Pergamon

CEMENT AND CONCRETE RESEARCH

Cement and Concrete Research 29 (1999) 1067–1076

# Shear bond testing of concrete repairs

Simon Austin[a,*], Peter Robins[a], Youguang Pan[b]

[a]Department of Civil and Building Engineering, Loughborough University, Loughborough, Leics LE11 3TU, UK
[b]Waterman Partnership, 99 Southwark Street, London SE1 0JF, UK

Received 18 December 1998; accepted 30 March 1999

**Abstract**

Good adhesion of a repair material to concrete is of vital importance in the application and performance of concrete repairs. This paper reviews and compares techniques and results of bond strength test methods that induce shear, including a tensile slant-shear test. The effect of surface preparation (particularly as it affects roughness and soundness) and modulus mismatch between repair and substrate are illustrated by experimental and theoretical data. While these tests can provide individually useful information on bond strength and a limited picture of bond characteristics, they can, taken in isolation, result in a misunderstanding of the behaviour of bonded cementitious materials. A more complete appreciation can be obtained by consideration of a bond failure envelope that encompasses all possible normal/shear stress states. Such an envelope is presented in the context of Mohr-Coulomb and Griffith's fracture criteria. 

*Keywords:* Bond strength; Mechanical properties; Microstructure; Repair

Good adhesion of repair materials on concrete is of vital importance in the application of concrete patch repairs. The strength and integrity of the bond depends on not only the physical and chemical characteristics of the component, but also the workmanship involved, such as surface roughness and soundness. A wide range of test methods has been proposed to evaluate bond properties and the performance of repair materials in general. These include the tensile bond [1], slant-shear [2–5], twist-off [6], flexural [5], and the authors' patch tests [7]. However, each test is influenced by different combinations of factors and cannot alone give a full picture. It is also important to know how to apply results obtained from these bond tests to practical situations, where the interface may be in compression, tension, or a multistress state. Bond strength depends on the stress state imposed at the bond interface, which in turn influences the effect of such factors as roughness and workmanship.

In a previous paper [1] tensile bond strength was discussed with respect to the effect of surface preparation, modulus mismatch, and variation of specimen size. This paper discusses three types of bond tests that apply shear to the interface of a repair material and substrate under different stress states, namely compression/shear [8], pure shear, and tension/shear. An objective of the paper is to demonstrate that while these individual tests can provide useful information on bond strength, they have limitations. More importantly, any one test provides a limited picture of bond characteristics that, taken in isolation, can result in a misunderstanding of the behaviour of bonded cementitious materials. A further objective is therefore to show how a more complete appreciation can be obtained by consideration of a bond failure envelope that encompasses all possible stress states.

## 1. Slant-shear test (compressive)

This method, which puts the bond interface into a combined state of compression and shear, first appeared in the form of the Arizona slant-shear test [9] and was later modified using rectangular prisms by Tabor [2]. It was adopted in BS6319: Part 4 [8] as a test method for evaluating repair materials. Some researchers claim the test represents stress states typical of real structures [3,10,11] and others claim this method is sensitive to variations in bond strength [3] and that it produces consistent results [4]. The test is still used by manufacturers and specifiers to characterise repair products, but the test has some serious shortcomings. Failure is crucially dependent on the angle of the plane that is fixed in the standard test, precluding the possibility of obtaining a bond failure on a different plane (where there may be a more critical combination of compressive and shear stresses). It is also relatively insensitive to surface roughness and condition, only producing bond failures with

* Corresponding author. Tel.: +44-1509-263171; fax: +44-1509-223981.
*E-mail address*: S.A.Austin@lboro.ac.uk (S. Austin)


PII: S0008-8846(99)00088-5

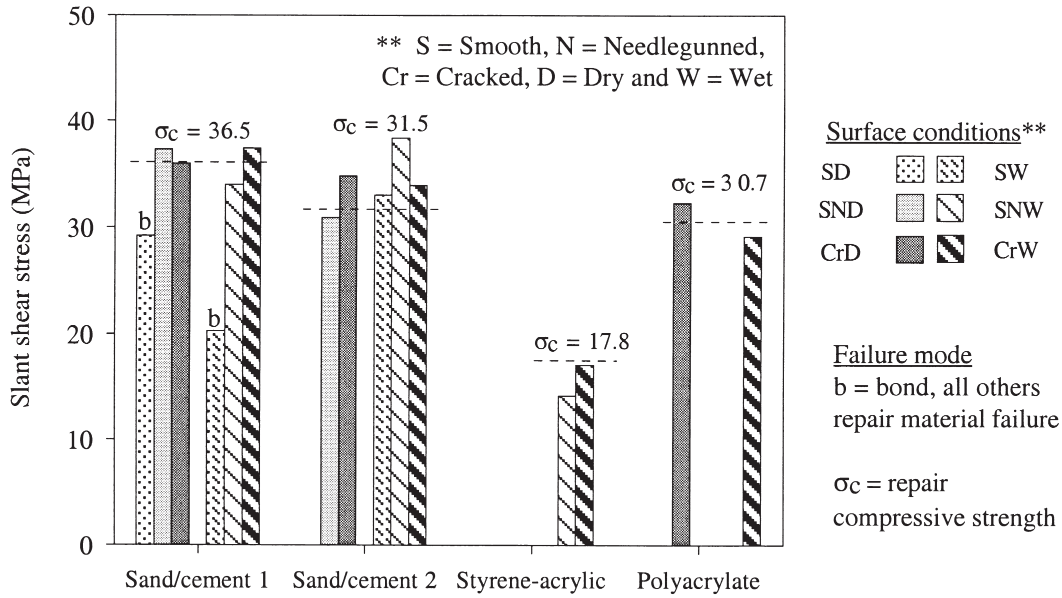


Fig. 1. Effect of surface conditions on slant-shear strength.

smooth surfaces [12]. Lastly, the test is sensitive to differences in elastic modulus of the repair and substrate materials that can cause stress concentrations.

### *1.1. Bond surface and orientation*

Surface roughness has a profound effect on the slant-shear test. Work by the authors [12] has demonstrated that bond failures occur only with relatively smooth substrates. As can be seen in Fig. 1 very few bond failures occurred (two out of the fifteen test surface conditions) and these were with the smooth, sawed surface. With a small increase in roughness caused by needle gunning, the failure mode switched from bond to compressive failure of the repair or composite material.

The authors have carried out experimental and theoretical studies of a 2:1 sand/cement repair mortar applied to a 1:2.3:2.3 concrete substrate; these mixtures were based on those used in previous research [1,12]. The compressive strength, tensile strength, and elastic modulus of the two materials were 66 and 64 MPa, 2.6 and 3.0 MPa, and 31 and 34 GPa, respectively. The effect of surface roughness and soundness is demonstrated by Table 1.

In the first series of tests, four groups of specimens were prepared from a smooth-cast surface subsequently needle gunned or sandblasted and in one case contaminated with demoulding oil. The slant-shear strength increased with surface roughness from 26.0 to 50.4 MPa; the contaminated medium rough surface produced a higher strength than the sound smooth surface. In the second series of tests, specimens were split by a line-load into two halves. Bond surfaces of half of this group of specimens were needle gunned to produce a rough but sound surface.

It is known that there are microcracks associated with a split surface, as shown by Naderi et al.'s results on tensile bond [13], but results from the second group showed no reduction in bond strength. This is because compressive stresses can be transmitted through microcracks, thus have no affect on the performance in a slant-shear test. Taking matters to an extreme, the authors [14] and Climaco and

Table 1
Effect of surface conditions on slant-shear strengths of sand/cement mortar

| Surface preparation method | Cast/needle gunned | Cast/sand blasted | | | Retarder/wire brushed | Split | Split/needle gunned | |
|---|---|---|---|---|---|---|---|---|
| Surface cleanliness | Clean | Oiled | Clean | Clean | Clean | Clean | Clean | Clean |
| Installation | Vibrated | Vibrated | Vibrated | Hand | Hand | Hand | Hand | Vibrated |
| Surface roughness index (mm) | >285 smooth | 230 medium | 200 rough | 230 medium | 210 rough | <190 rough | <190 rough | <190 rough |
| Age (days) | 14 | 14 | 14 | 14 | 14 | 28 | 28 | 28 |
| No. of tests | 3 | 3 | 3 | 3 | 6 | 3 | 3 | 6 |
| No. bond failures | 3 | 3 | 3 | 3 | 6 | 2 | 0 | 3 |
| SS strength (MPa) | 26.0 | 42.0 | 50.4 | 37.3 | 30.2 | 49.5 | 45.6 | 43.7 |
| Coefficient of variation (%) | 7.0 | 9.8 | 1.7 | 15 | 18.8 | 12.8 | 17.6 | 13.5 |

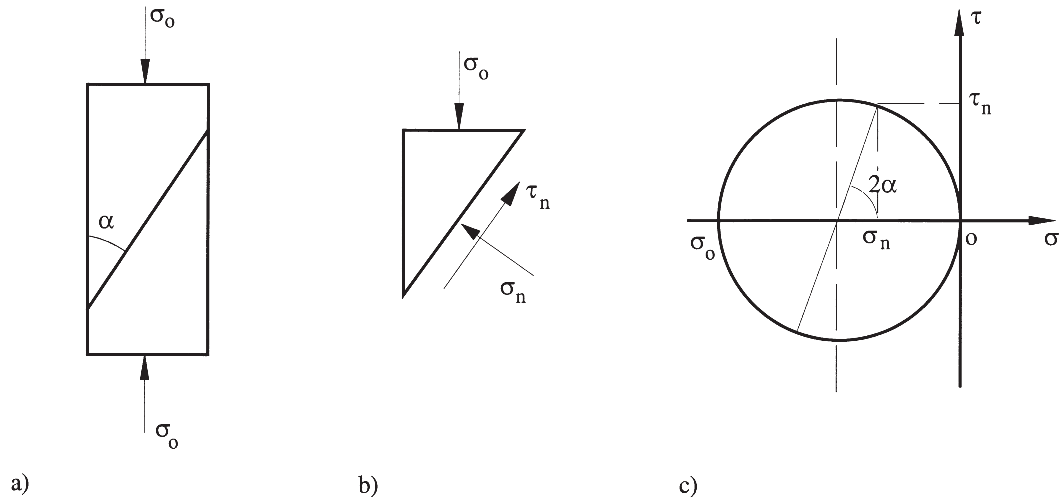


Fig. 2. Slant-shear configuration and Mohr circle.

Regan [11] have shown that the slant-shear test method produces strengths (i.e., load over cross-sectional area) even when the two rough surfaces are totally unbonded. Failure loads were as high as 50 percent of the solid control specimens. In fact, as will be shown below, the effect of surface roughness depends upon the inclination of the bond plane in a compression-shear test, and there is a critical angle associated with a particular surface roughness.

The orientation of the bond surface has a significant effect on the failure load and mode, but has received little attention, as most tests are done with the standard inclination of 30° to the vertical. A critical bond angle can be defined as the inclination at which the load required to produce a bond failure is a minimum. The failure load of a specimen will depend upon the bond angle selected, α, and the difference between this and the critical bond angle, $\alpha_{crit}$ (which is dependent upon surface roughness).

Coulomb theory can be used to describe the concept of bond failure criterion in which shear failure occurs if the following condition is satisfied [see Eq. (1)]:

$$\tau_n = c + \mu\sigma_n \quad (1)$$

or [see Eq. (2)]:

$$\tau_n = c + \tan(\phi) \cdot \sigma_n \quad (2)$$

where $\tau_n$ is the shear stress acting on the bond interface; $\sigma_n$ is the normal stress acting on the bond interface; $c$ is the adhesion strength (i.e., the pure shear strength); μ is the coefficient of friction; and φ is the internal friction angle [$\phi = \tan^{-1}(\mu)$].

Using the relationships that $\tau_n = 0.5\sigma_o\sin(2\alpha)$, and $\sigma_n = \sigma_o\sin^2\alpha$ (Fig. 2), the applied stress, $\sigma_o$, required to produce a shear failure along the bond plane is shown in Eq. (3):

$$\sigma_o = c[\cot\alpha + \tan(\tan^{-1}\mu + \alpha)] \quad (3)$$

where α is the angle between the bond interface and the longitudinal axis.

The validity of this simple failure criteria can be examined by comparing the predicted failure stress of the slant-shear test with the laboratory results described earlier. For the smooth surface the failure stress was 26 MPa, and the adhesion strength, $c$, can be determined from Eq. (3) as being 6.4 MPa. Substituting the internal friction coefficient, the failure stresses corresponding to the medium rough and rough surfaces can be determined be 35 and 53 MPa, respectively, which agree well with the test results (Table 1).

In order to maximise the likelihood of obtaining a bond failure, it is necessary to select a bond angle that corresponds to the minimum bond failure load. This critical angle and the associated minimum bond strength can be shown to be [see Eq. (4), Eq. (5), and Eq. (6)]:

$$\sigma_{min} = 2c \cdot \tan\left(45 + \frac{\phi}{2}\right) \quad (4)$$

$$\tau_{crit} = c(1 + \sin\phi) \quad (5)$$

$$\alpha_{crit} = 45 - \frac{\phi}{2} \quad (6)$$

from which it can be seen that the critical bond angle and the minimum bond strength are both dependent upon the internal friction angle φ and thus surface roughness.

Coefficients of friction have been determined from several researchers' bond work on various surfaces: 0.7 for smooth, sandblasted [10]; 0.75–0.87 for a smooth [15]; 0.8 for smooth [12]; 1.0 for roughened 6-mm profile, ACI318 [16]; and 1.1 and 1.4 for rough [12,15]. If values for μ of 0.75, 1.0, and 1.25 for smooth, medium rough, and rough surfaces are adopted, the relationship between bond angle and ratio of the applied stress, $\sigma_o$, to the strength in pure shear, $c$, shown in Fig. 3 is obtained, from which the critical bond angles corresponding to smooth, medium rough, and rough surfaces are 27, 23, and 19° respectively.

For the bond angle of 30° recommended in BS 6319 [8], the failure stress corresponding to a smooth surface is close

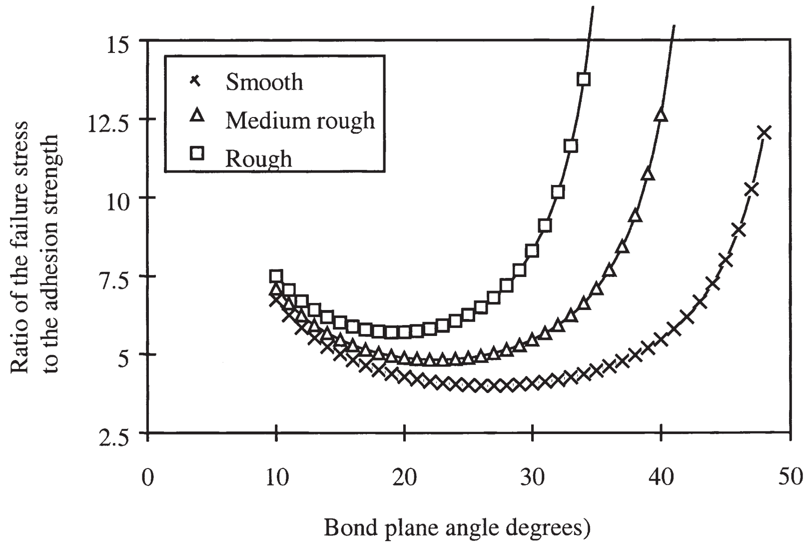


Fig. 3. Influence of bond plane angle and roughness on failure stress.

to the minimum stress. The failure stress for a rough surface with a bond angle of 30° is much higher than the minimum stress at the critical bond angle of 19°, increasing the probability of material as opposed to bond failure.

From Fig. 3 it is also clear that if the bond plane angle is significantly greater than $\alpha_{crit}$ the stress ratio to cause bond failure increases dramatically. Slant-shear specimens with bond angles between 40 and 80° have been tested by Zambas [17] and not surprisingly, only the specimens with 40° bond angle generated bond failure and the rest were controlled by material failure. From Fig. 3 it can be concluded that:

1. the external stress required to produce a shear failure along the bond interface varies with the bond angle selected;
2. there is a critical bond angle, $\alpha_{crit}$, at which direction the external stress required to produce a shear bond failure is minimised;
3. the coefficient of friction, $\mu$, affects the critical bond angle; and
4. rougher surfaces have lower critical bond angles, which reduce the possibility of obtaining a bond failure when using the standard 30° shear plane geometry.

Another geometrical consideration is the reliability of being able to form the bond plane at the desired angle. The method suggested in BS6319: Part 4 was found to produce inconsistent bond angles [12]. An incorrectly formed bond angle will affect the failure load, but the magnitude depends on the difference between the bond angle selected, $\alpha$, and

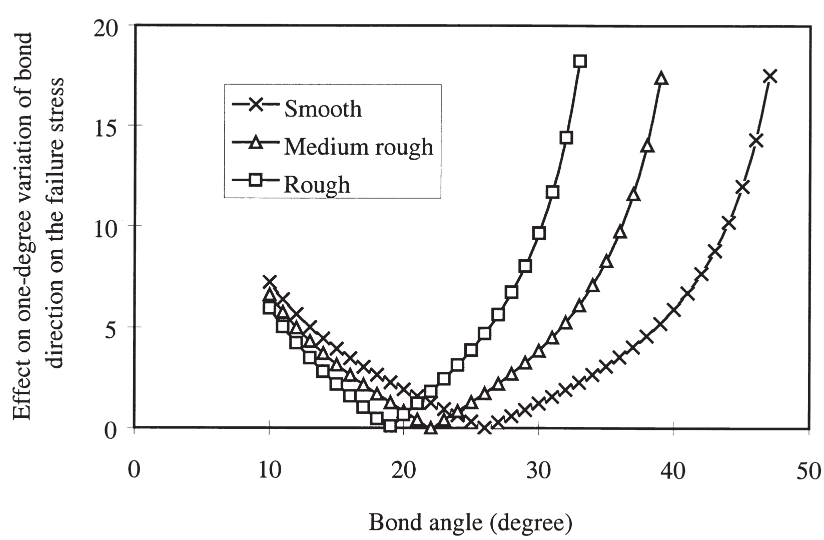


Fig. 4. Effect of one-degree variation in bond plane angle.

the critical bond angle, $\alpha_{crit}$. If $\alpha$ is very close to $\alpha_{crit}$, the change in the failure load caused by a small variation in $\alpha$ will be small. However, if $\alpha$ differs significantly from $\alpha_{crit}$, a small variation can cause a significant change in the failure load. Fig. 4 shows the variation in the failure load due to a one-degree variation in the bond angle. This level of error is realistic, since we have found this is typical with a line-load splitting method, which is more reliable than the BS6319 procedure. For the standard 30° bond angle, a one-degree variation causes 10, 5, and 1% changes in the failure load with rough, medium rough, and smooth surfaces, respectively. The curves in Fig. 4 demonstrate clearly that a rough surface is very sensitive to consistency of bond plane angle.

### *1.2. Modulus mismatch*

Modulus mismatch causes local stress concentrations in the slant-shear test in a similar manner to its effect in a tensile bond test [4]. In addition, in a slant-shear test modulus mismatch may also have the effect of producing an eccentricity of the loading. Finite element analyses were carried out to analyse the effect of modulus mismatch on the theoretical stress distribution over the bond interface [1]. When the modulus of the repair material is significantly lower than that of the substrate the tendency is for an increase in stress at the ends of the interface, with the maximum normal and shear stresses occurring at the side with least repair material (of the order of 25% greater than the stress at the centre with a modular ratio of 0.67). If there is a modulus mismatch, eccentricity of the loading can result, inducing a lower failure load. Based on an elastic stress analysis of a uniform displacement applied to the slant-shear setup (Fig. 2) the eccentricity, $e$, caused is given by Eq. (7) [18]:

$$e = \frac{M}{P} = \frac{\left[\dfrac{\dfrac{bK_2}{2} + K_1}{K_2} \ln \dfrac{K_1 + bK_2}{K_1} - b\right]}{\ln \dfrac{K_1 + bK_2}{K_1}} \tag{7}$$

where $\beta = E_1/E_2$, the modular ratio

$K_1 = S\beta + S + L$

$K_2 = \beta\cot(\alpha) - \cot(\alpha)\ (\beta \neq 1)$

and when $\beta = 1$, $e = 0$ and no eccentricity is caused.

A finite element analysis was also carried out and the results agree well with the elastic predictions for a standard specimen ($H = 155$ mm and $b = 55$ mm): the increase in the maximum stress is about 10% when the modular ratio is 0.6, and about 5% when it is 0.8.

Eccentricity effects due to modulus mismatch might explain a number of researchers' results including those of Ohama et al. [5], who carried out tests on bond performance of polymer-modified materials with slant-shear, tensile, flexural, and direct-shear tests. The bond strength measured with all but the slant-shear test increased with increasing polymer/cement ratio, whereas it decreased with the slant-shear test. Since the polymer/cement ratio was increased from 0 to 20%, it is likely that the modulus decreased, inducing increasing eccentricities and consequently lower failure stresses.

## 2. Shear tests

### *2.1. Shear failure of concrete*

Bond strength is not commonly measured in a pure shear stress state. The limited studies reported include twist-off shear tests [6,19] and direct shear bond tests [3,15,20]. Before discussing the factors that might influence test results, it is appropriate to remember that a pure shear stress state can be viewed as a combination of equal tension and compression occurring at 45° to the shear plane, and that failure will depend upon the relative values of compressive and tensile strengths of the materials and the strength of the bond. The following discussion includes comments on the roles of these strengths in measuring and interpreting shear bond test results.

For a tension-weak brittle material such as concrete, sand/cement mortar, or other cementitious-based materials, the compressive strength is far greater than the corresponding tensile strength. Under a shear stress state, failure is usually dominated by tensile cracking rather than shear slipping, which means that even if a shear stress is imposed, the failure load is an indication of the tensile strength, rather than the expected shear strength of the material. To explain this it is helpful to define a cementitious material at three levels: microlevel, mesolevel, and macrolevel, an approach adopted in fracture analysis of concrete [21]. At the microlevel, concrete consists of crystals of calcium silicate hydrate with primary and secondary bonds. The mesolevel considers the composite nature of concrete and distinguishes between hardened cement paste, aggregate, and a bond layer between these two constituents. At the macrolevel, concrete is modeled as a homogeneous isotropic material.

Using this approach, the macrolevel failure mode of concrete under a torque can be better explained by considering behaviour at the mesolevel. Because the bond between cement paste and aggregates is usually the weakest part of the concrete, failure will be initiated by tensile cracking in the direction of principal tensile stress, rather than by shear slipping along the shear plane. The shear plane will also pass through some aggregate particles, but failure will occur in the weak interfacial zone around each particle (i.e., at planes other than 45° involving varying combinations of tension and shear). The surface texture of the coarse aggregate affects the tensile bond strength between the cement paste and the aggregate and, as a consequence, the macrolevel tensile and compressive strengths of concrete are affected by sur-

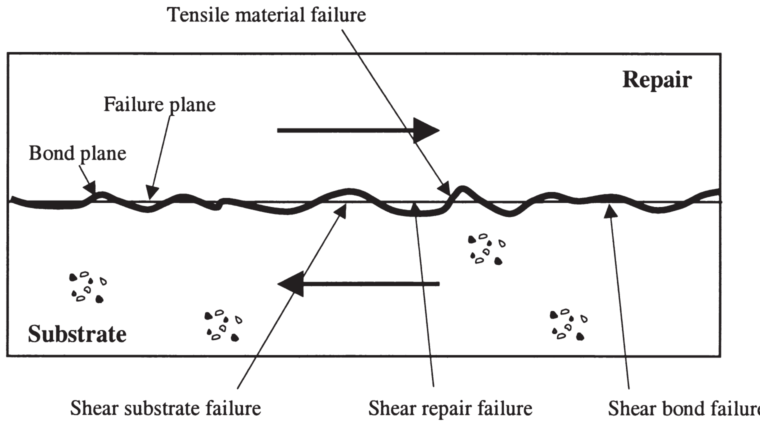


Fig. 5. Shear failure on a rough surface.

face roughness [15], but the nature of the failure (tensile cracking rather than shear slipping) remains unchanged.

The above discussion pertains to material failure. In a shear bond test for concrete repairs failure can occur in either material (repair/substrate) or at the interface. The bond plane between the substrate and the repair material is a macrolevel feature that requires careful consideration when postulating the nature of bond, as opposed to material, shear failure.

## 2.2. Bond surface roughness and soundness

Just as aggregate roughness affects shear failure in mortar or concrete, so will the roughness and soundness of the bond plane have a fundamental bearing on the behaviour of a bond test. If the bond interface is straight and smooth, such as might be produced by a saw cut, the shear failure line can pass along the bond interface, with no need to overcome any extra resistance caused by mechanical interlock. In such cases the chance of obtaining a true shear (i.e., slipping) failure, and hence measuring the shear bond strength, is increased. In reality bond surfaces will not be straight and smooth, and there will be a mechanical interlock contribution from the uneven surface texture, resulting in an increased shear load to cause failure; the result can be seen as an increase in nominal bond strength (shear force/nominal shear area), although the failure mechanism is more likely one of combined shear and tensile, material and bond failures along the failure plane (Fig. 5). As a result, the failure mechanism has a significant tensile cracking contribution, and some correlation with the results from a tensile bond test might be expected.

In a twist-off shear test, a torque is applied to the composite system. Based on the above discussions, it can be expected that a tensile crack will initiate at the periphery of the bond interface. However, due to the high tensile strengths of both the substrate concrete and the repair material (relative to the bond strength), cracks initiated in the bond interface cannot propagate into the repair material or the substrate. More work is needed to overcome the resistance, and new microcracks will develop elsewhere on the periphery of the bond interface. Due to the strain gradient in a twist-off test the microcracks will then propagate gradually into the bond area until failure occurs. The resulting failure stress will be higher than that obtained in a uniform shear arrangement (and also, of course, a tensile bond test). The twist-off shear and the core pull-off tests carried out by Yeoh et al. [19] produced shear bond strengths significantly higher than the tensile bond strengths, but at the same time the two methods showed similar trends concerning the influence of environmental conditions.

A sound substrate concrete is essential if a bond strength is to be measured in a tensile test configuration, otherwise microcracks will precipitate a tensile material failure. However, in a shear test such as the twist-off test the effect of surface defects such as microcracks may be small because they are unevenly distributed and may not occur in a region of high stress. In tests carried out by Naderi et al. [13] on chisel-hammer split surfaces and saw-cut surfaces, twist-off specimens achieved similar failure loads, whereas tensile pull-off specimens were on average more than 30% lower with the former rough and unsound surface (Table 2). The results indicate that for laboratory evaluation of repair materials the use of a sound substrate is less critical in a twist-off shear test than in a tensile bond test, due to its lower sensi-

Table 2
Tensile and shear test results [13]

| Repair material | Surface | Tensile strength (MPa) | Shear strength (MPa) |
|---|---|---|---|
| SBR sand/ | Sawed/smooth | 1.0 | 2.2 |
| cement mortar | Split/rough | 0.8 | 1.9 |
| Sand/cement mortar | Sawed/smooth | 1.2 | 2.3 |
| | Split/rough | 0.6 | 2.3 |
| Sand/cement mortar | Sawed/smooth | 1.8 | 3.2 |
| plus grout bond | Split/rough | 1.2 | 3.0 |
| Sand/cement mortar | Sawed/smooth | 2.5 | 4.1 |
| plus acrylic bond | Split/rough | 1.5 | 4.2 |

Table 3
Tensile slant-shear test results

| Plane angle (°) | Surface | Failure stress (MPa) | Coefficient of variation (%) | Bond failure (%) | Tensile stress (MPa) | Shear stress (MPa) |
|---|---|---|---|---|---|---|
| 0 | Smooth | 1.15 | 4.4 | 100 | 1.15 | 0 |
| | Rough | 1.44 | 2.4 | 88 | 1.44 | 0 |
| 15 | Smooth | 1.25 | 9.9 | 100 | 1.16 | 0.31 |
| | Rough | 1.53 | 2.6 | 90 | 1.43 | 0.38 |
| 30 | Smooth | 1.35 | 8.3 | 98 | 1.01 | 0.58 |
| | Rough | 1.73 | 2.8 | 98 | 1.30 | 0.75 |
| 45 | Smooth | 1.40 | 4.3 | 90 | 0.70 | 0.70 |
| | Rough | 2.03 | 3.6 | 58 | 1.01 | 1.01 |
| 60 | Smooth | 1.57 | 8.6 | 68 | 0.39 | 0.68 |
| | Rough | 2.27 | 6.3 | 0 | 0.57 | 0.99 |

tivity to surface preparation. However, if the purpose of the test is to measure the success of a repair on site, where maintenance of the integrity of the repair is essential, it can be argued that the twist-off test is not suitable because of its insensitivity to detecting the existence of the surface defects.

## 3. Tensile slant-shear test

We have demonstrated earlier that the compressive slant-shear test has some serious shortcomings. In particular, the failure stress is crucially dependent on the angle of the plane, relatively insensitive to surface roughness and condition, and, as with others, stress concentrations can arise due to differences in elastic modulus. The insensitivity to roughness can be overcome by testing in tension, to generate a combination of tensile and shear stresses (the ratio depends on the angle of the bond plane). Such an arrangement also has the merit of producing a different, but none the less realistic, stress state (e.g., in repairs to beam and slab soffits) that contributes to a fuller picture of a repair/substrate composite's bond characteristics.

A series of tensile slant-shear tests [22] were therefore conducted on specimens prepared in accordance with relevant parts of the BS6319 [8] using materials similar to those in the authors' compression slant-shear tests [12]. To the authors' knowledge, no tests of this type have been reported previously. Two surface roughnesses were investigated: a smooth surface produced by sawing and light needle gunning and a rough surface obtained by splitting the prism with a line load, followed by needle gunning to remove surface debris. The surface roughness index (SRI) of these two surfaces, determined in accordance with a proposed European Standard [23] on control cube samples prepared in an identical manner, were 197 and 309 mm for the smooth and rough surface, although the results had a high coefficient of variation (26 and 11%). The effects of the bond angle were studied by testing samples with five orientations of 0, 15, 30, 45, and 60° to the horizontal (i.e., perpendicular to the direction of loading). Four samples were prepared for each combination with a 2:1:0.4 sand/cement/water repair mortar, as used previously [1,12]. Unrepaired prisms of the repair and substrate were also tested, giving a total of 48 samples.

### 3.1. Bond surface and orientation

The average results of each set of tensile slant-shear tests are given in Table 3. The failure stress is the load at failure divided by the specimen cross-section (nominally 55 × 55 mm). The failure mechanism (bond and/or material) was determined by examination of the failure plane after testing. Where a combination of modes occurred, the proportion was estimated and the table gives the overall average value for the four specimens. The tensile and shear stresses given are the stresses on the bond plane at the failure load obtained by resolving the force in a simple elastic analysis. The average tensile strengths of the repair and substrate control samples were 2.03 and 2.42 MPa with coefficients of variation of 1.4 and 1.8%, respectively.

The elastic tensile and shear stresses on the interface at failure are plotted in Fig. 6. Inspection of the graph and Table 3 shows clearly that the rough surface, produced by splitting and needle gunning, produced consistently higher stresses, indicating a higher bond strength. With the bond surface in pure tension (0° orientation) the failure stresses of 1.15 and 1.44 MPa compare favourably with those of Monteiro [24] of 1.12 and 1.41 MPa, who conducted core pull-

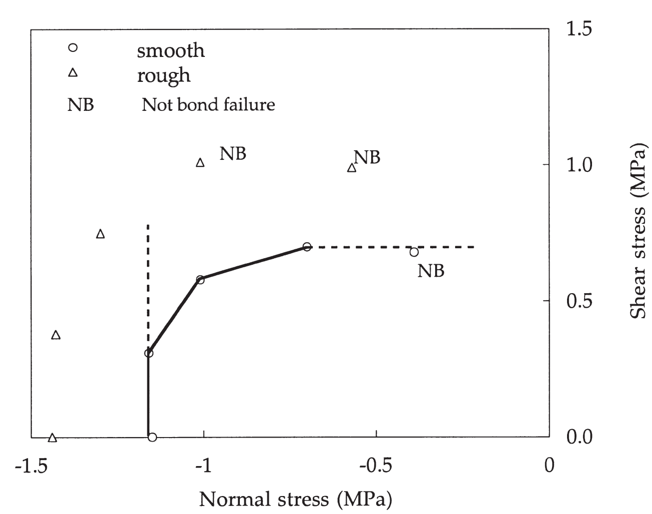


Fig. 6. Tensile slant-shear test results.

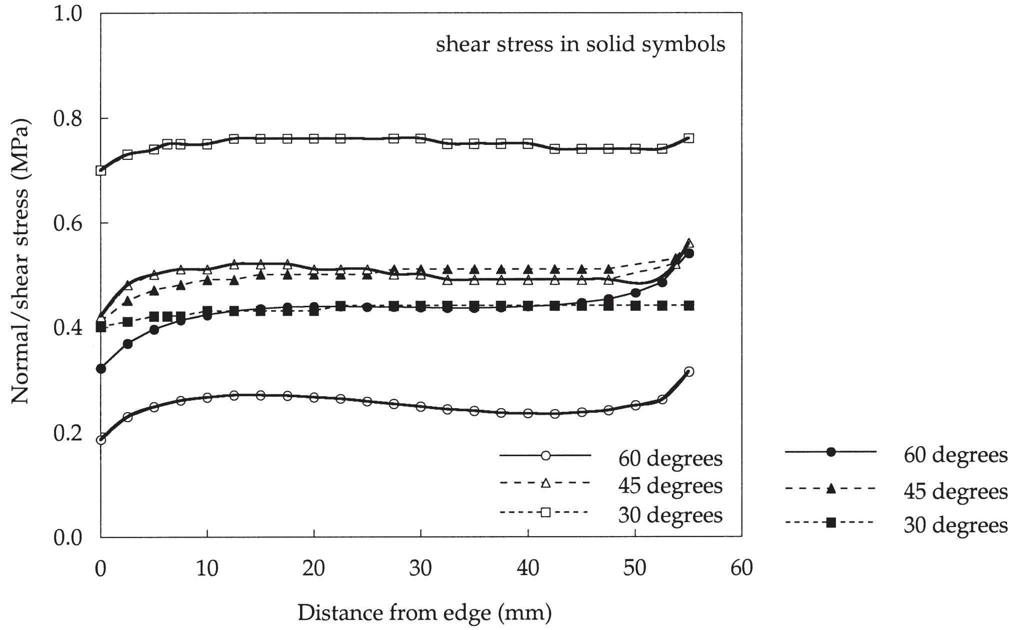


Fig. 7. Effect of modulus mismatch and bond plane orientation.

off tensile bond tests using similar materials, mixes, and surface roughnesses.

As the bond plane angle is increased, the table and figure reveal that the shear stress component has little effect up to values of 0.3–0.4 MPa occurring at angles up to 15°. At greater angles the shear stress is clear affecting the bond behaviour, resulting in combined tensile/shear bond failures. At angles greater than approximately 45° a plateau of limiting shear strength is suggested (see horizontal line drawn for the smooth results). However, this is misleading as these points represent material (not bond) failure, with the tensile/shear bond strength being at a higher, but unknown, level.

In order to identify the shape of the bond failure relationship at low (<0.5 MPa) tensile stress, we need results from different bond test arrangements that produce either zero or positive (i.e., compressive) normal stress. The results of Naderi et al. [13] give values of shear bond strength from core twist-off tests of 2.8 MPa for a sand/cement mortar on a sawed surface at 28 days (and a corresponding tensile bond strength of 1.2 MPa, which is close to our value of 1.15 MPa). Furthermore, as will be shown in the next section, the results can be added to the authors' data from compressive slant-shear and patch tests [7,12] to form a complete bond failure envelope, which provides further insight into the interaction between shear stress and normal stress at a repair interface.

### *3.2. Modulus mismatch*

The effect of differences in elastic modulus between repair and substrate in a compressive slant-shear test has been demonstrated previously [12], with FE analysis giving S-shaped normal and shear stress distributions with maximum values occurring on the stiffer side (most substrate) and increasing as the modular ratio increases. Reversal of load to give tension/shear results in identical distributions. Fig. 7 shows the effect of altering the bond plane angle when the moduli are 37 and 27 GPa for the substrate and sand/cement mortar. Steeper angles result in greater stress differential compared to that obtained from a simple statically elastic stress analysis: for a load equivalent to 1 MPa the edge normal and shear stresses on a 60° plane are 0.31 and 0.54 MPa, as compared to 0.25 and 0.43 MPa (i.e., around 25–30% greater) whereas at 30° they are almost the same at 0.75 and 0.43 MPa.

## 4. Bond failure envelope concept

Robins and Austin [12] presented the idea of a bond failure envelope for concrete repairs. This was based on core pull-off, slant-shear, and patch tests, which give pure tension and compression/shear stress states. By supplementing this data with the tensile slant-shear results, presented in the previous section, we can identify more clearly the shape of the failure envelope in the tension region. Fig. 8 shows the envelopes for the smooth and rough surfaces repaired with the sand/cement mortar. In all cases the failure stresses are based on the peak FE analysis results.

The curves are best-fit second order polynomials that exclude the pure tension values in order to produce a cut-off relationship suggested by the tension slant-shear results (Fig. 6).

In attempting to identify a potential failure envelope, it is helpful to consider material behaviour in a wider context with reference to relevant established failure theories. Our interest in combined normal/shear stress states naturally leads to a consideration of a Mohr-Coulomb approach. In its

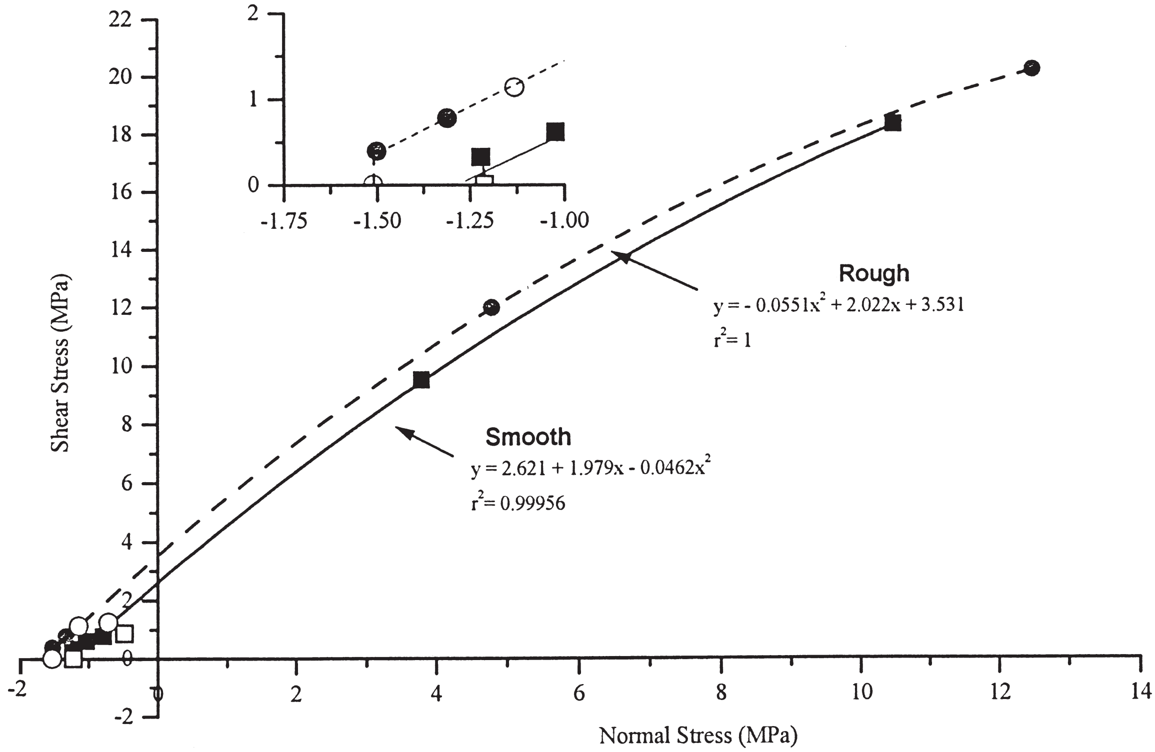


Fig. 8. Bond strength failure envelope.

simple form this has a bilinear relationship with a tensile cut-off (Fig. 9). It has been shown in the study of rock mechanics that this tends to overestimate the shear strength in the tensile region, and that better fits to experimental data are obtained by application of an envelope to the Mohr's circles obtained, like us, from a variety of tests that generate different combinations of stresses (e.g., direct tension, Brazilian cylinder-splitting, unconfined compression, and triaxial compression). This results in a curved interaction and some investigators will simply plot an empirical power curve to their data, avoiding the construction of Mohr's circles [25].

An alternative classical approach to dealing with the tensile region is to apply Griffith's fracture criteria for brittle materials. The extension of his theory from tensile to compressive stress environments can be expressed in terms of normal and shear stresses and is a parabolic relationship [Eq. (8)]:

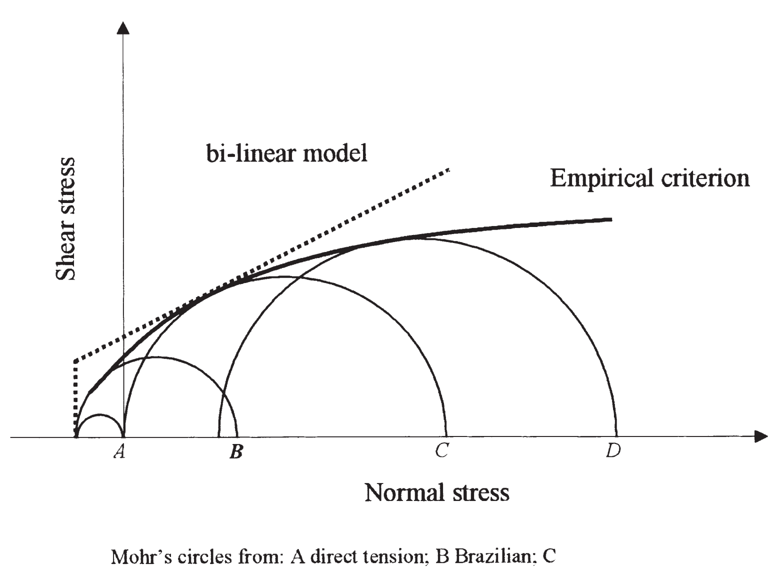


Fig. 9. Typical failure envelopes from rock mechanics.

$$\tau^2 = 4T_0(\sigma_n + T_0) \quad (8)$$

where $T_0$ is the uniaxial tensile strength (and the pure shear strength is $2T_0$).

This is of similar form to the empirical Mohr-Coulomb envelope, although attempts to base failure criteria of soils and rocks on plain compression Griffith theory have proved unsuccessful. Most researchers adopt the more empirical approach; however, in both this field and in concrete technology, there is now substantial interest in the application of linear and nonlinear fracture mechanics to the search for a more fundamental approach to predicting failure of brittle materials.

A study of bond failure, which involves cracking at the bond interface, might have a more natural affinity with a fundamental fracture failure criteria than a Mohr-Coulomb relationship, which is concerned with stress states within a material rather than at the interface between two bonded together. Nevertheless, it is more appropriate in this study to propose an empirical bond failure envelope, as shown in Fig. 8, and point out the similarity to these two classical failure concepts. It is of interest to note in passing that this gives a pure shear bond strength for the smooth surface of 2.6 MPa, which compares with 2.8 MPa obtained by Naderi et al. [13] and is 2.13 times the tensile bond strength (compared to 2.0 times predicted by Griffith theory).

## 4. Conclusions

A variety of shear bond tests have been described and the experimental and theoretical data demonstrate the effects of surface conditions and differences in elastic modulus between a repair material and the substrate concrete. As a consequence, bond test results should always be interpreted with caution, particularly as it has been shown how the normal/shear stress state has a strong influence on specimen behaviour. A fuller and more helpful picture of bond performance can be obtained by constructing a bond failure envelope that covers the full range of normal/shear stress combinations that can arise in practice and this can be used to predict bond capacity in a variety of repair configurations. Data can be obtained using slant-shear test specimens [8], both in compression and tension. The latter requires a range of bond plane orientations (0 to 45°) to capture the bond failure envelope in this critical region.

## Acknowledgments

The authors acknowledge the financial support of the Engineering and Physical Sciences Research Council under grant GR/H17510 and the help of J. Bishop with some of the FE analysis.

## References

[1] S.A. Austin, P.J. Robins, Y. Pan, Tensile bond testing of concrete repairs, Mat and Struct 28 (1995) 249–259.
[2] L.J. Tabor, The evaluation of resin systems for concrete repair, Mag Concr Res 30 (1978) 221–225.
[3] J.S. Wall, N.G. Shrive, Factors affecting bond between new and old concrete, ACI Mater J 85 (1998) 117–125.
[4] L. Knab, C.B. Spring, Evaluation of test methods for measuring the bond strength of portland cement based repair material to concrete, Cement, Concrete and Aggregate 11 (1989) 3–14.
[5] Y. Ohama, K. Demura, H. Nagao, T. Ogi, Adhesion of polymer-modified mortars to ordinary cement mortar by different test methods, in: Proc. RILEM Symp Adhesion between Polymers and Concrete, Chapman and Hall, London, 1986, pp. 719–729.
[6] M. Naderi, D. Cleland, A.E. Long, In situ test methods for repaired concrete structures, in: RILEM Symp. Adhesion between Polymers and Concrete, Chapman and Hall, London, 1986, pp. 707–718.
[7] S.A. Austin, P.J. Robins, Development of a patch test to study the behaviour of shallow concrete patch repairs, Mag Concr Res 45 (1993) 221–229.
[8] BS 6319: Part 4 Slant Shear Test Method for Evaluating Bond Strength of Epoxy Systems, BSI, London, 1984.
[9] J.D. Kreigh, Arizona slant shear test, ACI J 73 (1976) 372–373.
[10] L. Frank, The dimensioning of adhesive-bonded joints in concrete building components, in: RILEM Symp. Adhesion Between Polymers and Concrete, Chapman and Hall, London, 1986, pp. 461–473.
[11] J.C. Climaco, P.E. Regan, Evaluation of bond strength between old and new concrete, in: M.C. Forde (Ed.), Int. Conf. Structural Faults and Repair, Vol. 1, Engineering Technics Press, London, 1989, pp. 115–122.
[12] P.J. Robins, S.A. Austin, A unified failure envelope from the evaluation of concrete repair bond tests, Mag Concr Res 47 (1995) 57–68.
[13] M. Naderi, D. Cleland, A.E. Long, Bond strength of patch repair mortars for concrete, in: RILEM Symp. Adhesion between Polymers and Concrete, Chapman and Hall Ltd, London, 1986, pp. 235–244.
[14] S.A. Austin, P.J. Robins, The behaviour of concrete patch repairs—An initial study, Department of Civil and Building Engineering, Loughborough University, 1991.
[15] K.M. Alexander, J. Wardlaw, D.J. Gibert, Aggregate-cement bond, cement paste strength and the strength of concrete, in: A.E. Brooks, K. Newman (Eds.), The Structure of Concrete, Cement and Concrete Association, London, 1968.
[16] ACI Comm. 303, Guide to Cast-in-Place Architectural Concrete, ACI Publication 303R-91, Detroit, 1991.
[17] C. Zambas, Structural repairs to the monuments of the Acropolis—The Parthenon, Proc. Instn. Civ. Engrs., Civ Engng 92 (1992) 166–176.
[18] Y.G. Pan, Bond strength of concrete patch repairs, PhD thesis, Loughborough University, 1995.
[19] K.M. Yeoh, D.J. Cleland, A.E. Long, The effect of environmental conditions on interface adhesion properties of concrete patch repairs, in: Proc. 2nd Int. Conf. Inspection, Appraisal, Repair and Maintenance of Buildings and Structures, Jakarta, 1993, pp. 237–244.
[20] J.A. Lavelle, Acrylic latex-modified portland cement, ACI Mater J 85 (1988) 41–48.
[21] RILEM Report: Fracture Mechanics of Concrete Structures, L. Elfgren (ed.), Chapman and Hall, London 1989.
[22] M.A. Chestney, Concrete Patch Repair Bond Strength, Department of Civil and Building Engineering, Loughborough University, 1996.
[23] CEN TC104, prEN104 801—Draft European Standard on Products and Systems for the Protection and Repair of Concrete Structures, 1995.
[24] J.A. Monteiro, Evaluating patch repair bond strength, MSc Thesis, Department of Civil and Building Engineering, Loughborough University, 1993.
[25] E. Hoek, E.T. Brown, Empirical strength criterion for rock masses, ASCE J Geotech Eng 106 (1980) 1013–1035.