Effective stress intensity factor of rock-like brittle materials subjected to different mode of mixity

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Abstract: During comminution, fracture initially occurs because particles contain preexisting cracks (flaws), which propagate in response to tensile stresses generated during compressive loading. At the tip of all cracks within a loaded material, the stress is concentrated because the load cannot be uniformly distributed across the full area. In the present paper, the effects of crack inclination angle and crack length on the through-thickness mode I (KI), mode II (KII), and effective ($K_{eff} = \sqrt{K_I^2 + K_{II}^2}$) stress intensity factors (SIFs) have been analyzed by using three dimensional finite element analysis (3D FEA). Edge crack in semi circular bend specimen (SCB) was utilized in this investigation. The mode of mixity (Me) values are equal to 1 (pure mode I), 0.75, 0.5, 0.25, and 0 (pure mode II). The crack length ratio, crack length/specimen radius (a/R), ranged from 0.1 to 0.7 by step equal 0.1 has been studied. In SCB specimen, the mode I geometry correction factor (YI) decreased by increasing the crack length for all values of mode of mixity, while, in the case of Me = 1 & 0.75 YI reached its minimum value at a/R ≈ 0.3 then YI increased by increasing the crack length. For all values of Me, Keff increased with increasing the crack length. However, the increment of increasing in Keff for a/R ≤ 0.3 is lower than that for a/R > 0.3.
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Keywords: Stress intensity factor; Mixed mode I/II; SCB specimen; three dimension finite element.

1. Introduction

Comminution processes such as crushing and grinding are essential stages in mining and mineral processing operations to reduce the size of ore and rock, and to liberate the valuable mineral for beneficiation. Crushing is accomplished by compression of the ore against rigid surfaces, or by impact against surfaces in a rigidly constrained motion path. This is contrasted with grinding which is accomplished by abrasion and impact of the ore by the free motion of unconnected media such as rods, balls, or pebbles. Comminution is energy-intensive and responsible for most of the energy used during mineral recovery. Energy efficiency is very low since almost all the energy is dissipated as heat instead of generating new surface area (Wills and Napier-Munn, 1006), (Sadrai et al. 2011). Real particles of rock are irregularly shaped, and loading is not uniform but is achieved through points, or small areas, of contact. Breakage is achieved mainly by crushing, impact, and attrition, and all three modes of fracture (compressive, tensile, and shear) can be discerned depending on the rock mechanics and the type of loading (Wills and Napier-Munn, 1006). Breakage of rock material depends on the distribution and orientation of flaws and geological structure within the particles. Particle fracture occurs due to the induced tensile stress acting normal to the crack plane. The mode I stress intensity factor (K_I), which is independent of the nature of the material, relates the nominal stress and the depth of a crack to the stress concentration at the tip of the crack. With more intense stresses or with deeper cracks, the stress intensity becomes, sufficient for fracture to progress spontaneously. This threshold stress is a property of the material, which is called the critical stress intensity factor (K_{IC}). Fracture toughness (G_{IC}), resistance of rock to fracture under crack opening (mode I) conditions, is defined as the critical energy release rate per unit area of crack plane (Jm-2) that is necessary for crack propagation. Thus, fracture toughness is a material property of rock that is indicative of how rock behaves under load. For ideal brittle fracture where plastic deformation is negligible, G_{IC} is equivalent to 2γ where γ is the surface energy per unit area (Jm^{-2}). G_{IC} is related to K_{IC} via the following relation: $G_{IC} = (K_{IC})^2/E$ (Sadrai et al. 2011), (mubaraki et al., 2012), (Sallam, and Abd-Elhady, 2012).

If the plane of the crack (flaw), is inclined at an angle with respect to the applied load, the crack will grow under mixed mode I (opening) and II (sliding). Therefore, fracture toughness (G_C), under mixed mode conditions should be measured. Disc-type specimens are simple in geometry and have many advantages in terms of specimen preparation, testing and analysis.

These test specimens have been used frequently to investigate mixed mode crack growth of rock materials, concrete, biomaterials, and other material (Sallam, and Abd-Elhady, 2012), (Lim, e. al., 1994a). A semi-circular specimens, SCB, (Fig. 1) under three point bending were used for mixed Mode I-II fracture toughness calculation (Khan and Al-Shayea, 2000), (Lim et al. 1994b), (Atkinson et al. 1982). Depending on the crack length, its orientation with respect to the loading direction, and the distance between the supports, a variety of mixed-mode failure patterns can be achieved. For pure Mode-I, the crack is aligned parallel to the direction of the load and lies below the loading point. However, for pure Mode-II, a slight misalignment of the specimen and/or crack orientation may induce a component of Mode-I loading and pure Mode-II cannot be achieved (Khan and Al-Shayea, 2000). The semicircular specimen can give comparable results only when the proper span to diameter ratio is used. The specimen geometry requirement for a valid and representative fracture toughness value or stress intensity factor or other fracture properties of a rock material has been a matter of controversy among researchers. Crack length seems to be a more sensitive factor than specimen thickness on SIFs (Whittaker, 1992). According to Lim (Lim et al. 1994b), the SIFs become very sensitive at large a/R values for SCB specimens.

Schmidt and Lutz have suggested that the general nonlinear stress-strain response of some rocks such as westerly granite invalidations the use of LEFM and KIC tension is known to be rather nonlinear. Khan and Al-Shayea (Khan and Al-Shayea, 2000), show that, the fracture toughness for limestone rock (ranging from 0.39 to 0.42 MPa $m^{1/2}$) over the range of specimen thickness does not show any significant variation.

The present study investigated the effects of the sample geometry in terms of crack length and crack inclination angle on mode I and mode II stress intensity factors (SIFs) of edge crack in semi circular bend specimen (SCB). This study aims to make improvements in the testing techniques for fracture testing of brittle materials.

2. Numerical Analysis

The basic dimensions of SCB specimens R (specimen radius), and B (specimen thickness), were equals 75 mm and 22.5 respectively. SCB specimen is placed on two bottom supports of distance 2S and the ratio of S/R was 0.43. The crack length ratio, a/R, was range from 0.1 to 0.7 by step equal 0.1. Aliha et al. (Aliha et al., 2010) suggest five values for mode mixity by parameter called mixity parameter, Me,

$$M^e = \frac{2}{\pi}\arctan\left(\frac{K_I}{K_{II}}\right) \qquad (1)$$

The values of Me varied through 1 (pure mode I), 0.75, 0.5, 0.25–0 for pure mode II. This mixity parameter was valid by change the crack inclination angle, β, as 0, 18.5, 33, 42.5 and 50o. In the present analysis, the mode I and mode II normalized stress intensity factors are denoted as Y_I and Y_{II}, respectively, and it can be deduced from Ref. (Hutar et al., 2010), (Lim et al. 1993) the general formula for normalized stress intensity factor YI, which is defined as:

$$Y_i = \frac{4RtK_i}{P\sqrt{a\pi}} \qquad i = I, II \qquad (1)$$

Where:

K_I = mode I stress intensity factor
K_{II} = mode II stress intensity factor
t = half specimen thickness = B/2
P = applied load
R = radius of specimen
a = crack length

The mechanical properties of the Specimen were as follows: modulus of elasticity, E = 54 GPa, and Poisson's ratio, ν = 0.276. The specimen material are homogeneous, isotropic and elastic. The applied load, P, was equal 50 kN as shown in Fig. 1. The plane x-y (plane z = 0) is the mid plane of specimen and two specimen surface are $z = t$ and $z = -t$, respectively. In order to calculate stress intensity factors of the samples with different geometries, numerical computations were carried out. The package programs used in this study were ABAQUS. ABAQUS (ABAQUS 6.9, 2002) program, which is a finite element program, was used in the present work and all the numerical studies were conducted with 3D models. Disc type specimens require 3D modeling for stress analysis and stress intensity factor computations. For 3D modeling a choice had to be done among ABAQUS. To decide if this program produces accurate results for stress intensity factor calculations comparable to the result of other references (Ayatollahi and Aliha, 2007), simple models with known analytical results for model verification were first employed. After verification studies, the program was decided to be appropriate for further stress intensity factor computations.

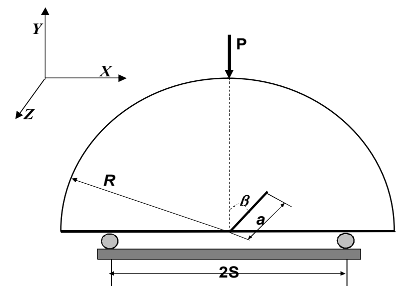

Fig. 1. Geometry and loading conditions of SCB specimens subjected to mixed mode I/II loading

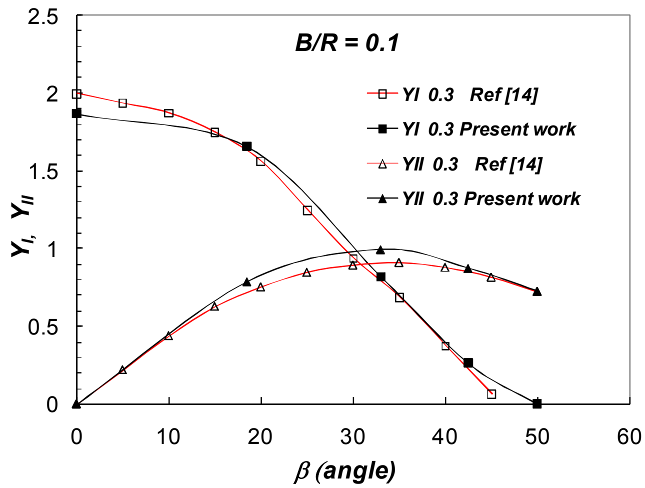

Fig. 2. Normalized mode I and mode SIFs calculated in present work compared with those presented by Ayatollahi and Aliha ((Ayatollahi and Aliha, 2007), for the SCB specimen (a/R = 0.3, B/R = 0.1 and S/R = 0.43)

3. Results and Discussion

Figure 2 shows the results obtained from finite element analysis in the present work for a/R = 0.3 and B/R = 0.1 and S/R = 0.43 and the results given by Ayatollahi and Aliha (Ayatollahi and Aliha, 2007) at the surface of the SCB specimen, $z = t$. There is a good agreement between the two sets of results and it can be considered as a validation for the present analysis.

Figure 3 depicts the relation between normalized mode I SIF and crack length at different site at crack front, z/t, for SCB specimen with different mode mixity. The value of YI increases by decreasing the value of z/t. this means that, the value of Y_I at surface point of SCB specimen was not the highest value on the crack front. By increasing the crack length, the value of Y_I decreases to reach a minimum value then it increases that for M^e equal 1 and 0.75 only that is agree with [3]. In other wise for M^e = 0.5 and 0.25, the value of Y_I decreases by increasing the value of crack length.

A little effect of z/t on the value of normalized mode II SIF, Y_{II}, with different crack length that can be shown in Fig. 4. the value of Y_{II} decreases by increasing the value of crack length to reach the minimum value then increases by increasing the crack length that for M^e = 0.5, 0.25 and 0. However, for M^e = o.75 the value of Y_{II} increases by increasing the crack length.

Figure 5 shows the effect of crack length, a/R on the effective stress intensity factor, Keff, ($K_{eff} = \sqrt{K_I^2 + K_{II}^2}$) through the SCB specimen crack front. The change of the effective stress intensity factor, K_{eff}, ($K_{eff} = \sqrt{K_I^2 + K_{II}^2}$) through the SCB specimen crack front can be neglect. By increases of the crack length the values of K_{eff} increasing. In the case of pure mode I and II, the effective stress intensity factor increases by increasing the crack length.

4. Conclusions

The present numerical analysis reveals the following conclusions:

1- For a/R < 0.3, the mode I geometry correction factor (Y_I) decreased by increasing the crack length for all values of mode of mixity.

2- For a/R > 0.3, Y_I increased by increasing the crack length for M^e = 1 and 0.75, while, Y_I continue decreased with increasing the crack length for M^e = 0.5 and 0.25.

3- For a/R > 0.3, Y_{II} increased by increasing the crack length for all values of M^e.

4- For all values of M^e, K_{eff} increased with increasing the crack length. However, the increment of increasing in K_{eff} for $a/R \leq 0.3$ is lower than that for a/R > 0.3.

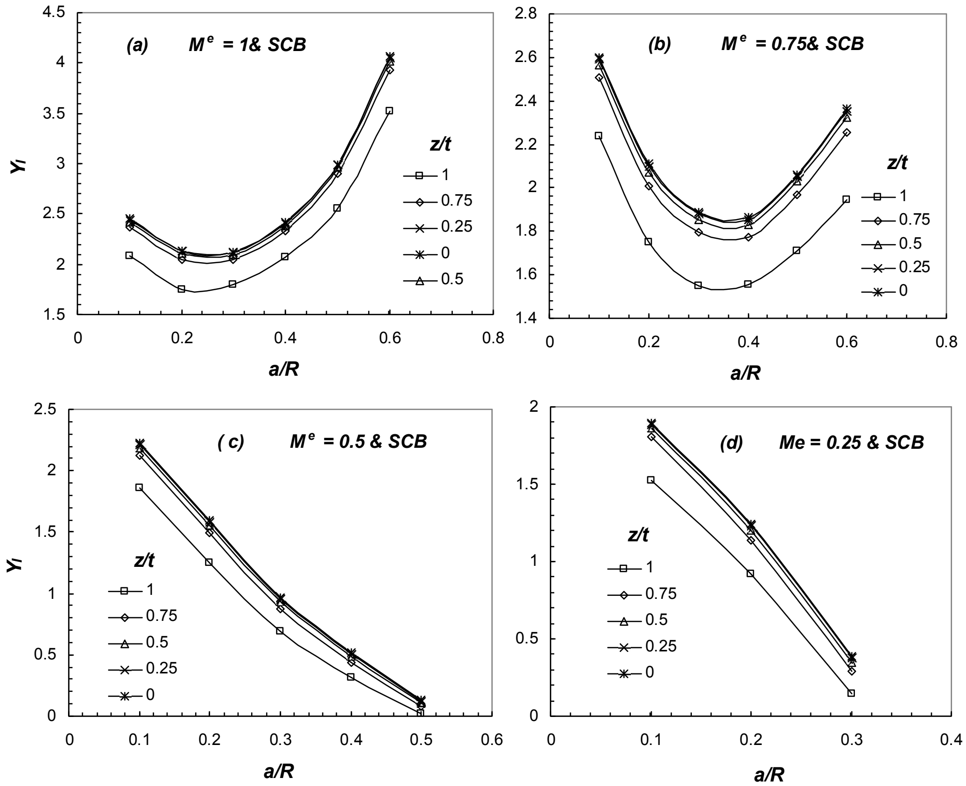

Fig. 3 The effect of SCB specimen crack length on the normalized mode I stress intensity factor for different the site on the crack front *z/t* and different mode mixity M^e (a) $M^e = 1$, (b) $M^e = 0.75$, (c) $M^e = 0.5$ and (d) $M^e = 0.25$.

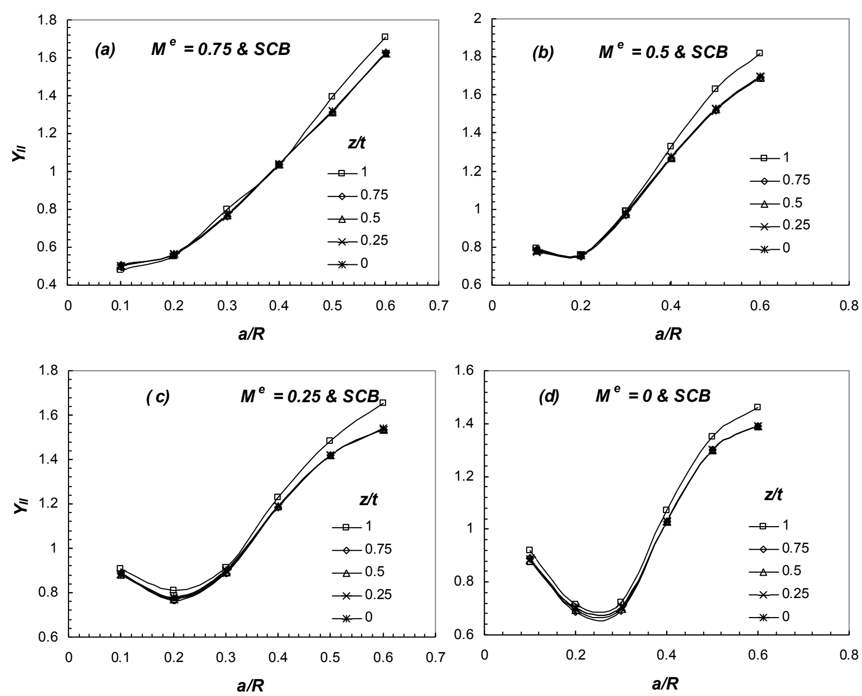

Fig. 4 The effect of SCB specimen crack length on the normalized mode II stress intensity factor for different the site on the crack front *z/t* and different mode mixity Me (a) $M^e = 1$, (b) $M^e = 0.75$, (c) $M^e = 0.5$ and (d) $M^e = 0.25$.

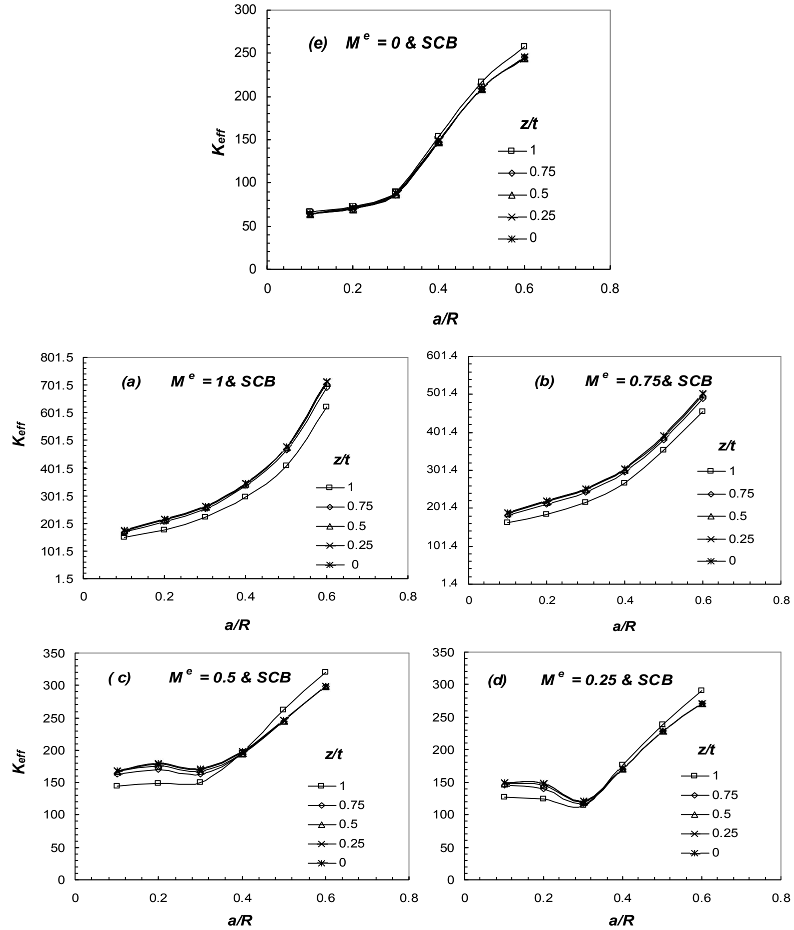

Fig. 5 The effect of SCB specimen crack length on the stress intensity factor effective for different the site on the crack front *z/t* and different mode mixity M^e (a) $M^e = 1$, (b) $M^e = 0.75$, (c) $M^e = 0.5$ and (d) $M^e = 0.25$.

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