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Deformation of continuous reinforced concrete beams during patch repair

J. Cairns and E. Coakley

This paper describes an experimental and numerical investigation examining the effect of reinforcement exposure during the patch repair process on the behaviour of continuous beams. Particular attention is paid to moment transfer and change in strain patterns during concrete breakout. The test programme embraced a range of parameters including the length and position of breakout and a variety of reinforcement arrangements. Moment transfer during concrete breakout was monitored to assess whether breakout at one location would cause overstressing in other parts of the structure. Results from tests and numerical analysis show increases in section deformations away from the breakout were small when compared to those within the breakout length. It is surmised that there is little danger of overstraining in locations away from the breakout zone while breakout does not extend past a point of contraflexure.

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Introduction

Deterioration of reinforced concrete (RC) structures has become a major problem for owners and engineers responsible for their maintenance. Although a variety of techniques for protection and restoration of durability of chloride-contaminated or carbonated concrete structures have been introduced in recent years, maintenance frequently requires patch repairs, during which concrete is broken out and reinforcement exposed wherever longitudinal cracking is deemed excessive. A number of studies (Eyre and Nokhasteh, 1992; Raoof and Lin, 1995) have investigated the effect of exposure of reinforcement on behaviour of simply supported (i.e. statically determinate) beams. Changes in structural action when tension reinforcement is exposed over a portion of the span have been described (Cairns and Zhao, 1993; Cairns, 1995) and a range of parameters including load arrangement, location of breakout, length and depth of breakout (Raoof and Lin, 1997), area of exposed reinforcement and concrete strength (Zhang and Raoof, 1995) have been investigated.

The use of temporary props to relieve load from the member during a repair may to some

extent avoid difficulties in assessing the consequences of altered structural behaviour and ensure a sufficient margin of safety against failure while reinforcement is exposed. Propping can, however, obstruct the repair process and increase the overall cost of the repair. While it would be advantageous to carry out repairs unpropped, assessment procedures to enable prediction of behaviour in the 'weakened' condition need to be developed and validated.

Exposure of reinforcement affects both strength and stiffness over the exposed length. While models for residual strength of simply supported beams have been developed and verified against test data, relatively little attention has been devoted to the influence of breakout on stiffness. This has given rise to concerns that loss of stiffness and consequent changes in the pattern of bending moments due to breakout in one part of a continuous beam could lead to overstraining elsewhere. Only one very limited investigation (Canisius and Waleed, 2002) based exclusively on a numerical analysis of a statically indeterminate structure subjected to patch repair is known. High stress concentrations were observed near the mid-span breakout region and also at the adjacent internal support. This investigation concluded that unpropped repair 'can have adverse implications for structural safety, serviceability and durability'. In view of the likely impact of propping on repair costs, a more extensive study of continuous beams was warranted.

When undertaking structural repairs to a RC beam, behaviour must be checked at both the 'weakened' state during breakout, possibly under restricted loading, and following

completion of repair when full load capacity must be restored. These checks will cover behaviour

(a) during breakout

- (i) increases in deflection and crack widths, at the breakout location and elsewhere within the member
- (ii) the margin of safety against collapse, possibly under a reduced design load

(b) following completion of repair

- (i) accumulated deflection and crack widths and/or stiffness under additional load increments
- (ii) the margin of safety against collapse under full design load.

This paper examines the first of these four topics. The change in pattern of moments due to reinforcement exposure in a two-span continuous beam was monitored and the parameters that affect it are examined. Structural behaviour and serviceability performance are assessed through changes in the pattern of bending moments and section strains at locations of maximum moment. Section strains may be affected in several interrelated ways as a result of reinforcement exposure.

- (a) Loss of tension stiffening within the exposed length, as reinforcement strains cannot reduce away from flexural cracks in the absence of bond.
- (b) Changes in the pattern of (elastic) bending moments throughout the length of the member as a result of loss of stiffness in part of the span.

- (c) Changes in the form of structural action caused by loss of composite behaviour when bond is eliminated.
- (d) Changes in rotation capacity at sections where reinforcement is exposed, which may influence the ability of the beam to accommodate redistribution of moments as ultimate load is approached.

As this paper is concerned with behaviour up to service load, only the first three of the above mechanisms are considered here.

Experimental work

Test programme

A series of eight tests was conducted on four pairs of two-span beams continuous over a central support. In one of the beams in each pair, concrete was broken out over the central support where the beam was subjected to hogging moment, while in the other breakout was centred on the left mid-span in an area subjected to sagging moment. A two-point load arrangement within each span was chosen to approximate the bending moment due to a uniformly distributed load. The test arrangement is shown in Figure 1.

It was decided to concentrate on breakout within the tension zone for several reasons. First, if all faces are subjected to the same environmental exposure, longitudinal cracking

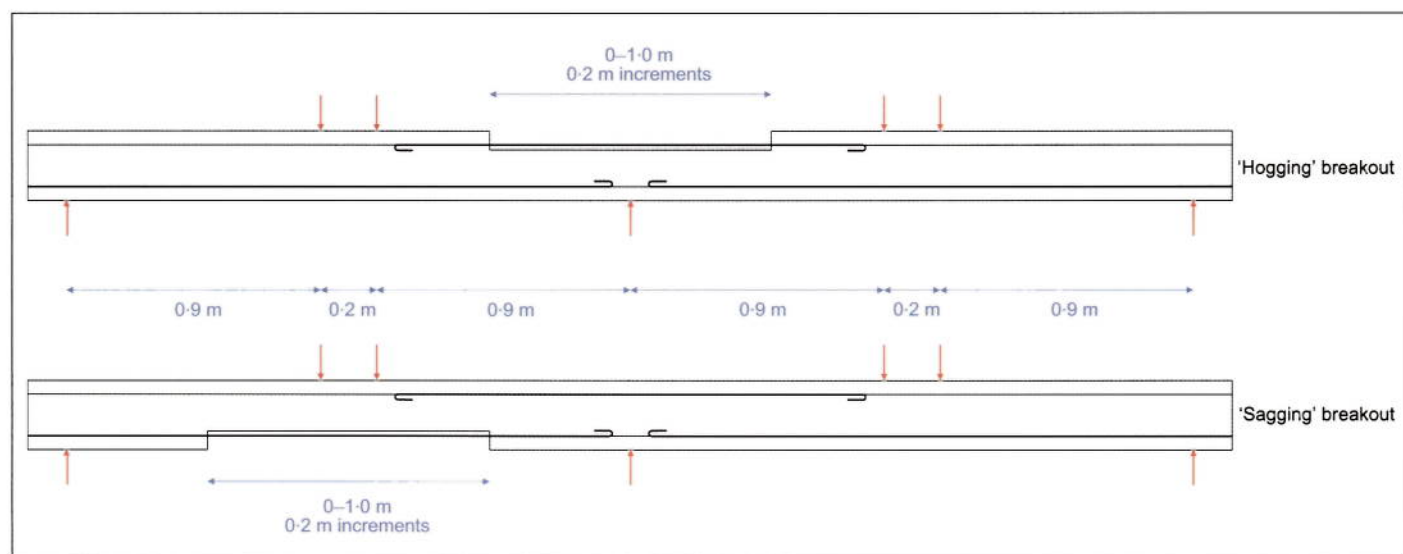
and spalling is more likely in the tension zone due to the larger bar diameter. Second, assessment of the effect of breakout in the compression zone can be estimated using conventional assumptions of beam behaviour and taking account of the reduced concrete cross-section, but exposure of tension reinforcement results in a change in the load-carrying mechanism (Cairns and Zhao, 1993). Third, compression zone breakout would lead to practical difficulties during the testing procedure, as breakout beneath the point loads would entail removal of the loading apparatus during testing.

Test parameters were selected on the basis of results from earlier investigations on simply supported beams with exposed reinforcement, but considering additional aspects of behaviour relevant to continuous members. The principal parameter varied in this study was the length of breakout, which was progressively increased in increments of 200 mm, equivalent to 10% of the span. It was decided to avoid extending the breakout length significantly beyond points of contra-flexure in this phase of the study, hence a limit to the breakout length of 1000 mm was chosen (equivalent to 50% of the span). The ratio of peak/average bending moment within the breakout length, a parameter related to the loading arrangement, thus differed for breakout over the support and within the span.

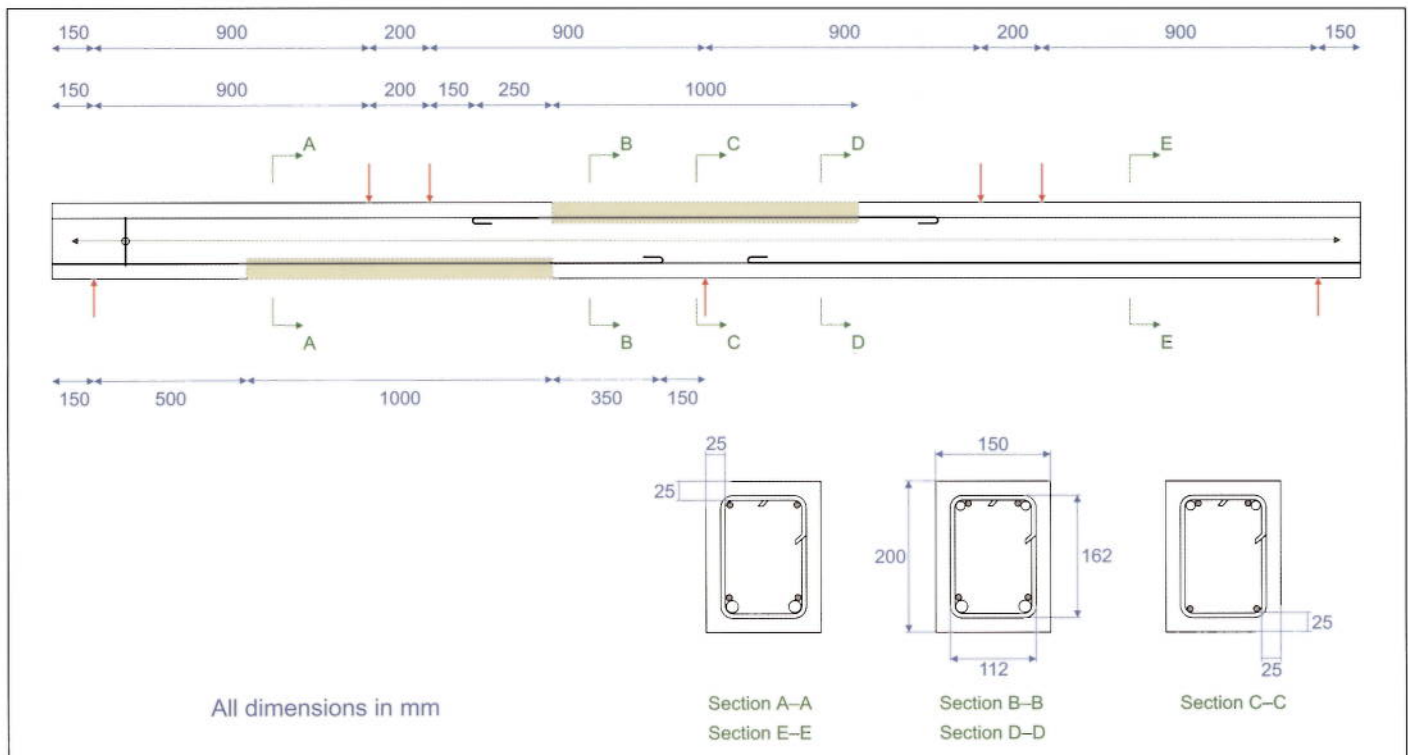
Reinforcement was designed taking account of the needs of both this phase of

the investigation and a subsequent investigation of ultimate strength. Earlier work (Cairns and Zhao, 1993) on simply supported beams demonstrated that more heavily reinforced sections are less tolerant of reinforcement exposure, hence the area of tension reinforcement was varied. Statically indeterminate beams may exploit the ability of a continuous member to redistribute the pattern of moments for design if the beam section possesses sufficient plastic rotation capacity at the most highly stressed sections. Specimen design therefore incorporated variations in the ratio of tension reinforcement in the hogging zone over the central support to that in the sagging zones within both spans, to vary the design moment redistribution.

Details of specimen reinforcement are presented in Figure 2 and in Table 1. AB11H and AB11S were reinforced with 12 mm diameter bars top and bottom, both continuous throughout the length of the beam. The remaining pairs of beams were detailed with different amounts of hogging and sagging reinforcement at the most highly stressed sections. The ratio of support/span reinforcement in pair AB21 reflects the pattern of bending moments calculated using an elastic analysis. Pairs AB23 and AB34 both reflect a pattern of moments derived from a redistribution of internal support moments of approximately 30%. Hooks were provided at the ends of the



△ Figure 1 Load arrangement and breakout locations



△ Figure 2 Typical reinforcement details

main bars to ensure sufficient anchorage beyond the breakout zone. As these beams would later be tested to failure, and as exposure of tension reinforcement tends to promote a concrete crushing failure, it was desirable to minimise compression zone reinforcement. 8 mm diameter bars were continuous through the whole length of the beam to facilitate tying of the steel cages. 6 mm diameter links were provided at 125 mm spacing in all test specimens.

Specimen manufacture

Longitudinal reinforcement was high-yield ribbed steel and links were of plain round bar. Results of control tests (average values from ten samples of each bar diameter) are shown in Table 2. Concrete was supplied by a local ready-mix supplier. Compressive strength of concrete was determined from cubes cast alongside each beam and cylinders were used to determine the tensile strength and elastic modulus. Results from concrete

control tests are also presented in Table 2. Specimen pairs AB21, AB23 and AB34 were cast from a single batch. The concrete supplied for the preliminary investigation (specimen pair AB11) was also produced by a ready-mix supplier but was below the specified grade, and is not representative of a structural grade of concrete. Although results from these specimens are included, they should be used only with caution in analysis.

Table 1. Details of test specimens

Beam	Breakout location	Breadth, <i>b</i> : mm	Depth, <i>d</i> : mm	Compression reinforcement		Tension reinforcement		A_s/bd : %		Link dia.: mm	Link spacing: mm
				Support	Spans	Support	Spans	Support	Spans		
AB11H	Hogging	150	170	2T12	2T12	2T12	2T12	0.89	0.89	6	125
AB11S	Sagging	150	170	2T12	2T12	2T12	2T12	0.89	0.89	6	125
AB21H	Hogging	150	170	2T8	2T8	2T8 + 2T12	2T8 + 2T10	1.28	1.01	6	125
AB21S	Sagging	150	170	2T8	2T8	2T8 + 2T12	2T8 + 2T10	1.28	1.01	6	125
AB23H	Hogging	150	168	2T8	2T8	2T8 + 2T12	2T8 + 2T16	1.29	1.99	6	125
AB23S	Sagging	150	168	2T8	2T8	2T8 + 2T12	2T8 + 2T16	1.29	1.99	6	125
AB34H	Hogging	150	166	2T8	2T8	2T8 + 2T16	2T8 + 2T20	2.01	2.92	6	125
AB34S	Sagging	150	166	2T8	2T8	2T8 + 2T16	2T8 + 2T20	2.01	2.92	6	125

Table 2. Concrete and steel material properties

Beam	Concrete			Yield strength reinforcement		
	Cube compressive strength, f_{cu} : N/mm ²	Splitting tensile strength, f_{ct} : N/mm ²	Modulus of elasticity, E_c : kN/mm ²	Flexural reinforcement, f_y : N/mm ²		Links, f_{yv} : N/mm ²
				Support	Spans	
AB11H	14.0	–	–	593	593	439
AB11S	14.0	–	–	593	593	439
AB21H	42.6	3.0	21.2	570	543	439
AB21S	42.6	3.0	21.2	570	543	439
AB23H	42.6	3.0	21.2	570	559	439
AB23S	42.6	3.0	21.2	570	559	439
AB34H	42.6	3.0	21.2	559	550	439
AB34S	42.6	3.0	21.2	559	550	439

Test procedure

The test load arrangement is shown in Figure 3. Load cells were used to monitor the total load applied and support reactions, and linear variable differential transducers (LVDTs) measured mid-span displacements. Load cell and LVDT output was continuously recorded by a digital data logger throughout testing. Surface strains were measured at four levels in the concrete cross-section at sections of maximum hogging and sagging moment using a demountable mechanical (Demec) gauge with a gauge length of 150 mm.

The applied load was increased in six increments to a notional service load, taken as 55% of the estimated ultimate load, and

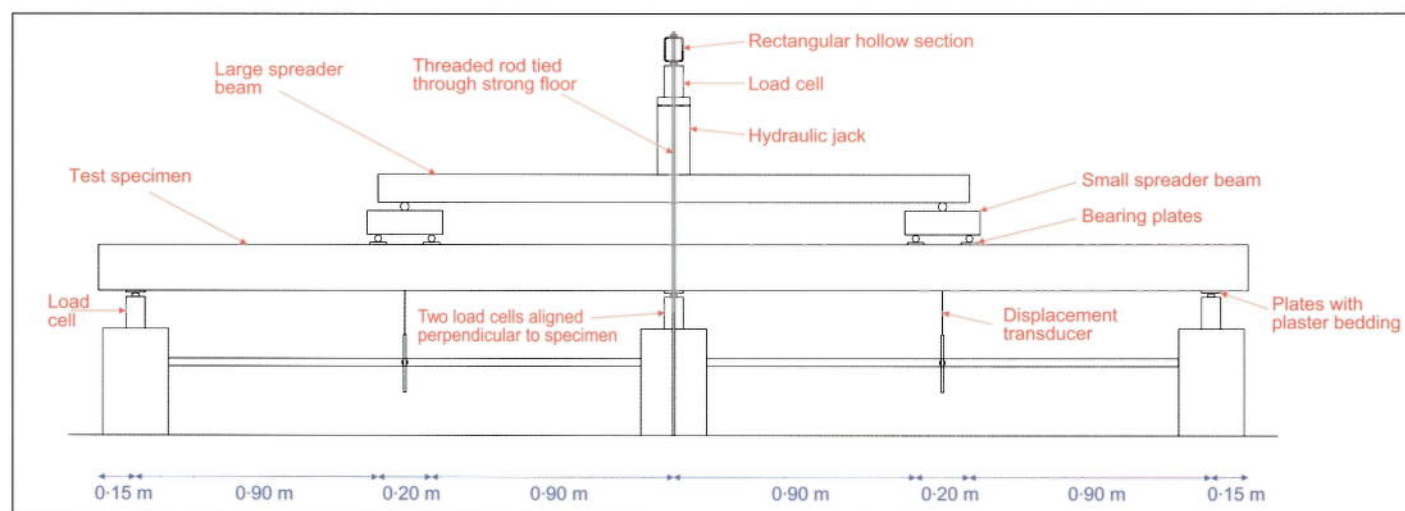
Demec readings were taken at each increment. To simulate a period of service prior to repair, the beam was loaded to service load and unloaded over ten cycles. Fifty per cent of the service load was then maintained on the beam overnight. The following morning, reinforcement was exposed over the first breakout segment while the beam carried 50% of its service load. Breakout was carried out manually to a depth of 10 mm beyond tension reinforcement. Displacement transducers were removed during breakout to avoid damage. Load was then increased to full service load in three increments with Demec readings recorded at each. Demec readings were also taken from buttons glued to the newly exposed reinforcement. The beam was

then fully relieved of load and reloaded to 50% of the service load. Further breakout intervals were subsequently tested in the same manner.

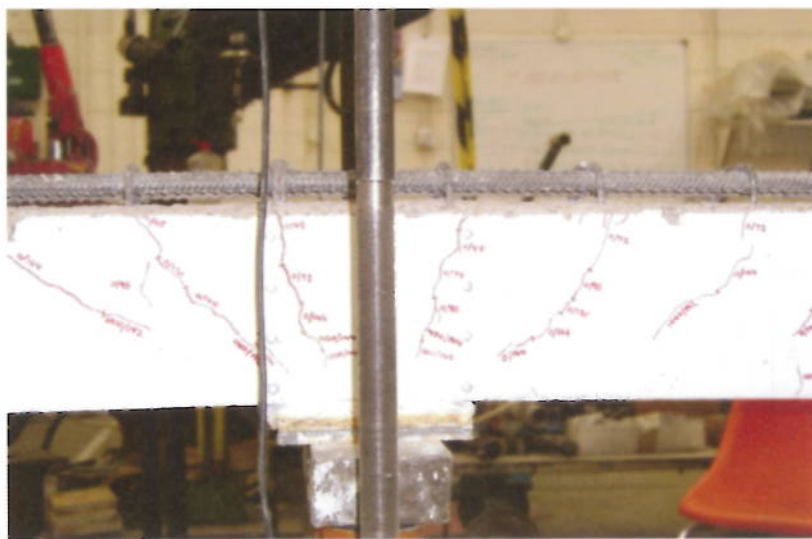
Numerical analysis

Analysis procedure

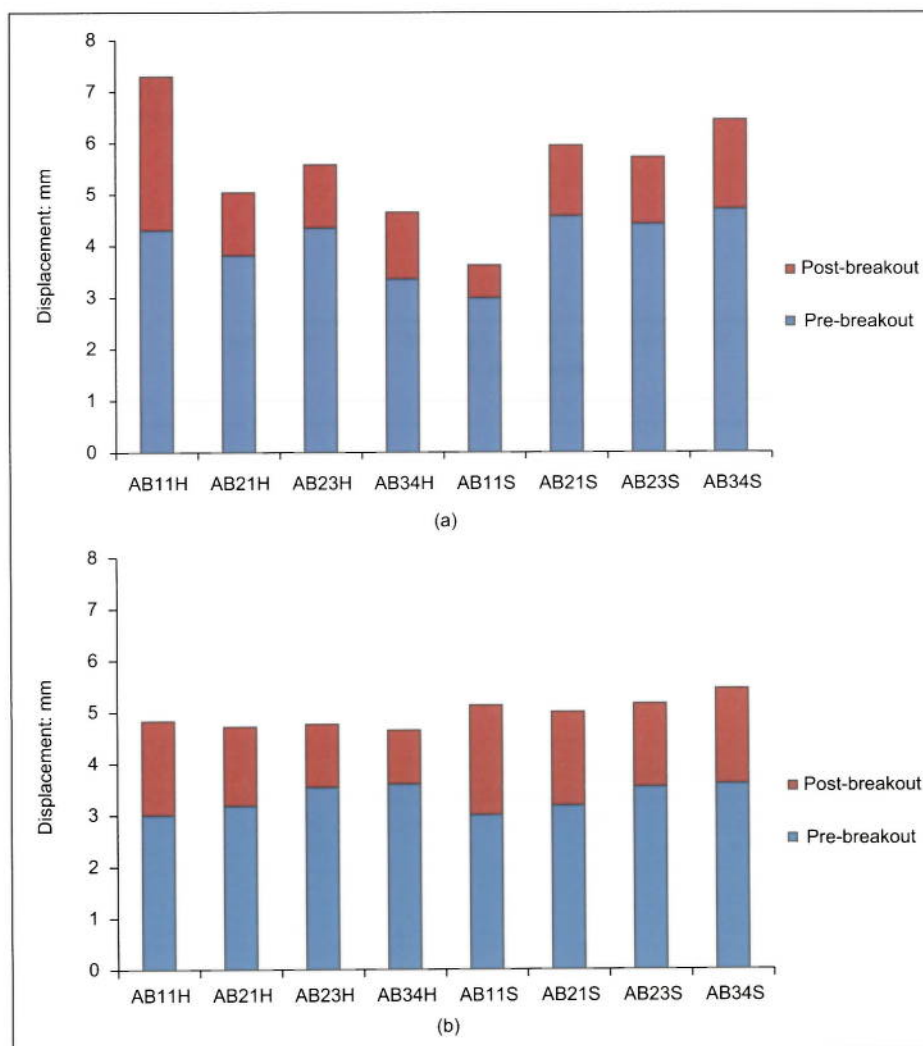
In parallel with physical testing, numerical modelling was carried out using Lusas finite-element software. A two-dimensional analysis was chosen with concrete represented by plane stress elements and reinforcement modelled by linear elements. Reinforcement was taken to be rigidly bonded to the concrete except where exposed. Shear rein-



△ Figure 3 Loading arrangement



△ Figure 4 Typical flexural crack pattern for breakout over the central support



△ Figure 5 Mid-span displacements at service load before and after breakout: (a) test measurements; (b) results from numerical model

forcement was represented in a similar manner. The Lusas concrete model (94) was used to describe the concrete material. Reinforcement behaviour was represented by a linear elastic model as yield was not reached in this part of the study. Properties determined from material tests in the experimental programme, Table 2, were used in the analysis.

To reflect the experimental procedure, the 'fully bonded' specimen was initially loaded to its nominal service load. It was then unloaded and the required length of concrete was 'broken out' using the 'birth and death' feature of Lusas, which allows the stiffness of a material to be activated or deactivated during the analysis. The geometry of the breakout region was specified as a series of surfaces (separate to those for the substrate concrete) before analysis began. These surfaces were then selected independently and deactivated as appropriate. Loading then increased to full service load and relevant measures of structural performance were interpreted from the output.

Results

During loading before breakout, flexural cracking near maximum moment locations usually began at 33–50% of service load. Flexural cracks generally coincided with shear links at 125 mm spacing. Crack widths were typically 0.2 mm over the central support and 0.1 mm within the spans at service load.

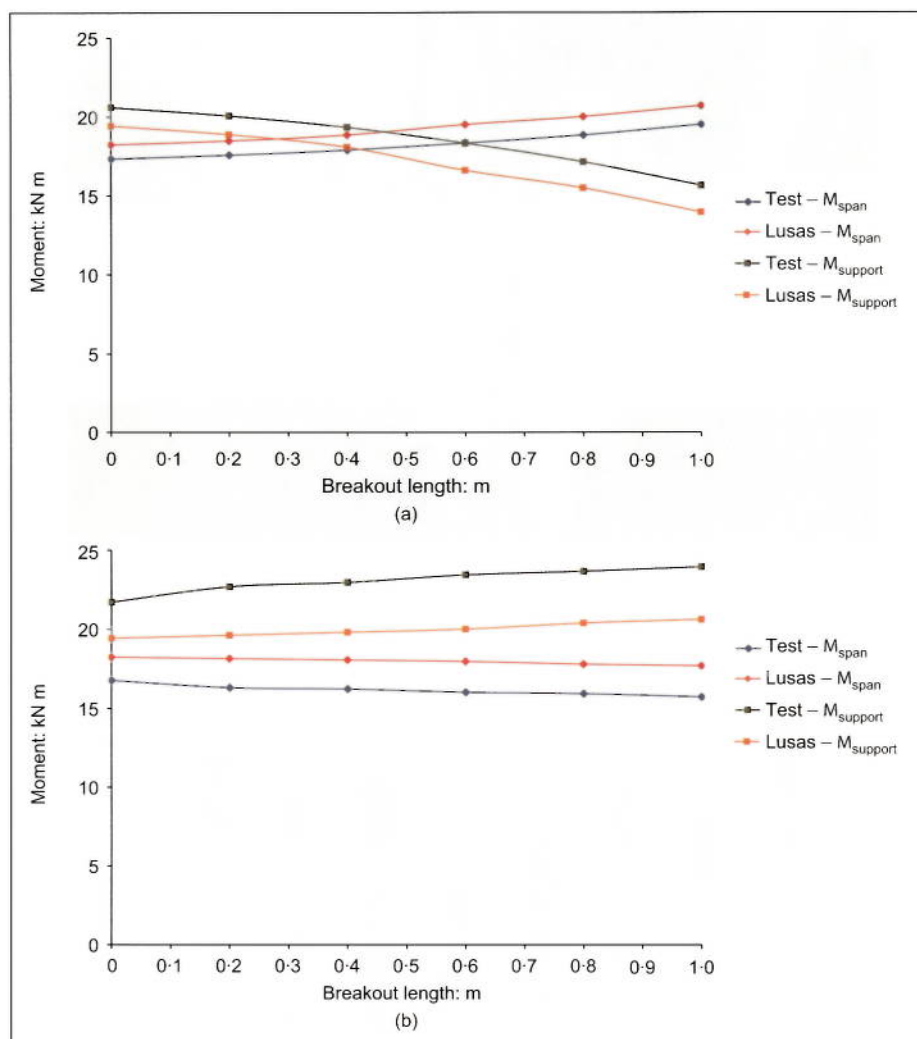
During breakout, flexural crack widths within the breakout length increased with breakout length, and significantly exceeded the 0.3 mm limit cited in many design codes such as BS 8110-1:1997 (BSI, 1997). In some cases, crack widths reached 1.0 mm, Figure 4. Crack widths elsewhere also increased during the breakout process due to moment transfer from the breakout region, but generally did not exceed the 0.3 mm limit at notional service load for the maximum breakout length.

Figure 5(a) plots measured displacements under service load for specimens when reinforcement was fully bonded and after exposure to the maximum breakout length. The average of the two mid-span displace-

ments is plotted for support breakout while the left (i.e. breakout span) mid-span displacement is plotted for span breakout specimens. Figure 5(b) shows the corresponding pre-breakout and post-breakout displacements calculated by the numerical analysis. With the exception of pair AB11 in which concrete strength was low, measured and calculated increases in displacement on breakout were similar, although the magnitudes of the calculated displacements were somewhat lower than the corresponding test measurements.

Bending moments at key sections were calculated from applied loads and reactions obtained in tests and from numerical analysis. Figure 6(a) plots the variation in maximum span and central support moments under service load in AB23H with breakout length, and shows that support moment reduced and span moment increased as breakout extended. Loss of section stiffness from breakout over the central support thus caused moment transfer away from the central support to the spans. While the magnitudes of measured and calculated moment differ, probably due to imperfections in the initial test set-up, changes in measured and calculated moments are consistent. Figure 6(b) shows the corresponding plots as span breakout increased in AB23S. In this case, moment transferred from the spans to the central support.

Measured changes in span and support moments at service load during breakout to 50% of the span length are presented for all specimens in Table 3. The relationship between change in span and support moments is fixed by equilibrium considerations at $\Delta M_{\text{span}}/\Delta M_{\text{support}} = -(0.9/2.0)$



△ Figure 6 Span and support moments under service load as the breakout extended: (a) AB23H – support breakout; (b) AB23S – span breakout

$= -0.45$. The last column in Table 3 demonstrates that test measurements satisfy equilibrium with reasonable accuracy. There is no evident correlation between reinforcement

layout and the change in moment, but changes in moment are consistently greater for breakout over the central support.

Figure 7 compares changes in moment

Table 3. Span and support moments at service load before and after breakout

Specimen	Breakout location	Initial M_{span} : kN m	Final M_{span} : kN m	ΔM_{span} : kN m	Initial M_{support} : kN m	Final M_{support} : kN m	$\Delta M_{\text{support}}$: kN m	$\Delta M_{\text{span}}/\Delta M_{\text{support}}$
AB11H	Support	8.73	10.26	+1.53	10.65	7.28	-3.37	-0.45
AB21H	Support	10.32	12.08	+1.76	22.09	18.17	-3.92	-0.45
AB23H	Support	17.62	19.80	+2.18	20.99	16.04	-4.95	-0.44
AB34H	Support	20.68	23.09	+2.41	26.02	20.57	-5.45	-0.44
AB11S	Span	8.78	7.92	-0.86	10.50	12.40	+1.90	-0.45
AB21S	Span	11.21	10.24	-0.97	20.47	22.67	+2.20	-0.44
AB23S	Span	17.10	16.02	-1.08	22.00	24.29	+2.29	-0.47
AB34S	Span	21.83	20.18	-1.65	23.37	26.93	+3.56	-0.46

from the numerical model with those obtained experimentally. The reduction in bending moment at the breakout location under service load relative to the corresponding moment in the 'fully bonded' specimen at breakout to 50% of the span measured during physical tests and calculated from numerical analysis are presented in Figure 7(a). Figure 7(b) plots the corresponding increase in moment at 'non-breakout' locations (i.e. at the central support for breakout within the span and vice versa). The two data sets are reasonably compatible and discrepancies when results are presented as a percentage change are at least in part

attributable to differences between test and numerical model in the fully bonded state.

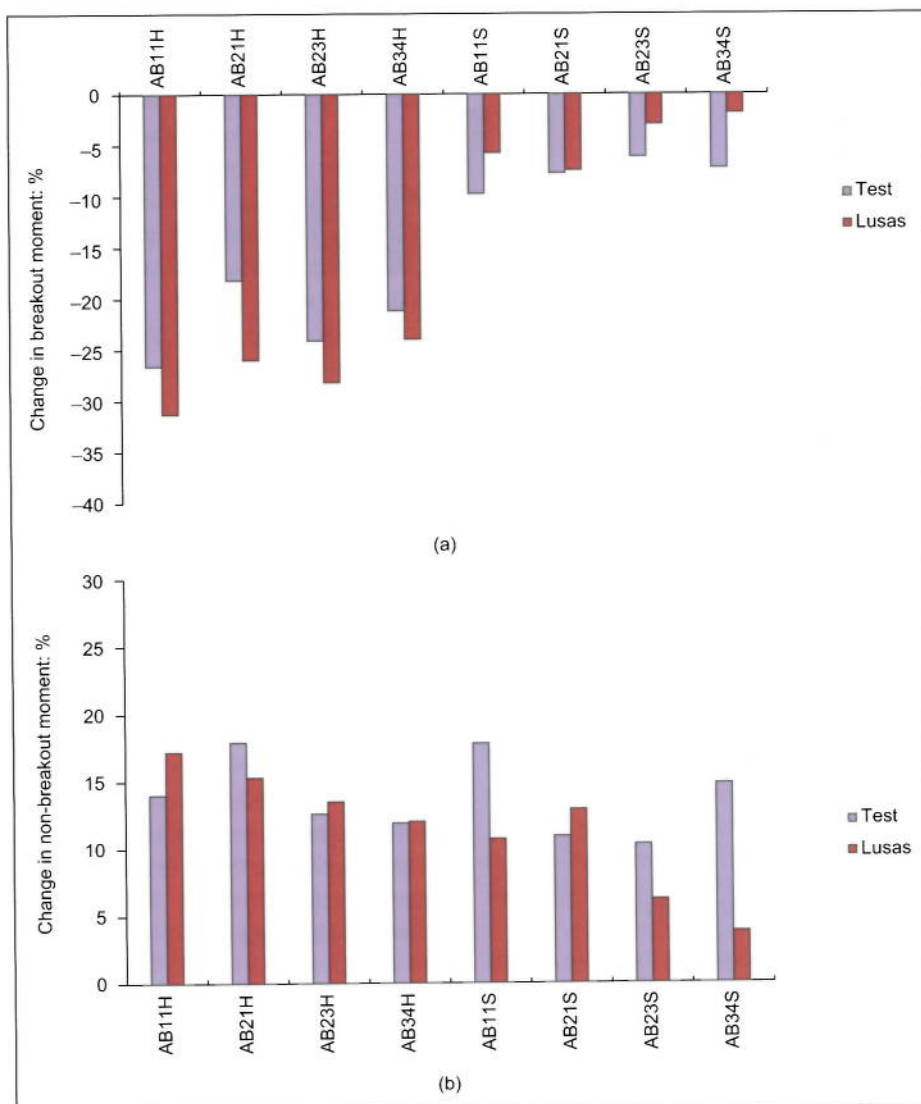
Extreme fibre compression strains at sections of maximum hogging and sagging moment are of particular interest as some codes set limits to compression stress in concrete under service loads. Figure 8(a) plots the extreme fibre concrete compression strains under service load during breakout over the central support of AB23H from test measurements and numerical modelling. An appreciable increase in strain was measured within the breakout zone in conjunction with an increase in concrete section curvature, despite moment being

transferred away from the section, and is primarily due to loss of composite interaction between steel and concrete (Cairns and Zhao, 1993). A slight increase in compression strain also occurred within the span due to the transfer of moment. Figure 8(b) shows the corresponding increase in compression strains as breakout extended within the span of AB23S. An appreciable increase in strain was again observed at the breakout location while the increase at the central support was small.

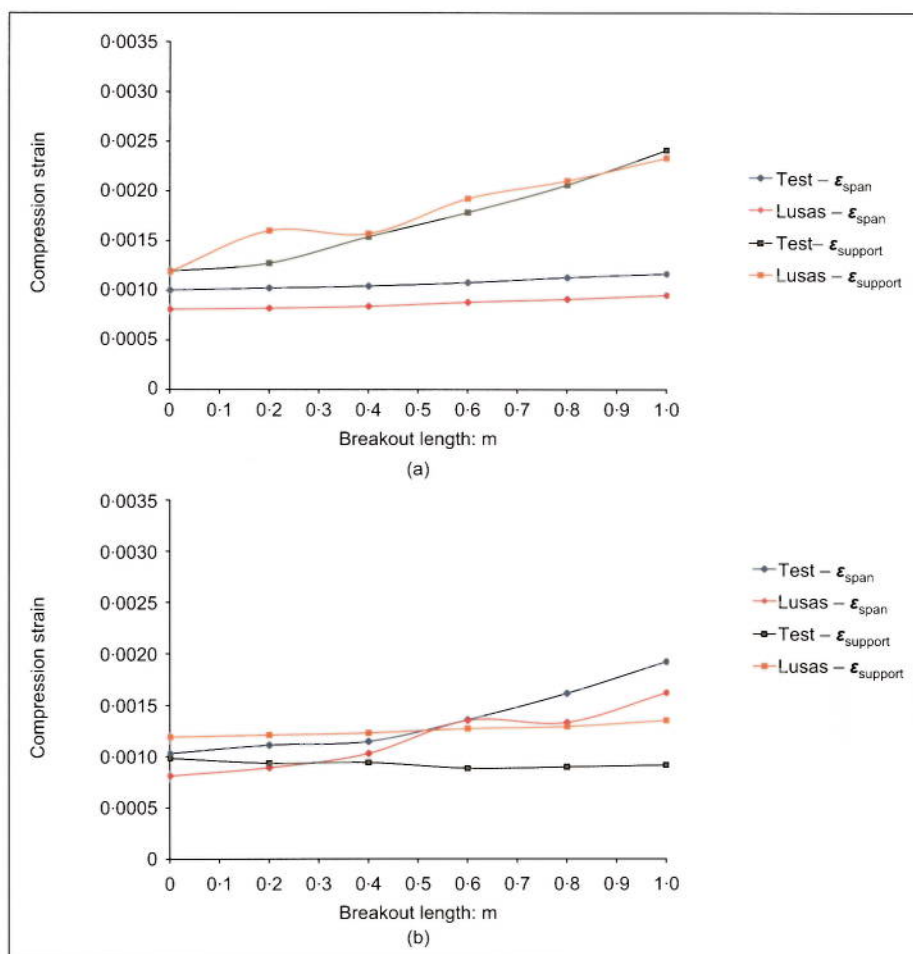
Figure 9 compares calculated values of extreme fibre compression strains at service load with measured values from test for support breakout specimens. Figure 9(a) shows strains for the fully bonded condition and for the maximum breakout length measured during testing, and Figure 9(b) plots the corresponding results from the numerical analysis. Significant increases in compression strain occurred at the breakout location over the central support for both data sets. Note that the large increase in compression strain for test specimen AB11H is associated with extreme fibre compression strains approaching the notional ultimate crushing strain for concrete of 0.0035, and is attributable to the weak grade of concrete in the AB11 pair. Pre-breakout strains are higher in more heavily reinforced beams, as is to be expected, but the ratio of post/pre-breakout strains is similar for all specimens. Increases in compression strain within the span where reinforcement remained bonded were markedly less than at the support where bars were exposed.

Figure 10 shows the equivalent results for specimens with breakout within the span. Appreciable increases in compression strain occurred at the breakout location within the span. Measured changes in strain at the support for breakout within the span were negligible.

Figures 9 and 10 both show increases of approximately 100% in compression strains at the breakout location. The increases calculated by the numerical model are consistent with those measured in tests. Increases in strains elsewhere within the member (i.e. within the spans for 'support' breakout and at the central support for 'span' breakout) due to moment transfer away from the breakout location were insignificant relative to those within the breakout itself.



△ Figure 7 Change in maximum moments under service load throughout breakout: (a) breakout location; (b) 'non-breakout' location



△ Figure 8 Maximum concrete compression strains under service load as the breakout extended: (a) AB23H – support breakout; (b) AB23S – span breakout

Analysis of results

As test beams were subjected to several load cycles prior to breakout of concrete, the crack pattern was well established before reinforcement was exposed. The spacing of cracks did not change on exposure of reinforcement. However, the width of one or two cracks near the centre of the exposed length widened significantly. It is clear from results presented earlier that section strains changed markedly where reinforcement was exposed, and to a lesser extent elsewhere. Changes in the pattern of strains in the beams are the result of the combination of three individual effects consequent to removal of concrete cover, namely

- (a) changes in reactions and in bending moments resulting from the change in beam stiffness at the breakout

- (b) loss of tension stiffening over the breakout length
- (c) loss of composite interaction between reinforcement and concrete.

Unless stated otherwise, analyses in this section are based on measurements at notional service load and on the full 1.0 m breakout length.

Transfer of moments

Loss of stiffness over the breakout length causes a change in the moment diagram, with a reduction in the magnitude of the bending moment at the breakout and an increase at adjacent peaks or troughs, see Figure 7. As mentioned earlier, the relationship between change in support and span moment is fixed by equilibrium considerations. The increases in

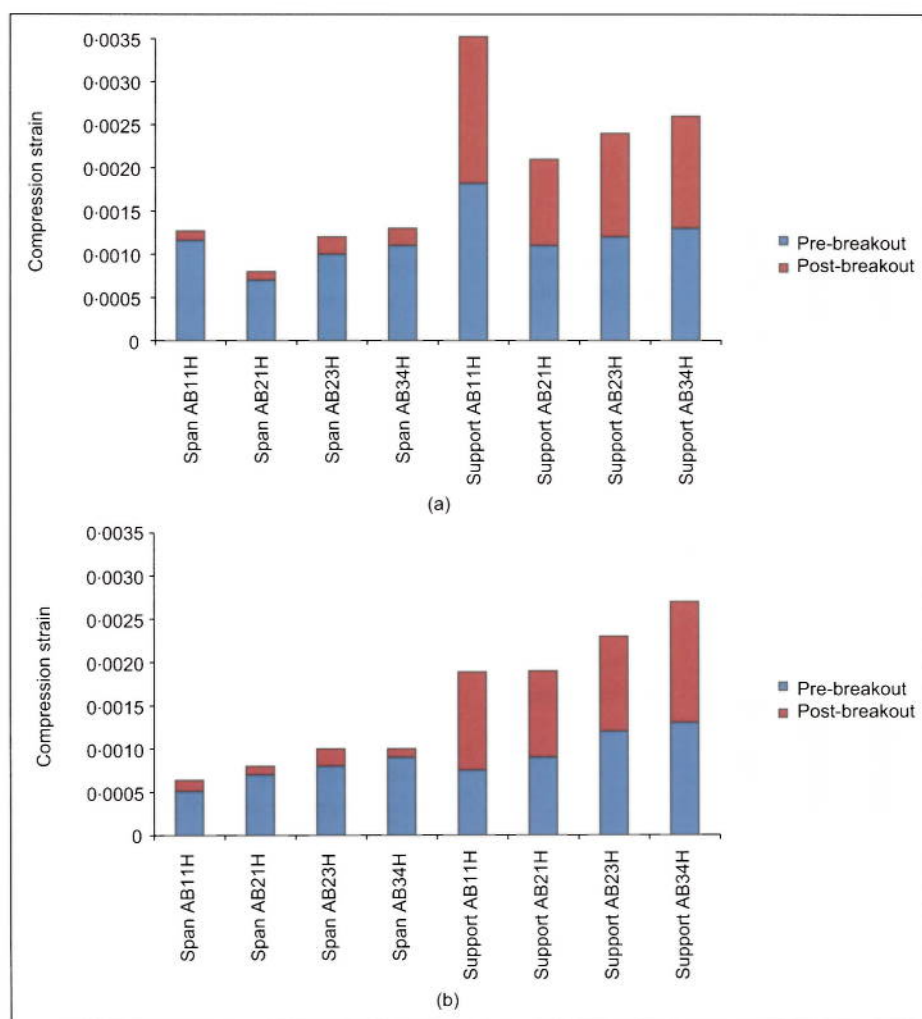
moment plotted in Figure 7(b) occur away from the breakout location and are all 18% or less, and show a tendency for smaller changes in more heavily reinforced specimens, in part reflecting the lesser influence of tension stiffening with higher reinforcement ratios, see below. Although an increase of 18% cannot be regarded as totally insignificant, it would not lead to serious overstressing of a member designed in accordance with normal code of practice procedures when subjected to service load.

Tension stiffening

The first breakout segment within the span (between the point loads) was located in a zone of approximately constant bending moment. The increase in curvature for this breakout segment thus gives an indication of the change in section deformation when tension stiffening is lost, Figure 11. Figure 12 plots measured section curvatures both before and after the first breakout segment of 0.2 m. Figure 12 also includes estimates of section curvatures calculated using the CEB-FIP Model Code 1990 (CEB-FIP, 1993) and measured material properties, Table 2, and taking the value of β_b (a factor which accounts for bond quality and load history of the member) as 0.7, intermediate between short- and long-term values. Curvatures calculated from CEB-FIP Model Code 1990 tend to underestimate measured curvatures, probably because the short-term elastic modulus was used in the calculations, but otherwise follow a similar trend to test measurements. Larger increases in curvature due to loss of tension stiffening are observed in sections with lower reinforcement ratios, as would be expected. The increases in curvature are small, typically 7% or less, for both data sets and it can be surmised that loss of tension stiffening is not a significant factor in changes to the pattern of section strains.

Loss of composite interaction

It is evident from Figures 9 and 10 that changes in section strains at the centre of the breakout zone as a result of exposure of reinforcement were much larger than else-



△ Figure 9 Maximum concrete compression strains under service load before and after breakout over the support: (a) test measurements; (b) results from numerical model

where. It is demonstrated above that tension stiffening is responsible for a relatively small portion of this change. Also, the moment near the breakout region tended to reduce, reducing strains at that location. Changes in section strains must therefore be largely attributable to the loss of composite interaction where bending moment varies over the exposed length. Overstressing of concrete within the exposed length is therefore the primary check that will be necessary if flexural reinforcement is to be exposed without provision of temporary propping.

Figures 13(a) and 13(b) plot the increase in extreme fibre compression strain at the breakout against the area of exposed reinforcement from measured test and calculated numerical results respectively. Both sets of results are

similar, with increases in strain of 0.0008–0.0013. (The significant increase in strain for test specimen AB11H ($A_{s, exp}/bd = 0.89\%$) is attributable to that specimen's very weak grade of concrete.) Also, increases in compression strain at the breakout location were generally greater for breakout over the central support. The increase in strain is unaffected by the area of exposed reinforcement.

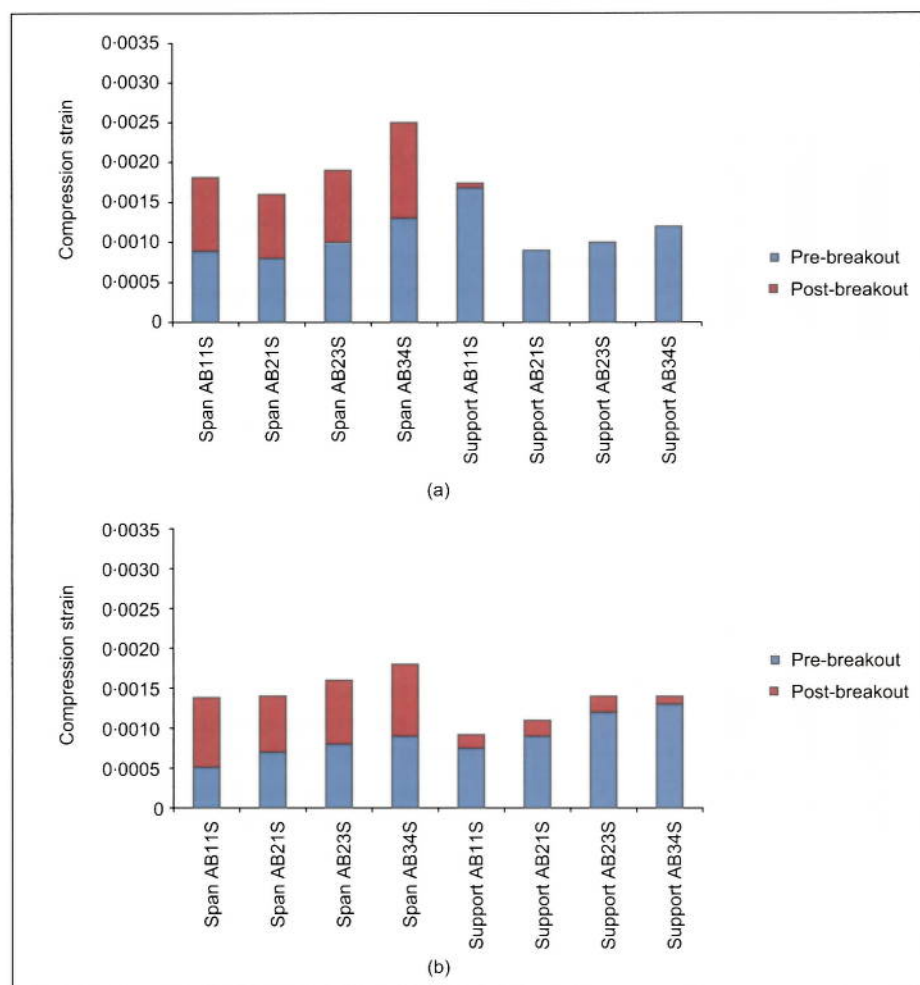
The shape of the bending moment diagram within the breakout length influences the change in strain pattern. Cairns and Zhao (1993) tested simply supported beams with exposed reinforcement subjected to symmetric two-point loading. It was evident that for a given value of moment at the mid-span, the change in elongation of the reinforcement on exposure was greater when loads were

closer together. Figure 14 demonstrates the effect of load arrangement when composite interaction is lost. The dashed lines in Figure 14 represent the shape of the bending moment diagram near the breakout region. The area of tension reinforcement is assumed to be constant throughout the length being considered.

Initially, a single point load arrangement within the breakout length is considered, Figure 14(a). Once the reinforcement is exposed, the tensile stress in the steel is uniform throughout the breakout length when bond is eliminated. Although there will be a minor change in neutral axis depth and a modest amount of moment transfer, the stress in the flexural reinforcement will not change markedly. The net elongation of the reinforcement over the exposed length will therefore increase, as shown by the shaded area on the diagram. Section curvatures must then also increase to maintain compatibility of deformations. Figure 14(b) shows the increase in stress due to loss of composite interaction for a two-point load arrangement. In this case, most of the breakout takes place within the constant moment zone between the point loads, where loss of bond affects only tension stiffening. The change in elongation of reinforcement and in concrete section curvature is less than for the single load configuration. Appreciable increases in stress thus only occur where the exposed length extends into the shear span. Therefore, changes in section curvature and in extreme fibre compression strains will be greater for breakout near a single point load or reaction, as at the support breakout in this investigation, than for the two-load-point condition as at the span breakout location here.

Discussion

It had been suggested that moment transfer away from the breakout location might cause overstressing in other parts of the member. Figure 7(b) shows that in the current study, the increase in moment elsewhere in the member (resulting from breakout) did not exceed 18% and was typically nearer 12%. The increase in extreme fibre compression strain at the corresponding locations was



△ Figure 10 Maximum concrete compression strains under service load before and after breakout within the span: (a) test measurements; (b) results from numerical model

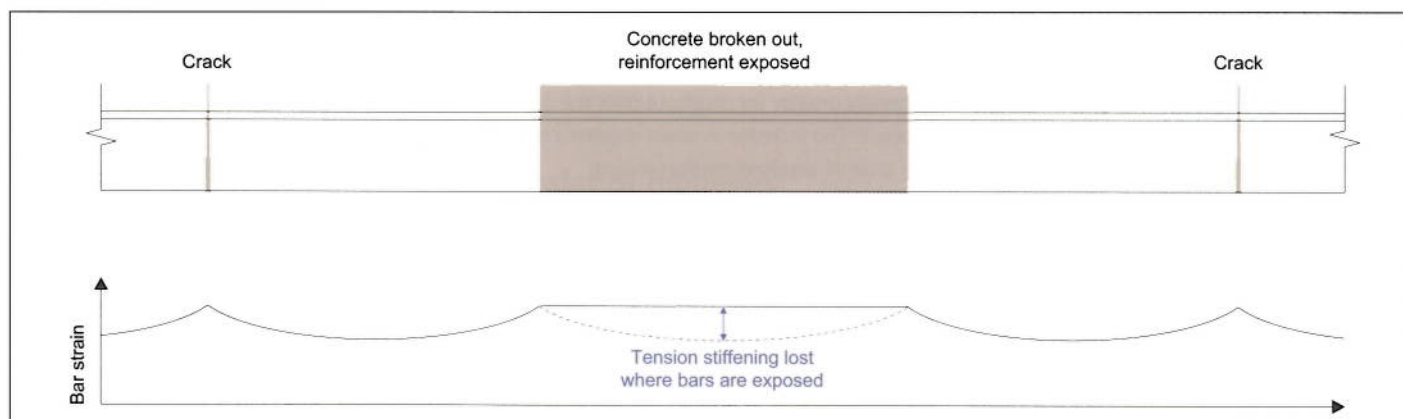
similar to the moment increase. Higher increases tended to be found in lightly reinforced members, in which the extreme

fibre compression strain at a given proportion of ultimate load tends to be lower. In comparison, increases in extreme fibre concrete

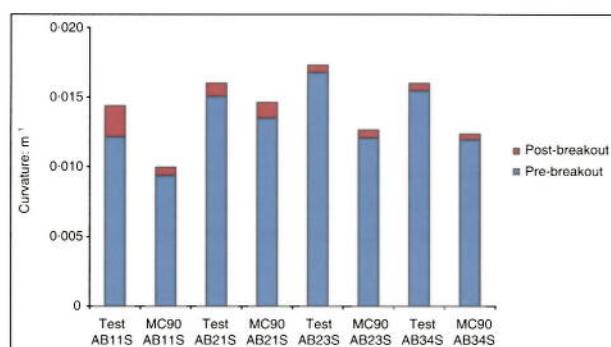
compression strains were of the order of 100% at breakout, Figures 9 and 10, where reinforcement area had a neutral effect. The primary check on the viability of conducting breakout without the use of temporary propping must therefore be the limiting concrete compression strain within the exposed length.

It was assumed in this investigation that beams carried the full service load at time of repair. Compression strains measured in concrete here correspond to stresses in excess of the normal code limits, typically around 50% of the cube compressive strength. Neglecting the issue of the time dependence of the stress-strain relationship, this limit would appear to be exceeded on breakout in some specimens under the conditions investigated here. Loading tests reported here extended over a period of approximately a week, during which time a certain amount of creep would have occurred. Ignoring this phenomenon provides a pessimistic view of the possibility of unpropped repairs. Obviously if the load to be carried during the repair process could be reduced below the full service load level, limiting compressive stresses would be less likely to be reached in the concrete.

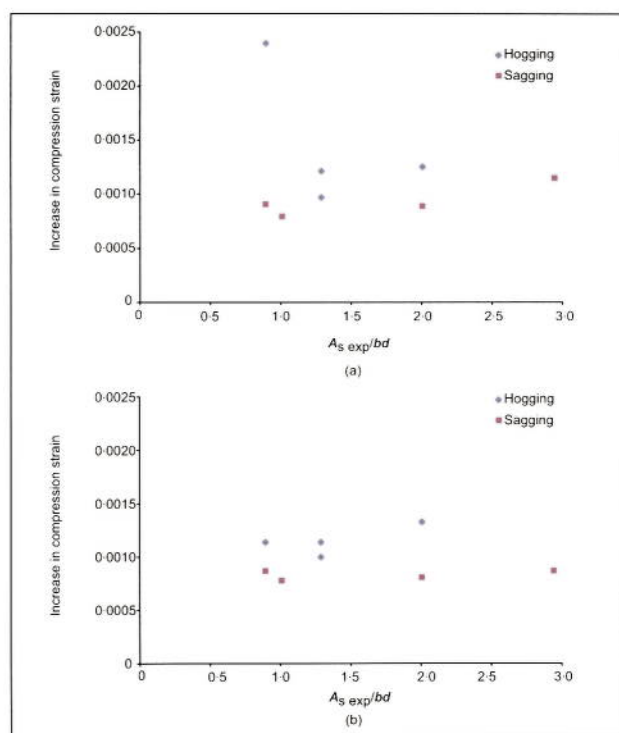
A few cracks within the breakout length showed significant increases in width as a consequence of loss of concrete-reinforcement bond. These cracks would exceed the typical serviceability limit of 0.3 mm and would potentially have an adverse impact on durability. These cracks would require sealing by injection of an epoxy resin. This step might



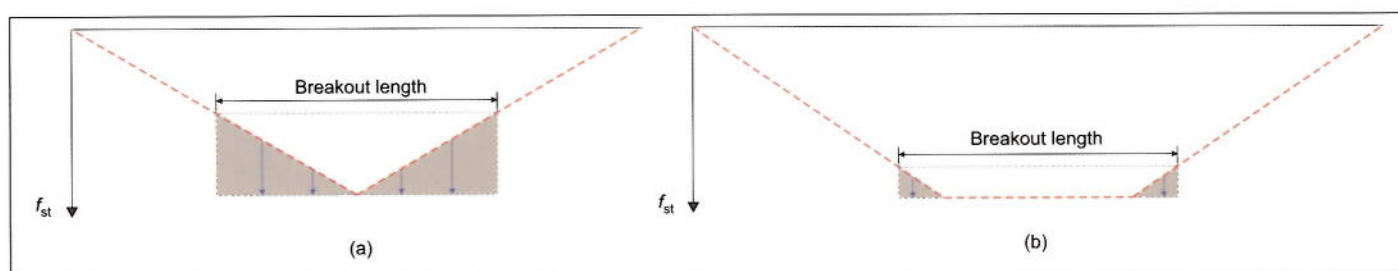
△ Figure 11 Loss of tension stiffening when reinforcement is exposed



△ Figure 12 Section curvature increases for the first breakout segment within the span



△ Figure 13 Increases in compression strain at the breakout location under service load during breakout plotted against area of exposed reinforcement: (a) test measurements; (b) results from numerical model



△ Figure 14 Schematic diagram of variation in reinforcement tensile stress near breakout region: (a) single point load arrangement; (b) two-point load arrangement

be unnecessary if the beam was propped during the repair.

Strain increases at the breakout location in this study were insufficient to cause collapse at service load. Nevertheless, the breakout length in this investigation did not extend significantly past points of contra-flexure and further extension of the breakout would have caused continuing strain increase at breakout locations, probably at a higher rate.

Conclusions

This study has analysed the effect of breakout of concrete and exposure of tension reinforcement on the distribution of moments and strains within a two-span reinforced concrete beam, with a view to assessing the need for temporary propping during patch repair. Within the scope of the study, the following conclusions can be reached.

- Changes in peak/trough values of bending moment during breakout were fairly modest, and do not support suggestions in an earlier report that exposure of reinforcement at one point in a beam would lead to significant overstressing elsewhere.
- The most significant change in member behaviour arises from loss of composite action between tension reinforcement and concrete. Transfer of moment away from the breakout location and loss of tension stiffening contribute to changes, but to a markedly lesser degree.
- Changes in behaviour were unaffected by the reinforcement layout within the member.

- (d) Changes in moments and strains were greater for breakout at the single point central support reaction than for the two-point load arrangement within the span, consistent with earlier observations on simply supported beams.
- (e) Increases in displacement were modest. Significant increases in width of some cracks were observed within the breakout length, and would require epoxy resin injection during the repair process. Increases in crack widths elsewhere were modest.
- (f) Tests here were conducted on a two-span continuous beam. In practical situations, joint restraint to beam deformations might be higher, resulting in a greater change in the pattern of moments. Investigation of other structural arrangements is desirable.

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