MASONRY FRACTURE MECHANICS THREE POINT BENDING TEST OF BRICK

Xiaosong Xiao[1] , Nigel Shrive[2]

ABSTRACT

Structural elements working in compression fracture with a Mode I type of crack displacement. Mode I fracture analysis has been widely and successfully applied to the failure of metals subject to tension for many years. Since Kaplan extended the applicability of fracture mechanics to concrete, fracture mechanics has become an area of increasing research activity in concrete: many fracture models have been proposed. Few investigators have explored the application of fracture mechanics to masonry structures.

In masonry, three-point bending tests have been proposed on small size specimens. The three bending tests on bricks described here are part of a wider series of tests being preformed to obtain basic fracture data for masonry. Cored and solid bricks were used in the tests. Different notch depths were used ranging from 1/6 to 4/6 in term of notch to depth ratio. The critical stress intensity factor K_{IC}, and the critical energy release rate G_{IC} were determined. Cored bricks were formed to have higher values of K_{IC} than completely solid bricks. KIC increase with increasing brick strength, but did not appear dependent on the notch to depth ratio.

Key words: Masonry, Fracture, Three-Point Bending Test, Stress Intensity Factor, Energy Release Rate

[1] Ph.D. Student, Department of Civil Engineering, University of Calgary, Calgary, Alberta T1N 1N4, Canada. E-mail: xiao@ucalgary.ca

[2] Professor, Department of Civil Engineering, University of Calgary, Calgary, Alberta T1N 1N4, Canada. E-mail: shrive@ucalgary.ca

INTRODUCTION

For structures subjected to earthquake, in which dissipative phenomena play an important role, failure criteria associated with energy as opposed to the classic stress approach, are more appropriate. With such criteria, the failure mechanism of the structure can be modelled more accurately and realistically. Fracture mechanics approaches to failure prediction are based on the satisfaction of two criteria: an energy condition for crack extension, and cohesive strength. Both criteria must be met for crack propagation to occur, so when one has been met, it is the satisfaction of the other that governs fracture. Steel elements are frequently subjected to tensile stress, and fracture mechanics methods based on the energy criterion have been particularly successful in predicting the strength of steel components. More recently, fracture mechanics concepts have also been applied successfully to concrete [1-4]. Hence fracture mechanics may be applicable and of considerable usefulness to the analysis and design of masonry structures.

In recent years, a few investigators have explored application of fracture mechanics to masonry structures. Carpinteri *et al*[5] considered shallow masonry arches and numerically verified how the cracks control the line of thrust by applying fracture mechanics concepts through a fracture benefit parameter. Bocca *et al*[6,7] assessed the applicability of fracture mechanics to masonry by applying the fictitious crack model initially developed for concrete, to historical masonry. The energy release rate G_{IC} and the critical model I (opening) stress intensity factor K_{IC} were evaluated by using a three-point bending test. Dukuze and Dawe[8] tested notched clay brick beams in flexure using three-point bending, and investigated the influence of the notch size on the critical stress intensity factor.

Here, we describe three-point bending experiments on bricks, one of a series of masonry fracture tests we are conducting. Specimens were divided into two types: Cored Brick and completely Solid Brick. For each type, three bricks with different strengths were used. Specimens were given different notch depths, ranging from 1/6 to 4/6 in terms of notch to depth ratio. 144 specimens were tested in total. The critical values of stress intensity factor, K_{IC}, and energy release rate G_{IC} were determined and the factors influencing on the stress intensity factors K_I were investigated.

The objective of the work is to understand fracture processes in masonry and the parameters which govern those processes. This should lead to the establishment of the framework of applicability of fracture mechanics within masonry. Current research is focused on mode I and mixed mode fracture of bricks and brick coupons, mixed mode and tensile fracture of the brick/mortar interface, mixed mode (shear) fracture of masonry and compressive fracture of masonry. Initial tests on bricks are described here.

MATERIAL TEST AND TESTING SPECIMENS

Three Cored and three completely Solid bricks as shown in Fig. 1 were used in this test. The cored bricks were: Victoria Gray Graintex Titan (CA), Williamsburg (CB), Columbia Spice Titans (CC), the solid bricks: Granville Gray Titan Solid (SD), Cinnamon Titan Solid (SE) and Columbia Solid (SF), all the bricks were manufactured by I-XL Industries, Medicine Hat, Alberta. The material properties of the bricks were determined according to CAN3-A82.2-M78[9]; and are given in Table 1. The specimen details are listed in Tables 2 and 3. The notches were formed with a masonry saw. The notch depths provide a range of notch to depth ratios from 1/6 to 2/3. The notch to depth ratio is a/H as shown in Figure 2.

Fig.1 Dimensions of Specimens

Table 1. Material Properties

Specimen series	Absorption(%)	Compressive strength (MPa)	Modulus of rapture (MPa)
CA	6.6	72.4	6.0
CB	7.6	62.4	4.0
CC	11.4	62.8	4.9
SD	8.0	60.6	5.3
SE	7.7	93.0	7.2
SF	10.3	72.8	6.7

<u>Specimen naming rule</u>: the first character stands for brick type, H for hole brick, S for solid brick; the second stands for brick with different strength (A, B, C, D, E, F);

SPECIMEN DETAILS

Cored Bricks.

Table 2. Specimen Details for Cored Bricks

Specimen	No. of specimens	Notch depth (mm)	Notch-to-depth ratio
CAA	6	10.5	1/6
CAB	6	21	2/6
CAC	6	31.5	3/6
CAD	6	42	4/6
CBA	6	10.5	1/6
CBB	6	21	2/6
CBC	6	31.5	3/6
CBD	6	42	4/6
CCA	6	10.5	1/6
CCB	6	21	2/6
CCC	6	31.5	3/6
CCD	6	42	4/6

Solid Bricks.

Table 3. Specimen Details for Solid Bricks

Specimen	No. of specimens	Notch depth (mm)	Notch-to-depth ratio
SDA	6	10.5	1/6
SDB	6	21	2/6
SDC	6	31.5	3/6
SDD	6	42	4/6
SEA	6	10.5	1/6
SEB	6	21	2/6
SEC	6	31.5	3/6
SED	6	42	4/6
SFA	6	10.5	1/6
SFB	6	21	2/6
SFC	6	31.5	3/6
SFD	6	42	4/6

Specimen naming rule: the first character stands for brick type, C for cored brick, S for solid brick; the second stands for the different bricks (A, B, C, D, E, F); the third stands for different notch depths (A for notch-to-depth of 1/6, B for 2/6, C for 3/6, D for 4/6).

TESTING PROCEDURE

All specimens were tested in three-point bending as shown Fig.3. Cored bricks were tested in an INSTRON testing machine with a crosshead displacement speed of 0.5mm/min. The solid specimens were tested in an MTS machine. These latter tests were stroke controlled at a crosshead displacement speed of 0.015mm/min (Fig.2).

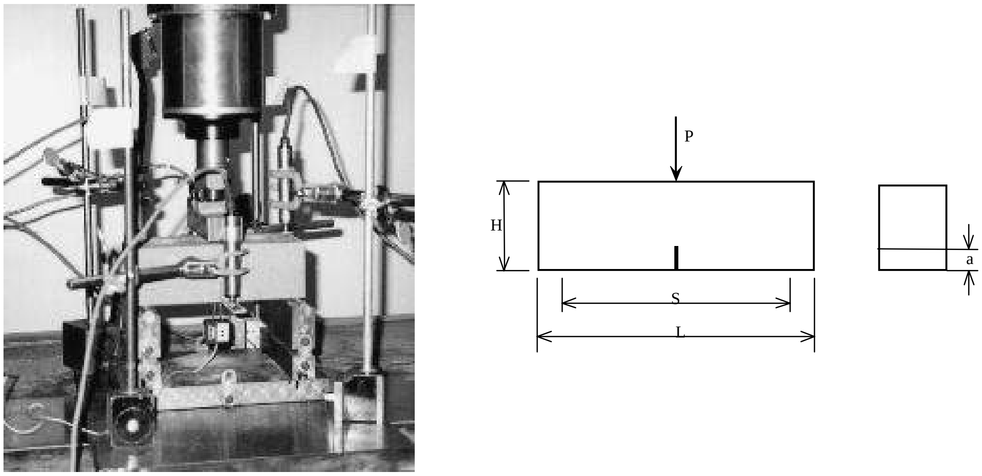

Fig.2 Three-point bending scheme

EXPERIMENTAL RESULTS AND DISCUSSION

Typical Load-CMOD Curve

Crack mouth opening displacement (CMOD) is the amount the crack opens at the base of the specimen. CMOD is measured with a standard clip gauge(MTS Mode 632.02). A typical load versus CMOD curve (ascending and descending branch) of brick beam obtained from the experiments is shown in Fig.3. Non-linearity is observed near the peak load. The Load-CMOD curve is linear to about 80% of peak load, followed by non-linear behaviour. The nonlinear behaviour can be due to microcracking and slow crack growth. To evaluate the applicability of Linear Elastic Fracture Mechanics (LEFM) parameters, the inelastic part has to be extracted from the overall behaviour.

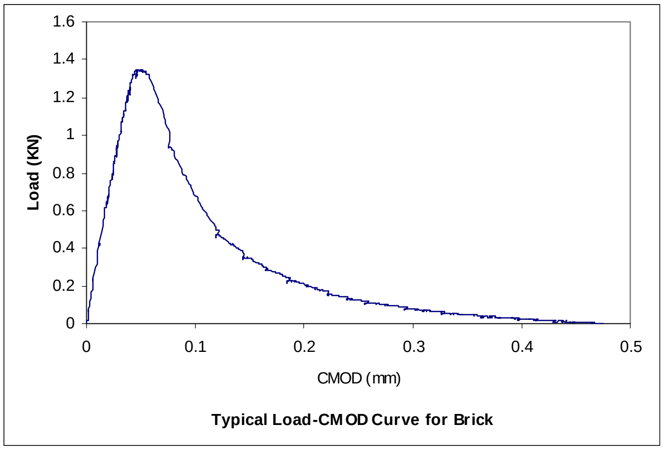

Fig. 3 Typical Load-CMOD Curve for Brick

At any given load, the total crack mouth opening displacement $CMOD^T$ at peak load is composed of the sum of the elastic crack mouth opening displacement $CMOD_o^e$, the opening at peak load if there is only linear elastic (i.e. no nonlinear) deformation, the inelastic crack mouth opening displacement $CMOD^*$ (essentially the residual opening on unloading from peak load) and the elastic crack mouth opening displacement $CMOD_s^e$ due to the nonlinear elastic effect (as shown in Fig.4). Note that the slope of the unloading line from the peak load is not the some as the initial modulus because the material has been degraded in the non-linear zone, and the modulus is now reduced.

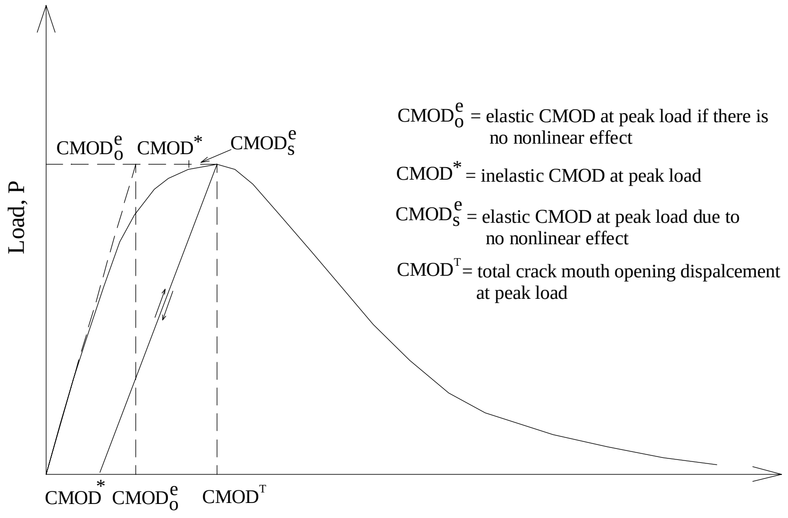

Fig. 4 Composition of CMOD due to nonlinear effect

The inelastic displacement at peak load can be related to the total displacement at the peak load as shown by [10]:

$$CMOD^T = \alpha CMOD^* \tag{1}$$

where the constant α is considered a material property and was established from the cycle tests.

Table 4 Experimental Results of K_{IC}

Specimen	Notch-to-depth ratio	Peak Load (KN)	G_{IC} (KN/m)	K_{IC} ($KN/m^{3/2}$)	Mean S.D.
CAA	1/6	3.855	355	821	20.75
CAB	2/6	2.473	351	816	15.05
CAC	3/6	1.623	390	860	17.72
CAD	4/6	0.748	290	742	8.61
CBA	1/6	2.642	167	563	20.32
CBB	2/6	2.107	255	695	7.18
CBC	3/6	1.203	214	638	13.83
CBD	4/6	0.444	102	441	24.08
CCA	1/6	3.39	274	722	9.79
CCB	2/6	2.159	267	713	17.53
CCC	3/6	1.409	294	747	17.22
CCD	4/6	0.621	200	616	11.50
SDA	1/6	3.519	110	458	10.99
SDB	2/6	2.153	90	426	13.45
SDC	3/6	1.297	90	413	20.49
SDD	4/6	0.554	57	330	7.50
SEA	1/6	4.910	207	627	25.87
SEB	2/6	2.651	145	525	20.62
SEC	3/6	1.578	133	502	25.52
SED	4/6	1.085	220	646	9.87
SFA	1/6	4.496	178	582	21.99
SFB	2/6	2.590	138	513	22.51
SFC	3/6	1.757	164	559	13.98
SFD	4/6	1.007	186	595	22.55

Determination of K_{IC}

The critical stress intensity factor K_{IC} defined as the fracture toughness of the material. K_{IC} represents a measure of how much and how far the local stress field is altered [11]. For a three-point bending test specimen, the corresponding LEFM equations are given:

Stress Intensity Factor K_I [12].

$$K_I = \sigma\sqrt{\pi a}F(a/H) \tag{2}$$

$$F(a/H) = \frac{1}{\pi}\cdot\frac{1.99 - A(1-A)(2.15 - 3.93A + 2.7A^2)}{(1+2A)(1-A)^{3/2}} \tag{3}$$

$$A = a/H \tag{4}$$

The above approximate formula is valid for any a/H within 0.5%.

Crack mouth opening displacement (CMOD).

$$CMOD = \frac{4\sigma a}{E} V(a/H) \tag{5}$$

$$V(a/H) = 0.76 - 2.28A + 3.87A^2 - 2.04A^3 + \frac{0.66}{(1-A)^2} \tag{6}$$

Crack Opening Displacement (COD)[11].

$$COD(x) = CMOD \cdot \left\{ \left(1 - \frac{x}{a}\right)^2 + (-1.149A + 1.081)\left[\frac{x}{a} - \left(\frac{x}{a}\right)^2\right] \right\}^{1/2} \tag{7}$$

The stress intensity factors K_{IC} obtained from the tests are listed in Table 4. K_{IC} of these bricks is of the same order of magnitude, but slightly lower than those of concrete[13], and than for the bricks of Bocca et al [7].

K_{IC} increases with brick compressive strength, as shown in Fig.5and 6. and is higher in solid compared to cored brick. According to our experiments, K_{IC} does not increase consistently with the notch depth. Our results demonstrate a random relationship with notch depth. This is somewhat different from Dukuze and Dawe's experimental results where the stress intensity factor increased slightly with the notch depth[8].

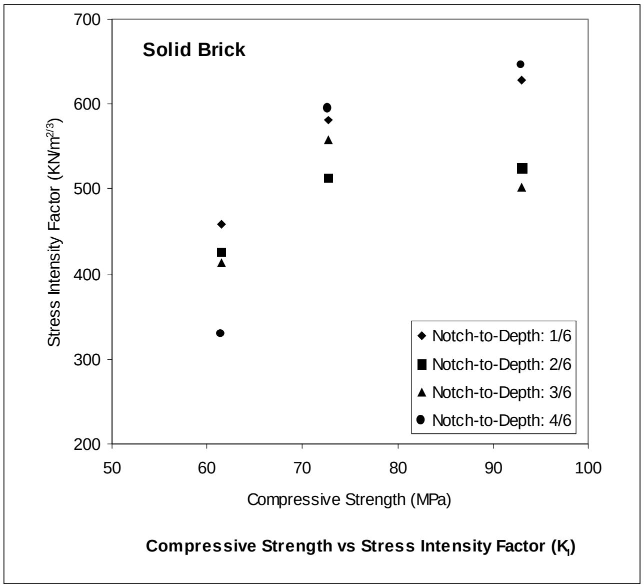

Fig. 5 Stress intensity increases with compressive strength (Solid Brick)

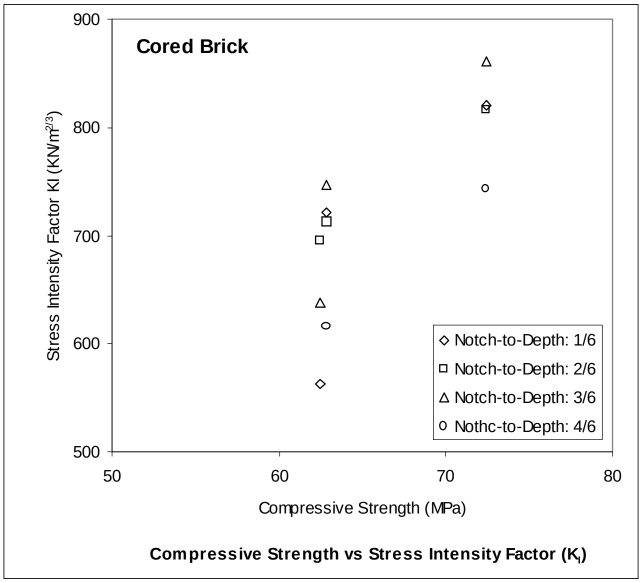

Fig. 6 Stress intensity increases with compressive strength (Cored Brick)

Fracture Energy G_F

G_{IC} is critical energy release rate usually used as a LEFM parameter to express the fracture toughness. G_{IC} can be derived from the following well-known relation:

$$K_{IC} = (G_{IC}E)^{1/2} \tag{8}$$

The values of G_{IC} are given in Table 4.

BRITTLE BEHAVIOUR OF BRICK SPECIMENS

In the Figure 7, the variation of the softening branch with initial notch depth in the brick specimen is shown. Specimens with shallow notches behave in a more brittle fashion than those with deeper notches. The result is consistent with that reported by Bocca et al [7].

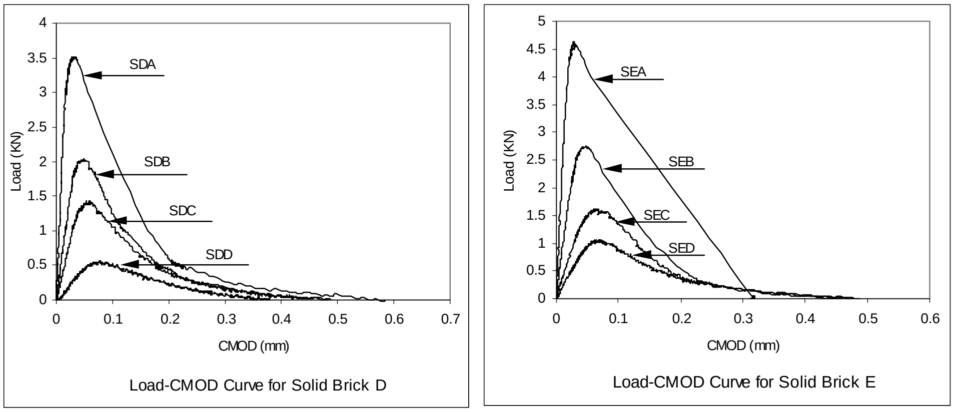

Fig.7 Specimens Behaves Brittle with Notch Depth

CONCLUSIONS

(1) Brick fracture toughness can be evaluated by three-point bending testing of notched specimens.

(2) The critical stress intensity factor of Cored brick is higher than that of Solid brick because of the smaller net thickness. The stress intensity factors obtained from our experiments are of the same order of magnitude, but slightly lower than those of concrete.

(3) The stress intensity factors of Cored bricks and Solid bricks increase with their compressive strengths.

(4) The brick notch sensitivity is not pronounced. According to our experimental results, the stress intensity factor does not increase consistently with the notch depth. Our results demonstrate no clear relationship with notch depth.

(5) The softening branch of load-CMOD curve obtained from experiments varies with the initial notch depth in the brick specimen. Specimens with shallow notches behave in a more brittle fashion than those with deeper notches

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