研究速報

Behaviour of repaired RC beams under cyclic loading

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INTRODUCTION

Reinforcement corrosion is one of the main causes of premature deterioration in reinforced concrete (RC) structures. Depending on the extent of corrosion, longitudinal cracks along the reinforcing bars may be formed or the cover concrete may spall off. Structures with high levels of deterioration are often repaired by removing loose concrete, providing additional reinforcement and laying a fresh layer of concrete. This invariably leads to the formation of an 'interface' between the old concrete and the repaired layer, and in order for the structure to perform in a satisfactory manner, monolithic behaviour across the interface is very important[1]. There is limited evidence in literature that the static load carrying capacity of repaired beams may not be seriously impaired provided adequate care is taken in (i) selecting the repair material, in terms of mechanical properties, and, (ii) care is taken to ensure a proper bond between the parent concrete and the repair material[2,3,4].

A detailed study to better understand the structural behaviour of beams with such interfaces was undertaken using RC beams cast in two stages— with normal concrete in Phase I and with repair material in Phase II[5]. This paper gives the details of the study directed to understand if repeated application of loads causes the interface to disintegrate or otherwise affect the performance of repaired beams.

EXPERIMENTAL

Programme

Fatigue tests were carried out using eight repaired beams in addition to non-repaired control beams, cast only with concrete, as summarised in **Table 1**. Two commonly used repair materials were used, and the position and depth of repair was varied in the repaired beams. As far as position is concerned, beams were repaired on either the tension or the compression faces over a length extending to 80% of the span (i.e. a length of 128 cm). Keeping in mind that efforts are often made to remove all loose concrete and expose the reinforcing bars 'completely' before carrying out any repair in structures, the depth of repair was kept at two levels - '1' and '2', which refer to conditions when the repair depth was (a) limited to cover thickness plus about half the diameter of the bar, and, (b) extended 20mm beyond the reinforcing bars. Thus, the total depth of the repair layer was 30mm and 60mm in the levels 1 and 2, respectively. Following the nomenclature followed in the Table 1, a specimen 'AC1' refers to a beam made using the cement based repair material (Material 'A'), repaired on the compression face (represented by the second letter 'C') with the repair extending only upto the reinforcement level (with the third character '1' representing the level of the repair).

Materials used

In addition to the normal concrete used in the first phase of the casting, two commonly used repair materials— cement modified material (A) and polymer modified material (B), were used in the

Table 1 Experimental programme for structural testing of RC beams

Repair material	Location of repair	Depth of repair
Cement based (**A**)	Compression face (**C**)	Only upto reinforcement level (**1**)
Polymer based (**B**)	Tension face (**T**)	Extending 20mm beyond repair level (**2**)

Note: Control beams cast using only concrete were also tested for reference.

Table 2 Details of concrete used

Water	Cement	Sand	Gravel	Slump	Air content	Temp.
(kg/m^3)				(cm)	(%)	(°C)
165	254	908	935	11.5	5.5	21.5

Note: 4.96 kg/m^3 of NaCl and 250 ml of AE admixture per 100kg of cement were also added to the concrete.

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second phase. The mix proportion and properties of the concrete used and the properties of all the materials are given in **Table 2** and **Table 3**. Experiments for determination of basic material properties were carried out using standard procedures outlined elsewhere[5]. Both repair material came in ready to use 25 kg packs and only required mixing with water. Five kilograms of water were added to each pack of repair material based on the mixing specifications.

Details of specimens used and specimen preparation

The dimensions and reinforcement details of the beams used in the study are given in **Figure 1**. The beams were designed as under-reinforced sections (main reinforcement ratio of 1.18%) and had a neutral axis to effective depth (x/d) ratio 0.24, far less than 0.63, which is the requirement for under reinforced sections. Only nominal shear reinforcement was provided, as the shear capacity of even the unreinforced beam was adequate to resist the applied shear at the time of flexural failure[6].

The steps followed in preparing the 'repaired' beams are outlined below:

1. The first part of the beams were cast with 'original' concrete using an appropriate thermocoal piece at the location to be later covered with repair material. This 'beam' was cured for 4 weeks under wet gunny bags, before the thermocoal was removed.
2. The exposed concrete surface was roughened using a high-pressure water jet, and frequently visually inspected, to ensure that laitance was removed to make sure only half the coarse aggregate (about 10mm) was exposed.
3. Primer was applied on the concrete surface to improve the bond between the parent concrete and the repair material. In the case of beams repaired on the tension face the repair was carried out by positioning the beam(s) at an elevated location and shotcreting the repair material on to the repair surface in two layers, much in the manner of repair carried out in the field. In the case of repair on the compression face, the repair material is cast using an appropriate formwork, with the beams being placed on the floor.

Table 3 Properties of concrete and repair material used

Material	Compressive strength (M Pa)	E (kN/mm^2)	Poisson ratio	Tensile strength (M Pa)
Concrete	38.8	29.0	0.2	4.15
A	105.2	33.6	0.24	6.67
B	67.7	27.7	0.23	4.47

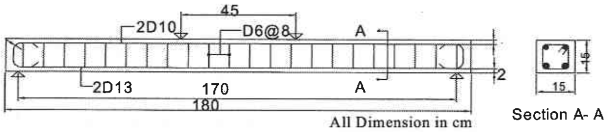

Figure 1 Dimensions and reinforcement details of RC beams used

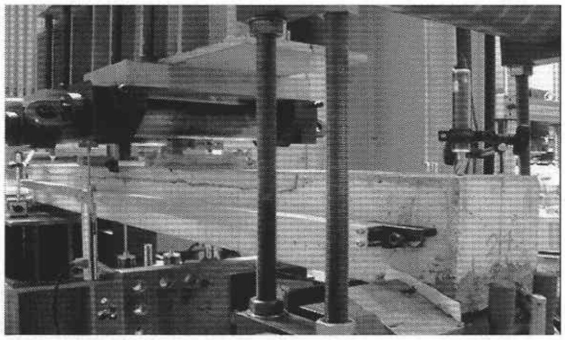

Figure 2 Setup for fatigue of repaired beam

Conditions for testing

Keeping in mind the need to ensure failure in flexure[7], the four-point loading for all beams was carried out at an a/d ratio of 5.1. **Figure 2** shows the loading and displacement arrangement used for the fatigue loading. The repaired face can be clearly seen in the top portion of the beam. The upper and lower limits of the fatigue cycle tests were set at 20%-75% of the maximum static load carrying capacity of the control beam determimed separately, and the loading applied without load reversal at a frequency of 1.5 Hz. The deflection was measured using a non-contact inductive type dynamic transducer attached to the dynamic data logger capable of reading almost continuously. The horizontal bar connected to the two supports at neutral axis depth eliminates the need to measure the support displacements.

RESULTS AND DISCUSSION

Table 4 shows the results of the fatigue tests in terms of the

Table 4 Fatigue lives of beams tested

Beam	Cycles to failure (x 10^3)	Fatigue life (% of control)
Control	1297	100
AT1	691	53.3
BT1	491	37.8
AC1	1575	121.4
BC1	365	28.1
AT2	322	24.8
BT2	244	18.8
AC2	997	76.8
BC2	756	58.3

number of loads applications to failure. It should be reiterated that all beams were under-reinforced and tested at an a/d of 5.1. Thus, failure in all cases occurred by rupture of the reinforcement. **Figure 3** shows a close up of one of the beams clearly showing a ruptured reinforcing bar. From **Table 4** it is clear that the performance of all repaired beams, except one (which failed at 121% of the control beam), was well below that of the control beam, and they failed at values ranging between about 20% and 76% of the fatigue life of the control beam, regardless of the material used for the repair and location and depth of repair. The following paragraphs briefly discuss some other observations that can be made from the results.

Effect of type of material

For the same experimental condition, beams repaired with material 'A' (Cement modified) performed better compared to the ones repaired with material B (Polymer modified). Now, this difference could be attributed to the higher stiffness and compressive strength of 'A'.

Location of repair

The data obtained in this study show that whereas the beams repaired on the compression face failed at varying levels of 28%, 58%, 77% and 121%, the failures for the beam repaired on the tensile face occurred at 19%, 25%, 38% and 53%, compared to the control beam. Though obviously the evidence is not conclusive, it clearly shows that it is not easy to restore the structural integrity, especially in cases when the repair work is carried out on the tensile face.

Depth of repair

A comparison of the observed fatigue lives for different levels of repair, i.e. when the depth of the application was varied, it can be seen that in tensile face repaired beams, beams with the greater depth of repair (level 2) failed at roughly half the number of cycles of applied load compared to beams with the smaller depth of repair. Though the extent of experiments carried out in this study is indeed limited, there is a need to clarify the effectiveness of actually exposing tensile reinforcement completely and then casting the repair material.

Maximum deflection and change in stiffness

The deflection of the beams was observed using inductive type transducers and **Figure 4** shows the variation of the maximum deflection observed in the beams as they were subjected to increased number of loading cycles. The results show that in all cases, the deflection increases rapidly in the initial phase as rapid cracking occurs, followed by a relatively stable phase, during which phase the crack propagation is possibly only nominal. However, as failure approaches, most beams again show a tendency of rapid increase in the deflections, as unstable cracking takes place In a study on application of acoustic emission to propagation of cracks in concrete, an essentially similar pattern was observed by Uomoto in terms of the rate of emission of AE events[8].

Cracking pattern

Besides the cycles to failure, and the changes in the maximum deflection over time, the propagation of flexural cracks in all the beams was followed over the period of testing, and a sketch of the cracks observed at failure in the various beams is shown in **Figure 5**. As can be expected, the initial cracking took place in the tensile zone, and these flexural cracks propagated towards and finally beyond the neutral axis. Due to the presence of adequate amount of shear reinforcement and the a/d of the tests, no significant propagation of shear cracks was observed in any of the beams.

For the sake of discussion, the figures in **Figure 5** have been

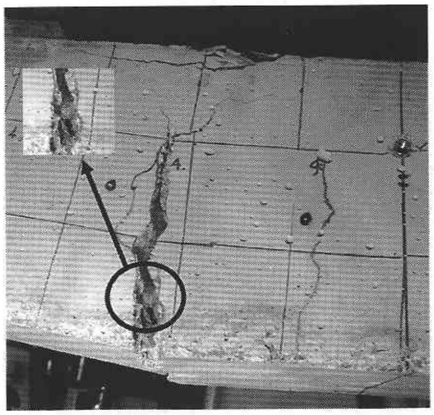

Figure 3　View of beam after failure with inset showing rupture of reinforcing bar

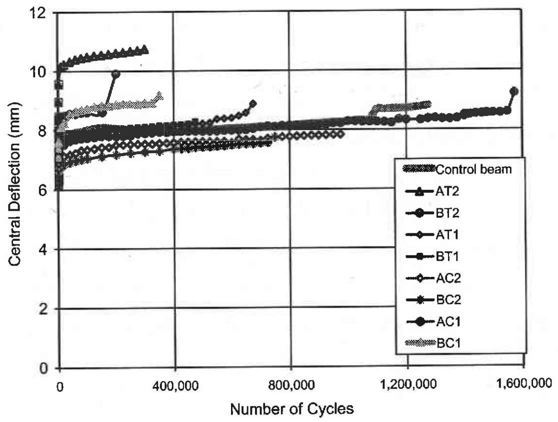

Figure 4　Maximum central deflection of beams vs. number of cycles

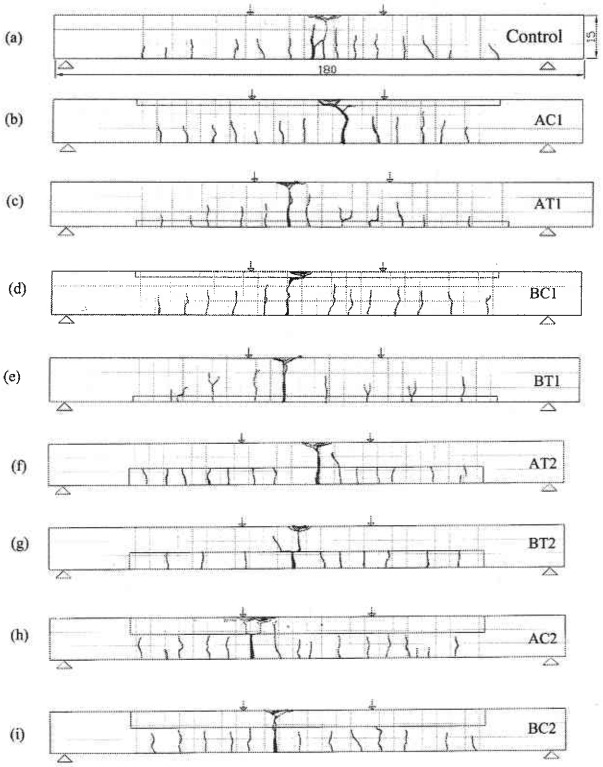

Figure 5 Schematic representation of final cracks in beams

arranged from (a) through (i), where besides the control beam (a), the beams with repairs carried out to levels 1 and 2, are given in (b) to (e) and (f) to (i), respectively.

As far as beams with Level 1 repair are concerned, an observation of Figures (b) through (e) reveals that there is no substantial difference in the cracks sketched at failure. However figures (b) and (c) reveal some evidence of 'separation' of the parent concrete and the repair material at the interface.

In the case of beams with Level 2 repair, Figures (f) through (i) show that in the case of repair being on the tension side, almost no flexural cracks propagate beyond the interface, and to that extent the interface acts to 'arrest' cracks formed. Crack propagation in Figure (g) also shows that flexural cracks beyond the interface (into concrete), take off from different places, compared with the crack on the repair material side. In the case of repair work on the compressive face, as observed in the Level 1 repairs, the evidence of 'separation' of the parent concrete and the repair material at the interface, and a change in the orientation of the cracks was clear.

CONCLUDING REMARKS

The results from a series of fatigue tests carried out using control and beams repaired in the compression or the tension faces using two different repair materials have been reported in this paper. On the basis of the limited experiments carried out, the following conclusions can be drawn.

There could be a considerable reduction in the fatigue life of the repaired beam compared to the control beam. In particular, tensile face repaired beams showed a marked deterioration in fatigue performance.

Further consideration is urgently required to better understand the effects of completely exposing corroded or deteriorated bars before application of the repair materials.

Though the extent of bonding across the interface was not a variable in the present study, crack propagation characteristics and reduced fatigue life indicate that the load carrying mechanism in the repaired beams could be different from unrepaired control beams.

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References

1) Technical guideline committee of ICRI, "Guide for surface preparation for the repair of deteriorated concrete resulting form reinforcing steel corrosion," International Concrete Repair Institute, Guideline No. 03730, January 1996.
2) Emberson, N.K., and Mays, G.C., "Significance of property mismatch in patch repair concrete, Part I: Properties of repair system," *Magazine of Concrete Research*, V. 42, No. 152, Sept. 1990, pp. 147–160.
3) Emberson, N.K., and Mays, G.C., "Significance of property mismatch in patch repair concrete, Part II: Axially loaded reinforced concrete members," *Magazine of Concrete Research*, V. 42, No. 152, Sept. 1990, pp. 161–170.
4) Emberson, N.K., and Mays, G.C., "Significance of property mismatch in patch repair concrete, part III: Reinforced concrete members in flexure," *Magazine of Concrete Research*, 48, No. 174, Mar. 1996, pp. 45–57.
5) Sooriyaarachchi H.P., "Structural performance of mechanically repaired reinforced concrete flexural elements", Thesis submitted to the University of Tokyo for Master of Engineering degree, September 2002
6) BS 8110: Part I and Part II, "Structural use concrete," *British Standard Institute*, London, 1985.
7) Kani, G.N.J., "The riddle of shear and its solution," *Proc., ACI Journal*, V. 61, No. 4 Apr. 1964, pp. 441–467
8) Uomoto, T. "Application of acoustic emission to the field of concrete engineering", Seiken Symposium, IIS, University of Tokyo, October 27–28, 1986