

Static and Fatigue Performance of Repaired Reinforced Concrete Beams

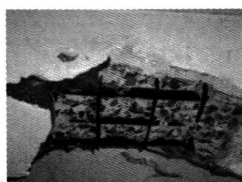
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Abstract: Deteriorated concrete structures due to corrosion cracks and with fallen concrete cover are often repaired by removing the cracked concrete around the corroded reinforcement and replacing it with new concrete or with special repair mortar. This process is often referred to as “Mechanical Repair” and is widely used for repairing deteriorated reinforced concrete members. Mechanical repair leads to the formation of an ‘interface’ between the ‘parent concrete’ and repaired material. The structural behaviour of the repaired members is critically depended on the performance of the interface. This paper reports the results of static and fatigue tests performed on a total of 21 beams, cast in two stages to resemble the mechanical repair. Location and dimensions of the repair and the repair material are taken as variables in the study. Results of the static tests on repaired beams reveal that static performance can be restored by the mechanical repair. Compressive face repair can even improve the performance depending on the properties of repair material and the performance of the bond. However, the fatigue performance of the repaired members is found very different to their static performance. All most all repaired beams either the repair of the compression face or of the tension face failed at substantially lower number of cycles compared to the control beam. Among the repaired beam, tension face repaired beams showed the most significant reduction in the fatigue performance.

Keywords: Deteriorated concrete structures, reinforcement corrosion, Mechanical repair, Interface, Static performance, Fatigue performance.

1. Back ground

Old concrete structures, and some time even the new ones, built in corrosive environments (eg. Structures close to costal belt with high Cl⁻ concentration in the surrounding environment) are vulnerable to corrosion damage. Fig 1 shows corrosion damages to an old hospital building situated in Galle which was commissioned in July, 1960 by the then Ministry of Public works. It is not difficult to find many more such structures, both old and new (due to lack of attention to durability aspects) along our costal belt.



Damaged beam



Damaged slab

Figure 1 - Element damaged by corrosion of reinforcement

The building which is only few meters off the costal line has been abandoned since the tsunami in 2004. Assessment of carbonation depths determined by applying phenolphthalein solution to the core samples obtained from various parts of the structure confirm that the depth of carbonation, or the

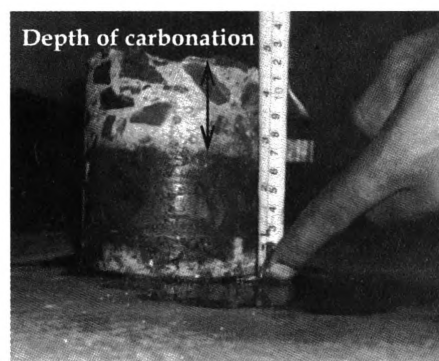


Figure 2 - Carbonation depth measured from cores extracted from the slab.

loss of alkalinity, in the concrete now extends more than half the depth of slab (see Fig. 2). Alkalinity of concrete, which is resulted mainly from the $\text{Ca}(\text{OH})_2$ in the pore solution, is a measure of protection for reinforcement. It helps to form a protective oxide layer ($\beta\text{Fe}_2\text{O}_3$) around steel reinforcement and protects reinforcement against corrosion [1]. As $\text{Ca}(\text{OH})_2$ in concrete react with CO_2 in the atmosphere to form CaCO_3 , alkalinity of concrete depletes and hence the protection concrete provide for the steel reinforcement.

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It is not always practical nor economically viable to demolish and replace a building with corrosion damage, especially, when the building is found to be structurally sound and very expensive to replace like in the case of this hospital building with a floor area in excess of 3,000 m² (30,000 Square feet) [2]. In such circumstances, repair and restore corrosion damage seems the most obvious solution.

Removing the concrete around reinforcements and replacing it with new materials is the best repair procedure for deteriorated concrete structures due to reinforcement corrosion. Repair can be done with new concrete or repair mortar with improved properties like early strength development and improved thermal and shrinkage properties. The repair, when taken beyond the reinforcement depth, can provide an extended durability to the repaired structure.

This repair technique is commonly referred to as Mechanical repair and is adapted world over to repair concrete structures deteriorated due to corrosion of reinforcement. Now, with many deteriorated structures along the coastal belt being considered for mechanical repair, the need to understand the correct techniques and its possible limitation and structural implications is considered invaluable. It is in this backdrop that the result of the behaviour of repaired beams is presented here. The paper provides insight to the best known practices of mechanical repair, the performance, limitations and the structural implication of the technique.

2. Introduction

Accumulation of corrosion product exerts pressure on the surrounding concrete which leads to de-bonding of reinforcement bars and cracking and spalling of concrete. Loss of composite action between concrete and reinforcement leads to change of structural action from one of beam action, characterised by the composite behaviour of reinforcement and concrete, to a tight arch action, characterised by lack of composite action and compatibility of strain along the de-bonded length [3][4][5]. The structural behaviour of deteriorated structures due to reinforcement corrosion has been fairly well researched [3][4][5][6]. More often beams with exposed reinforcements are used to simulate the conditions of corroded structures.

Mechanical repair, which involves laying a fresh layer of concrete or other suitable repair material over existing concrete invariably leads to the formation of an 'interface' between the

old concrete and the repaired layer. The performance of this interface is critically important for the composite behaviour of the repaired beams.

Significant portion of research work on the behaviour of repair has been on the selection of material for repair [7][8][9]. Emerson and May (1996), based on the parametric study, recommended to use Young's modulus to select repair material. They found use of repair material with Young's modulus within the range of ± 10 kN/mm² of parent concrete avoids unnecessary stress concentrations and results optimum performance.

Recommendations for material selection, repair techniques and other valuable information relating to mechanical repair can be found from the Repair manual published by the International Concrete Repair Institute [10] and stands out as state of the art guideline on repair of concrete structure.

3. Research significance

In relation to actual conditions, whether a Mechanical repair can restore the composite action and respond to cyclic loading without delaminate or deterioration of stress transfer mechanism across the interface has not been comprehensively addressed. Furthermore, the structural implication of existing guidelines when employed is not fully explored with the commonly used repair material and techniques adopted in the industry. There is also a need to understand the extent to which the repair can restore the static and fatigue performance of repaired beam, and how the dimensions, location and properties of repair material will influence the overall static and fatigue performance of the restored beams. This paper reports static and fatigue tests of a total of 21 beams, cast in two stages to simulate repair. The tests conducted have used common repair materials based on existing knowledge of selecting material and have followed the commonly practiced techniques in the industry for repair. Results indicate, that mechanical repair is capable of restoring the static performance, but cast serious doubts of its ability to restore the fatigue performance.

4. Methodology

4.1 Experimental programme

In this study, beams were cast in the laboratory in two stages. In the first phase beams were cast leaving void for the repair dimension. This is achieved by attaching packing material to the reinforcement skeleton. In the second phase

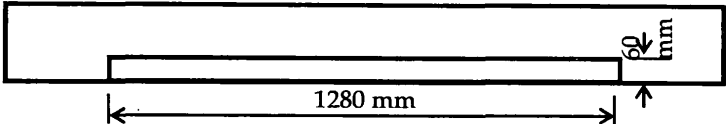
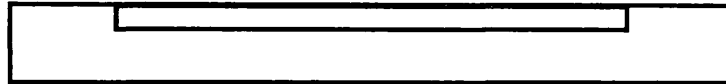
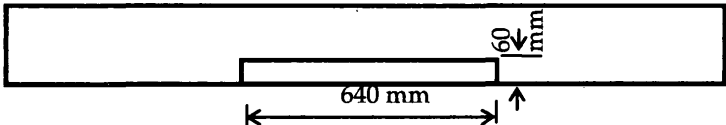
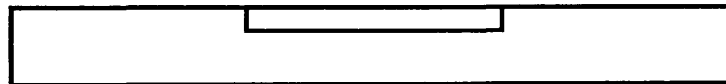
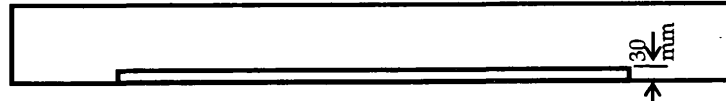
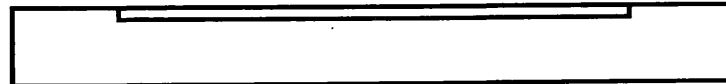
packing material was stripped off and cavity was repaired. Details of the repaired beams in the experimental programme with the explanation of the nomenclature used to identify the beams are given in Table 1. Details of the repair variables; Length, depth, location (tension face or compression face) and the selection of repair materials are summarised in Table 2.

In addition to repaired beams various lengths of tensile reinforcement exposed beams with exposed dimensions similar to the tensile phase repaired beams and fully monolithically cast

concrete beams were included in the testing as control specimens. It is expected that beams with exposed reinforcement will provide a good estimate of the effectiveness of mechanical repair in restoring the composite action and load carrying capacity of the repaired beams.

The study involved testing of twelve beams under static loading and nine beams under fatigue loading. Repair beams under static loading had repair lengths of 40% and 80% of their spanning lengths. In static loading all beams had their repair extended beyond 20mm from the reinforcement level, making the depth

Table 1 - Specimen detail in the static and fatigue testing

Schematic representation of specimen	Specimens tested (*)			
	Static test		Fatigue test	
	RAT80HS	RBT80HS	RAT80HF	RBT80HF
	RAC80HS	RBC80HS	RAC80HF	RBC80HF
	RAT40HS	RBT40HS		
	RAC40HS	RBC40HS		
			RAT80LF	RBT80LF
			RAC80LF	RBT80LF

Notes:

In addition to the beams above, beams E-40, E-60 and E-80 were tested with 40, 60 and 80% of the tension reinforcement fully exposed with 60 mm depth of opening similar to the repair dimension of the beams with repair extending 20mm beyond reinforcement.

* The nomenclature followed in the above table:

R	b	c	d	e	f
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R: Repaired beam

b: Material used : A or B

c: Face on which the repair is carried out (Compression - C, or tension - T)

d: Length of repair (40% or 80% of the span length)

e: Depth of repair (only up to reinforcement level - L (30mm repaired depth) , extending 20mm beyond reinforcement - H (60mm repaired depth))

f: Testing condition (Static - S, Fatigue - F)



of repair 60mm. Both composite beams and beams with tensile face exposed to a 60mm depth, with exposure length extended over 40%, 60% and 80% of spanning length (E40, E60 & E80) were included as control specimens of static load test. Table 1 and 2 indicate full details of the repaired beams tested under static loading and fatigue loading.

All beams subjected to fatigue loading had their length repaired over 80% of the spanning length. Keeping in mind that effort in the field is often limited to repair the fallen cover but the guidelines requires to extend the repair beyond

Table 2 - Details of repair variables

Description	Variable	Remarks
Repair material	Cement based (A) Polymer based (B)	
Location of repair	Compression face (C) Tension face (T)	
Depth of repair	Only up to reinforcement level (L) Extending 20mm beyond repair level (H)	L - Repair 30 mm H - Repair 60 mm
Length of repair	40% of span length 80% of span length	Fatigue testing was limited to 80% repair length
Notes: - Control beams cast using only concrete were also tested for reference. - Beams were also cast using fully exposed tensile reinforcement with varying exposure lengths of 40%, 60% and 80% of the span length.		

the reinforcement level [10], both the beams with two depths of repair; beams repaired up to reinforcement level and beams repaired 20mm beyond reinforcement level were included in the fatigue testing. The total thicknesses of the repair material thus used in the two cases were 30mm and 60mm respectively. As there is less danger in delaminating the repair under a single loading (static loading), only specimens with higher repair depth was used in the static test.

4.2 Materials used

Two materials were used for repair in this experimental programme. The repair material A -Cement modified repair material had higher Young's modulus compared to the parent concrete while repair material B - Polymer modified repair material had lower young's modulus compared to the parent concrete. However, both materials have confirmed to the required ± 10 kN/mm² Young's modulus range from the parent concrete recommended by the

ICRI guide lines for selecting material for mechanical repair [10]. The two repair materials came in ready to use 25kg packs and only required mixing with water. Five kilograms of water were added to each pack of repair material based on the mixing specifications. The properties of the two materials and the parent concrete as found at the time of testing are tabulated in the Table 3.

4.3 Details of the specimen used and Table 3 - Properties of repair material and parent concrete

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

specimen preparation

The dimensions and reinforcement details of the beams used in this experiment investigation is shown in Fig. 3. The beams were designed as under-reinforced sections($x/d=0.24$) with a calculated static load carrying capacity of 36.4 kN under the testing arrangement depicted in Fig. 3[11]. The beams were provided only the nominal shear reinforcement (mild steel 6 mm bars at $80\text{mm} < 0.75d$) since the demand for shear is kept minimum under the loading arrangement with shear arm to depth (a/d) ratio at 5.1.

Both the exposed beams and the composite beams used as control specimens were prepared in a single cast and tested as control specimens. The repaired beams involved two stage cast. Detailed procedures of preparation and casting of the repaired beams are explained below.

First the packing material was attached to the reinforcement skeleton as shown in the Fig. 4(a). Then the skeleton was lowered into the mould and concrete was cast (see Fig. 4(b) and 4(c)). After curing the beams for 28 days packing material was stripped off exposing the repair cavities (see Fig. 4(d)). Repair surfaces were then water blasted to create the required roughness for better bond between the repair material and parent concrete (Fig. 4(e)). Thereafter, appropriate shuttering work was done to cast the repair mortar to the required dimension (see Fig. 4(f)). Primer was then applied on the prepared surfaces (see Fig. 4(g)) before they are stacked in the correct

orientation and shot-created with the appropriate repair mortar (see Fig 4(h)).

4.4 Conditions for testing

Fig 5 shows the loading and measuring arrangement used for static testing of repaired beam, while Fig. 6 shows the loading and measuring arrangement for fatigue testing. For

both testing identical four points loading arrangement with a shear arm to depth ratio (a/d) equal to 5.1 was used. In the static testing deflection was measured using LVDT's, while inductive type displacement transducer connected to the horizontal bar and attached to the neutral axis depth of the beam at the two ends, is used for measuring displacement in the fatigue test (see Fig. 6). The upper and lower

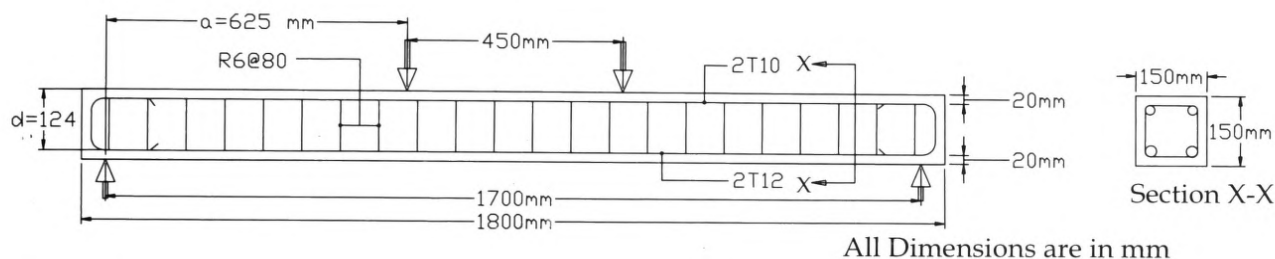


Figure 3 - Loading arrangement for the static and fatigue testing of the beam and reinforcement detail

4(a) Provision for the required repair dimension attached to the reinforcement skeleton	4(b) Reinforcement Skelton lowered to the mould	4(c) Cast concrete	4(d) Strip off the packing material and expose the repair cavity
4(e) Preparing repair surfaces using water blasting	4(f) Complete the required shuttering work for the repair	4(g) Application of primer to the prepared surface before being repaired	4(h) Shotcrete the repair mortar to the cavity

Figure 4 - Various steps involved in the preparation of the repaired beams

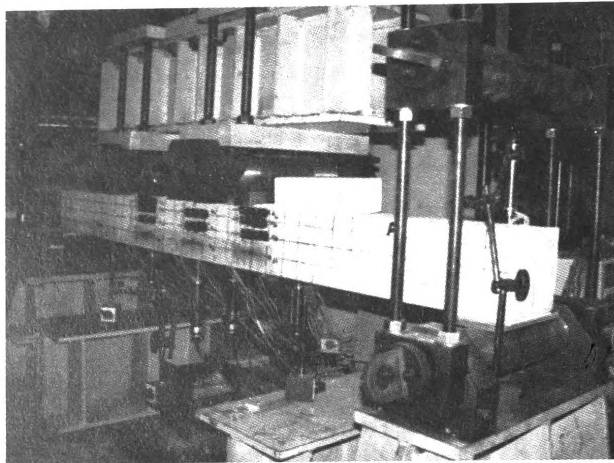


Figure 5 - loading arrangement for static test

limit of the fatigue cycle were set at 20% and 75% of the ultimate load carrying capacity of the control beam and operated at a frequency of 1.5 Hz. Amplitude and frequency of the fatigue test was decided based on duration of the test and limitations of the machine. In the fatigue test deflection was measured using non contact inductive type dynamic transducers (one of special kind that required no mechanical contact between the moving head and the circuit and therefore can be left attached to the specimens throughout the test). These transducers, together with the use of a computerised dynamic data logging system, enabled measurement of deflections at predetermined intervals without having to stop the fatigue test.

In order for continuous recording of the maximum deflection over full fatigue life two types of automatic recording were taken. In the first kind, the deflections were recorded at predetermined cycle number and in the other instructions were given to the logger to record deflections when the monitored deflection is significantly different to the last record. This enables almost continuous recording with all critical recording been taken, especially, towards the end of the fatigue life, where the deflections are bound to change significantly during the crack propagation and difficult to be recorded otherwise. Maximum deflection at any given cycle number was taken as the maximum over 20 consecutive cycles scanned at 1/100 of second intervals and was recorded against the first cycle number of the twenty consecutive cycles being considered. To record over twenty cycles was decided as reading over twenty cycles at 1/100 of a second scanning interval would ensure maximum deflection to a very high degree of accuracy. This system of measuring deflections can be called as a system of continuous monitoring and intermittent recording and considered more accurate

compared to the traditional method where fatigue test has to be temporally stopped at a predetermined cycle number to do the recording.

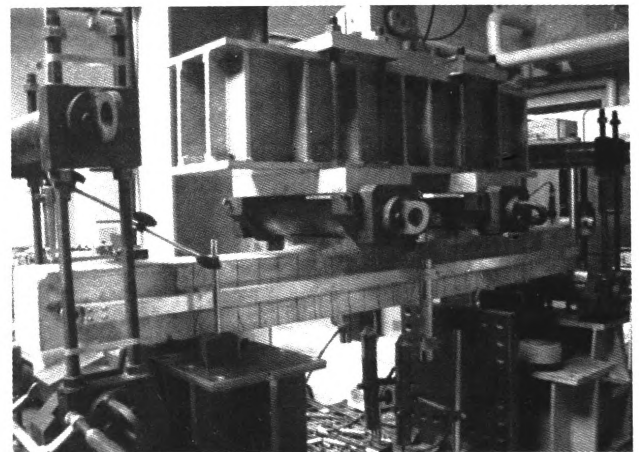


Figure 6 - Loading arrangement for Fatigue test

5. Structural behaviour under static loading

Total of 12 beams were tested under static loading. This includes eight repaired beams one composite beam and three exposed beams (E-40, E-60 & E-80). The results in terms of the load carrying capacity of the beams and the maximum deflection observed at failure are summarised in Table 4. A comparison of the values observed for repaired beams with respect to the control beam and the corresponding beam with exposed tensile reinforcement, whenever applicable, has also been included in the Table 4. As expected for the given x/d ratio and the loading arrangement (a/d ratio) all composite beams recorded under-reinforced behaviour characterised by yielding of the bar followed by crushing of concrete [13][14]. Similar failure modes were observed for the repaired beams. However, there were clear signs of stress reversal in the exposed beams. At times, especially in E80, the stress reversal was found to be significant to cause tensile cracking in what would be considered compressive region face in simple bending. Fig. 7 shows tensile cracks on the top surface which is normally considered the compressive face in the simple beam bending.

Table 4 - Results of static loads test of control and repaired beams.

No	Specimen	Ultimate Load (k N)	Ultimate Load Ulti. of control	Ultimate Load Ultimate of exposed	Central deflection at peak load (mm)	Repaired control beam	Repaired Exposed beam
1	Control	36.13	1.00	-	32.01	1.0	-
2	E-40	31.50	0.87	-	23.26	0.73	-
3	E-60	29.51	0.82	-	22.05	0.69	-
4	E-80	26.46	0.73	-	24.75	0.77	-
5	RAT40HS	34.65	0.96	1.10	25.83	0.81	1.11
6	RBT40HS	35.32	0.98	1.12	31.61	0.99	1.36
7	RAT80HS	32.47	0.90	1.24	33.87	1.06	1.37
8	RBT80HS	32.75	0.91	1.24	40.76	1.27	1.65
9	RAC40HS	38.80	1.07	-	36.5	1.14	-
10	RBC40HS	36.60	1.01	-	35.5	1.11	-
11	RAC80HS	42.00	1.16	-	67.21	2.10	-
12	RBC80HS	36.60	1.01	-	35.37	1.10	-

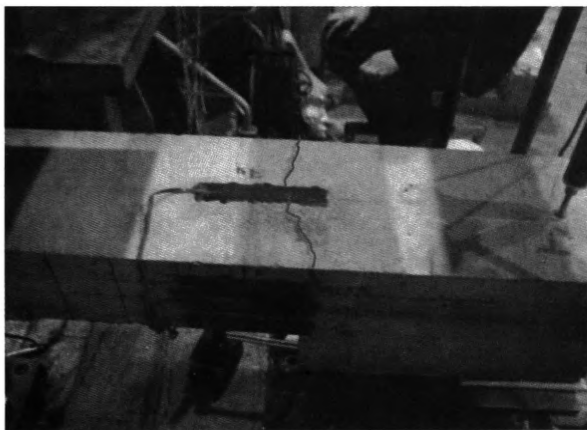


Figure 7 - Tensile cracks starting from the compression face.

5.1 Behaviour of exposed beams

Fig. 8 shows the observed load-deflection curves for the exposed beams E-40, E-60 and E-80 compared with control beam. Table 4 summarise and compares the performance of exposed beam with composite beam in terms of ultimate load capacity and deflection at failure. Maximum load carrying capacity of E-80 is found to be about 73% of the fully composite concrete beam (control specimen). All reinforcement exposed beams failed at lower levels of ultimate deflection compared to the control beam. Furthermore, stiffness of the repaired beams dropped with the increase in exposure length. Strain reading and the observed crack pattern confirmed, that structural action of exposed beams is one of tied arch and is very similar to the findings of

other researchers [3][4][5][6]. Reduce section modulus of exposed beams and absence of tension stiffening effects along the exposed length of the bar can be considered as the main causes of reduced stiffness of exposed beams.

5.2 Effect of location and length of repair

Fig. 9 shows the 80% tensile face repaired beams compared with the composite beam and beam with tensile reinforcement exposed over 80% of the spanning length, whilst Fig. 10 shows the load deflection relationship of the 40% of the tensile face repaired beams compared with composite beam and beam with tensile reinforcement exposed over 40% of the spanning length. Table 4 along with other beams summarises and compares the key behavioural characteristics of tensile face repaired beams compared with composite beam and beam with exposed reinforcements. There is about 5% and 10% reduction in the load carrying capacity of the 40% and 80% of tensile face repaired beams respectively, compared with the composite beam (see Table 4). However, it should also be noted that these loads are clearly higher than the beams with exposed tensile reinforcement. When compared with the 80% against the 40% repair length in the tensile face, it is clear that lesser the length of tensile face repair more effectively it restores the static performance in terms of initial stiffness and ultimate load carrying capacity. Both RAT40HS vs. RAT80HS and RBT40HS and



RBT 80HS confirms this trend (see also Fig 9 and

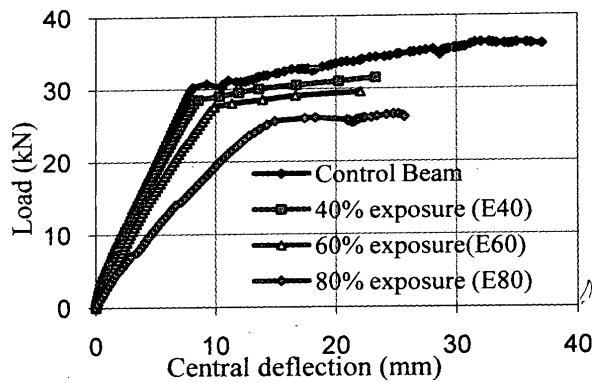


Figure 8-Static performance of exposed beams.

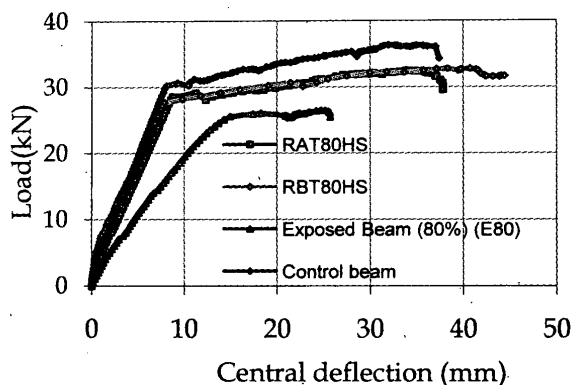


Figure 9-Static performance of the beams with tensile face repaired over 80%.

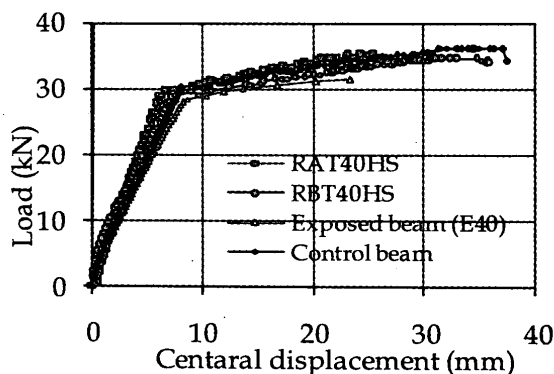


Figure 10 - Static performance of the beams with tensile face repaired over 40%.

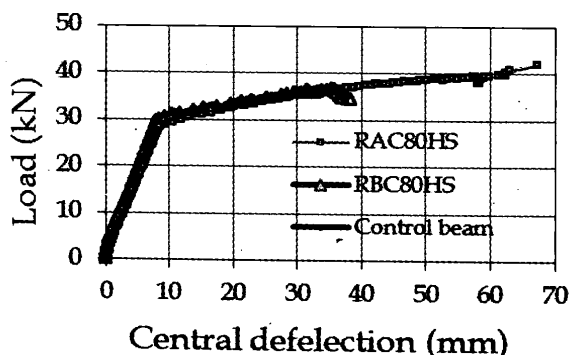


Figure 11 - Static performance of the beams with compressive face repaired over 80%

Fig 10). Fig. 11 shows static performance of beams with compression face repaired over 80% of its spanning length compared with composite beams. Results indicate full recovery of the load carrying capacity when repair is done on the compression face over 80% of the spanning length. Beams repaired on the compression face with material A showed 7% and 16% increase for 40% and 80% of repair respectively, while beams repaired with material B show almost the same load -carrying capacity as the control beam. Further, the performance of the compressive face repair over 80% of the spanning length is found to be better than the 40% repair length.

Static test provide evidence that stresses are transferred through the interface and that repair can restore the composite action of the beam to a reasonable degree. The effective stress transfer is further confirmed by the strain gauge readings across the repaired section. Although load-deflection behaviour for the control and most of the repaired beams was found to be almost similar, there was an instance where repair beam failed before maturing deflection and load carrying capacity. RAT40HS failed before maturing around 80% of the ultimate deflection of control beam. An examination of the failed beam showed evidence of de-bonding of the repair material from the parent concrete. This highlight the importance of ensuring good bond between repair and the parent concrete, and that unexpected responses could happen due to bond failure.

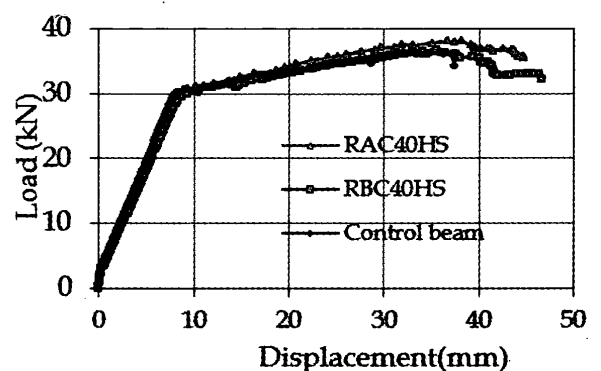


Figure 12 - Static performance of the beams with compressive face repaired over 40%.

Effect of material of repair

As far as load carrying capacity is concerned, results in Table 4 show that there is virtually no difference between beams repaired with the two materials so long as the repair was on the tension face (Specimens RAT40HS Vs.

RBT40HS and RAT80HS Vs. RBT80HS). However when the repair is carried out on the compression face, the cement based repair material (A) with higher Young's modulus and compressive strength gives improved results compared to material B (RAC80HS Vs. RBC80HS). This implies that higher compressive strength and Young's modulus contributes to increase the ductility of the beam repaired in compressive face and therefore are better suited for compression face repair. In the light of the repaired beam under static loading it can be concluded that current surface preparation and the standard procedure of application of repair material are adequate against delaminating of the bond between the parent concrete and repair mortar. This is provided that the selected repair materials are within Young's modulus ± 10 kN/mm² of the parent concrete.

6. Behaviour of repaired beams under fatigue loading

This part of the study was included in the research programme to understand the fatigue performance of repaired beams and clarify if repeated application of loads causes the interface between the repair material and the concrete to disintegrate or otherwise affect the fatigue performance of repaired concrete beams. As there is a general tendency in practice to repair only the fallen cover up to the reinforcement level, and it is possible that these repair easily delaminate due to applied cyclic loading, in addition to the beam repaired beyond reinforcement level (RAT80HF,

RBT80HF, RAC80HF and RBC80HF) beams repaired up to reinforcement level (RAT80LF, RBT80LF, RAC80LF and RBC80LF) was also included in the study. Now, given that all beams were under-reinforced ($x/d=0.24$), failure in all cases should be by rupture of the reinforcement [12]. All beams, control and repaired, did in fact follow the expected failure mode and failed by rupture of reinforcement. Fig. 13 shows a close up of one of the beams after fatigue failure clearly showing a ruptured reinforcing bar. Table 5 shows the results of the fatigue tests in terms of the number of cycles to failure. From Table 5 it is clear that the performance of all repaired beams, except compressive face repaired up to reinforcement level with material A was well below that of the control beam. Plot of maximum central deflection against the number of cycles for the entire series of beams tested under fatigue loading are shown in the Fig. 14. According to Fig. 14 it is clear that most of the compressive face repaired beams which showed higher initial stiffness compared to the composite beam, have still failed to endure the fatigue life closer to the control beam.

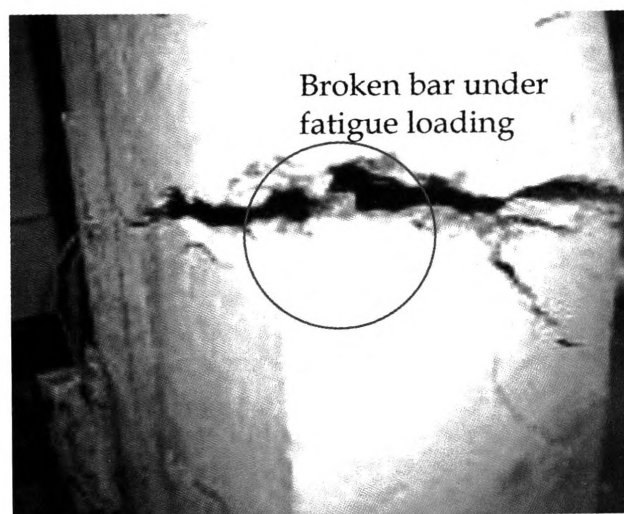


Figure 13 - Failure of reinforcement (RBC80HF)

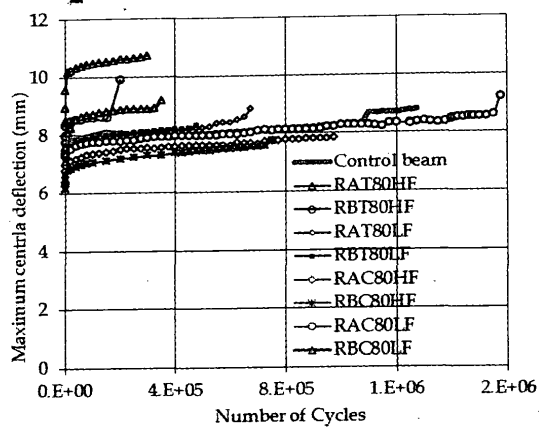


Figure 14 - Maximum central deflection against number of cycles.

Before discussing individual results of different specimens under fatigue loading, it is important to be reminded that the fatigue failure triggered by the rupture of reinforcement is a localised phenomena and the failure is governed by the level of strain in the reinforcement bar at the point of failure [12].

Table 5 - Fatigue performance of repaired beams

Specimen	Cycles to failure ($\times 10^3$)	Fatigue life (% of control)
Control	1297	100
RAT80LF	691	53.3
RBT80LF	491	37.8
RAC80LF	1575	121.4
RBC80LF	365	28.1
RAT80HF	322	24.8
RBT80HF	244	18.8
RAC80HF	997	76.8
RBC80HF	756	58.3

Results of fatigue behaviour of tensile face repaired beams seems to suggest that repair material with higher Young's modulus and tensile strength, material A, perform better than the material B (compare RAT80HF Vs. RBT80HF). Higher stiffens and therefore the lower bar strain is possible explanation for better performance of Material A over Material B. However, the significantly lower fatigue performance of tensile face repaired beams compared with composite beam is difficult to be explained. Out of the two tensile face repair geometries, beams repaired up to the reinforcement level have recorded better fatigue performance compared to the beams repaired beyond the reinforcement level. As the reinforcement skeleton is expected to provide better resistance against possible bond deterioration between repair mortar and parent concrete, beams repaired beyond the reinforcement level is expected to have better fatigue performance had it been the performance of bond that cause poor fatigue response. Therefore, it is safe to assume that the cause of poor fatigue performance of repaired beams is a reason beyond the deterioration of interface.

Fig. 15 is an extract of crack patterns of tensile face repaired beams depicting RAT80HF RBT80HF and the composite beam. From Fig. 15 it is seen that the most of the crack in the repair specimens have stopped penetrating beyond the repair level, whereas control specimen has not encountered such restrictions. It is also highlighted in the Fig 15 that the number of cracks, and in particular number of cracks penetrate through the interface, is substantially less in the tensile face repaired

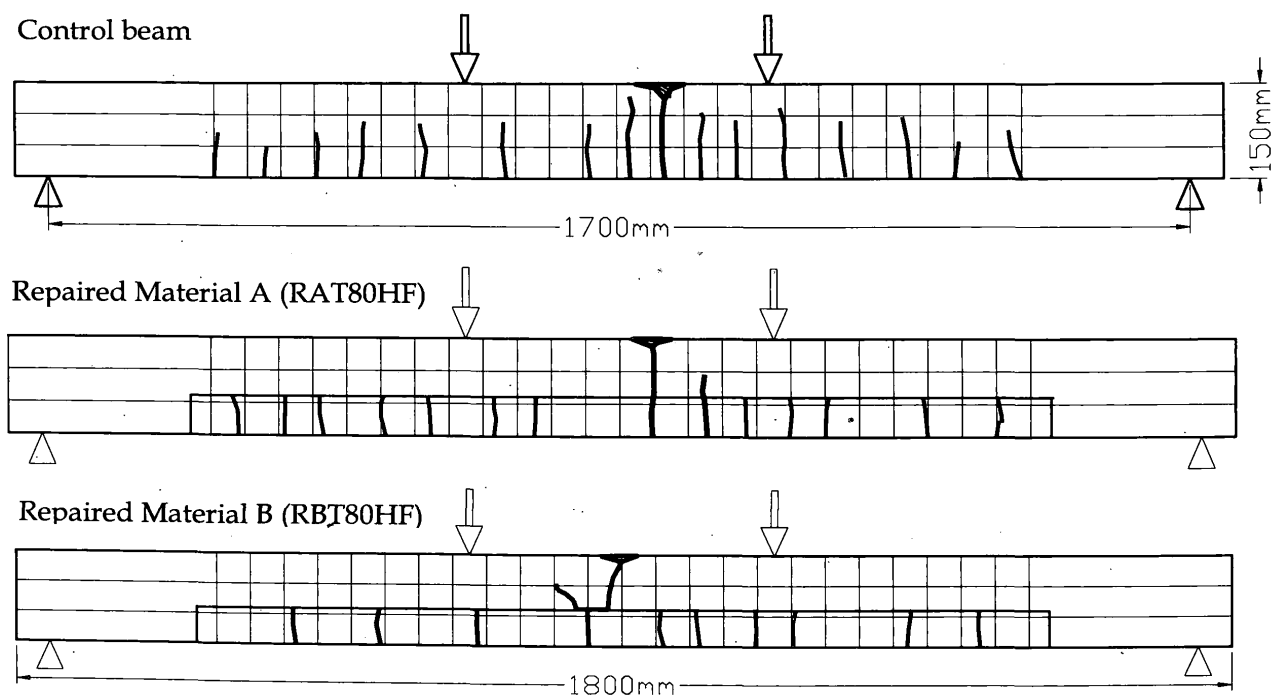


Figure 15 -Show crack pattern of the beam repaired beyond the reinforcement level

beams compared to composite beams. Most of the cracks in the repaired beams seem to have trapped in the boundary between the parent concrete and repair mortar. In other words, the interface has acted as crack trapping device preventing majority of cracks propagating across the interface.

Fewer numbers of penetrating cracks cause wider crack opening and excessive straining of reinforcement at the cracks. The direct relationship between the fatigue response and strain makes, this excessive straining due to changes in crack pattern potentially be the main cause for poor fatigue performance of the repaired beams.

Observations of crack patterns tend to suggest that, the influence of interface continue to exist even in the compressive face repaired beams, but at a lesser degree due to the higher depth to the interface. Fig 16 show crack bifurcation at the interface between the parent and repair material of a compressive face repaired beam, which is a clear sign of the influence of interface on crack propagation.

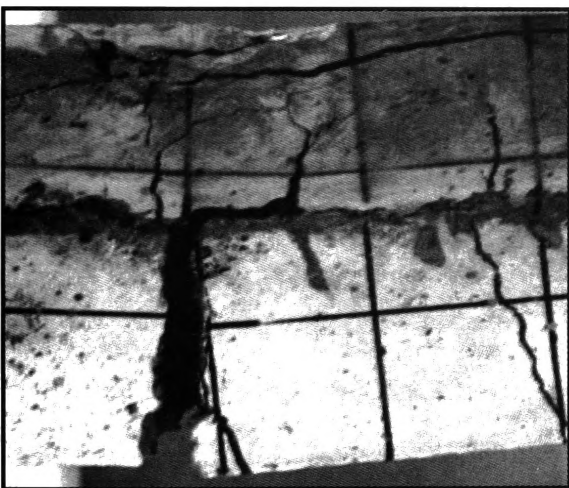


Figure 16 - Crack bifurcation at interface of a compressive face repaired beam (RAC80HF)

7. Concluding remarks

Results of static and fatigue tests of beams cast in the laboratory simulating the actual repair techniques and procedures are presented in this paper. As the reinforcement and the testing conditions of the beams were chosen to ensure flexural failure, the study is limited to the flexural behaviour of repaired beams.

- From the test of beams cast with the tension reinforcement fully exposed to simulate deterioration of bars, spalling of concrete and de-bonding, results in substantial reduction in load carrying capacity and the change in the structural action.
- According to the static loading test, compression face repair has been found very

effective in restoring the static behaviour. Beams repaired on the tensile face have also shown significant improvement in static performance.

- Higher Young's modulus of repair material compared with parent concrete (but within the ± 10 kN/mm² guideline) can be considered a better choice compared to lower Young's modulus for restoring performance of repaired beams.
- Fatigue life of repaired beams has been found to be much lower compared to control beams in all most all beams. In particular beams repaired in tensile face showed significant decrease in fatigue life.
- It has been found that repair extended beyond the tensile reinforcement level (ICRI (1996) recommended method of repair) has the lower fatigue response compared with beams repaired up to reinforcement level.
- Horizontal interface significantly reduces the number of cracks passing through the interface causing excessive strain localisation in the bar at the penetrating cracks. This unusually high strain is considered a strong possibility for the poor fatigue performance of repaired beams.
- Deterioration of interface bond between repair material and parent concrete and therefore stress transfer across interface under repeated cycles of loading is another concern for the poor fatigue performance of the repaired beams. However, stakes of such deterioration affecting fatigue performance is expected to be higher in the beams with repair extended only up to the reinforcement level, as the extra connection from skeleton in beams repaired beyond reinforcement level provide additional resistance against bond deterioration. The opposite trend of fatigue behaviour of repaired beam reinforces the hypothesis that the cause for poor fatigue performance is beyond delaminating or deterioration of interface. This further confirms that change in crack propagation and possible unusual strain localisation is the main cause for the poor fatigue performance of repaired beams. However, current data are not conclusive and therefore require more research effort to validate this hypothesis.

This study establishes a strong link between repair and poor fatigue performance of repaired beams. Findings of the present study expose the limitations of the existing guidelines for selecting material and the techniques that have been recommended and used in the industry. Therefore users are cautioned to use Mechanical repair without additional



strengthening in structures subjected to cyclic loading. As mechanical repair done in a similar procedure to the one described above only restores static performance, use of such method should be limited to structures that are not frequent subjected to cyclic loading. Further research is called for, to better understand the role and mechanisms of stress transfer across the interface, which could enable development of a more rational methodology for design and implementation of repair strategies in deteriorated structures.

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