PROPOSAL FOR AN EXPERIMENTAL TESTING OF BONDING STRENGTH BETWEEN MORTAR AND BRICK

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Abstract

Geometry of mortar and brick construction in monumental masonry led to the development of a multitude of specimens for de-bonding strength of the two materials. All of them -overview in [3]-apply a tensile compression shear or a mixed mode loading condition on the bi-material specimens and use empirical fracture criteria, but they do not guarantee pure de-bonding. Moreover, their phenomenological theory is not able to explain a) why de-bonding usually appears along the interface of the two materials and b) the fracture procedure under environmental influences (humidity, pollution). Especially for monuments, an accurate knowledge of materials behavior is important.

The proposed specimen design is more deterministic, is able to give accurate stress and displacement conditions, is pliant to explain environmental fracture procedure and can be easily constructed. The design itself bases on the elastic fracture mechanics theory. According to this theory a body always contains defects which are modeled as macro-or micro-cracks. This theory is able to express stresses and displacements around crack tips. For an interface crack a mathematical solution has been used witch is able to give pure tensional or shear de-bonding in the be-material interface for an appropriate relation of external applied loads.

Because of the different Poisson ratios of brick and mortar, the neighborhood of the interface gets micro-cracks for loads lower than the critical ones for each material.

In order to determine the critical external load for pure crack tip opening displacement and pure crack lips sliding displacement, a stress intensity factor criterion in relation to a maximum tangential stress analysis (on the process zone periphery) has been applied. For environmental solute diffusion and material damage, the criterion developed in [9, 15] has been used. This criterion is based on a stress-assisted diffusion theory which relates critical environmental conditions and hydrostatic stresses in the body. The result of the present analysis is able to determine pure de-bonding strengths.

Introduction

The weak point in all masonry is usually the mortar layer. When, as is the general rule, bricks and mortar have differing Poisson ratios, the typical fracture is an interface debonding. The effects of chemical solutes and of humidity, together with external loads cause destruction and fraction of mortar and/or brick. Establishing the differing strengths of mortar and brick, and also of the bimaterial brick-mortar therefore, is of great importance. For new and modern constructions, the strength of a brick-mortar system can be estimated experimentally: test sections are built with bricks and mortar of the same consistency and geometry as specified in the plans or in the masonry of the building. The standard theory of material resistance is applied to these sections, and norms are established for specimen geometry and for loading conditions during the experiment.

Unfortunately this method is not applicable to not contemporary monuments. The opportunity to remove samples for debonding tests, destructive in nature, is severely limited. Nor is it possible to have large simples and to use specimens described in the norms applied on modern buildings. Their geometry has to be different according to the special character of each monument, and there has been little attempt to standardise these experiments making comparative studies almost impossible to conduct. It is almost impossible to reconstruct old brick-mortar samples when neither the consistency of the mortar, nor the consistency of bricks and the method of manufacture is fully known. Another way to determine the resistance of brick-mortar to debonding could be to estimate experimentally the strength of each material separately, employing a fracture theory appropriate to take into account the mechanical behaviour of a bimaterial involved and verifying the theory by experiments.

The selection of the most appropriate configuration for de-bonding measurements has led researchers to propose many kinds of geometry for bi-material masonry and as many experimental procedures. They used the commonly accepted Theory of Material Resistance, i.e. Tassios [1], Penelis [2], Miltiadou [3] and Ignatakis [4]. International norms for de-bonding testing have not been established and therefore the experimental results cannot always be compared. For ancient monuments, test sections have been used which consist of one to four bricks, masonry fragments, or whole masonry as given in overview in [3] (see Figure 1) and [4].

All of these have been subjected to shear loading on the mortar layer, but the results whatever the specimen used, suffer from the same defects:-

a they cannot provide theoretically precise information (length, direction) about the expected fracture surfaces and the surrounding stress field, especially in the neighborhood of the crack tip.

(In order to calculate the stress field attention has to be given to stress singularity to the interface; the stress singularity at the starting point of the fracture [crack tip or notch]; the ratio of the shear moduli of the two materials [dependent upon their Poisson Ratios and their moduli of elasticity]; and the amount of plane strain/stress)

b the results do not allow for the different strength of the interface bonding brick and mortar.

It is especially the case that bonding strength cannot be exactly estimated, if the path of the expected crack growth (and of the micro-cracks in the interface) is not known. The Theory of Fracture Mechanics is to be preferred to the standard Theory of Material Resistance as the appropriate tool here, because it can focus the analysis on the immediate neighborhood of the fracture process zone, and because it is based on a mathematical theory - in this paper the linear theory of elasticity has been used - developed by Muskelishvili [5], Irvin [6], Sih [7] and many other researchers. For mixed mode loading in homogeneous solids, Carpinteri et all [8] have developed a connection between the Theory of Fracture Mechanics and the Theory of Material Resistance. The present work proposes the selection of a suitable bi-material specimen in order to measure de-bonding, so as to avoid the inadequacies inherent in the procedures described above.

The first section deals with the stress field analysis in the neighborhood of an interface crack and the fracture path direction is determined. In the second section the influence of environmental solutes is determined using the theory for stress assisted diffusion of Aifantis [9-15], the fracture path direction is calculated and compared with the one in the first section. In the third section necessary principles for planing of fracture mechanics specimens are described and an interpretation of the experiment results is given. In the fourth section conclusions are summarised.

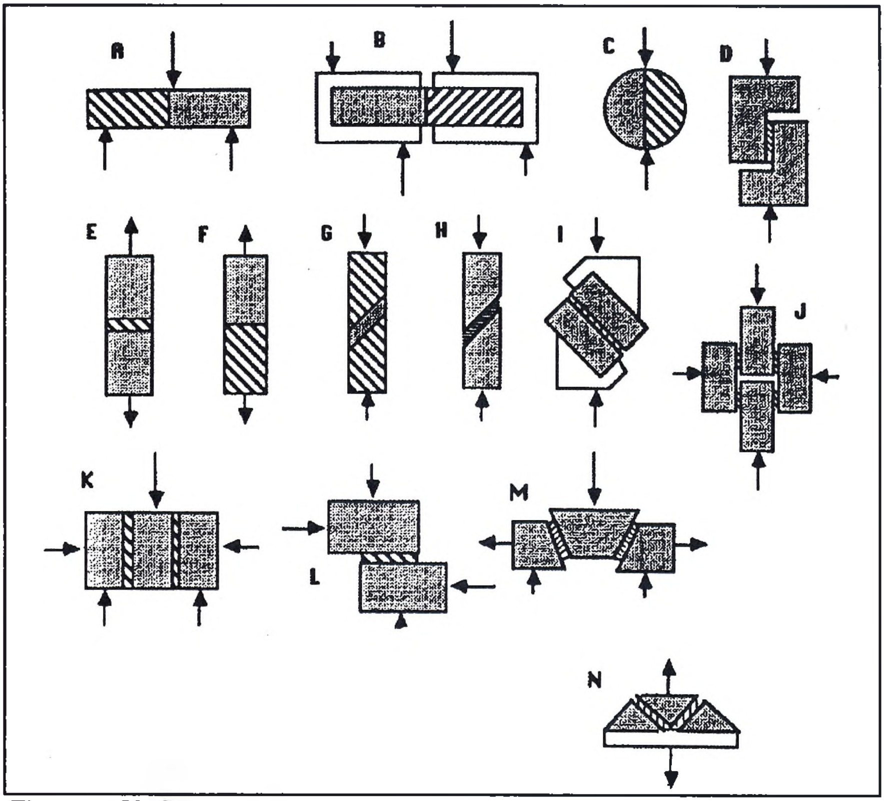

Figure 1: Various specimens and load devices for the measurement of de-bonding strength of brick and mortar [3].

Stress-concentration profiles at the tip of an interface crack

Let us assume that the two solids, brick and mortar, are perfectly bonded along their interface. The normal stresses in the two solids which act perpendicularly to the interface, are equal. This is the case also for the shear stresses on the two sides at the interface:

$$\sigma_{yy,m} = \sigma_{yy,b}, \quad \sigma_{xy,m} = \sigma_{xy,b} \tag{1}$$

The normal stresses parallel to the interface are not equal and must satisfy the relation

$$\sigma_{xx,b} = \{g(1+\varkappa_m)\,\sigma_{xx,m} + [3-\varkappa_b-g(3-\varkappa_m)]\,\sigma_{yy,m}\} / (1+\varkappa_b) \tag{2}$$

where $g=G_b/G_m$. G_m and G_b are the shear moduli for mortar and brick respectively, ν_m and ν_b the corresponding Poisson ratios (see Figure 2).

Therefore, if the applied load normal to the interface is σ_{yy}^{∞} on the mortar, the corresponding one on the brick must be $-\sigma_{yy}^{\infty}$ (similar to Figure 2). If the applied loads parallel to the interface and on the mortar are $\sigma_{xx,m}=k\sigma_{yy}^{\infty}$ and $-k\sigma_{yy}^{\infty}$, then the applied loads on the two free surfaces of the brick must be $\sigma_{xx,b}$ and $-\sigma_{xx,b}$. Usually, the moduli of elasticity is $E_m<E_b$ and for the Poisson Ratios $v_m>v_b$, which point to $g=G_b/G_m>1$ and $\sigma_{xx,b}>\sigma_{xx,m}$. For tensile loads which are applied normal to the plane of the interface it is expected that close to the interface, secondary tensile deformations will be developed, in the mortar having a orientation parallel to the interface. For compressive loads normal to the interface, secondary tensile deformations are developed in the brick having a orientation parallel to the interface.

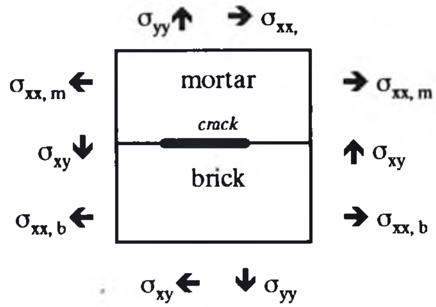

Figure 2: Loads applied on brick and mortar for equilibrium.

Let us now analyze the brick-mortar solid using the theory of Fracture Mechanics: We examined a bi-material sample with a crack of length 2a along the interface loaded with distributed normal and shear stresses, σ_{yy}^{∞} and σ_{xy}^{∞}, at infinity. According to the fracture mechanics analysis of linear elasticity (which is the simplest approach), the stress distribution in the neighbourhood of the crack tip has a square root singularity as given by Shih [16]

$$\sigma_{ij} = (2\pi r)^{1/2} (Q_I g_{ij}^{(I)} + Q_{II} g_{ij}^{(II)}) \tag{3}$$

where $i=r, \theta$ and $j= r, \theta$, with r the distance of the observed material point from the crack tip and θ its polar co-ordinate, Q_I and Q_{II} denote respectively the generalised mode I and mode II stress intensity factors which for an interface finite crack in infinite plate (see Figure 2) are defined by

$$Q=Q_I+iQ_{II}=[(\sigma_{yy}^{\infty} - 2H_m \sigma_{xy}^{\infty})+i(\sigma_{xy}^{\infty}+ 2H_m \sigma_{yy}^{\infty})] (\pi a)^{1/2} \tag{4a}$$

and for an interface semi-infinite crack subjected to point loads (see Figure 3) are defined by

$$Q=Q_I+iQ_{II}=(P+iT) \cosh(\pi H_m)(\pi a)^{1/2} \tag{4a}$$

where the geometric factor $g_{ij}^{(I)}$ and $g_{ij}^{(II)}$ depends on the bi-material constant H_m and the position of the point under consideration. In fact, eqs (4) above holds for mortar ($\theta>0$). A corresponding formula holds for brick ($\theta<0$). The definition of the bi-material constant H_m is given by

$$H_m=(2\pi)^{-1}\log G_0, \quad G_0=(G_m+\kappa_m G_b)/(G_b+\kappa_b G_m) \quad (5)$$

where $\kappa_i=3-4v_i$ (for plane strain) and $\kappa_i=(3-v_i)/(1+v_i)$ (for plane stress); $1<\kappa_i<3$. For the constant H_b describing the stress field in brick, is

$$H_b = (2\pi)^{-1}\log G_0^{-1} \quad (6)$$

The constants G_0, G_m, G_b denote shear moduli with G_0 given by eqn (5) above and (G_m, G_b) represent the shear moduli of mortar and brick respectively. For $G_0>1$, which is the case for $G_b/G_m<(1-\kappa_b)/(1-\kappa_m)$, it follows that $H_m>0$ and $H_b<0$. For $G_0<1$, which is the case for $G_b/G_m>(1-\kappa_b)/(1-\kappa_m)$, it follows that $H_m<0$ and $H_b>0$. For $G_b/G_m=0$ it follows that $H_m<0$, and for $G_b/G_m=\infty$ it follows that $H_m>0$. Finally, we note that $H_m=0$ only for $G_0=1$, so that for $G_b/G_m=(\kappa_m-1)/(\kappa_b-1)$. Setting for mortar as brick respectively $E_m=1.0$ Gpa and $E_b=2.2$ GPa, it follows that $H_m>0$.

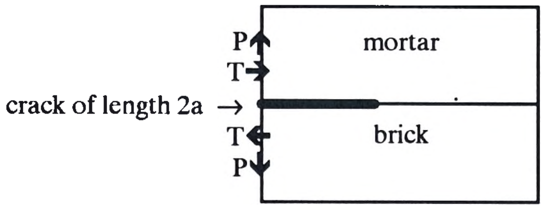

Figure 3: a) semi-infinite crack subject to point loads.

In the following, only the analysis for mortar and H_m will be examined. The relation between $Q=Q_I+iQ_{II}$ and the stress intensity factor of Sih and Rice [17] $k=k_I+ik_{II}$ is

$$Q=k\,\pi^{1/2}\cosh(\pi H_m)\,(2a)^{i\,Hm} \quad (7)$$

In this connection, it is noted that, in contrast to eqn (3) above, the expressions of Sih and Rice for the stress intensity factor k and the corresponding stresses contain the logarithm of a length. Moreover, they cannot be applied in the concise form used there. The trace of the stresses gets the form

$$\mathrm{tr}\,\sigma=C\{Q_I\cos[\theta/2+H_m\log(r/2a)]-Q_{II}\sin[\theta/2+H_M\log(r/2a)]\}\,/\,(\pi r)^{1/2} \quad (8)$$

where

$$C=2^{1/2}\,[\exp[H_m(\pi-\theta)]\cosh(\pi H_m)]^{-1}>0$$

The maximum value of the trace is obtained for $\partial\,\mathrm{tr}\sigma/\partial\theta=0$, $\partial^2\mathrm{tr}\sigma/\partial\theta^2<0$ and for interfacial crack propagation, θ_0 must be zero. This points to

$$Q_{I,\,cr}/Q_{II,\,cr}=(2H_m\,s+c)/\,(2H_m\,c+s) \quad ((9)$$

where

$$s=\sin[H_m \ln(r_{cr}/2a)] \text{ and } c=\cos[H_m \ln(r_{cr}/2a)]$$

As a first approach, the value r_{cr} could be chosen for the diameter of a mortar grain, about 1mm. More accurately, r_{cr} could be estimated experimentally with a mortar-brick specimen having an interface crack subjected to an appropriate external load to induce interfacial cracking . According to the fracture criterion of the strain energy density developed by Sih [7], the critical strain energy density for plane stress conditions is given as

$$(dW/dV)_{cr} = K_{Icr}^2 (1-2v_m)(1+v_m)/(2\pi E_m r_{cr}) \qquad (10)$$

The critical strain energy density for the brick-mortar solid under consideration is the area between the stress-strain curve in the graph of the experiment and the strain axis. Also the critical stress intensity factor K_{Icr} can be estimated experimentally.

The tangential stress is given for $i=j=\theta$ in eqn (3). It's maximum value is given if $\partial\sigma_{\theta\theta}/\partial\theta=0$, $\partial^2 \sigma_{\theta\theta}/\partial\theta^2<0$. This condition also expresses a maximum tangential stress fracture criterion. For $\theta=0$, the critical generalised stress intensity factors $Q_{I,cr}$ and $Q_{II,cr}$ and (according to eqs (4)) the applied load components, σ_{xy}^{∞} and σ_{yy}^{∞} or P and T, are obtained:

$$Q_{I,cr}/Q_{II,cr} = (e^-+e^+)(H_m s-3c/2) / [(e^--e^+-2) H_m c - (e^-+e^+)(3s/2)] \qquad (11)$$

where

$$e^-=\exp(-\pi H_m),\ e^+=\exp(\pi H_m)$$

Obviously, the right part in eqn (9) is not the same as the one in eqn (11). Eqn (9) is used for fracture criteria based on the hydrogen stress (i.e. for stress assisted environmental diffusion and fracture) and eqn (11) is valid for the maximum tangential fracture criterion, usually applied for brittle materials which are not influenced by environmental solute diffusion.

Water diffusion

We consider a bi-material plate with a crack of length 2a through the interface loaded with distributed normal and shear stresses, σ_{yy}^{∞} and σ_{xy}^{∞}, at infinity (Figure 4). The plate is subjected to a gaseous hydrogen environment of pressure p. Atomic hydrogen diffuses in mortar and brick at their free surface. The hydrogen solute has a concentration ϱ_0 which is a value different for mortar and brick. At any randomly selected point on each solid of the plate, the distribution of hydrogen is given by the stress-concentration equilibrium relation [9]

$$\varrho= \varrho_0 (1+\beta\, tr\sigma)^{\alpha} \qquad (11)$$

where $tr\sigma$ is the trace of the stress and the coefficients α and β are given by $\alpha=M/N$, $\beta=N/D$ (the physical meaning of the constants M, N and D is as defined in [12] and their value is different for mortar and brick). The environmental fracture criterion states that the direction of crack growth θ_{cr} is determined by the fracture condition $\varrho_{max}=\varrho_{cr}$ i.e fracture occurs at a point on a circumference of a core region of radius r_{cr} surrounding the crack tip where the hydrogen concentration ϱ reaches a critical value ϱ_{max} (ϱ_{max} is a fracture constant different for each material). The radius r_{cr} , which is a fracture behavioural parameter, is assumed to be larger than the overlapping region of the crack surfaces. The fracture criterion described here bases on the trace of the stress and eqs (8) and (9) can be used.

Principles for the design of a specimen

The maximum tangential stress fracture criterion is more appropriate for crack propagation in brittle materials which are in environments without diffusive solutes. If hydrogen is not to ignore, the diffusion criterion must be employed. For both of them pure debonding in a bi-material plate occurs only if the applied load has not only a tensile, but also a shear component. For pure debonding, these load components have a constant ratio depending on the materials used. For mixed mode experiments in isotropic materials many kinds of loading device and specimen configurations with internal or external cracks have been proposed. For our purposes, the most appropriate specimen and load device seems to be the ones of Richard [18]. He developed a load device which transduces the tensile load of the testing machine to a mixed mode load on the crack tip of the specimen, and applied the load device successfully to the measurement of stress intensity factors in isotropic specimens and in specimens that show an orthotropy in the process zone of the crack tip [19]. This loading device has been improved by Meyer [20].

The specimen and the load device proposed here are similar in their geometry to the ones of Richard. The specimen (see Figure 4) consists of a mortar layer sandwiched with two bricks which is a part of the simple abstracted from the masonry of the monument. The interface crack has to be cut by the thinnest saw cut possible. For a distributed applied load on the specimen, the depth of the cut has to reach the line where the resultant of the applied load passes. Care must be taken to leave the curvature at the end of the cut (the crack tip) as small as possible, to express the nearest practical equivalent to a mathematical crack tip.

The loading device (Figure 5) has to be from steel and therefore it is heavy. This construction guaranties during the loading procedure small deformations of the bolds, which connect the specimen with the load device. The weight of the specimen and the load device are expected to bc large in comparison to the load applied for interface crack propagation. To minimise the influence of the self-weight, it is proposed that specimen and load device lay horizontally on a table. To minimise the friction between the supporting horizontal table and the load device, the specimen can be set on cars. In this way the mass of the specimen and the load device is removed from influencing the mixed mode (tensile and in-plane shear) stress field at the crack tip. Using weights as loading, unstable crack growth is expected. Applying displacements, the crack growth can be controlled.

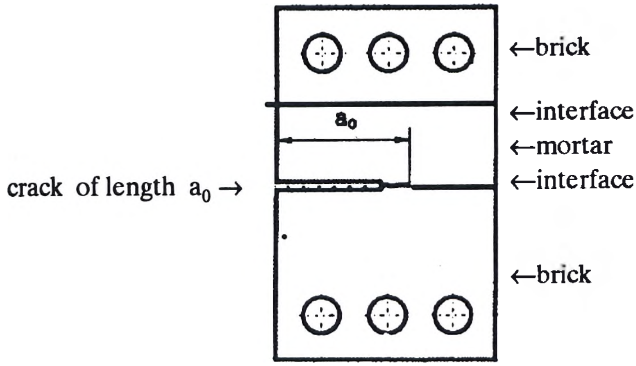

Figure 4: The specimen with interface crack appropriate for the load device in Figure 5.

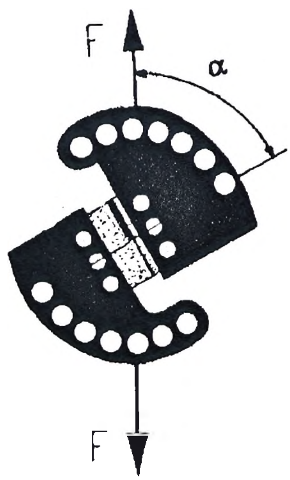

Figure 5: The modified load device with specimen for application of pure shear stress in the interface crack tip.

Conclusions

To obtain an exact measurement of the bonding strength in mortar-brick masonry there has to be clear interface crack spreading conditions. This is only possible if both theory and experimental procedure are appropriate. These, the stress analysis for the interface crack, a load device and the specimen of masonry, have been theoretically described in the present paper. It has been shown that not only the modulus of elasticity and the strength for each material must be ascertained, but also their Poisson ratios. The generalised stress intensity factors have to be calculated, in the case of bi-material plate, along an interface. The ratio of the two components of the generalised stress intensity factor which has to be applied for pure debonding strength measurement, is different for the two environmental cases, presence of hydrogen and absence of it. The presentation of experimental results is the subject of a forthcoming paper.

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