MIXED-MODE FRACTURE TESTING OF THE MORTAR/UNIT INTERFACE

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SUMMARY

Mixed-mode fracture tests of the interface between clay units and mortar were conducted. Two-brick high specimens were constructed from two types of brick and two types of mortar. The specimens with a 2mm x 5mm pre-set crack were tested under mixed-mode loading. Behaviour at three levels of stress normal to the interface was examined: $\sigma = 0.5MPa$, $\sigma = 1MPa$, and $\sigma = 1.5MPa$. The types of interfacial fracture of masonry were investigated. The stress intensity factor for an interface crack was analyzed, and its influencing factors are discussed.

INTRODUCTION

Interfacial fracture mechanics can be used to define a measurable and usable material property – toughness - a measure of the fracture resistance of an interface. The two most important issues in interface fracture mechanics are definition of the stress intensity factor of the interface crack and oscillation of the singularity.

On the experimental side, a lot of work has been devoted to the study of interfaces, their character and behaviour, in materials science terms. A standard joint design is the Sandwich type where two parts made from the same materials are bonded by a thin adhesive layer. Such joints contain flaws (Yuuki et al. 1989, 1992, 1994). The observed strength of a joint depends upon the location and size of the flaws, and upon the crack path through the joint. Typically, crack paths are within the adhesive or the substrate, or along the interface. Various attempts have been made with different approaches to develop analytic models such as the Sandwich or Contact zone models. Ideally, a test specimen should cover a range of phase angles so that a variety of material mismatch and mixed mode loading conditions may be characterized, like the Brazilian disk specimen (Atkinson 1982). An early experimental study on the measurement of the fracture toughness of mortar-aggregate interfaces in concrete was performed by Hillemeier and Hilsdorf (1977). They reported limited test results that involved mode I loading conditions only (direct opening/separation of the surfaces). Buyukozturk (1998) investigated the influence of mortar, aggregate, and interfacial fracture properties on the performance of concrete composites.

In this paper, experimental and analytical results of tests on the fracture of the mortar/unit interface are reported.

INTERFACE FRACTURE MECHANICS

Definition of Stress Intensity Factors for an Interface Crack

The elastic solution for the stress field around an interface crack was derived by the Williams (1959), Erdogan and Gupta (1971), and England (1965). Consider an interface crack with the crack length 2a in dissimilar materials, as shown in Figure 1. The two materials are isotropic elastic materials with different shear modulus μ and Poisson's ratio ν.

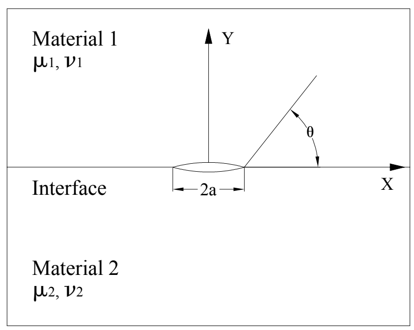


Figure 1 Interfacial Crack

Here the stress intensity factors for the interface crack are defined from:

$$\left[\sigma_y + i\tau_{xy}\right]_{\theta=0} = \frac{K_1 + iK_2}{\sqrt{(2\pi r)}}\left(\frac{r}{2a}\right)^{i\varepsilon} \tag{1}$$

Where, $i = \sqrt{-1}$

Here ε is the bi-material constant, also called the oscillation index, which can be expressed as

$$\varepsilon = \frac{1}{2\pi}\ln\left(\frac{k_1/\mu_1 + 1/\mu_2}{k_2/\mu_2 + 1/\mu_1}\right) \tag{2}$$

$\kappa_j = 3 - 4\nu_j$ for plane strain

$= (3 - \nu_j)/(1 + \nu_j)$ for plane stress

Where the subscripts 1 and 2 refer to the materials 1 and 2, μ_j and ν_j are the shear modulus and the Poisson's ratio of the materials, respectively.

$K_1 + iK_2$ is the complex stress intensity factor for the interface crack, which is quite different from the usual definition of the stress intensity factors for a crack in a homogeneous material. Because of the oscillatory singularity in the asymptotic stress field, the complex stress intensity factors K_1 and K_2 cannot be interpreted as the mode I and mode II stress intensity factors K_I and K_{II} in a homogeneous material.

The energy release rate, G, can be related to the stress intensity factor amplitude $|K|$ and Young's Modulus, E, through the relation

$$G = \frac{1}{E}\frac{|K|^2}{\cosh^2(\pi\varepsilon)} \quad (3)$$

$$|K|^2 = K\overline{K} = K_1^2 + K_2^2 \quad (4)$$

where

$$\frac{2}{E} = \frac{1}{\overline{E_1}} + \frac{1}{\overline{E_2}},$$

$\overline{E_i} = E_i$ for plane stress

$\overline{E_i} = \dfrac{E_i}{1-\nu_i^2}$ for plane strain

One important feature of bimaterial interface cracks is that the phase angle, ψ, is often non-zero; even when the external loading is normal to the interface plane (Wang et al.1990). This situation arises because of the elastic mismatch across the interface. Consequently, when solving interface fracture problems, it is essential to calculate ψ. This feature of interface fracture represents the major difference from the familiar treatment of fracture within an elastically homogeneous medium.

The phase angle ψ is a measure of the relative proportion of shear to normal traction ahead of the crack tip. It is defined through the relation

$$\psi = \tan^{-1}\left(\frac{\operatorname{Im}\left[Kl^{i\varepsilon}\right]}{\operatorname{Re}\left[Kl^{i\varepsilon}\right]}\right) = \tan^{-1}\left(\frac{K_1}{K_2}\right) \quad (5)$$

MATERIALS AND SPECIMENS

The specimens for the mixed-mode fracture testing of the mortar/unit interface were two-brick high stacked, as shown in Figure 2. The specimens were made from combinations of different

bricks and mortars. The dimensions of the pre-crack were a depth of 2mm and a length of 5mm, made with a pre-set piece of plastic when the specimens were built. This size pre-crack was used as it was larger than any flaw that might be expected in the masonry and would therefore be the critical flaw from which a crack should propagate. The pre-crack could not be too big as additional effects would be introduced from proximity to the edges of the specimen. The specimens were of solid brick and constructed with one of two different mortars, Type S and Type N. The specimens were named following the rule: the first character S stands for solid brick: Granville Gray Titan Solid (A), Cinnamon Titan Solid (B), (all bricks manufactured by I-XL Industries, Medicine Hat, Alberta); the second stands for the different brick (A, B); and the third stands for mortar type: N for type N mortar, S for type S mortar. The specimens were thus SAS, SBS, SAN and SBN.

EXPERIMENTAL ARRANGEMENT

The experimental test arrangement is shown in Figure 2. The tests were conducted with an MTS closed-loop, electro hydraulic test machine. The applied vertical loads gave average stresses of 0.5MPa, 1.0MPa and 1.5MPa. The horizontal actuator was displaced at 0.01mm/second. The relative displacement between the upper and lower bricks was measured using LVDT's. It is difficult to do such experiments without a moment developing across the region of interest because of the physical size of the plates and the thickness of the mortar joint. The horizontal load was applied to as close to the mortar joint as possible.

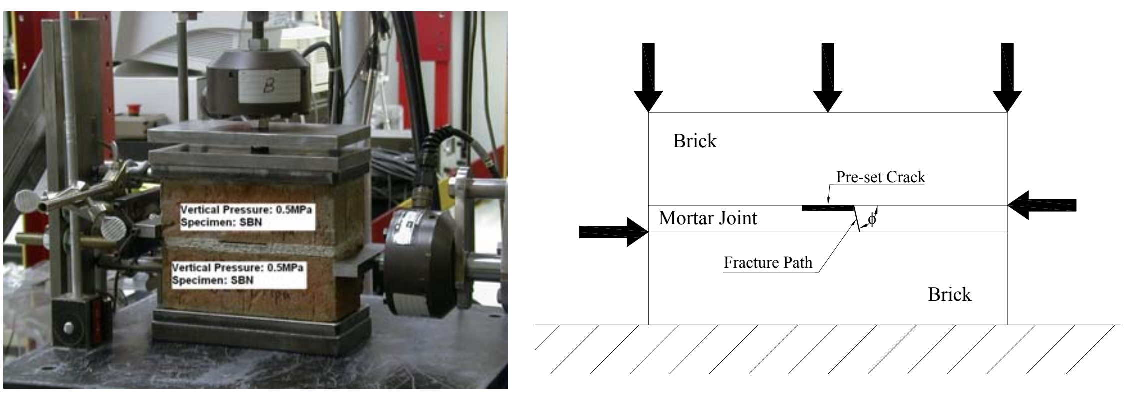


Figure 2 Test Configuration

RESULTS AND DISCUSSION

Experimental Results

The interface fracture toughness test results are listed in Tables 1 to 3, including fracture load, failure mode and fracture angle.

Table 1 Interface Shear Experimental Results, Vertical Load Level σ=0.5 MPa

	Peak Shear Load (KN)	Failure Mode	Fracture Angle ϕ (Degree)
SAS-1	17.64	Kink out of interface into mortar	78
SAS-2	11.18	Along the interface	0
SAS-3	12.28	Along the interface	0
SAS-4	18.57	Kink out of interface into mortar	71
SAS-5	-	Not fail	-
SAS-6	11.72	Along the interface	0
SBS-1	13.10	Along the interface	0
SBS-2	11.47	Along the interface	0
SBS-3	14.92	Along the interface	0
SBS-4	13.57	Along the interface	0
SBS-5	12.17	Along the interface	0
SBS-6	14.95	Along the interface	0
SAN-1	18.07	Kink out of interface into mortar	79
SAN-2	19.01	Kink out of interface into mortar	80
SAN-3	18.49	Kink out of interface into mortar	76
SAN-4	15.76	Along the interface	0
SAN-5	18.24	Kink out of interface into mortar	77
SAN-6	20.57	Kink out of interface into mortar	74
SBN-1	20.35	Kink out of interface into mortar	75
SBN-2	18.86	Kink out of interface into mortar	78
SBN-3	19.48	Kink out of interface into mortar	72
SBN-4	17.33	Kink out of interface into mortar	76
SBN-5	18.86	Kink out of interface into mortar	71
SBN-6	20.24	Kink out of interface into mortar	77

Table 2 Interface Shear Experimental Results, Vertical Load Level σ=1.0 MPa

	Peak Shear Load (KN)	Failure Mode	Fracture Angle (Degree)
SAS-1	14.95	Along the interface	0
SAS-2	12.52	Crack at the end	80
SAS-3	14.19	Along the interface	0
SAS-4	18.72	Kink out of interface into mortar	80
SAS-5	19.68	Kink out of interface into mortar	81
SAS-6	14.48	Along the interface	0
SBS-1	13.59	Along the interface	0
SBS-2	12.11	Along the interface	0
SBS-3	14.59	Along the interface	0
SBS-4	-	Not fail	-
SBS-5	15.95	Along the interface	0
SAN-1	20.21	Kink out of interface into mortar	79
SAN-2	14.46	Along the interface	0
SAN-3	20.20	Kink out of interface into mortar	83
SAN-4	16.41	Crack at the end	80
SAN-5	19.55	Kink out of interface into mortar	77
SAN-6	20.31	Kink out of interface into mortar	78
SBN-1	20.94	Kink out of interface into mortar	81
SBN-2	16.41	Along the interface	0
SBN-3	20.10	Crack at the end	82
SBN-4	19.14	Kink out of interface into mortar	80
SBN-5	20.83	Kink out of interface into mortar	79
SBN-6	15.61	Along the interface	0

Table 3 Interface Shear Experimental Results, Vertical Load Level σ=1.5 MPa

	Peak Shear Load (KN)	Failure Mode	Fracture Angle (Degree)
SAS-1	19.36	Crack at the end	81
SAS-2	20.64	Kink out of interface into mortar	80
SAS-3	20.81	Kink out of interface into mortar	75
SAS-4	19.94	Kink out of interface into mortar	79
SAS-5	17.55	Along the interface	0
SAS-6	16.83	Along the interface	0
SBS-1	18.03	Along the interface	0
SBS-2	20.46	Kink out of interface into mortar	81
SBS-3	18.32	Along the interface	0
SBS-4	-	Not fail	-
SBS-5	-	Not fail	-
SBS-6	-	Not fail	-
SAN-1	19.00	Kink out of interface into mortar	81
SAN-2	20.36	Kink out of interface into mortar	83
SAN-3	20.56	Kink out of interface into mortar	81
SAN-4	21.33	Kink out of interface into mortar	80
SAN-5	19.89	Kink out of interface into mortar	78
SAN-6	18.09	Kink out of interface into mortar	79
SBN-1	18.78	Along the interface	0
SBN-2	21.17	Kink out of interface into mortar	81
SBN-3	20.45	Kink out of interface into mortar	83
SBN-4	21.64	Kink out of interface into mortar	80
SBN-5	-	Not fail	-
SBN-6	-	Not fail	-

Finite Element Anylsis-FRANC2D

FRANC2D (Cornell University 2007) was employed to calculate the interface fracture parameters, and investigate the influence of the strengths of brick and mortar on the fracture parameters. FRANC2D uses eight-node quadrilateral elements with quadratic shape functions. The crack tip is modeled using a rosette of six-node triangular elements.

The brick and mortar were taken as elastic materials with the material constants listed in Table 4.

Table 4 Material Properties

		Compressive Strength (MPa)	Modulus of Elasticity (MPa)	Poisson's ratio
Brick	A	60.6	14000	0.2
	B	93	15000	0.2
Mortar	S	17.4	12000	0.28
	N	12.96	10000	0.28

The calculated fracture parameters are listed in Tables 5 to 7.

Table 5 Fracture Parameters, Vertical Load Level σ=0.5 MPa

	SIF K1($kNm^{-3/2}$)	SIF K2 ($kNm^{-3/2}$)	K ($kNm^{-3/2}$)	Fracture Toughness G (Nm^{-1})	Phase Angle Ψ (Degree)
SAS	167	412	445	14.9	67.9
SBS	154	387	417	12.7	68.3
SAN	147	349	379	12.0	67.2
SBN	163	398	430	15.0	67.7

Table 6 Fracture Parameters, Vertical Load Level σ=1.0 MPa

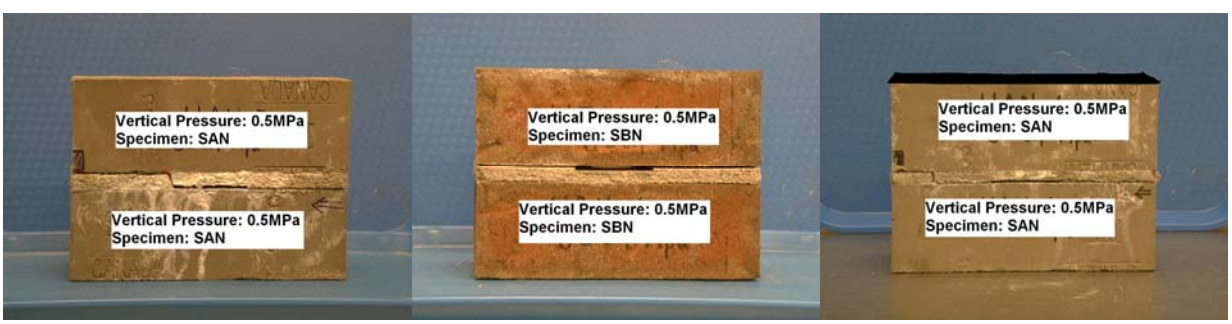
	SIF K1($kNm^{-3/2}$)	SIF K2 ($kNm^{-3/2}$)	K ($kNm^{-3/2}$)	Fracture Toughness G (Nm^{-1})	Phase Angle Ψ (Degree)
SAS	169	482	511	19.7	70.7
SBS	178	521	551	22.2	71.1
SAN	171	479	509	21.6	70.4
SBN	157	454	480	18.8	70.9

Table 7 Fracture Parameters, Vertical Load Level σ=1.5 MPa

	SIF K1($kNm^{-3/2}$)	SIF K2 ($kNm^{-3/2}$)	K ($kNm^{-3/2}$)	Fracture Toughness G (Nm^{-1})	Phase Angle Ψ (Degree)
SAS	161	592	614	31.5	74.8
SBS	159	597	618	31.0	75.1
SAN	144	503	523	20.7	74.0
SBN	155	567	588	25.3	74.7

Interface Failure Modes and Crack Paths

Three failure types were observed, illustrated schematically in Figure 3. For the first type failure, debonding started at some point along the interface, ran onto the pre-set crack, then kinked to the other interface. Secondly, the interface containing the pre-set crack separated, cracking along the interface, leaving the unbroken mortar joint layer on the other side. The third type of failure started outside the pre-set interface crack, at some point close to the end of specimen.



(a) (b) (c)

Figure 3 Possible Cracking Paths (a) Cracking kinks into mortar out of the interface (b) Cracking along the interface, (c) Cracking at the end

Interface Failure Parameters and the Influencing Factors

The calculated interfacial toughness curve is plotted in Figure 4. The interfacial toughness varies with the phase angle ψ. It is clear that the interfacial toughness depends significantly on the phase angle, increasing substantially over a small range of phase angle. Interfacial fracture energy release rates for a variety of mortar-aggregate interfaces have been assessed through Sandwich beam and Brazilian disk specimen tests (Buyukozturk 1993, Lee 1992). The fracture toughness curve for the concrete specimens shows a similar trend as that for our specimens. Rougher aggregate surfaces have also been shown to increase the interfacial toughness.

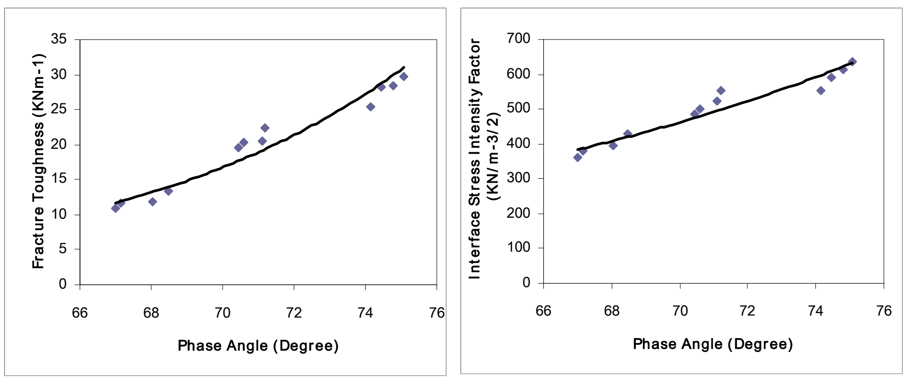


Figure 4 Fracture Parameters versus Phase Angle

The interfacial stress intensity factors are also plotted against the phase angle in Figure 4. Our tests cover a small range of phase angle, from approximately 65 degrees to 75 degrees. Figure 4 indicates that the interfacial stress intensity factor also increases with phase angle. An interface fracture toughness test (Pang 2002) for adhesive bonded joints shows a similar trend. Figure 4 also indicates that the maximum fracture toughness will occur under a mode II loading condition.

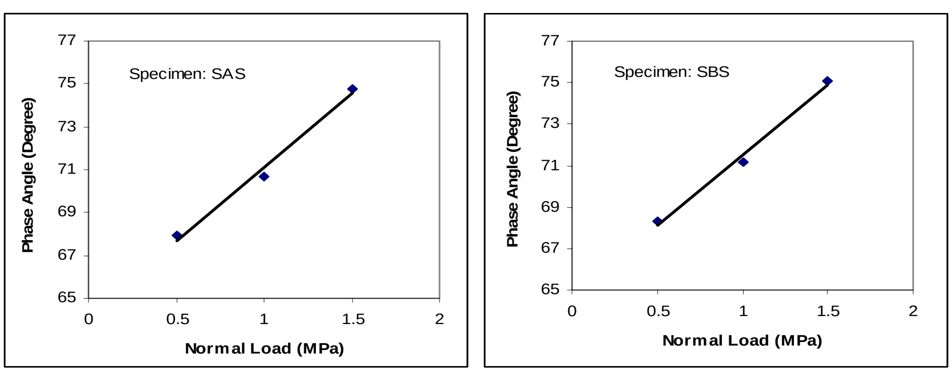


Figure 5 Phase Angle increases with Vertical Pressure – Specimens SAS and SBS

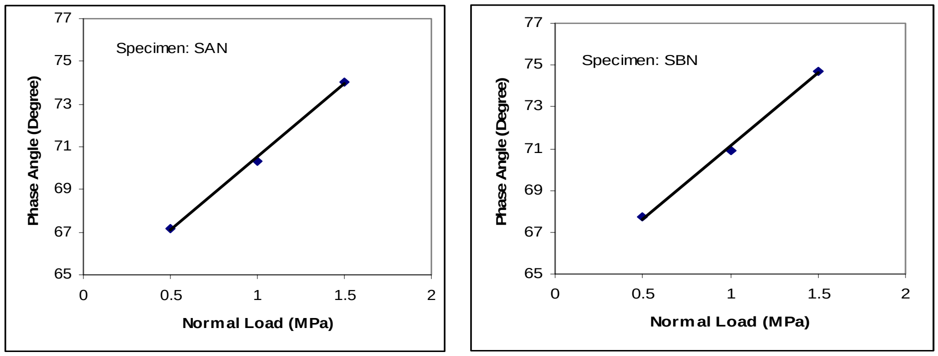


Figure 6 Phase Angle increases with Vertical Pressure – Specimens SAN and SBN

The stress normal to the joint affects the phase angle. The variations of the vertical loads are reflected into the variations of loading angles like a Brazilian disk specimen. The relationship between phase angle and normal stress are shown in Figures 5 and 6 for the different specimens. The phase angle increases slightly with normal stress.

The Type S mortar has higher bond strength than Type N mortar. Thus, there is a change in modular ratio of mortar to brick from Type S mortar to Type N mortar in the specimen. The change in modulus has an influence on the phase angle and interfacial fracture parameters. The phase angle and interfacial fracture parameters increase with the mortar and brick strengths.

CONCLUSIONS

The experimental results and analysis presented here demonstrate the interfacial fracture toughness of the masonry. This initial investigation indicates that normally the interface between mortar and brick fails in one of three ways: start at the interface, then kink out of the interface into the mortar joint; crack propagation along the interface; and cracking starting at some point close to the end of specimen. The normal stress affects the loading angle of the resultant of the vertical and horizontal loads, and thus the phase angle. The phase angle increases slightly with normal stress. The phase angle and interfacial fracture parameters increase with the mortar and brick strengths. The interfacial fracture toughness increases as the phase angle increases.

The range of the phase angle falls between 65 degrees and 75 degrees in our study. A larger range of phase angles needs to be achieved. Further work should therefore be aimed at assessing interfacial fracture toughness as a function of a bigger range of phase angles. The values of interfacial toughness need to be compared at the same phase angle. A 2mm by 5mm pre-set crack in the interface of the mortar and the brick was used in our test. As interfacial fracture toughness is dependent on crack length, further work should be undertaken to investigate the influence of the crack length on the interfacial fracture parameters.

We have conducted an initial investigation into interface fracture in masonry. This was the first work in this area. Much more research is needed.

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