Fracture energy of full scale and half scale masonry bricks

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ABSTRACT:- *The failure of masonry brick units is usually characterised by fracture of the brick. This is as a result of the energy release mechanism of the material. Understanding the energy release mechanism of brick fracture should help in understanding the mechanics of the fracture formation in composite masonry. In this paper, the fracture energy of full scale and half scale masonry bricks were compared, with the results showing that the load-deflection diagrams of clay units exhibit a softening branch that indicate strain softening and stable crack growth. This is significant since it implies that fracture mechanics concepts could be used to understand the process of crack propagation and failure in small scale masonry modelling. The fracture energy for the full and half scale bricks were 47.4 N/m and 58.2 N/m respectively.*

Keywords:- *fracture, brick, masonry, full scale, half scale, model.*

I. INTRODUCTION

Clay bricks as used in this study are a type of ceramic formed by burning clay or shale at very high temperatures. Physically they are hard, brittle, non-ductile and highly temperature resistant. They are made up of varying composition of silicates and metallic oxides like alumina, kaolinite, mica etc, which are chemically stable and therefore make clay bricks suitable as a construction material.

The mechanism of failure in a brick unit is mainly occasioned by fracture of the brick. This is due to the energy release characteristic of the material. Understanding the energy release mechanism of brick fracture should help in understanding the mechanics of the fracture formation in composite masonry.

The aim of the paper is to determine the fracture energy of brick masonry at full scale (prototype) and model scale (half) in order to understand their respective fracture behaviour with a view to determining the suitability of modelling brick behaviour model scales.

II. THEORY

Fracture mechanics characterisation of masonry properties has been carried out by a number of authors[1-3], and their studies has shown that fracture mechanics can be used for the determination of the fracture parameters like fracture energy of masonry from adaptations to the standard RILEM[4] test set up for the determination of fracture energy for concrete. Bocca et al[1] undertook a series of three-point bending tests on clay brick units of 20 by 40mm in cross section and 200mm long, including varying the notch lengths. Their findings showed that load-deflection curves with post-peak softening branches can be obtained by controlling the crack mouth opening displacement. This finding is significant as it implies that clay brick units show a process of crack growth as evidenced in the strain softening (from the load-deflection graphs) and can therefore be modelled by Linear Elastic Fracture Mechanics (LEFM) techniques. Numerical models can then be used to predict fracture properties of masonry as well as gain a further insight into the mechanics of the composite behaviour of masonry using LEFM concepts.

Carpenteri et al[3] carried out perhaps the first test for the determination of the fracture parameters of a complete masonry assembly. Three-point bending tests were carried out on five notched masonry walls of different sizes (same thickness but varying span and depth) by controlling the crack mouth opening displacement. The load-deflection diagrams show a softening branch, an indication of strain softening and stable crack growth. From the diagrams, the fracture energy of the specimens was calculated and analysis with respect to the Multi Fracutral Scale Law (MFSL) using fractal fracture mechanics concepts. Also carried out was the analysis of the nominal strength from the tests according to the MFSL. The normal log-log plot of the nominal strength and reference structure size showed good agreement of the test data with the MFSL.

In a further study by Olivito and Stumpo[2] to characterise the mechanical behaviour of masonry using fracture mechanics concepts, they concluded that masonry can support low tensile stress conditions and exhibits a bimodular behaviour which must be defined individually, because it is related to masonry composition and texture. Their results also show that masonry exhibits a strain softening behaviour caused by the start and growth of cracking. The fracture specimens were masonry walls built in the form of a beam of two different sizes; (length x height x thickness) 720 x 225 x 120mm and 720 x 225 x 60mm. Instead of cutting a notch on the masonry, the central mortar perpend joint in the lowest brick row was left unfilled in order to initiate cracking in the central part of the specimens.

Using numerical simulations to model size effect in masonry structures, Lourenco[5] found that, for a masonry pier subjected to a point load in which failure was mainly due to a tensile failure mechanism, there is evidence of a size effect for the range of sizes simulated. The observed size effect closely followed the MFSL law as well as the size effect law (1), but more in agreement with the former. The reason for that, as has been discussed previously, is that the comparison should have been made to Bazant's other law for crack initiation from a smooth surface (2), which is identical to the MFSL (3). In the simulations for a shear wall with an opening and open on the top edge, in which a shear or sliding failure was dominant, no size effect was seen. The analysis was not conclusive about another configuration of shear walls tested that were restrained on the top edge in which a compressive failure was dominant.

$$\sigma_N = \frac{B_o f_t}{\sqrt{(1+\beta)}}, \beta = \frac{D}{D_0} \tag{1}$$

Where f_t = is a measure of material strength introduced to make Bo non-dimensional and B_o and D_o are empirical constants; coefficients B_o and D_o represent specimen shape and size. This assumes that the thickness b = constant for different D and also the specimen proportions are constant for all sizes. When the specimen is small, plasticity is also small, size effect does not manifest at these smaller values of β, and effectively results in a horizontal curve as seen in Fig. 1. At intermediate values, there is a smooth transition and in the case of LEFM at large sizes ($\beta \rightarrow \infty$) at which case size effect is very pronounced it approaches the asymptote with slope of 1:2[6]
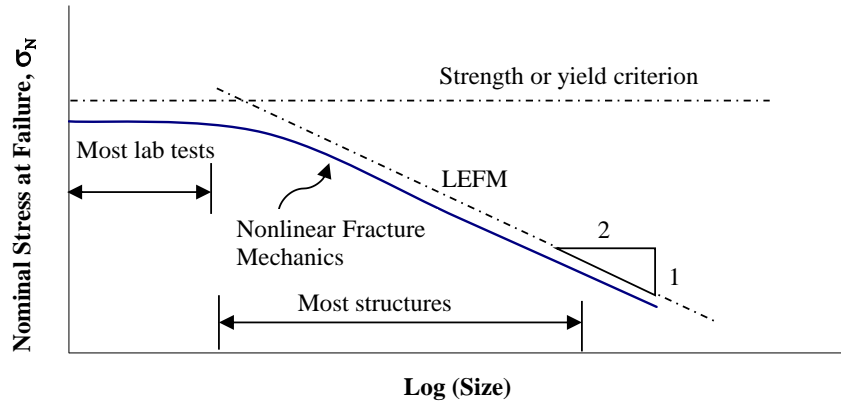

Figure 1- Size effect according to strength criteria, linear and nonlinear fracture mechanics.

$$\sigma_N = \sigma_0 \left(1 + \frac{2D_b}{D}\right)^{1/2} \tag{2}$$

$$\sigma_U = f_t \left(1 + \frac{l_{ch}}{b}\right)^{1/2} \tag{3}$$

where b is the characteristic dimension of the structure and l_{ch} is a characteristic length related to the material microstructure.

III. MATERIALS AND METHODS
a)   Prototype and Half Scale Model Bricks
The prototype brick used for the study was Baggeridge Mellowed Red Stock, while the model bricks were cut from it using a cutting method used by Taunton[1]. It involves first trimming all the four sides of a

prototype brick to make it 197 x 96 x 62 mm. Followed by a longitudinal cut through the brick at half its depth. Two other cuts were then made; one transverse across the brick at mid span and another longitudinal cut across the brick at half its width. The average dimensions of the prototype and half scale model bricks are given in Table 1.

b) **Fracture Energy Tests**

The facture energy is defined as the amount of energy required to propagate one unit area of crack, and the area of crack is the projected area on a plane parallel to the main crack direction. Since there is no specific standard test for fracture energy of masonry bricks, the RILEM recommendation, FMC 1[2] for the determination of the fracture energy of mortar and concrete was adapted. Two separate tests were carried out; one involving three brick units glued together (brick beam) and another consisting of only one unit. Three brick units joined together at their ends, as in the case of flexural energy test for brick units was tested in the first instance according to the procedures outlined in FMC 1. A central notch 5mm wide and cut to half of the unit height was made in the central unit of the specimens prior to being immersed in water for a period of 24hrs. The setup was then placed in the rig, where a transducer and a clip gauge were fitted to measure the vertical deflection at mid span and the crack mouth opening displacement (CMOD) respectively. The test was carried in the form of a three-point bending test and controlled by the CMOD gauge at a displacement rate of 0.0004mm/s. The measurements/readings were recorded on a data logger for later analysis. Plate 1 shows the set up for brick beam while Plate 2 shows the set up for the single unit test. It can be seen from the Plate 1 that while the LVDT for measuring the central mid span displacement was suspended from a jig mounted on the brick beam, the LVDT for the single brick test was supported from an attachment screwed into the unit. The drilling of the holes for the attachment of the screws in the unit, could have some undesired effect on the test even though it is difficult to quantify the exact effect.

A similar test was also undertaken using three half scale units glued together with a central 5mm wide, 10mm deep notch (1/3 of the unit height) in the middle unit. The test was also undertaken in the same machine at a displacement rate of 0.0002mm/s. Because of the expected low loads, a 250kgf Z-load cell was attached to the base of the loading platen to apply the load as well as to record it. With this set up, it was possible to use the 500kN capacity testing machine to measure loads to the accuracy of 0.1N. A set up for the test is shown in Plate 3 with the 250kgf Z-load cell on top of the specimen.

As stated earlier since there is no standard test for the fracture energy test for bricks, some authors like Baker[3] have used both brick beams and single units for brick fracture tests, while Bocca et al[4] used the single brick configuration for the their fracture tests. In order to compare the two tests, both single unit and brick beam configurations were used for the determination of the fracture energy in the current work

Calculations for the fracture energy were undertaken using Equation 4. This was done after determining the value of W_o, which is the area under the load- deflection graph calculated numerically on the PC using (5).

$$G_F = \frac{(W_o + mgd_o)}{A_{lig}} \tag{4}$$

Where:

G_F = fracture energy in N/m;

W_o = area under load- deflection graph in N/m;

$m = m1 + 2m2$ in kg;

$m1$ = weight of beam between supports in kg;

$m2$ = weight of loading arrangement not attached to machine in kg;

g = acceleration due to gravity in m/s^2;

d_o = deformation at the final failure of the beam in m;

A_{lig} = area of ligament, defined as the projection of the fracture zone on a plane perpendicular to the beam axis in m^2.

$$W_o = \sum_{i=1}^{n} (x_{i+1} - x_i).\frac{(y_i + y_{i+1})}{2} \tag{5}$$

IV. RESULTS AND DISCUSSION

Though the mean fracture energy from both the single brick and brick beam prototype tests as shown in are close; 50.7 N/m for the former and 47.4 N/m for the latter, the results from the single brick test are more variable with a COV of 54% compared with 10% for the brick beam tests. In the identification system used for the tests, B and FRC refer to Brick and Fracture test respectively, while BM and U refer to beam and single unit specimens respectively. The load/deflection curves for the brick beam tests are shown in Fig. 1 while those for

the single unit tests are shown in Fig. 2. The figures reveal that the load/deflection response for the beam test is softer than that for the single unit test. Similar results have also been obtained by Baker[8]. The difference is more noticeable when typical load/deflection curves for the two tests are combined on the graph as shown in Fig. 3, it shows that the single beam tests have a sharper peak and steeper gradient than the beam tests which show a gentler slope and flatter peak. This may be due to the greater bending effect because of the increased span on the crack propagation process in the central unit in the case of beam, while in the case of the single brick there is no such effect and hence the sharper peak and more brittle response. Another advantage of the beam test could be that, because of the restraining effect, it stabilises the specimen and hence variability is reduced as is apparent in the results. For these reasons the prototype fracture energy results shown in Table 2 are those from the beam test.

From the combined flexural stress/deflection response for the prototype and half scale tests in Fig. 4, it is seen that the half scale exhibits greater ductility than the prototype, as well as a capacity to withstand a marginally higher load. The mean fracture energy from the half scale test results was determined to be 58.2N/m, which is about 23% more than the prototype beam fracture energy. Therefore about 23% more energy is needed to propagate a unit area of crack in the half scale model unit compared to the prototype beam.

Table 1 - Average dimensions of prototype and model bricks.

Scale	Length ,mm	Width, mm	Depth, mm
Prototype	215.0	102.5	65.0
Half	96.8	46.1	29.3

Table 2 - Mechanical properties of prototype and model bricks.

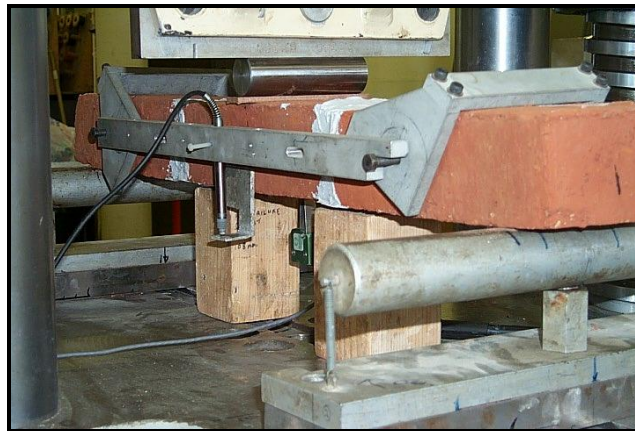| Test	Prototype	Half
Fracture Energy, N/m	47.4	58.2
COV, %	10.5	25.8

Plate 1 - Set up for brick beam fracture energy test.

Plate 2 - Set up for single brick unit fracture energy test.

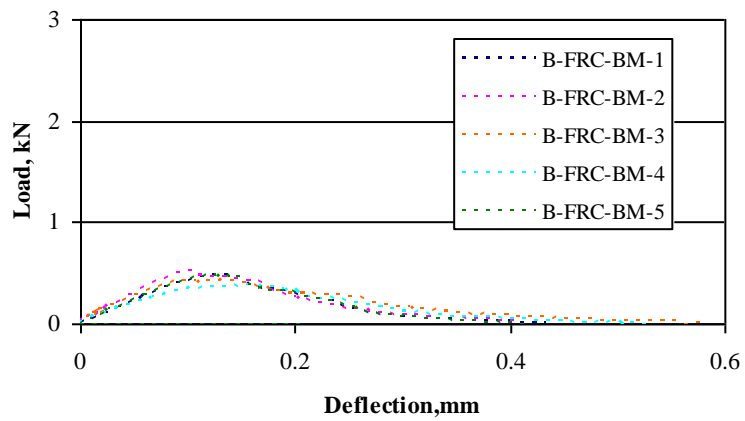Plate 3 - Set up for half scale model unit fracture test.

Figure 1- Load/deflection curves for prototype brick beam fracture test.
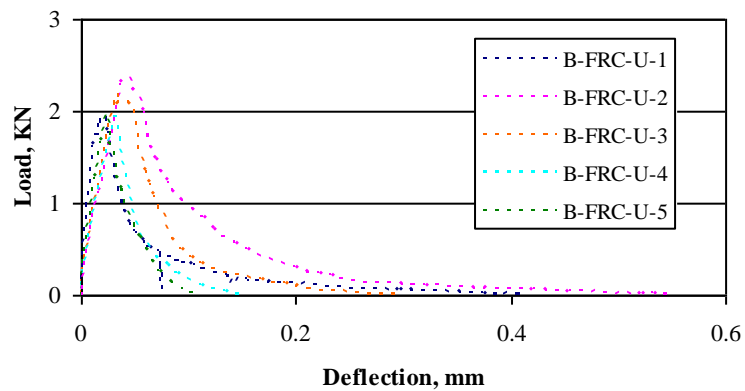

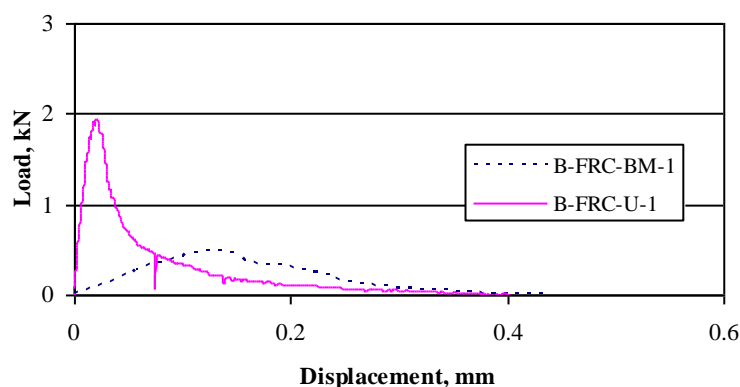Figure 2 - Load/deflection curves for prototype unit fracture test.

Figure 3 - Typical load/deflection response for beam and single unit prototype fracture energy tests.
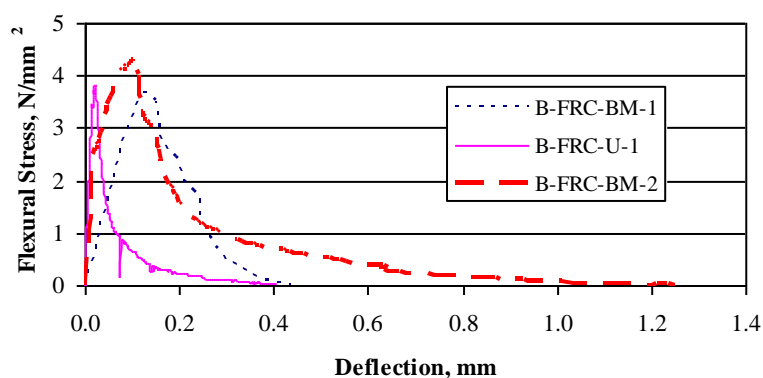

Figure 4 - Flexural stress/deflection response for prototype and half scale unit Fracture Energy tests.

V. CONCLUSION

The results have confirmed the findings in the literature [4] that load-deflection diagrams of clay units exhibit a softening branch that indicate strain softening and stable crack growth. This is significant since it implies that fracture mechanics concepts could be used to understand the process of crack propagation and failure in reduced scale masonry modelling studies. The mean fracture energy from the half scale test results was determined to be 58.2N/m, which is about 23% more than the prototype beam fracture energy. Therefore about 23% more energy is needed to propagate a unit area of crack in the half scale model unit compared to the prototype beam.

REFERENCES

[1].   Bocca, P., A. Carpinteri, and S. Valente, Fracture mechanics of brick masonry: size effects and snap-back analysis. Materials and Structures, 1989(22): p. 364-373.
[2].   Olivito, R.S. and P. Stumpo, Fracture mechanics in the characterisation of brick masonry structures. Materials and Structures, 2001. **34**: p. 217-223.
[3].   Carpenteri, A., B. Chiaia, and P. Bocca, Size dependence of strength and fracture properties of brick masonry. Journal of Engineering Mechanics, ASCE, 1997. **123**(8).
[4].   RILEM, FMC 1. Determination of the fracture energy of mortar and concrete by means of three-point bend tests on notched beams, in RILEM. 1994, E & FN Spon: London.
[5].   Lourenco, P.B. Simulations of size effect in masonry structures. in Proceedings FRAMCOS-3. 1998. Freiburg, Germany.
[6].   Harris, G.H. and G.M. Sabnis, Structural Modelling and Experimental Techniques. 2nd ed. 1999, Florida: CRC Press LLC.
[7].   Taunton, P.R., Centrifuge modelling of soil/masonry structure interaction. 1997, Cardiff University, UK.
[8].   Baker, M.G., Finite element analysis of masonry with application to arch bridges. 1996, University of Wales Cardiff.