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Autor: Cairns, John
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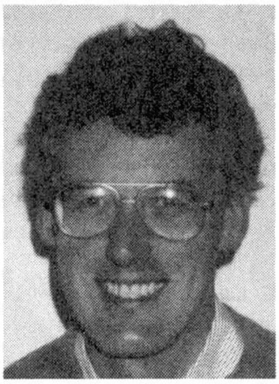
Strength of Concrete Beams during Concrete Breakout

Résistance de poutres en béton armé en cours de réparation

Tragfähigkeit von Betonbalken während des Ausspitzens

John CAIRNS
Lecturer
Heriot-Watt University
Edinburgh, UK



John Cairns is a Chartered Structural Engineer with research interests in structural aspects of concrete repair and bond between reinforcement and concrete. He currently serves on a Task Group of CEB and on the Concrete Society Working Party on Epoxy coated reinforcement.

SUMMARY

The paper provides guidance on assessment of the load carrying capacity of reinforced concrete beams when weakened by exposure of tension reinforcement during structural repairs.

RÉSUMÉ

Cette étude porte sur l'évaluation de la capacité de charge de poutres en béton armé, présentant une armature apparente lors de réparations.

ZUSAMMENFASSUNG

Der Beitrag gibt Empfehlungen zur Beurteilung der Tragfähigkeit von Stahlbetonbalken, wenn diese durch Freilegen der Zugbewehrung zu Reparaturzwecke geschwächt sind.

1 INTRODUCTION

Repairs to reinforced concrete beams suffering from chloride induced corrosion frequently necessitate breaking out of concrete around the full perimeter of reinforcing bars. Bond between bar and concrete is then lost over the length exposed. In the absence of bond, an exposed bar cannot act compositely with the remainder of the member, and normal assumptions of plane section behaviour no longer hold true. The usual Code of Practice procedures for evaluation of section strength are no longer directly applicable.

Although the need to ensure structural stability of a member weakened by removal of concrete cover to tension bars is mentioned in many texts on repair, little detailed guidance is available. Design calculations for structures so weakened therefore tend to be based on conservative assumptions. It is common practice to ignore any contribution from exposed bars when assessing structural strength of weakened members. As exposed bars are assumed ineffective, temporary support will in many cases be required to ensure an adequate margin of safety is maintained. Where it is not feasible to utilise props, repairs have to be carried out in a piecemeal fashion, necessitating a long and slow repair programme.

The assumption that an exposed bar makes no contribution to member strength errs on the side of caution, and significant stress may develop in an exposed (unbonded) bar if the ends are adequately anchored[1]. Substantial savings in repair costs might be possible if reliable methods were available for evaluation of the strength of members with all or part of the reinforcement exposed.

The aim of this paper is to show that relatively simple procedures may be employed to estimate the length over which bars may be exposed without loss of strength.

2. SECTION BEHAVIOUR WHEN BARS EXPOSED

2.1 General Aspects Whether reinforcement is bonded to concrete or not, conditions of equilibrium of forces and compatibility of deformations must be satisfied. Equilibrium of a reinforced concrete beam may be described by an equation of the form :

$$M = f_{st} . A_{st} . z \qquad \text{Eqtn. 1.}$$

where
- M = applied bending moment.
- f_{st} = tensile stress in reinforcement.
- A_{st} = cross sectional area of reinforcement, assumed constant.
- z = lever arm between centroid of reinforcement and concrete in compression.

When reinforcement is bonded, the lever arm, z, is sensibly constant, and stress in the reinforcement varies in proportion to the applied bending moment. In the absence of bond, however, stress in reinforcement cannot vary along the bar, and it is instead the lever arm which must change in response to a varying applied moment. For equilibrium to be satisfied, the centre of the concrete in compression must therefore move towards the tension reinforcement under a reducing bending moment, Figure 1. Structural action of the member alters from the flexural behaviour of a beam towards that of a tied arch.

2.2 Bending strength

Where reinforcement is rigidly bonded to concrete, compatibility of deformations is satisfied through normal assumptions of plane section behaviour. If bars are disbonded, however, plane section assumptions no longer hold true, and compatibility must be satisfied over the length of bar between points of anchorage. Strains reduce towards the support when bars are bonded, Figure 1(a), but remain constant when bars are exposed. Elongation of the exposed bar will therefore exceed that of an equivalent bonded bar under a given load. To satisfy compatibility, there must also be an increase in elongation of the concrete between anchorages. The necessary increase in elongation of the concrete is achieved through an increase in curvature of the concrete section near midspan. This will in turn increase the maximum compressive strain in the concrete at midspan. As failure of reinforced concrete is deemed to occur at a limiting compressive strain, it is clear that bending strength may be affected by loss of bond.

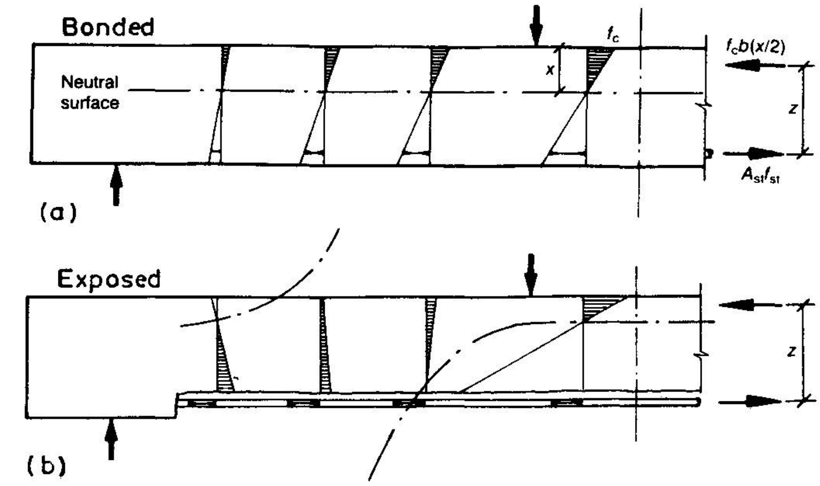


Figure 1 Pattern of strains in reinforced concrete beams

2.3 Shear strength

Normal assumptions of dowel action, of aggregate interlock effects, and of the state of stress in the compression zone of the beam no longer hold when concrete is broken out around tension bars. Links will be ineffective when their corners are exposed. This leads to fears that shear strength will be reduced when bars are exposed. Equation 1 may be differentiated to give Equation 2.

$$V = dM/dx = d(f_{st}.A_{st}.z)/dx = f_{st}\ A_{st}\ dz/dx + z\ A_{st}\ df_{st}/dx \qquad \text{Eqtn 2.}$$

The first component on the right of Equation 2 represents the contribution of arch action, the second represents beam shear. In flexural behaviour of elastic materials, only beam action is present, and the lever arm between tension and compression parts of the couple remains constant along the length of the member. The term (dz/dx) is then zero. If bond is lost through exposure of reinforcement, (dz/dx) is non-zero, for the reasons discussed above, but (df_{st}/dx) is instead zero. Leonhardt & Walther[2] (amongst others) have reported an increase in shear strength in beams detailed to fail in shear with normal bonded reinforcement when bond strength was reduced. Cairns and Zhao[1] & Raoof[3] have conducted tests which show strength of beams which would fail in shear if reinforcement were fully bonded is not reduced by exposure of bars. Cairns[4] has demonstrated an increase in shear capacity when 50% of the bars in a section are exposed. An increase in the shear contribution of arch action therefore offsets a reduction in the beam contribution.

2.4 Other failure modes

Figure 1 also shows that if the exposed length extends close to the support, tensile strains start to develop in the top 'compression' face of the beam, and compressive stresses develop in the 'tension' zone. A compression failure of the concrete may occur as the lever arm reduces towards the support and the centre of compression of the concrete moves towards the "tension" face. Flanged 'T' sections are more vulnerable to this mode of failure, as the compression force carried in the flange near midspan must be resisted within the thickness of the web. The possibility of end anchorage failure is also increased if bond is lost within the shear span.

The potential modes of failure are summarised graphically in Figure 2. In subsequent sections, simplified methods for predicting the length of bar which may be exposed without significant strength loss are developed for each mode.

3. DERIVATION OF SIMPLIFIED ANALYSIS

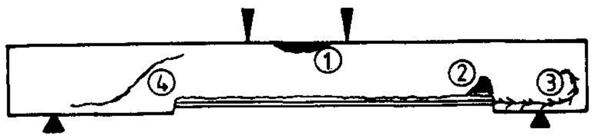


Figure 2 Failure Modes of beam with exposed bars.

Cairns and Zhao[1] have undertaken finite element analyses of flexural strength of beams with all reinforcement exposed over a portion of the span of simply supported beams. Behaviour of the entire member, and not just the behaviour of critical sections, must be considered. Eyre also developed analytical expressions for analysis of beams with disbonded bars[5]. These analytical methods both require to be implemented on computer, and it is desirable to have simpler (if less accurate) methods of calculation for practical use. As a first stage, this paper develops methods that could be used to estimate the length of bar that may be exposed without significant loss of strength. The analysis is based on the following observations and assumptions :

a) bending strength is little affected if reinforcement attains yield strength f_y (although ductility is reduced).
b) the pattern of stress in the concrete at midspan at ultimate load is little affected by the loss of bond if reinforcement attains yield.
c) bond slip at the ends of the bar may be neglected.
d) at ultimate load, strains in the concrete within the shear span are small in relation to those within the constant moment zone.

Each of the four failure modes represented in Figure 2 must be verified separately, and the least strength calculated for the various failure modes will control. Only simply supported beams are considered. Mode 1, crushing of concrete at the point of maximum moment within the exposed length, is considered first.

The elongation of reinforcement over the exposed length when reinforcement yields, d_{st}, is given by Equation 3. Notation is described in Figure 3.

$$d_{st} = L_{exp}.f_y/E_{st} \qquad \text{Eqtn. 3.}$$

If concrete is assumed to fail at a limiting compressive strain of 0.0035, and from assumption (d) above, the elongation of the concrete at the level of the tension bars at ultimate is given by Equation 4. Neutral axis depth x_1 should be calculated in the normal way for a section with bonded reinforcement at the ultimate limit state.

$$d_c = L_0.0.0035(d/x_1-1) \qquad \text{Eqtn. 4.}$$

In circumstances where the loading pattern does not provide a constant moment zone, or where the constant moment zone is very short, the length L_0 should instead be taken as the length of beam L_{cr} over which crushing of the concrete develops. From an expression derived by Phipps[6], this may be taken as :

$$L_{cr} = 3.5\ x - 0.0075x^2 \quad \text{, and} \quad L_0 \geq L_{cr} \qquad \text{Eqtn. 5.}$$

For compatibility to be satisfied, elongation of tension reinforcement over the exposed length must equal that of the concrete at the corresponding level. If the elongation of the concrete at ultimate load d_c equals or exceeds that of the reinforcement at yield d_{st}, then the reinforcement will attain yield at ultimate, and beam strength will be unaffected by exposure.

Figure 4 shows a comparison between the ratio d_{st}/d_c as calculated using Equations

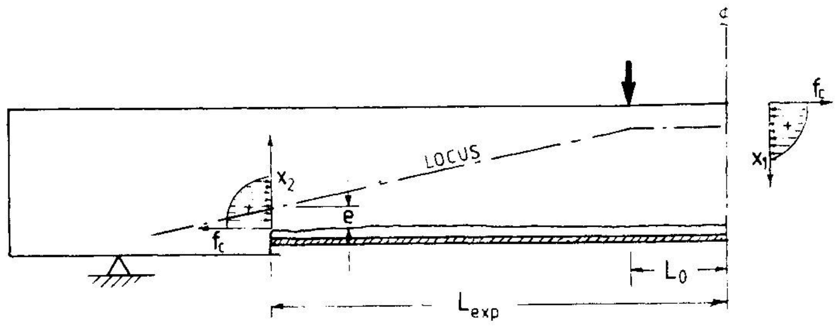


Figure 3 Pattern of stress at critical sections.

3-5 and the ratio of M/M_{bonded} obtained in tests by Cairns & Zhao[1], Minkarah and Ringo[7], and by Eyre[8]. The reduction in strength as a result of exposure of reinforcement will be less than 10% provided the ratio of d_{st}/d_c exceeds 1.5. The limiting value of 1.5, and not 1.0 as might be expected, reflects errors introduced by the various simplifying assumptions. Equating d_{st} and d_c from Eqtns 3 & 4 and introducing the 1.5 factor leads to Equation 6, which provides an estimate of the maximum length of bar which can be exposed while retaining at least 90% of fully bonded strength (for this failure mode). It should, however, be noted that only a very limited amount of data is available for cases where the more highly stressed end of the exposed length lies within the shear span and more than one effective depth distant from the constant moment zone, and the Equations presented here should be treated with great caution in such circumstances until more data is available to permit validation.

$$L_{exp} < (d/x_1-1)\ 0.0023.E_{st}.L_0/f_y \qquad \text{Eqtn. 6.}$$

Now consider the second mode of failure, Figure 2, crushing of the concrete in the 'tension' face of the beam at the end of the exposed length close to a support. The chain dashed line in Figure 3 denotes the locus of the centroid of concrete in compression between midspan and support. The least distance between the locus and the face of the concrete is denoted 'e'. As before, it is assumed that beam strength will not be significantly reduced if reinforcement attains yield. The total force in the tension bars, P_{st}, is then :

$$P_{st} = A_{st}\ f_y \qquad \text{Eqtn. 7.}$$

and must be equal in magnitude to the compression in the concrete, P_c. Assuming the rectangular stress block of Fig. 5 for concrete, a limit is reached when

$$P_{st} = 0.67\ f_{cu}.b_w\ 0.9x_2 \qquad \text{Eqtn. 8.}$$

It may be assumed with acceptable accuracy that $e = x_2/2$. Therefore, in order to avoid a reduction in strength, the distance from the centroidal locus to the concrete surface, e, should not exceed

$$e = 0.83\ A_{st}.f_y/(f_{cu}.b_w) \qquad \text{Eqtn. 9.}$$

This analysis neglects the presence of 'compression' reinforcement. Limitations on space prevent a more detailed consideration of this aspect. However, compression bars will increase the length of bar which can be exposed without

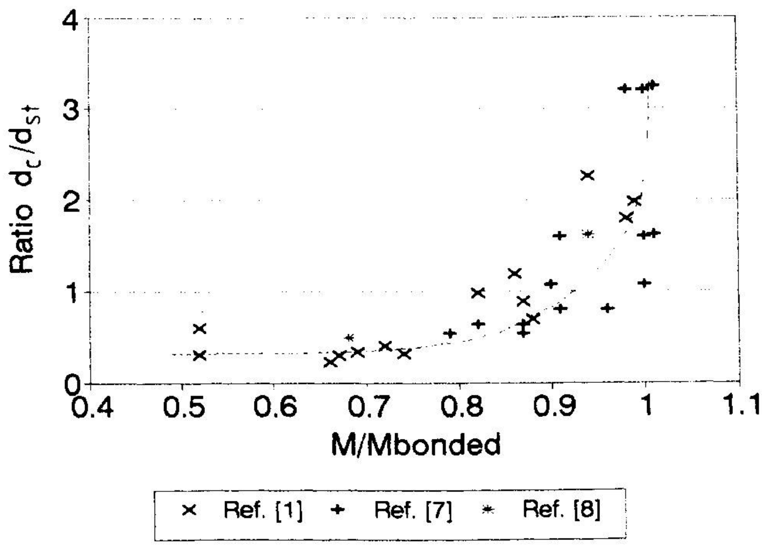


Figure 4 Comparison with test data.

significant loss of strength. Tests by Raoof[3] have confirmed that strength loss is reduced by provision of compression reinforcement.
It must also be verified that end anchorage of bars is adequate to develop the yield strength, Failure Mode 3, Figure 2, This may be done using standard Code of Practice procedures. If bars suffer from corrosion, due allowance should be made.

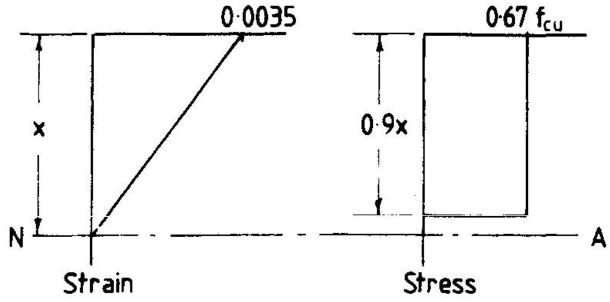


Figure 5 Simplified stress block for concrete at ultimate limit state.

Finally, it must be verified that shear strength is adequate within the portion of the member over which reinforcement is fully bonded. Normal Code of Practice procedures may be used. As mentioned above, there is no experimental evidence that shear strength is reduced by bond loss/exposure of reinforcement.

Partial safety factors on materials have been omitted in derivation of the above expressions, but should be included in any practical application.

The Author is not aware of any test data on strength of reinforced concrete beams with exposed bars under torsional loading.

4 CONCLUSIONS

The paper has demonstrated that it will be possible in certain circumstances to expose bars over a significant proportion of span without loss of strength, and simplified methods of analysis to estimate allowable exposure lengths have been presented. The expressions presented will assist in planning of repair programmes.

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