in their concrete specimens failed completely at high loading rates but remained largely intact at relatively lower ones. Even smaller aggregate particles with higher toughnesses were cleaved under higher loading rates, as shown in Fig. 1. Cotsovos and Pavlović [4,5] stated that most of the experimental investigations on impacting show that the dynamic strength of brittle materials increases with the loading rate, but there is a considerable data scatter among the experimental results, which may have resulted from various experimental techniques for different materials. This effect becomes increasingly apparent as the loading rate increases [7,8]. In addition, the majority of experimental results shows a sudden increase in the dynamic strength of concrete when a certain loading rate is reached (see Fig. 2). In our opinion, this fracture phenomenon is due to the failure of the aggregate particles in the concrete (i.e., SPF) because, from a physical point of view, this failure characterises the exclusive breaking mechanism at the moment.

It is well-known that the SPF is essentially caused by a matrix crack penetrating through the matrix–inclusion interface and propagating into the inclusion, making research on the deflection/penetration behaviour of a crack at a matrix–inclusion interface one of the most active fields in the fracture dynamics of composites. Beginning in the 1970s, some of the literature (see [9–12] for example) was devoted to both analytical and experimental studies on crack deflection/penetration behaviour under quasi-static loadings, of which interfacial strength has been shown to be a crucial factor. Similar dynamic loading issues have also received great attention since the early 1990s. Tan and Meguid [13] studied the transient response of a two-dimensional composite solid that contained a crack terminating at a right angle to the bi-material interface and derived the dynamic stress field near the crack-tip and the associated dynamic stress intensity factor. Paskaramoorthy and Meguid [14] obtained the stress field around a spherical inclusion, and Xu et al. [15] conducted an experimental study to examine the deflection/penetration

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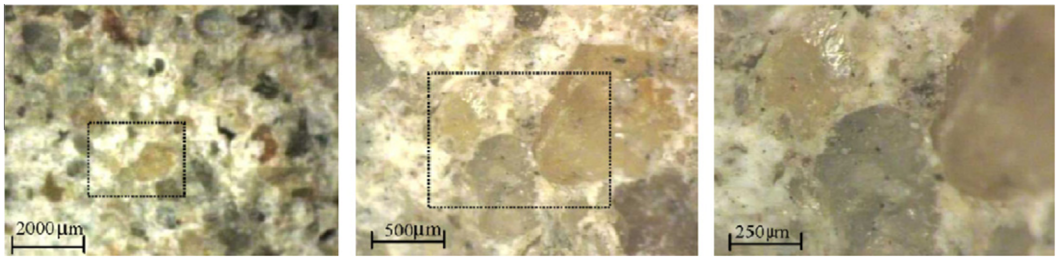

Fig. 1. Fracture surface of concrete specimen with intra-granular dominant separation under higher loading rates.

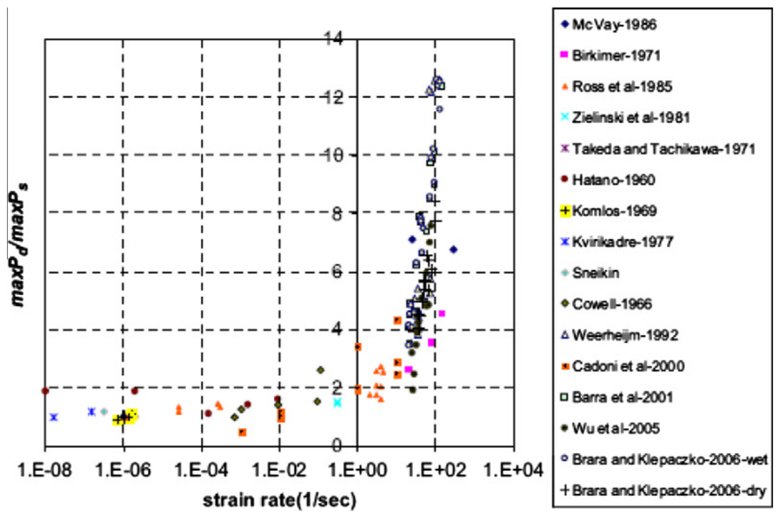

Fig. 2. Variation of load-carrying capacity with strain rate for concrete in uniaxial tension (max P_d = load-carrying capacity, max P_s = load-carrying capacity under static loading).

behaviour of dynamic Mode I cracks propagating at various speeds towards an inclined interface with various strengths in homogenous isotropic plates. Lei et al. [16] adopted the time-domain boundary element method to numerically simulate dynamic crack deflection/penetration behaviour at the interface of a bi-material system with different oblique angles. However, it appears that none of the previously mentioned investigations discussed the effects of strain rate and inclusion size on the crack deflection/penetration process.

In this paper, by using the ABAQUS software together with a type of Cohesive Zone Model [17] to describe the constitutive relationships of both the interface and the cohesive crack, the growth behaviour of a crack terminating perpendicular to a circular matrix–inclusion interface under dynamic loadings was investigated numerically and the effects of the loading rates or the strain rates and inclusion sizes on the crack deflection/penetration behaviour were shown. In Section 2, the numerical model, including details of the model geometry, meshes employed, boundary conditions used and locations of the cohesive zones, is described briefly. The numerical results of the relationships among the interfacial strengths, strain rates, inclusion radii and the critical amplitudes of loadings to realise the penetration are presented and discussed in Section 3. Section 4 contains the conclusions of the study.

2. Numerical model

To analyse the dynamic behaviour of a composite material under different strain rates, a two-dimensional y_1–y_2 plane strain model was used, as shown in Fig. 3a. The dimensions of the computation field were L = 10 mm and W = 6 mm. A cylindrical inclusion was embedded in the matrix with a circular bonded interface located between the matrix and the inclusion. To verify the effects of the inclusion size, three calculations were performed with the inclusion radii R = 0.5, 1.0 and 2.0 mm. Hereinafter, the physical variables related to the matrix, inclusion and interface are denoted by the superscripts "(1)", "(2)" and "(i)", respectively. A semi-infinite-like matrix crack was assumed to terminate perpendicular to the matrix–inclusion interface.

The finite element mesh adopted in the simulations is depicted in Fig. 3b with a uniform region in the inclusion and the initial crack tip surrounded by gradual enlarged meshes out to the specimen's boundaries. The sides of the elements in the uniform region were approximately 20 µm in length. Both the matrix and the inclusion materials are described by the corresponding linear elastic Hooke's laws and meshed with conventional normal four-noded plane strain elements, which, for convenience, can be called "bulk elements". To simulate cohesive crack growth, two zero thickness cohesive zones from Xu and Needleman's model [17] were inserted along the circular matrix–inclusion interface as well as the self-similar crack growth direction in the inclusion using ABAQUS UEL, as shown in Fig. 3a. Along each of the zero thickness cohesive zones, each of the common nodes linking two original neighbouring bulk elements was assumed to split into two overlapped nodes, which were designated by different node numbers. Under the action of the loadings, the overlapped nodes, i.e., the original neighbour bulk element nodes, could move relative to each other as shown in Fig. 4.

The material properties, including Young's modulus E, Poisson's ratio ν and the mass density ρ for both the matrix and the inclusion

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