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An Experimental Study to Evaluate Failure Surface of the Concrete-Repair Material Interface

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Introduction

With appearance of clear signs of deterioration in the case of reinforced concrete (RC) structures built in the 50s and 60s and the prohibitive cost of their dismantling and building new ones, repair of concrete structures has attracted a lot of attention[1,2]. Research in this area is also fuelled by the rapid development in the field of repair materials and construction technology. The need to repair and 'retrofit' existing structures is also increased by a better understanding of structural behaviour and more stringent design criteria.

Figure 1 shows a schematic representation of a repaired reinforced concrete beam, and it can be seen that the concrete-repair material interface can be subjected to different combinations of stresses, depending upon the extent and location of the repair. Compatibility of the repair material with parent concrete in terms of material properties (such as the coefficient of expansion and shrinkage) and mechanical properties (such as strength and modulus of elasticity) needs to be ensured for effective repair[3]. Besides these properties, the bond at the interface also needs to be appropriately modeled in order that analysis using FEM, etc. can be carried out to simulate the behaviour of repaired structural members.

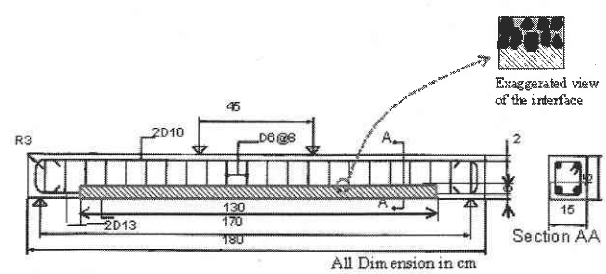

Figure 1 Schematic representation of a repaired RC beam

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Though the importance of the modeling the bond at the concrete-repair material interface (inset in Figure 1) has been emphasized in the literature[3,4], not many attempts have been made to model the bond with firm experimental basis and evidence. This paper seeks to cover this important gap in our understanding and presents the results of experiments carried out to estimate the fundamental characteristics defining the bond at the concrete-repair material interface. Experiments were directed to quantitatively establish the failure interfacial surface through tests carried out in pure tension, pure shear and a combination of compression and shear. Limited analytical work has also been carried out using these results, to actually model the behaviour of repaired beams.

Experimental

Experimental programme

To begin with, tests to determine the basic properties of concrete and the repair materials were carried out. Experiments were carried out using a cement-modified repair material. Table 1 summarizes the size and nature of the specimens used in the determination of the various of properties concrete and the repair material.

Preparation and testing of specimens

Experiments for determination of fundamental properties of the

Table 1 Specimens used to determine properties of concrete and repair material

Test	Size		Comments
	Concrete	Repair material	
Compressive strength	100 x 200	50 x 100	ASTM C-39, C-192
Tensile strength	100 x 200	100 x 200	ASTM D-496
Modulus of elasticity and Poisson's ratio	100 x 200	50 x 100	ASTM C-469, E-6, C-192

Note: All specimens used were cylindrical and the dimensions given are [(dia) x (ht)]in mm.

concrete and the repair materials were carried out using standard procedures. Tests were carried out after the specimens had been cured under gunny bags for at least 28 days.

In preparation of all specimens tested for bond under different loading conditions, an effort was made to ensure a proper bond between the concrete and the repair material and also keep in mind the normal field conditions. Methods used in the literature were also studied for reference[4]. The (base) concrete was cast and left to cure under gunny bags for more than 28 days. The surface was then roughened using a water-jet. Visual inspection during the process ensured that the loose mortar was removed and about half the aggregate (about 10mm) was exposed. The repair material was then cast (or shotcreted) and the composite specimens were left to further cure in air at 20°C and 100% relative humidity for more than 4 weeks.

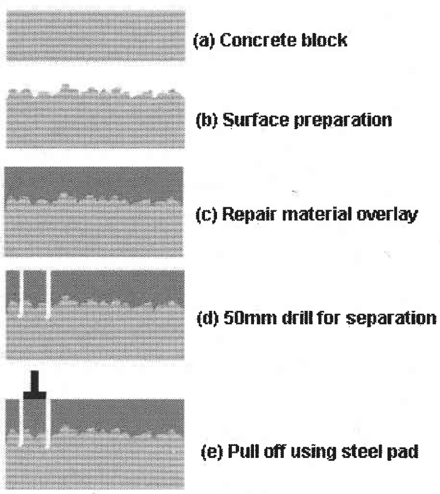


Figure 2 Steps in preparing repaired specimens in direct tension

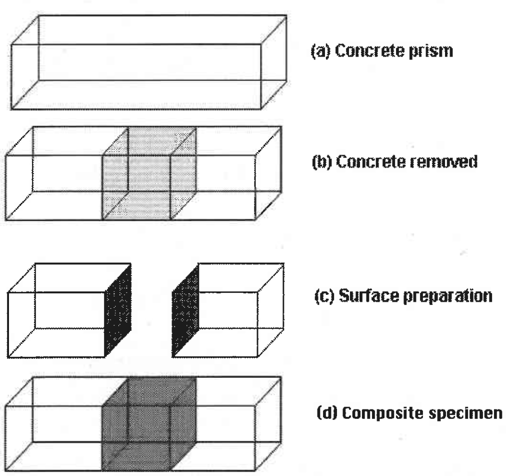


Figure 3 Steps in preparing repaired specimen in direct shear

A schematic representation of the different steps in the preparation and testing of the specimens for the various tests is shown in Figures 2 and 3.

In the case of specimens tested for failure in pure tension, concrete prism of 500x500x80mm were cast, on which a 20mm layer of repair material was shotcreted after appropriate surface preparation. Cores with a diameter of 50 mm were then driven in a manner that they penetrated at least 15–20 mm into the parent concrete as shown in Figure 2 (d). A pull-off test was then carried out through an appropriately fixed steel pad as shown in Figure 2 (e).

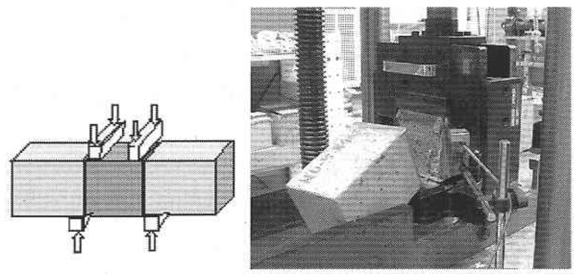
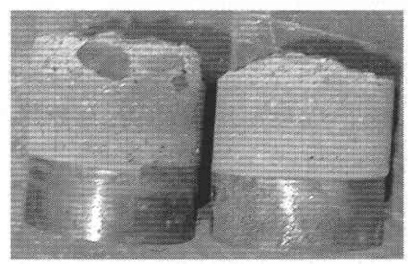
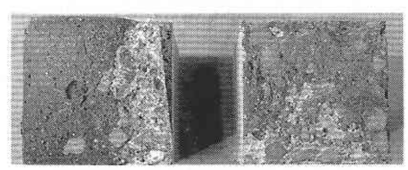


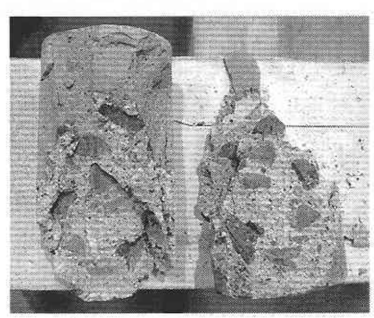
Figure 4 Schematic view of testing specimens in direct shear



(a) Direct tension



(b) Direct shear



(c) Shear and compression

Figure 5 Specimens after failure

Steps in the preparation of specimens for direct shear test are shown in Figure 3. 100x100x400mm concrete specimens were cast and a 100mm long portion was cut and removed from the middle of this specimen as shown in Fig 2 (b). The exposed surfaces were prepared as shown in Figure 2 (c). Repair material was then shotcreted into this 100x100x100mm gap, to make the composite specimen shown in Figure 2 (d).

Preparation for the test specimens for the combined shear-and-compression test was in principle similar to that depicted in Figure 3, except that the specimens were cylinders (75mm diameter and 150mm long). The cylinders were cut at 30° to the longitudinal direction and the concrete was replaced by the repair material. In this case the casting of the repair material was done using an appropriate mould and casting the repair material after appropriate surface preparation.

Figure 4 shows a representation of the tests carried out in pure shear. Figure 5 shows some of the specimens after testing under the different loading conditions.

Results

Table 2 shows the mechanical properties of material namely concrete and repair material. It can be seen that though there is a substantial difference in the compressive strengths, the modulus of elasticity, Poisson's ratio and the tensile strength of the concrete and the repair material are more comparable.

Table 3 shows the failure loads observed during the bond tests for the different combinations of testing conditions. It should be mentioned that only those results have been considered for further analysis where the failure occurred along the concrete repair material interface. For example, results in the tests in direct tension tests, where failure occurred in the concrete layer (i.e. the bond strength in tension was larger than the tensile strength of concrete) were ignored.

Table 2 Properties of concrete and repair material used

Material	Compressive strength (M Pa)	Young's modulus kN/mm^2	Poisson ratio (υ)	Tensile strength (M Pa)
Concrete	38.8	29.0	0.2	4.15
Repair material	105.2	33.6	0.24	6.67

Table 3 Failure loads in bond tests

Condition	Failure load (*) kN	
	Actual values	Average
Pure tension	3.3, 4.14, 4.08	3.84
Pure shear	93.2, 111.0, 105.2	103.13
Compression and shear	202.7, 188.7, 192.5	194.63

Note: Only results for specimens with substantial bond failure have been included

Modeling the concrete repair material interface

Model used

Carol's formulation for stress transfer between discrete cracks in concrete has been used to model the bond behaviour at the concrete-repair material interface and a hyperbolic failure surface is used to represent failure surface of the bond between repair material and concrete[5]. In a 2-D formulation, the failure surface, F(σ_N ,σ_T), can be represented as,

$$F = \sigma_T^2 - (C - \sigma_N \tan\varphi)^2 + (C - X\tan\varphi)^2 \quad \cdots\cdots\cdots\cdots (1)$$

where, C and X are cohesion and tension cut-off respectively, φ is the angle of internal friction, and, σ_N and σ_T are the normal and shear stresses, respectively.

Derivation of failure parameters

Using the experimental results given in Table 3 (in terms of failure loads), failure stresses under different loading conditions have been estimated using areas of appropriate failure surfaces. For example, in the case of tension pull out test, the area of the concrete-repair material interface has been taken to be that of a circle of diameter 50 mm. Similarly, in the case of pure shear, the load has been considered to be acting to induce failure at two parallel surfaces, and the area considered to be 200 cm^2 (i.e. 2 faces of 10x10cm). Thus, the values of and *C* and *X* in the formulation are directly evaluated from the pure shear and tension pull off experiments and found to be 5.15 and 1.95, respectively. In the case of failure under combined compression and shear, the relevant components of the failure load have been taken to be acting at an inclined failure surface. Based on the values of pure shear and combined compression shear, the value of φ, the angle of friction, was found to be 52°.

Results of bond test as coordinates of stress combinations (σ_N , σ_T) are shown in Table 4. The failure surface in bond as given in Eq. (1) can thus be written as:

$$F = \sigma_T^2 - (5.15 - \sigma_N \tan(52^0))^2 + (5.15 - 1.96\tan(52^0))^2 \quad \cdots (2)$$

A diagrammatic representation of the failure surface is given in Figure 6. It also shows the experimentally determined points given in Table 4.

Application to study of repaired beams

As stated above, the concrete repair material interface can be

Table 4 Failure stresses defining failure surface

Pure tension	Pure shear	Compression-shear
(1.95,0)	(0,5.15)	(-11.01, 19.07)

Note: (x,y) above refer to the normal (x) and (y) stresses at failure in MPa

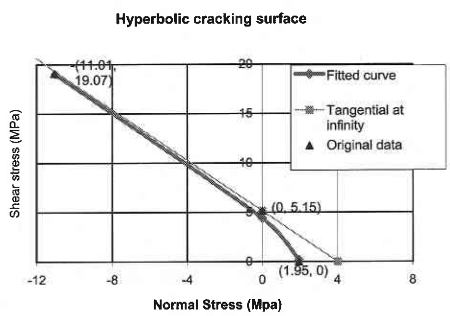


Figure 6 Failure surface of the concrete-repair material interface

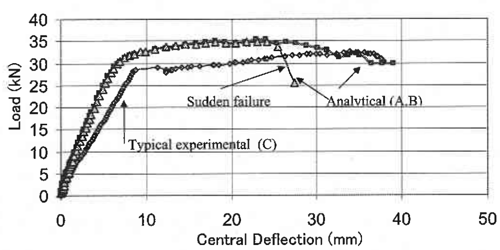


Figure 7 Analytical and experimental load deflection curves for repaired beams

subject to different combinations of normal and shear stresses, depending on the type of member, and location and extent of repair. Using the failure surface determined above, a parametric finite element study was carried to estimate the load-deflection curve of a beam repaired to an extent of 80% of the length along the tensile face[6]. The other geometric details of the beams and the reinforcement details used in the study are given in Figure 2. The extent of energy required for crack propagation (G_f) was varied. It may be noted that a change in G_f would represent the extent of the surface preparation carried out before application of the repair material, with a lower value reflecting an imperfect preparation (inadequate bond).

Figure 7 shows the load deflection curves obtained analytically (Curves A and B) for the two different levels G_f used. The figure also shows a typical load-deflection curve experimentally obtained for a repaired beam (Curve C). It can be seen that (a) the analytical and experimental results are reasonably close at the initial levels of load, (b) the analytical curves do not accurately represent the loss of stiffness seen after the initiation of initial flexural cracking[6], (c) a sudden failure in beams sometimes reported in beams[7] where the delamination on account of corrosion, etc has occurred, is accurately simulated by the analytical results. This sudden failure essentially reflects a loss in ductility and reduction in the energy absorption capacity in the beam. The clear difference between the behaviours of the beams in curves A and B, shows that the bond between the concrete and the repair material cannot be treated as 'complete'.

Concluding remarks

The study emphasizes the need to appropriately model the bond characteristics at the concrete-repair material interface in studying the structural behaviour of repaired RC beams. Using Carlos' formulation for stress transfer in discrete cracks, an effort has been made to experimentally determine the parameters for limiting values for cohesion and tension cut-off. A quantitative representation of the failure surface of the concrete-repair material interface for different combinations of loads has been reported.

With improvements such as direct determination of the energy required for crack propagation, it is hoped that the model can be used as a general tool for modeling the bond at the concrete-repair material interface.

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