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Research Paper

Size effect, material ductility and shape of fracture process zone in quasi-brittle materials

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ABSTRACT

Numerical three-point bending tests were conducted on a softening material model to study the effect of specimen size and material ductility on the shape of the fracture process zone. A bonded particle model (BPM) was used for simulation of the rock. The particles at the contact points were allowed to follow a softening behavior to be able to capture the initiation and development of the process zone. Five different beam sizes of 20 (height) × 60 (span), 40 × 120, 80 × 240, 160 × 480, and 320 × 960 mm^2 were used. All beams had a notch at their mid-span to study the mode I fracturing of rock. For each specimen size, six different realizations were introduced to study the effect of particle arrangement on the induced damage zone. The material ductility was controlled and modified by introducing different slopes for the post peak behavior of the contact points between the particles. The shape of the process zone was obtained by calculating both the width and the length of the process zone at the peak load. The results suggest that as the specimen size increases, the process zone expands in its size. In addition, the results indicate that for quasi-brittle materials, the length to width ratio of the process zone is greater compared to that of ductile materials. Furthermore, it is shown that the sizes of the representative elemental volumes corresponding to the width and the length of the process zone may not be identical in the quasi-brittle materials.

1. Introduction

It is well known that during crack propagation in quasi-brittle materials such as rock and concrete, a localized damaged zone is created which can affect the peak load and the deformational behavior of the material. This damaged zone or process zone is made of micro-cracks between the grains or through the grains. With continuation of loading, the severely deformed and loaded micro-cracks in the process zone are eventually extended and coalesced to form the macro-cracks which subsequently can result in failure of the rock structure.

Due to the importance of the process zone in the fracture mechanics of quasi-materials, this topic has been investigated by many researchers. Otsuka and Date [1] used the X-ray and 3D acoustic emission (AE) techniques to investigate the effect of specimen size and aggregate size on the fracture process zone in concrete. Their results showed that as long as the maximum aggregate size is identical, the width and length of the fracture process zone increase as the specimen size increases. Their results also demonstrated that the rate of change of the length of the fracture process zone was much larger than that of the specimen size. On the other hand, it was shown that the rate of change of the width of the fracture process zone was smaller than that of the specimen size. Consequently, the shape of the process zone is affected by the specimen size.

The effect of aggregate size on the fracture process zone of asphalt mixture at low temperature was monitored using an acoustic system in three point semi-circular bending tests by Li and Marasteanu [2]. Based on their results, the authors claimed that the size of the fracture process zone depends on many parameters such as aggregate particles, preexisting cracks and presence of voids in the material. Their experimental data revealed the importance of the temperature of the asphalt specimen on the size of the process zone as well; the fracture process zone is longer at lower temperatures.

Zhang and Wu [3] performed several physical three point bending tests using concrete beams with different notch depths. The acoustic emission method was used to study the process zone. The results revealed that the length of the fracture process zone is not a material parameter as it is greatly influenced by the fracture ligament length.

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A meso-scale approach was used by Grassl et al. [4] to investigate the effect of specimen size on the fracture process zone of concrete beams. Their study concluded that the width of the fracture process zone for notched specimens does not depend on the specimen size. On the contrary, they showed that the fracture process zone length along the ligament is dependent on the specimen size.

Finite element numerical simulations of fracture tests were carried out by Vesely et al. [5] to investigate the influence of structural size and geometry on the size and shape of the fracture process zone. Two different types of stress constraint at the crack tip, single edge notched beam under three point bending (SEN-TPB) and double edge notched panel under tension (DEN-T), were studied. Five different specimen sizes were considered for each testing configuration. The results indicate that the size and shape of the fracture process zone are affected by the specimen size and the structural geometry.

In this paper, the effect of specimen size and material ductility on the size and shape of the process zone is studied. Three-point bending tests are conducted on notched beams to create crack extension in mode I fracture. To capture the process zone, a softening contact bond model is used in the numerical bonded particle model (BPM). Material ductility is controlled by changing the micromechanical softening behavior of the particles at the contact points. It is shown that both the specimen size and material ductility can affect the shape and size of the process zone. To the best knowledge of the authors, the applications of the BPM in studying the shape of the process zone in mode I fracture and the associated representative elemental volume are being investigated for the first time in this study.

2. Numerical model

The computer program CA2 [6,7] which is a hybrid finite element–discrete element code for static and dynamic simulation of geomaterials is used in this study. The rock is simulated by discrete circular particles that are glued at the contact points (bonded particle model). The simple contact bond model for interaction of the particles at the contact points in this numerical technique, has a few micromechanical parameters including normal and shear stiffnesses (k_n and k_s), normal and shear bond strengths (n_b and s_b), and a friction coefficient (μ). A contact breaks in shear if the applied shear contact force exceeds the bond strength. On the other hand, if the applied tensile force exceeds the contact normal bond strength, gradual loss of bond strength with further deformation is assumed in our softening model (Fig. 1). With this technique, gradual weakening of the material in mode I fracture can be simulated. To change the material ductility, the post-peak slope of the softening curve in Fig. 1a (k_{np}) is modified. Note that no softening in shear is studied in this paper as all the observed micro-cracks in the conducted three point bending tests are tensile; softening in shear was not included because this effect is only pronounced for loading under significant (>10% q_u) mean stress. Following complete failure of a contact, the contact is forced to follow a Coulomb type behavior using the contact friction coefficient μ. In addition to the above micromechanical parameters, the particles radii (R) and genesis pressure (σ_0) must be specified. The genesis pressure is the applied surrounding pressure during sample preparation that allows some initial small overlap of the particles which helps to more realistically simulate the macro-properties of the rock [8].

The simulated material was calibrated to mimic the mechanical behavior of the Berea sandstone. The sandstone has an elastic modulus of 14 GPa, a Poisson's ratio of 0.32, a uniaxial compressive strength (q_u) of 55–60 MPa, and a bending tensile strength (for a 80 mm × 240 mm beam) of 8.6 MPa. The calibration procedure was conducted using the technique introduced by Fakhimi and Villegas [8] and resulted in the following model properties: k_n = 22.0 GPa, k_s = 5.5 GPa, n_b = 2800 N/m, s_b = 12300 N/m, μ = 0.5, σ_0 = 2.2 GPa, and k_{np} = 1.83 GPa (k_n/k_{np} = 12). To obtain the appropriate k_n/k_{np} value, the calibration was conducted to get a realistic width for the fracture process zone of the sandstone consistent with that from the physical testing [9]. The circular particles or disks in the bonded particle model were assumed to have radii with uniform random distribution within the range of 0.27–0.33 mm (R_{ave} = 0.3 mm). The simulated material with the above micro-parameters was tested in uniaxial compression (40 mm × 80 mm specimen) and three point bending (80 mm × 240 mm specimen) to verify the accuracy of the calibration procedure. An elastic modulus of 13.3 GPa, a Poisson's ratio of 0.19, a uniaxial compressive strength of 60.5 MPa, and a tensile strength of 8.7 MPa were obtained that are in reasonable agreement with the corresponding properties of the physical samples.

3. Numerical results

Three point bending tests (Fig. 2a) on five different specimen sizes (20 × 60, 40 × 120, 80 × 240, 160 × 480, and 320 × 960) were conducted. The first and second numbers for each sample size are the height and the span of the beams in millimeters. Each beam has a notch at its mid-span which is 3.6 mm in width. The notch length to the beam height ratio (a/D) is constant for all beams and is equal to 0.25. The numbers of discrete particles or disks for the smallest and largest beams were 1850 and 465,280, respectively. For each beam size, 6 different random distributions of disks locations were used; six different realizations were conducted. To reduce the computational time (for the largest beam, a few weeks were needed to finish the run using a desk top computer with an i7 processor. For each beam size, six different realizations and four different ductility values were needed), each beam was divided along its span to three equal pieces. The outer pieces were covered by disks with the average radius four times the average radius of the particles in middle part (Fig. 2b). The normal and shear stiffness of the disks in the three regions of the beam are the same to assure the same elastic modulus for all parts of the beam [8]. Furthermore, the normal and shear bond values for the contacts

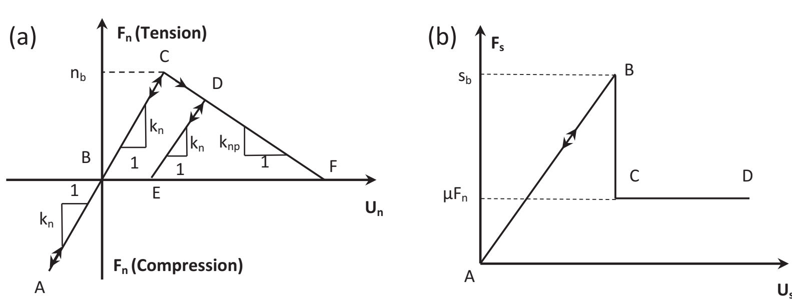

Fig. 1. The relationship between (a) normal contact force and normal contact displacement and (b) shear contact force and shear contact displacement.