Ball-on-three-ball Flexural Test: Crack Propagation on Disc Sample with a Notch along the Axis

Loganathan Rajakumar, Keisuke Sawano, Sivarasa Arumugam

Abstract: Ball-on-three-ball (B3B) test is a multiaxial method providing flexural strength for disc-shaped samples. Due to its advantages over traditional uniaxial bending tests, it has been commonly used for a variety of materials, such as ceramics and cement composites in the last two decades. To date a number of reports have performed thorough investigations in this test with analytical, numerical, and experimental approaches. The studies however, only focus on the stress distribution and peak strength for intact samples. This paper, for the first time, studies the crack propagation of notched samples under B3B tests. An analytical solution is provided based on classical double cantilever beam theory. Experimental data on two different ceramic materials show consistency with the theoretical solution.

Keywords: ball-on-three-ball test, flexural strength, crack propagation, notched sample, multiaxial

1 Introduction

THE characterization of mechanical properties for materials has been an important area for thousands of years. As technology progresses into the new era with demands of more complicated paradigms, accurate and specific characterization techniques have arisen [1,2,3]. Flexural strength is a significant parameter which denotes the resistance of the material to bending, and therefore is crucial to applications such as bridge. Traditionally three or four-point bending tests have been employed to find out the flexural strength [4,5]. These uniaxial tests, however, are only sensitive to longitudinal detects/cracks in the samples, while they are not revealing of those in vertical directions. This is not a trivial issue as a plethora of anisotropic materials have been developed recently. For example, fiber-reinforced composites are (at least) two-phase materials with matrix phase embedded with high aspect ratio particles (fibers) [6,7,8,9,10]. When the fibers are oriented in certain directions, we cannot rely on the bending tests to conclude an unbiased characterization. Addressing this issue, a few researchers have developed more complicated and specific tests that are able to detect detects/cracks in randomly distributed directions [11]. Among all these tests, ball-on-three-ball (B3B) flexural tests are receiving much attention. Figure 1 gives a schematic of this test configuration. During the experiment, three balls are beneath the disc sample with equal distance from each other. A fourth loading ball is above the sample moving downwards at the sample center until a final failure happens. Other than a complicated stress distribution, this configuration also possesses advantages of ease to prepare large amount of samples and low requirements on surface conditions. There are different failure modes [11] for B3B test, with at least one crack initialed along one of the axes (Fig. 1). As a consequence, the cracks along the three axes are much more important than other locations. In other words, if the surface cracks are distributed evenly in the tensile surface, the ones along the axes are to determine the crack propagation, and hence the mechanical properties of the sample. As a result in this paper, the surface cracks along axes are investigated.

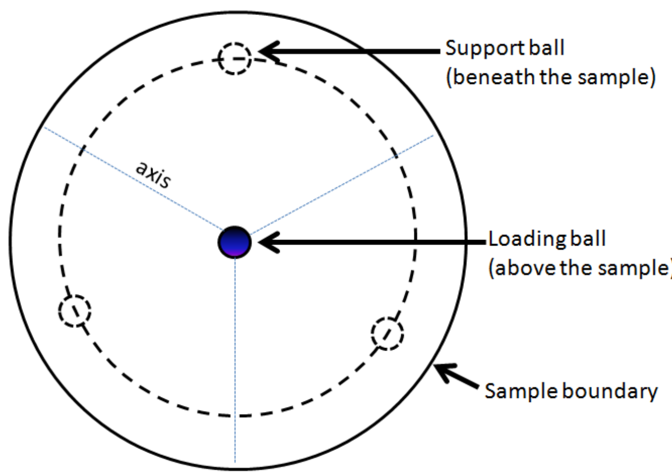

Fig. 1. Top view of the B3B test configuration

The B3B has been originally devised to study various ceramics materials, such as empress, procera allceram [12], silicon nitride [13], yttrium oxide partially stabilized zirconia [14], alumina [11], VITA in-ceram zirconia, and cercon base zirconia [15]. Other than ceramics, recently Cao et al. [16,17] for the first time implemented this test on cement composites and found that the B3B flexural strength received an extraordinary improvement of ~50% with

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sonicated cellulose nanocrystal additions. In their work they cast the raw materials in cylinder molds and cut the hardened samples into thin discs. With this facile method, large amount of samples were efficiently generated in one batch. In addition, the surface roughness after sectioning did not affect test results and the authors also demonstrated that even for heterogeneous multiphase cementitious materials, the B3B test showed high statistical consistency. As the B3B test found their utilities in a variety of materials, all work to date focuses on the strength of the intact samples. In this work, we study the crack propagation of the B3B samples with notch along one axis. Both analytical and experimental approaches are implemented.

2 Analytical Method

The three-fold symmetry of the B3B test allows one to analyze only one third of a disc sample, i.e., the sector shown in Fig. 2., which shows the sample geometry of the top and side views. As introduced earlier, the most important cracks are along the axes, and therefore the notch (crack) is given along the one of the axes on the bottom surface. In this problem, a thin strip that is vertical to the axis is analyzed, given in Fig. 2 side view. Then the mechanical behavior of this sector can be considered as a combined effect of integrated strips. Based on the side view of this cross-section area, this problem can be treated as the double cantilever beam (DCB).

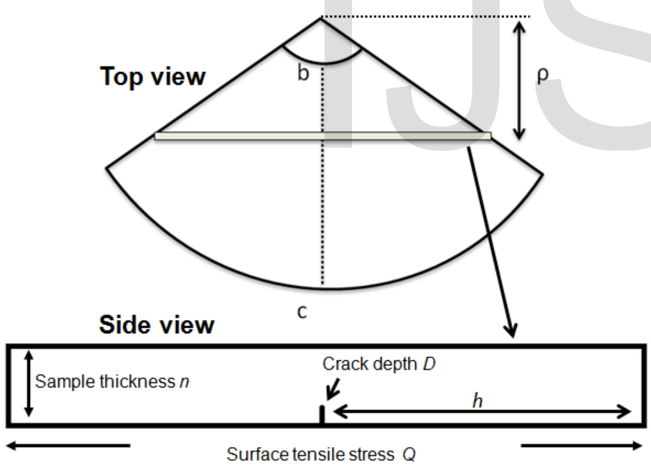

Fig. 2. The top view of the sector analyzed for the disc sample and the side view of the strip treated as a DCB

For DCB problem, the classical analytical solution gives [18]:

$$G = \frac{12Q^2D^2}{\rho^2h^3E} \quad (1)$$

where G is energy release rate, D the crack depth. It is important that the G is not a constant along the axis as the surface stress varies with ρ:

$$dQ = \sigma_{rr}(\rho, \theta)\ \rho d\rho d\theta \quad (2)$$

Then we have:

$$G(\rho) = \frac{12\left(\int_0^{\pi/3}\sigma_{rr}(\rho,\theta)d\theta\right)^2 D^2}{Eh(\rho)} \quad (3)$$

where

$$h = \begin{cases} \frac{\rho}{\sqrt{3}} & when\ b < \rho < \frac{c}{2} \\ \sqrt{c^2 - \rho^2} & when\ \rho \geq \frac{c}{2} \end{cases} \quad (4)$$

and the stress distribution function [19]:

$$\sigma_{rr} = P\overline{f_{rr}}(\rho, \theta)\frac{6}{n^2} \quad (5)$$

As the energy release rate along the axis is not a constant, we treat the total effect as an effective average:

$$G_{tot} = \frac{\int_b^c G(\rho)d\rho}{b-c} \quad (6)$$

As a summary, the total energy release rate is a function of the crack depth, the load at the center, and the sample thickness:

$$G_{tot} = f(P, n, D) \quad (7)$$

Provided that the material has the property of critical energy release rate Gc, the relationship between the maximum load and the crack depth is:

$$S = \frac{P}{n^2} = K\frac{1}{D} \quad (8)$$

S is defined as the nominal tensile strength and K is the coefficient including other parameters.

3 Experimental

Two different ceramic materials Al_2O_3, yttria stabilized tetragonal zirconia (Y-TZP) are tested to validate the analytical results. The sample preparation procedures are described in literatures [11,20]. The notch is made via a highly sharp blade with nominal thickness of 0.02 mm, from the radius b to c (the loading area to the outer circumstance, Fig. 2). An MTS universal test equipment is used to perform the B3B tests on the disc samples. The nominal thickness of the sample is 8 mm and the diameter of the sample is 45 mm. The loading area is not notched to avoid any affect to the contact between the loading ball and the sample surface. Five different notch depths: 0, 0.4, 0.8, 1.2, and 1.6 mm are made. For each depth, three samples are prepared to obtain an average. The loading rate is 0.1 mm/min.

Figure 3 shows the experimental and analytical results of relationship between the nominal strength and the notch depth for the two materials. With increasing the depth in the sample surface, the nominal strength is decreasing considerably, which is as expected. It is noteworthy that for both the two materials, there are strong consistency between the experimental results and the analytical solution. This suggests that this analytical model can be used as a universal formula which is independent of specific materials.

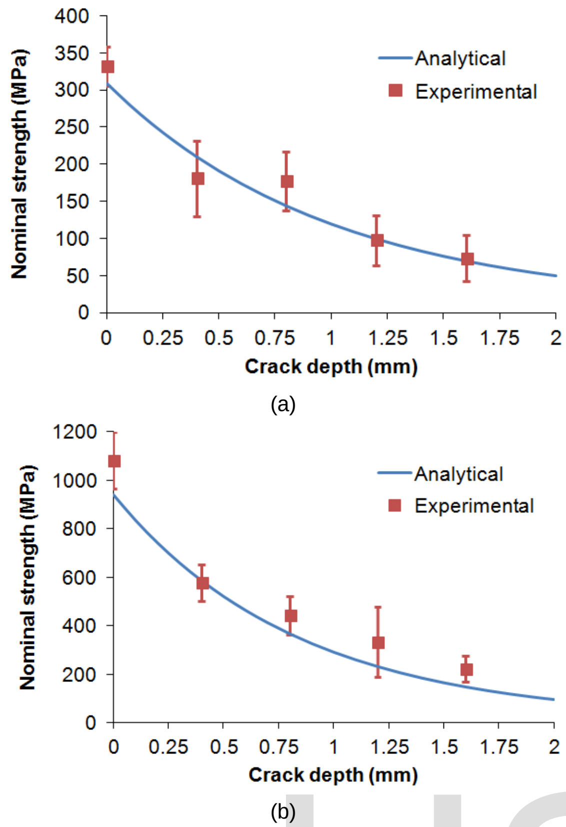

Fig. 3. The relationship between nominal strength and crack depth of (a) Al2O3; (b) Y-TZP

4 Conclusion

The relationship between the crack depth (notch) and the load of the ball-on-three-ball flexural test is investigated with an analytical approach. The analytical method uses an energy approach with a critical strain energy release rate. The experimental results show that the cracking load decreases with increasing the notch depths. Great consistency was observed correlating the experimental and analytical results. This work opens up opportunities improving understanding of the B3B tests on samples with cracks, which is necessary for realistic testing situation.

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