Bond Strength of Highly Corroded Reinforcement and Cover Delamination

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ABSTRACT: A recent experimental and analytical research program is described, providing bond strength values for highly corroded bars. The test program included both main reinforcement and stirrup corrosion. These results must be compared to the rather wide but scattered database of test results in this field. Two relevant sources for comparison are the indications of FIB MC2010, based on the existing literature, and some recently published test results (Regan and Kennedy Reid, 2009). The latter simulated the delamination of the concrete cover by casting the concrete either with zero minimum cover or at mid-barrel i.e. the bars had either no cover or even were partly external to the concrete; the reinforcement was not corroded. The conclusions discuss the choice of bond strength values for the assessment of existing structures and future research outlooks.

1 INTRODUCTION

Bond deterioration caused by corrosion of the reinforcement is a central aspect in the study of the safety of deteriorating reinforced concrete structures.

An experimental and analytical research has been recently carried out at Chalmers University of Technology and Politecnico di Milano (Zandi et al. 2011-a; Zandi et al. 2011-b; Coronelli et al., 2012). The tests aimed at reproducing the conditions of ribbed reinforcement undergoing high levels of corrosion leading to spalling of the cover; a part of the tests included corrosion of the stirrups. Corrosion cracking measurements showed the effect of transverse steel corroding or not (Coronelli et al., 2012). Bond tests measured the residual bond strength with or without transverse steel. The tests were modeled by 3D nonlinear finite element analysis (Zandi et al., 2011-a). The effect of corrosion product flow was modelled (Zandi et al., 2011-b).

High levels of deterioration were considered also in a wide experimental campaign carried out by Regan and Kennedy Reid (2009), to assess the residual bond strength of reinforcement with delaminated covers. The corrosion effects were simulated by loss of the cover, casting specimens with zero minimum cover to the main bars, or with the concrete at mid-barrel, i.e. the bars had either no cover or even were partly external to the concrete. The reinforcement surface was not corroded. On the basis of the tests results, simple analytical equations were proposed, including the effects of several parameters such has concrete strength, bar diameter, transverse reinforcement ratio and support pressure.

Model Code 2010 (Fib, 2010) gives indications to quantify bond deterioration caused by corrosion of both smooth and ribbed reinforcement, either without or with links. The basis of this proposal is a wide set of test results in the literature, mostly obtained from artificially corroded specimens, as reported in Chapter 4 of Fib Bulletin 10 (Fib, 2000). The values in Model Code 10 are provided as indications for use in the assessment of deteriorated structures.

In the following the paper describes the main aspects of the two studies and the Model Code indications. The results springing from these are compared. Conclusions are drawn regarding the choice of bond strength values for corroded reinforcement to carry out the assessment of a deteriorated structure.

2 TESTS AND EMPIRICAL MODELS

2.1 *Tests on beam-end specimens*

Eccentric pull-out tests were carried out to investigate the anchorage capacity of a severely corroded bar. The geometry of the eccentric pull-out specimens was similar to that used by Magnusson (2000), which had the shape of a beam-end after inclined shear cracking. (Fig.1) The specimens (Fig.2) were of three types with respect to the reinforcement arrangement and corrosion of main bars and stirrups: (a) without stirrups, main bars were subjected to corrosion; (b) with stirrups, only main bars were subjected to corrosion; and (c) with stirrups, main bars and stirrups were subjected to corrosion. The location of the bar, middle or corner position, the amount of transverse reinforcement, and the corrosion level of longitudinal and transverse reinforcement were included in the study.

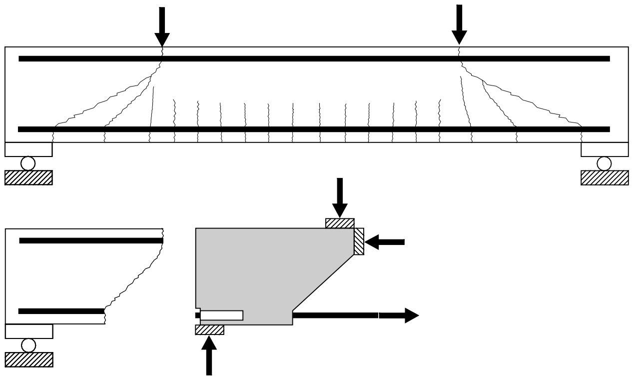


Figure 1. Schematic illustration of the eccentric pull-out specimen (Zandi et al., 2011-a).

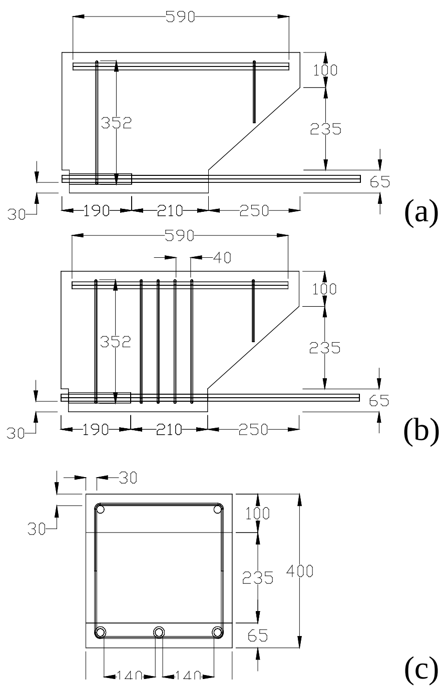


Figure 2. Specimen geometry and reinforcement: (a) without stirrups; (b) specimens with stirrups and (c) cross-section of all the three types of specimen. All dimensions are in mm

The specimens were cast with the main longitudinal reinforcement diameter of 20 mm, and with transverse reinforcement of 8 mm. A small concrete cover to the main bar, 1.5 times the main bar diameter, was used. The main bars were in contact with the concrete over a 210 mm embedment length; the bond-free zone over the support reduced the direct effect of support pressure. The mean concrete strength was f_c'=30MPa.

Specimens were corroded by an electrochemical method using impressed current. The current flowed through the main bars across the concrete cover to a cathode placed inside a tank containing a solution of 3% chloride. Stirrups in some of the specimens with stirrups were insulated using PVC electrical tape to prevent corrosion; in other specimens the stirrups were not protected and corroded with the main bars. The current density average value was 100 $\mu A/cm^2$. This is 10 to 100 times lower than in several other experimental studies, though current densities in field conditions are between 20 to 100 times lower than the value used here.

Specimens were corroded up to 10 months, reaching approximately 2% weight loss for each month. When compared with artificial corrosion tests in the literature, this can be considered a rather low value. Other researchers have used faster rates, by as much as one order of magnitude. Spurious mechanical concrete-steel bond deterioration has been measured for high current density values (Yuan *et al.*, 2007). Bar pull-out tests (see Figure 1) were carried out on reference specimens and corroded specimens at three levels:

- Level 1 corresponded to cracks occurring along the main reinforcement; at a corrosion level lower than 2% weight loss in the main bars;
- Level 2 corresponded to a corrosion level of 2-10% weight loss in the main bars; and
- Level 3 corresponded to extensive cover cracking, at a corrosion level greater than 10% weight loss in the main bars.

Corrosion attack was determined theoretically using Faraday's law and *a posteriori* by weight loss measurements. This was done for all specimens except one which was kept for another phase of the research program. The average difference between the two methods was approximately 10%; the corrosion penetrations were overestimated by Faraday's law. Crack widths on the bottom and side covers were measured during the corrosion process using a microscope up to corrosion level 1. Crack widths at levels 2 and 3 were measured before the load testing using a reference ruler with a range of graded lines, each corresponding to a specified width.

The specimens were tested in a specially designed test rig. The test set-up is outlined in Figure 1. Deformation control was adopted to permit measurements of the post-peak behaviour. In each test either the middle bar or the two corner bars of the specimen were pulled out. When the corner bars were tested, the two bars were loaded simultaneously. Displacement was controlled using two LVDTs, and the loads were read using two load cells mounted on each individual bar; it was, therefore, possible to register the individual response of each bar.

The bond strength of the bars is calculated as an average bond strength along the embedment length.

2.2 *Tests and empirical models for bars with delaminated cover*

A wide experimental campaign was carried out (Regan and Reid, 2009). The corrosion effects were simulated by loss of the cover, casting specimens with zero minimum cover for the main bars, or with the concrete at mid-barrel. The reinforcement surface was not corroded. Different types of specimens were tested. An example of the pull-out specimens is shown in Fig.3.

Parameters included concrete cover, stirrup restraint (percentage and arrangement of transverse steel), support pressure, splicing of reinforcement, concrete strength, type of bar (smooth or deformed), position in casting (top or bottom), anchorage length. The number of bars cast in bottom position was small, and the effect was ignored for simplicity by Regan and Reid; other Authors measured a sizeable difference with higher residual bond for bottom cast bars.
A large set of results was obtained. The results for bond strength were obtained as average stress values along the embedment length in correspondence of the failure load. On the basis of the test results simplified equations were obtained for bond strength.

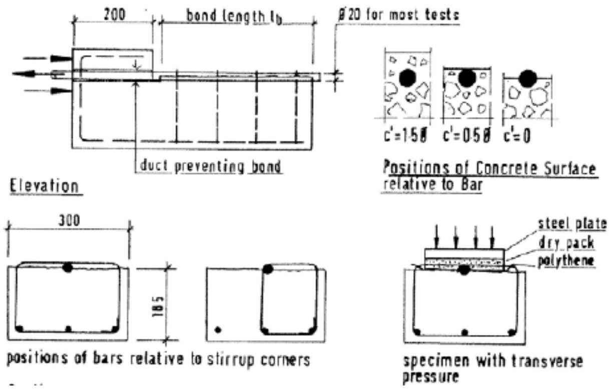


Figure 3. Pull-out tests with delaminated covers (Regan and Kennedy Reid, 2009).

2.2.1 *Expressions proposed for bond resistance with delaminated covers*

On the basis of the experiments, Regan and Kennedy Reid (2009) proposed empirical models for bond strength. These Authors state that the equations cannot be considered to provide characteristic values, due to the lack of a rigorous definition of such quantity for a "plastic" bond strength, measured in a bond test on a relatively long anchorage. The equations determine lower bounds to the tests results. The choice was made in order to obtain characteristic values of strength for beams on the basis of the bond strength values.

In view of the limits of the test data available and the limited detail in which the conditions of existing structures can be defined, Regan and Kennedy Reid (2009) restricted expressions for bond strength to relatively simple forms taking account of only those influences found to be of major importance.

Irrespective of how much of a bar is embedded in sound concrete, in all the expressions given in the following f_b is the nominal bond stress = change of bar force per unit length/$\pi\phi$.

For bars with sound cover greater than or equal to ϕ:

$$f_{b1} = 0.7\, f_{cu}^{1/2} \qquad (1)$$

For bars with zero minimum cover:

$$f_{b2} = (0.3 + 15\, A_{ss} / s\phi)\, f_{cu}^{1/2} \leq 0.7\, f_{cu}^{1/2} \qquad (2)$$

or

$$f_{b3} = 0.6\, f_{cu}^{1/2} + 2p \leq 0.7\, f_{cu}^{1/2} \qquad (3)$$

For bars in concrete with delamination at mid-barrel level:

$$f_{b2} = (0.1 + 15\, A_{ss} / s\phi)\, f_{cu}^{1/2} \leq 0.7\, f_{cu}^{1/2} \qquad (4)$$

or

$$f_{b5} = 0.25\, f_{cu}^{1/2} + p \leq 0.7\, f_{cu}^{1/2} \qquad (5)$$

where: A_{ss} = effective stirrup cross section (depends from position of the main reinforcement relative to the stirrup corners; $A_{ss}=A_b$ for corner bars, with A_b stirrup cross-section; A_{ss} = 0. for bars in central position in the cross section); s = transverse steel spacing; ϕ = main bar diameter; f_{cu} = cylinder compressive strength of concrete; p = support pressure.

These expressions are subjected to the following restrictions.

Equations (3) and (5) apply only if p > 0.05 $f_{cu}^{1/2}$
The upper limit of equation (3) is not justified by test results but is included to be consistent with BD 44/95's treatment of bars with cover.

If $A_{ss}/s\phi = 0$, equation (4) is applicable only if all bars contributing to the main steel's resistance are treated as having a limiting bond stress of 0.1 $f_{cu}^{1/2}$
As an alternative the bar lengths with $A_{ss} / s\phi = 0$ may be treated as having zero bond resistance and the relevant values from equations (1) to (5) may then be used for the other bar lengths. The latter option allows account to be taken of the resistance from equation (5) if the bars with mid-barrel exposure and A_{ss} = 0 are restrained by transverse pressure.

Where the delamination is at a depth greater than mid-barrel the bond resistance of a bar should be treated as unreliable.

2.3 *Bond of corroded bars in Model Code 2010*

Model Code 2010 (Fib, 2010) proposes the values for residual bond strength for ribbed and smooth bars stating that these may be taken as indicative values within an assessment. Reinforcement with or without transverse steel confinement is considered. Corrosion is measured by the penetration depth or an equivalent surface crack width. Upper and lower bound values for each corrosion level are given. Values for ribbed bars are reported in Table 1.

The maximum corrosion level is not very high, approximately 5-10% weight loss - depending on the bar diameter.

Most data on bond resistance of corroded reinforcement used to work out these indications were obtained from artificially accelerated corrosion tests, with respect to those measured in field exposure. The caution needed interpreting these experimental data is recognized in the proposal, with the need to seek detailed guidance in cases where residual strength of a corroding structure is of concern.

The commentary to these indication states that on the formation of longitudinal cracking along the bars bond strength deterioration may be very low or bond may even increase. Furthermore the strong influence of the transverse reinforcement confinement is recognised; also when the corrosion level is rather high significant bond strength is maintained. The positive effect of support pressure in anchorage zones is also highlighted.

Table 1. Model Code 2010 Indications (Fib, 2010)

Corrosion penetration (mm)	Equivalent Surface Crack (mm)	Residual Bond Strength %
No Transverse Reinforcement		
0.05	0.2-0.4	50-70
0.10	0.4-0.8	40-50
0.25	1.0-2.0	25-40
With Transverse Reinforcement		
0.05	0.2-0.4	95-100
0.10	0.4-0.8	70-80
0.25	1.0-2.0	60-75

3 COMPARISON OF RESULTS

In the following bond strength for the tests by Zandi et al. (2011-a) is calculated as if the bond is constant along the anchorage length. Since the anchorage length was rather long, this will differ from the local bond. It is relevant to use the bond strength calculated in this way, since that is a common assumption at design. Both the model in FIB MC2010 and the equations from Regan and Kennedy Reid (2009) do the same. This is important so that a fair comparison of results can be carried out.

The comparison of test results by Zandi et al. (2011-a) with the indications of Model Code 2010 is shown in Fig.4. For bars without transverse reinforcement the latter are quite conservative. For bars with transverse steel, the correspondence for corrosion levels up to 5% is rather good. The tests results for higher corrosion levels (ranging 7.5%-17% approximately) show quite limited bond deterioration, and are higher than the minimum values in Model Code 2010 for 5% corrosion.

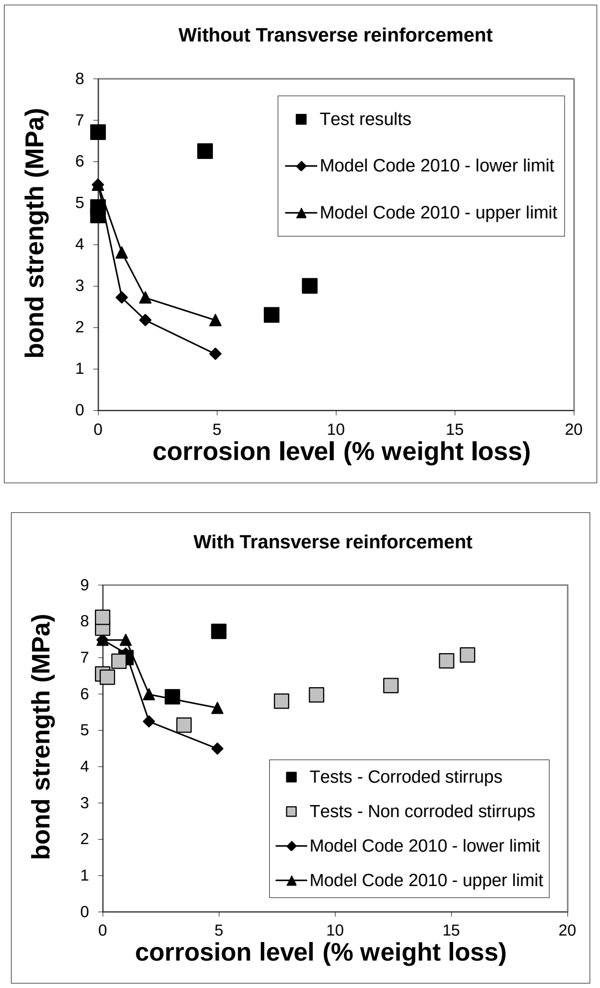


Figure 4. Comparison of bond deterioration predicted by Model Code 2010 and measured by Zandi et al., 2011-a.

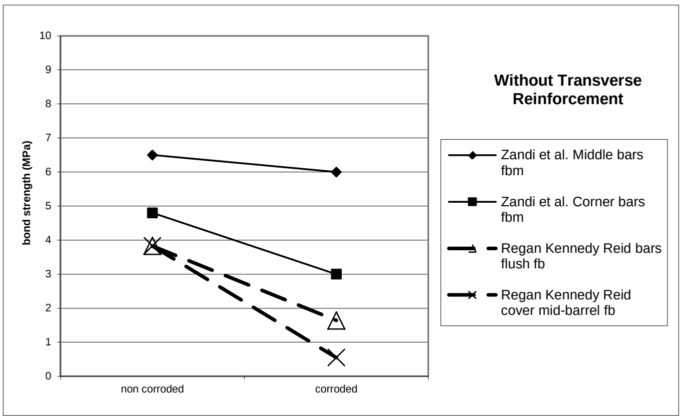
For the model by Regan and Kennedy Reid (2009) the results of Equations (2) and (4) are shown, calculated using the transverse steel ratio and other parameters in the tests by Zandi et al. (2011-a).

The equations that were previously introduced proposed an upper limit of 0.7 $f_c^{1/2}$ for bond strength, both for bars with or without transverse reinforcement. Here this limit seems quite conservative, taken into consideration for instance the values proposed in Model Code 90 for bond of bars with transverse steel. It must be considered, to explain the low limit values, that the equations are proposed as lower bounds to test results. The limit value 0.7 $f_c^{1/2}$ is shown in Fig.5b for the case with stirrups; it is not considered in the trend lines connecting the non-corroded to the corroded values, where values determined on the basis of the experimental results are used for the non-corroded reinforcement, and the results of Equation (4) for the bars with delaminated covers.

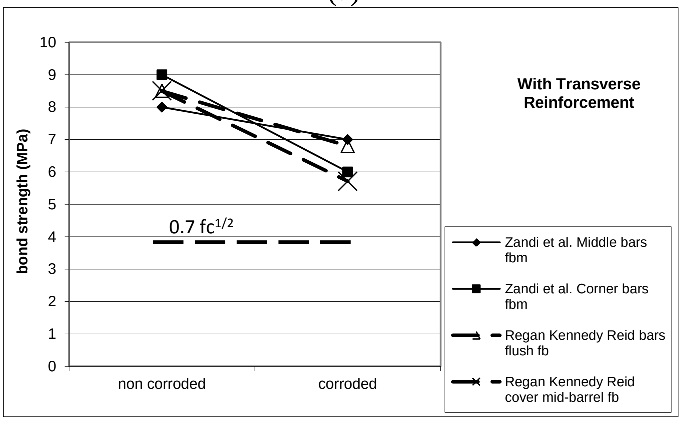
As already mentioned, Equations (1)-(5) take into consideration only couples of values, i.e. the bond strength of non-corroded bars with full cover and of the bars with delaminated covers. Two couples are calculated, one for zero minimum cover and one for cover at mid-barrel.

For comparison, the mean bond strength values in the experimental results by Zandi et al. (2011-a) are presented, for non-corroded bars and in correspondence of the maximum level of corrosion measured. Two such couples of values are shown, one for bars in corners and the other for bars in the middle position (see Fig.2).

The analytical values for bars without links are rather conservative (Figure 5a). For the specimens with transverse reinforcement, there is a rather close correspondence of test and model results (Figure 5b) for the trend lines connecting non-corroded and corroded (i.e. delaminated cover) values. A conservative lower bound value is provided by the limit $0.7f_c^{1/2}$, as indicated by Regan and Kennedy Reid (2009).



(a)



(b)

Figure 5. Comparison of bond deterioration predicted by Models by Regan and Kennedy Reid (2009) and measured by Zandi et al., 2011.

4 DISCUSSION

The test results by Zandi et al. (2011a) show quite high residual bond strength values. The values are higher than those proposed by model Code 2010, taking into account also higher corrosion levels than those considered by the code.

This result can be interpreted as the effect of the transverse steel and the concrete surrounding the bar, that are active in confining the bar even beyond the corrosion crack formation and propagation (Lundgren, 2002; Coronelli, 2002).

Regan and Kennedy Reid (2009) proposed equations for the bond strength of reinforcement with delaminated covers. Their model does not consider a progressive deterioration as a consequence of corrosion cracks propagating and widening. Only one condition of high deterioration is taken into account.

The level of damage considered is of two different types, with different severity: either the bars are still embedded in concrete, or the bar surface is exposed to mid-barrel.

It is meaningful that also the bond deterioration proposed by Regan with delaminated covers and without bar corrosion is rather limited.

As already commented, the equations proposed by Regan and Kennedy Reid (2009) should provide lower bounds for bond strength. Taking into consideration the values measured by Zandi et al., both in the case without transverse steel and with transverse steel, the analytical results are actually lower than the test mean values (Figure 5a).

The equation for bars with transverse steel proposed by Regan and Kennedy Reid corresponds to the tests by Zandi et al. (2011-a), provided that a sufficiently high upper limit of bond strength for bars with stirrups is used.

The tests by Zandi et al. (2011) used bars corroded artificially with a reasonably moderate corrosion rate. This can be related to the quite low bond deterioration measured. Other studies (Yuan *et al.*, 2007) suggest that spurious bond deterioration can be induced by higher rates of artificial corrosion.

The Model Code 2010 proposal for bond deterioration considers corrosion levels causing up to 1-2mm crack opening, but do not take into account the delamination of the cover. Although the levels of corrosion considered are not very high, bond deterioration down to 25% or 60% (for bars without or with links respectively) are indicated. Such conservative indications of the Model Code should also be put in relation to the scatter of results in the literature, the uncertainties connected with the lack of bond tests on bars with natural corrosion and finally the aim to provide safe indications for structural assessment.

5. CONCLUSIONS

Recent analytical and experimental results for bond of corroded bars with high levels of corrosion have been compared.

In the tests by Zandi et al. (2011-a) artificial corrosion with moderate corrosion rates was used. The bond test results show relatively low bond deterioration, for specimens without and with stirrups; both non-corroded and corroded transverse reinforcement was tested. The maximum corrosion level reached was nearly 20% weight loss for the main bars and 35% for the stirrups.

The Model Code 2010 indications for bond deterioration of corroded bars are conservative, compared to the test results in this study. They appear adequate for initial stages of structural assessment.

The Model Code proposal is based on a wide database of experimental tests in the literature, mainly obtained with artificial corrosion; part of these used very high corrosion rates, possibly providing excessive spurious bond deterioration. More results with naturally corroded specimens are needed. Comparisons for different artificial corrosion rates are very important too.

Moreover, the maximum corrosion level in the Model Code is relatively low, around 5-10% weight loss; to take into consideration highly corroded structures, indications for higher levels should be provided.

The empirical models proposed by Regan and Kennedy Reid (2009) for bond strength of highly corroded bars, based on tests for bars cast with delaminated covers, have been compared to the tests by Zandi et al. (2011-a). The models are conservative both for bars without and with transverse reinforcement. Hence, on the basis of this comparison these models appear adequate to define lower bounds to the bond strength of highly corroded reinforcement. This conclusion should be corroborated by more bond test results with such high levels of corrosion.

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