Effect of corrosion on ductility of reinforcing bars

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An experimental investigation into the effect of corrosion on the ductility of steel reinforcement is reported. Both accelerated and simulated corrosion tests were conducted on bare bars and on bars embedded in concrete. The mechanism and degree of the reduction of ductility of reinforcement due to corrosion were examined. The influence of bar type and diameter on ductility of corroded reinforcement is discussed. The experimental results indicate that, since local attack penetration results in a significant variation of residual cross-section along its length, corrosion significantly reduces ductility of reinforcement. Although the strength ratio, elastic modulus and hardening strain only vary with bar type rather than corrosion level, the elongation, ultimate strain and ductile area of corroded reinforcement reduce much more significantly than do those of their yield and ultimate strengths. There is concern regarding bar ductility since about 10% corrosion may possibly decrease the ultimate strain of reinforcement below the minimum requirement specified in CEB Model Code 90 for class S reinforcement. Even though the elongation, ultimate strength and ductile area parameter of corroded small diameter and/or plain bars reduce more than those of large diameter and/or ribbed ones, such differences are not significant and can be neglected. Finally, a set of simple empirical equations is proposed to assess the ductility of corroded reinforcement in practice.

Notation

\( A^* \) area parameter proposed by Creazza and Russo\(^ {12} \)
\( A_d \) ductile area proposed by Beeby\(^ {13} \)
\( A_{\alpha\varepsilon} \) area under stress–strain curve of reinforcing bar
\( A_{d0} \) ductile area of non-corroded reinforcements
\( A_{cor} \) actual cross-sectional area of corroded reinforcement
\( A_{\bar{A}} \) average cross-sectional area of corroded reinforcement
\( A_{d0} \) initial cross-sectional area of non-corroded reinforcement
\( d \) diameter of non-corroded reinforcement
\( F \) force of corroded reinforcement
\( f_0 \) strength of non-corroded reinforcement
\( f_\varepsilon \) yield strength of corroded reinforcement
\( f_{\varepsilon 0} \) yield strength of non-corroded reinforcement
\( f_u \) ultimate strength of corroded reinforcement
\( f_{\varepsilon 0} \) ultimate strength of non-corroded reinforcement
\( Q_{cor} \) corrosion percentage of reinforcement
\( Q^{*}_{cor} \) critical corrosion percentage regarding ductility of reinforcement
\( L \) gauge length of reinforcement
\( r_{x} \) ratio of maximum to minimum corrosion penetration
\( x_{max} \) maximum local attack penetration of corroded reinforcement
\( x_{corr} \) average attack penetration of corroded reinforcement
\( \rho_{min} \) minimum value of ratio of ultimate to yield strengths of reinforcement
\( \varepsilon_y \) yield strain of corroded reinforcement
\( \varepsilon_{ym} \) hypothetical yield strain of reinforcement at ultimate stress
\( \varepsilon_u \) ultimate strain of corroded reinforcement
\( \varepsilon_{umin} \) minimum value of ultimate strain of reinforcement
\( A_{\bar{A}} \) elongation of corroded reinforcement

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(MCR 41267) Paper received 2 April 2004; last revised 17 November 2004; accepted 1 February 2005

Magazine of Concrete Research, 2005, 57, No. 7, September, 407–419
The conventional definition of reinforcement ductility which is specified in some international codes, such as CEB Model 90, defines the ductility of reinforcement in terms of two independent criteria: the strength ratio and ultimate strain. The first criterion is that the ratio of ultimate strength to yield strength must not be less than a specified minimum value, namely, \( \frac{f_u}{f_y} \geq \rho_{min} \) and considers the strain-hardening ratio of steel reinforcement which specifies an interval between the ultimate strength and yield strength, as shown in

\[
\begin{align*}
\lambda_0 & \quad \text{elongation of non-corroded reinforcement} \\
\alpha_c & \quad \text{regression parameters for ultimate strain of corroded reinforcement} \\
\alpha_A & \quad \text{regression parameters for ductile area of corroded reinforcement} \\
\alpha_L & \quad \text{regression parameters for elongation of corroded reinforcement} \\
m & \quad \text{sectional coefficient of corroded reinforcement} \\
\eta & \quad \text{length coefficient of corroded reinforcement}
\end{align*}
\]
The second criterion is that the ultimate strain \( \varepsilon_u \) must not be less than a specified minimum value, namely, \( \varepsilon_u = \varepsilon_{u\text{ min}} \), and specifies an indicator of maximum deformation capacity. For Class S reinforcement, which is used for highly ductile structures, Model Code 90 specifies that \( \rho_{\text{min}} = 1.15 \) and \( \varepsilon_{u\text{ min}} = 6\% \). Because the three parameters, \( f_y, f_p \) and \( \varepsilon_y \), used in the above two criteria can be obtained directly by simple tensile tests without considering an actual stress–strain curve, these two criteria have been widely adopted to verify bar ductility in engineering practice.

However, the above conventional criteria fail to reflect fully the ductile behaviour of a reinforcing bar under monotonic force. As shown in Figs 1 (a) and (b), even if two specimens of steel reinforcement have the same ultimate strain, the same yield strength and the same ultimate strength, they can still have different ductility and produce different influences on concrete structures.

By considering the strain at the beginning of the strain-hardening phase, \( \varepsilon_{sh} \), Creazza and Russo12 defined bar ductility as an area parameter \( A^* \), as shown in Fig. 1(b). Geometrically, the parameter \( A^* \) is the area between the post-hardened stress–strain curve and a horizontal line at the yield strength. By assuming that the strain-hardening curve is a parabolic curve, the area \( A^* \) can be determined using equation (1)

\[
A^* = \frac{2}{3} (f_y - f_y)(\varepsilon_u - \varepsilon_{sh}) \tag{1}
\]

It is clear that Creazza and Russo’s criterion for bar ductility not only unequivocally defines the deformation work of a steel bar during its strain-hardening phase, but also simultaneously considers the influence of ultimate strength \( f_y \), yield strength \( f_y \) and ultimate strain \( \varepsilon_u \) on bar ductility.

Although Creazza and Russo’s proposals do indeed improve the conventional definition of bar ductility, some new problems arise. First, as shown in equation (1), one more new parameter \( \varepsilon_{sh} \) is introduced to represent bar ductility. This parameter is not very objective if there is no distinct point between the yield plateau and the strain-hardening phase on the stress–strain curve (see Fig. 1(a)). Second, some difference exists between the assumed parabolic curve and the shape of the real strain-hardening curve.

In studying the influence of bar ductility on ultimate plastic rotation of reinforced concrete beams, Beeby13 employed another area parameter \( A_d \) to describe the bar ductility, as shown in Fig. 1 and defined by equation (2)

\[
A_d = f_y(\varepsilon_u - 0.5\varepsilon_{sh}) - A_{sh} \tag{2}
\]

\( A_d \) is a ductile area parameter, \( \varepsilon_y \) is the yield strain, \( \varepsilon_{sy} = (f_y/f_y)\varepsilon_y \) is a hypothetical yield strain at ultimate stress, and \( A_{sh} = \sum (0.5(\sigma_{i+1} + \sigma_i)(\varepsilon_{i+1} - \varepsilon_i) \) is the area under the stress–strain curve.

It is clear that Beeby’s area parameter \( A_d \) is geometrically, the area between the post-yield stress–strain curve of a reinforcing bar and a horizontal line at its ultimate strength. It integrates the yield strength, ultimate strength, ultimate strain and the stress–strain curve of a steel bar, and can be easily calculated and used to evaluate bar ductility, based on the stress–strain curve of a reinforcing bar under monotonic load.

To date, the area parameters of neither Creazza and Russo nor Beeby, \( A^* \) and \( A_d \), respectively, have been widely adopted in practice. Most researchers and practising engineers still adopt the conventional criteria to evaluate the ductility of bars. Hence, in the current research, the two conventional criteria of strength ratio and ultimate strain are used to investigate the ductility of corroded reinforcement, and to compare the authors’ results with those of other researchers. In addition, the effect of corrosion on elongation, hardening strain, Beeby’s ductile area \( A_d \) and elastic modulus are also discussed.

**Experimental programme**

The details of the experimental programme and comments on the practical implications of the techniques used to obtain corrosion information have been re-
ported in a previous paper.\textsuperscript{4} Hence, only a brief description is given here.

A total of 108 test specimens, including 30 bars embedded in concrete cylinders of 50 mm diameter (referred to as the CEB specimens) and 78 single bare bars (referred to as the SBB specimens), were manufactured. In addition to 21 non-corroded control specimens, 84 specimens were subjected to accelerated corrosion with a direct current impressed and the three remaining specimens were subjected to simulated corrosion with bare bars mechanically machined in the workshop, before they were tensioned until rupture to measure their residual strength\textsuperscript{4} as well as their ductility.

The concrete used for the cylindrical specimens had a water/cement ratio of 0.65 and contained 4% calcium chloride by mass of cement. The average cube compressive strength at the time when the impressed current was first applied on to bar specimens, at an age of 198 and 240 days for specimens RC16 and TC16, respectively, was 46.4 N/mm\textsuperscript{2}. All reinforcement specimens had the same length of 450 mm with at least three specimens from the same casting for each combination of the following variables.

- Specimen type: single bare bars and bars embedded in concrete
- Reinforcement type: plain bars and ribbed bars
- Reinforcement diameter: 8, 16 and 32 mm
- Corrosion times: 7, 14, 21 and 28 days

The corrosion apparatus is shown schematically in Fig. 2. Corrosion currents of 0.5, 1.0 and 2.0 mA/cm\textsuperscript{2} were impressed onto the 8, 16 and 32 mm diameter bars, respectively, to attain similar corrosion percentages for the same corrosion durations. The corrosion percentage was calculated from the ratio of the weight loss to the initial weight. The corrosion products were removed from the bar surface with acid solution prior to weighing and allowance was made for the influence of such acid cleaning on bar weight loss.

A Denison Testing Machine, equipped with a data-processing computer, an electrical extensometer and a linear variable displacement transducer (LVDT), was used for uni-axial tension tests performed on the reinforcement specimens under a 2 mm/min displacement control rate. Prior to reaching the yield load, extension was measured by means of an electrical extensometer with a maximum stroke of 0.3 mm over its 50 mm gauge. Following initial yield, extension was recorded until bar fracture by the LVDT with a maximum stroke of 35 mm over its 43 mm gauge length. Prior to a tension test, two marks at a spacing of 200 mm were made on a bar’s surface for the measurement of bar elongation.

\textbf{Results and discussion}

The main experimental results were a force–extension curve and the elongation of each bar measured after its rupture. On the basis of these results, the effect of corrosion percentage on ductility of reinforcement is analysed and discussed.

In the following analysis, bar stress and strain were calculated, respectively, by dividing force by average cross-sectional area\textsuperscript{4} and extension by the gauge length of either the extensometer or the LVDT, as appropriate. The elongation of a reinforcing bar was taken as the ratio, expressed as a percentage of the increase in the distance between the two marks on the bar surface after its rupture to their initial distance of 200 mm. The ductile area parameter was based on the stress–strain curve of each reinforcing bar and was calculated from equation (2). The elastic modulus was determined by dividing the increment of stress within the middle third of the linear elastic range by the corresponding strain increment. This approach eliminated the influences of initial loading and yielding on the elastic modulus.

\textit{Ductility of non-corroded reinforcement}

The average of the three measured values of the various ductility parameters of the non-corroded reinforcing bars are summarised in Table 1. The individual values were generally within ±6.8\% of their mean.
values. It is clear that all reinforcing bars used in the experimental investigation met the minimum requirements for Class S reinforcements for high-ductility structures. The strength ratio, elongation, ultimate strain and ductile area of plain bars are greater than those of ribbed bars and, therefore, they are more ductile than the ribbed bars. The elastic moduli of all of the non-corroded bars are very close to the typical code value of 200 kN/mm², with a maximum difference of 5.5%.

The unit weights were obtained by weighing 300 mm lengths of bar, and the actual diameters were determined from the weights by using a density of 7.85 g/cm².

It should be pointed out that, except for the 8 mm diameter plain bar R08, the stress–strain curves of all bars exhibited an initial linear elastic portion, a yield plateau and a strain-hardening phase, as shown schematically in Fig. 1(b). The plain bar R08 lacked a well-defined yield plateau. Hence, its maximum linear elastic stress was taken as its nominal yield strength, as shown in Fig. 1(a). A proof stress was not used because corrosion was found not to change the shape of the stress–strain curve.  

**Effect of corrosion on ductility of reinforcing bars**

A visual examination of the corroded reinforcement showed that the conditioning corrosion did indeed change the external surface of a steel bar. Compared with the non-corroded reinforcement, as corrosion time increased from 7 days to 28 days under an impressed direct current, the corrosion pits on the reinforcement surface developed in different ways: They increased in number and expanded in size, while some of them joined up with each other to give an appearance between that of the reasonably uniform corrosion due to concrete carbonation and the localised corrosion due to chloride penetration. Corrosion of the reinforcement not only altered the approximately round cross sections into very irregular ones, but it also caused the residual sections to vary significantly along its length.

In addition, for the reinforcement specimens embedded in concrete, some corrosion also occurred on the 75 mm length of bar projecting out of the concrete. There was more corrosion at the location of air voids at the steel interface, although the bars were well protected with a primer coating and an epoxy coating to avoid crevice corrosion. During the tension tests, however, the measurement location was always positioned at the middle of the 300 mm length of bar which had been embedded in concrete to minimise the influence of crevice corrosion on bar properties.

**External surface and residual section of corroded reinforcement**

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**Effect of corrosion on strength ratio, hardening strain and elastic modulus**

The effects of corrosion on strength ratio, hardening strain and elastic modulus of reinforcing bars are shown in Figs 3 to 5 for bare bars, and in Figs 6 to 8 for bars RC16 and TC16 embedded in concrete. In the latter figures the embedded bars are compared with bare bars R16 and T16. Linear regression lines are plotted on each figure.

It is clear that, for all situations, the regression lines for strength ratio, hardening strain and elastic modulus of reinforcing bars are almost horizontal and, hence, these parameters varied little with corrosion percentage. Although a small rise or fall trend could be observed for some bars, no systematic and logical relationship could be found between the strength ratio, hardening strain or elastic modulus of reinforcing bars and the corrosion percentage. Regression lines of strength ratio, hardening strain and elastic modulus of bars embedded in concrete are parallel to those of bare bars. Furthermore, for up to 25% corrosion, the strength ratios of almost all corroded bare bars are greater than the minimum value of

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**Table 1. Ductility of non-corroded reinforcements**

<table>
<thead>
<tr>
<th>Reinforcement Number</th>
<th>Plain Bars</th>
<th>Ribbed Bars</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R08</td>
<td>R16</td>
</tr>
<tr>
<td>Unit weight</td>
<td>W₀ (g/mm)</td>
<td>0.332</td>
</tr>
<tr>
<td>Actual diameter</td>
<td>d₀ (mm)</td>
<td>7.34</td>
</tr>
<tr>
<td>Yield strength</td>
<td>f₀ (N/mm²)</td>
<td>284</td>
</tr>
<tr>
<td>Ultimate strength</td>
<td>f₀ (N/mm²)</td>
<td>413</td>
</tr>
<tr>
<td>Ratio of strength</td>
<td>f₀/f₀₀</td>
<td>1.45</td>
</tr>
<tr>
<td>Elasticity</td>
<td>E₀ (kN/mm²)</td>
<td>196</td>
</tr>
<tr>
<td>Yield strain</td>
<td>ε₀₀ = f₀₀/E₀</td>
<td>0.0014</td>
</tr>
<tr>
<td>Hardening strain</td>
<td>ε₁₀₀ = ε₀₀</td>
<td>NA</td>
</tr>
<tr>
<td>Ultimate strain</td>
<td>εₙ₀₀ = ε₀₀</td>
<td>0.182</td>
</tr>
<tr>
<td>Bar elongation</td>
<td>Δ₀ (%)</td>
<td>23</td>
</tr>
<tr>
<td>Hardening strain ratio</td>
<td>ε₁₀₀/ε₀₀</td>
<td>NA</td>
</tr>
<tr>
<td>Ultimate strain ratio</td>
<td>εₙ₀₀/ε₀₀</td>
<td>128</td>
</tr>
<tr>
<td>Rupture strain ratio</td>
<td>ε₁₀₀/ε₀₀</td>
<td>162</td>
</tr>
<tr>
<td>Application in test specimen</td>
<td></td>
<td>SBB</td>
</tr>
</tbody>
</table>

NA not applicable.
1.15 specified in CEB Model Code 90 for class S reinforcement. Hence, corrosion of reinforcement hardly affects strength ratio, hardening strain and elastic modulus of reinforcing bars.

Significance tests performed on the experimental results of the bare bars at the 5% significance level showed that there were significant differences between the mean values of the strength ratio, hardening strain and elastic modulus of bars of different diameter and/or type. However, at the same significance level, the mean values of strength ratios, hardening strain and elastic modulus of bars in concrete were not significantly different to those of bare bars. Hence, strength ratio, hardening strain and elastic modulus of corroded bars varied mainly with bar type and bar diameter, rather than corrosion condition (i.e. whether a bare bar or a bar embedded in concrete).

The explanation for the above observation is that the strength ratio of a reinforcing bar is determined by its yield and ultimate strengths, which are both functions of the minimum cross-sectional area. Hence, when corrosion reduces bar section, the yield and ultimate strengths are reduced by similar amounts and the strength ratio is largely unaffected. Furthermore, the hardening strain and elastic modulus of a reinforcing bar are dependent on their chemical composition and manufacturing process. Corrosion removes iron ions.
only from the bar surface and does not change the
nature and composition of the remaining steel bar. As a
result, corrosion of reinforcement does not change sig-
nificantly the strength ratio, hardening strain and elastic
modulus.

With regard to the effect of corrosion on the strength
ratio, different researchers have reported apparently
contradictory results. Regression results of the tabu-
lated test data of Andrade et al. show that corrosion did
not decrease bar strength ratio. However, Zhang et al.
reported that corrosion reduced bar strength ratio \( f_u/f_c \)
from 1.5 to 1.1.

In the authors’ opinion, the reason for such contra-
dictory results is the use of different types of bar and
different testing techniques. An extensometer with the
60 mm gauge length used by Andrade et al. may be
more sensitive to the yielding of a steel bar than the
measurement of displacement from the movement of a
testing machine’s platen over a distance of 200 to
400 mm as used by Zhang et al.

**Effect of corrosion on ultimate strain, ductile area and
elongation**

The effect of corrosion percentage on ultimate strain,
ductile area and elongation of bare bars is shown in
Fig. 9, and on the ultimate strain of bars embedded in
concrete in Fig. 10 where embedded bars are compared
with bare bars. Since the effects of corrosion on ductile
area and elongation of bars embedded in concrete are
very similar to that on ultimate strain, they are not
shown in Fig. 10, although they are included in the
following analysis. Here, \( \varepsilon_u/\varepsilon_{0,\text{cor}}, A_d/A_{0,\text{cor}} \) and \( \lambda/\lambda_0 \) and
are ratios of ultimate strength \( \varepsilon_u \), ductile area \( A_d \) and
elongation \( \lambda \) of corroded bars to the non-corroded va-

\[
\begin{align*}
\varepsilon_u &= (1 - \varepsilon_c Q_{\text{cor}})\varepsilon_{0,\text{cor}} \\
A_d &= (1 - \alpha_A Q_{\text{cor}})A_{0,\text{cor}} \\
\lambda &= (1 - \alpha_{\lambda} Q_{\text{cor}})\lambda_0
\end{align*}
\]

where \( \varepsilon_c, \alpha_A \) and \( \alpha_{\lambda} \) are regression coefficients for
ultimate strain, \( \varepsilon_u \), ductile area, \( A_d \), and elongation, \( \lambda \),
respectively, of reinforcing bars, and are listed in Table
2 for different bar types and diameters and different
corrosion conditions.

Equations (3) to (5) show that, for a positive value of
a regression coefficient, an increase of corrosion per-
centage decreases the ultimate strain, ductile area and
elongation of corroded bars. Furthermore, the larger is
a regression coefficient, the greater is the rate of re-
duction of a bar’s ultimate strain, ductile area and elon-
gation.

Table 2 indicates that, except for the bar T32 that
was corroded under a 2.0 mA/cm² current, for the
same type of reinforcement specimen, the smaller the
bar diameter, the greater are the regression coefficients
\( \varepsilon_c, \alpha_A \) and \( \alpha_{\lambda} \). For the same reinforcement diameter,
the regression coefficients \( \varepsilon_c, \alpha_A \) and \( \alpha_{\lambda} \) for plain bars
are always larger than those for ribbed bars. Furthermore,
for the same type of reinforcements with an
identical diameter, the regression coefficients \( \varepsilon_c, \alpha_A \)
and \( \alpha_{\lambda} \) of bars embedded in concrete are much greater...
than those of bare bars. Hence, for an identical corrosion percentage, the ultimate strain, ductile area and elongation of smaller diameter bars and of plain bars decrease more than those of larger diameter bars or ribbed bars. It is again apparent that the ductility of bars embedded in concrete reduces more rapidly than that of bare bars in terms of ultimate strain, ductile area and elongation.

Although bar diameter and bar type do indeed affect the reduction of ultimate strain, ductile area and elongation of corroded bars, their influences are not significant at the 5% significance level. Consequently, the reductions of ultimate strain, ductile area and elongation of different type and diameter bars are determined primarily by the corrosion percentage, rather than bar type or diameter. Hence, by taking the results of all bars as one population, equations (6) to (8) are obtained.

\[
\begin{align*}
\varepsilon_u &= (1 - 0.029\sigma_{\text{cor}})\varepsilon_{d0} \\
A_d &= (1 - 0.029\sigma_{\text{cor}})A_{d0} \\
\lambda &= (1 - 0.028\sigma_{\text{cor}})\lambda_{d0}
\end{align*}
\]

It should be noted that the coefficients 0.029 and 0.028 in equations (6) to (8) have almost the same value. Hence, the reduction coefficient, due to corrosion, of ultimate strain, ductile area and elongation of bare bars are similar to each other and can be taken conservatively as 0.03 for practical use.

Although the influence of both bar type and its diameter on reductions of ultimate strain, ductile area and elongation of both bare bars and bars in concrete is not significant, the effect of corrosion condition, that is, bare bars or bars in concrete, is significant. A regression analysis for bars embedded in concrete, similar to that described above for bare bars, resulted in equations (9) to (11).

\[
\begin{align*}
\varepsilon_u &= (1 - 0.044\sigma_{\text{cor}})\varepsilon_{d0} \\
A_d &= (1 - 0.037\sigma_{\text{cor}})A_{d0} \\
\lambda &= (1 - 0.039\sigma_{\text{cor}})\lambda_{d0}
\end{align*}
\]

It should be pointed out that, in contrast to those in equations (6) to (8), the coefficients of 0.037 to 0.044 in equations (9) to (11) are not very close to each other. The scatter of the test data, as well as the smaller number of specimens, may possibly have been the reason for these results. The number of bars corroded in concrete was 24, which is less than half of the 63 bare bars. It is the authors’ view that a coefficient with a conservative value of 0.05 may be adopted. Hence, it is suggested that the ductility of corroded reinforcement can be determined by equations (12) and (13) for bare bars and bars embedded in concrete, respectively.

\[
\begin{align*}
\varepsilon_u &= (1 - 0.03\sigma_{\text{cor}})\varepsilon_{d0} \\
\varepsilon_u &= (1 - 0.05\sigma_{\text{cor}})\varepsilon_{d0}
\end{align*}
\]

**Critical corrosion and critical aspects of bar ductility**

From equations (12) and (13), a critical corrosion percentage can be determined above which the reinforcement would not meet the minimum ductility requirements. For example, the critical percentage to ensure that the ultimate strain criterion is achieved is given by equation (14).

\[
Q_{\text{cr}}^U = (1 - \frac{\varepsilon_{\text{umin}}}{\varepsilon_{d0}}) \frac{1}{\alpha_e}
\]

where \(\varepsilon_{\text{umin}}\) is the minimum requirement for bar ductility specified in the appropriate design standard, \(\varepsilon_{d0}\) is the ultimate strain of the reinforcement prior to corrosion, \(\alpha_e\) is the regression coefficient which can be taken as 0.03 for bare bars and 0.05 for bars in concrete.

When the actual corrosion percentage exceeds its critical value, that is, \(Q_{\text{cor}} > Q_{\text{cr}}^U\), there is a significant probability that the ultimate strain may be reduced to a value less than the minimum requirement for some combinations of variables tested.

**Table 2: Regression and correlation coefficients and correlation for bar ductility in terms of ultimate strain, ductile area and elongation**

<table>
<thead>
<tr>
<th>Specimen type</th>
<th>Bar type</th>
<th>Ultimate strain</th>
<th>Ductile area</th>
<th>Elongation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(\varepsilon_u = (1 - 0.029\sigma_{\text{cor}})\varepsilon_{d0})</td>
<td>(A_d = (1 - 0.029\sigma_{\text{cor}})A_{d0})</td>
<td>(\lambda = (1 - 0.028\sigma_{\text{cor}})\lambda_{d0})</td>
</tr>
<tr>
<td>Bare bars</td>
<td>All bars</td>
<td>0.029</td>
<td>0.660</td>
<td>0.028</td>
</tr>
<tr>
<td></td>
<td>R08</td>
<td>0.032</td>
<td>0.781</td>
<td>0.034</td>
</tr>
<tr>
<td></td>
<td>R16</td>
<td>0.026</td>
<td>0.632</td>
<td>0.024</td>
</tr>
<tr>
<td></td>
<td>T08</td>
<td>0.027</td>
<td>0.572</td>
<td>0.028</td>
</tr>
<tr>
<td></td>
<td>T16</td>
<td>0.023</td>
<td>0.660</td>
<td>0.022</td>
</tr>
<tr>
<td></td>
<td>T32</td>
<td>0.031</td>
<td>0.586</td>
<td>0.024</td>
</tr>
<tr>
<td>Bars in concrete</td>
<td>All bars</td>
<td>0.044</td>
<td>0.735</td>
<td>0.039</td>
</tr>
<tr>
<td></td>
<td>RC16</td>
<td>0.052</td>
<td>0.868</td>
<td>0.048</td>
</tr>
<tr>
<td></td>
<td>TC16</td>
<td>0.037</td>
<td>0.648</td>
<td>0.031</td>
</tr>
</tbody>
</table>
The previous discussion of the experimental results indicated that corrosion does not affect ductility in terms of strength ratio, but does decrease it in terms of ultimate strain, ductile area and elongation. However, the effect on structural ductility and robustness depends not only on the reinforcement properties but also on the characteristics of the applied load and of the structural response.

For structures subjected mainly to heavy static loads, such as live loads in a library, that are independent of structural response, the strength ratio of reinforcement plays a more dominant role in structural robustness than ultimate strength or elongation. A high value of strength ratio gives a significant margin between the yield and ultimate strengths and allows a structure to accommodate an overload. Hence, corrosion of reinforcement used in such structures, which mainly resist static loads, hardly influences structural robustness.

For structures located in a seismic zone or subjected mainly to dynamic loads, however, the ultimate strain or elongation of the reinforcement is more critical than its strength ratio. The reason is that a dynamic load depends not only upon the level of action itself, such as earthquake intensity, but also on structural response. An intense earthquake may cause a moderate effect on a ductile structure, but a moderate earthquake can induce an intense effect on a less ductile structure. This is because the dynamic loads due to such an action are dependent on structural stiffness, and reduce as the reinforcement yields and plastic rotations of sections occur. Hence, although an action may theoretically cause the ultimate strength of reinforcement with a low strength ratio to be exceeded, in practice the reinforcement will not rupture if it has sufficient elongation capacity. Hence, corrosion of reinforcement used in structures which are mainly subjected to dynamic loads can decrease their ductility and robustness significantly, because the ultimate strain and elongation of the reinforcement are reduced.

From the above discussion it is apparent that, from the point of view of structural ductility and robustness, the ultimate strain of reinforcement is more critical than its strength ratio. Consequently, henceforth, ultimate strain is taken as the critical ductility parameter.

Due to irregular and local attack penetration, the residual cross-sectional area of a corroded bar varies significantly along its length, as shown schematically in Fig. 11(a). From non-corroded reinforcement with an initial section \( A_{\text{bar}} \) over a gauge length of \( L \), the corroded bar can be idealised as a composite with three different portions. Portion I has an average cross-sectional area of \( A_s \) over a length of \((1 - \eta)L\), whereas portions II and III are assumed to have minimum and maximum residual cross-sectional areas of \( mA_s \) and \((2 - m)A_s\), respectively, over identical lengths of \(0.5\eta L\).

The coefficient \( m \) is the ratio of the minimum residual cross-sectional area of the corroded reinforcement to its average value and, as shown in Reference 4, can be determined by equation (15).

\[
m = \frac{A_{\text{min}}}{A_s} = \frac{1 - 0.01Q_{\text{cor}}[2r_s/(1 + r_s)]}{1 - 0.01Q_{\text{cor}}}
\]

where \( r_s \) is the ratio of maximum corrosion penetration \( x_{\text{max}} \) to the minimum value \( x_{\text{min}} \), \( Q_{\text{cor}} \) is the corrosion percentage. It is clear that, for either \( Q_{\text{cor}} = 0 \) (non-corroded bars) or ratio of penetration \( r_s = 1/0 \) (uniform residual section), the coefficient \( m \) is always equal to 1.0. Otherwise, it is less than 1.0 and decreases with the corrosion percentage as well as the ratio of penetration.

The coefficient \( \eta \) describes the distribution of different residual sections along the bar length. It is clear that both the sectional coefficient \( m \) and the length of the corroded section are affected by \( \eta \). For a uniform distribution, \( \eta = 0 \), the corroded section is distributed uniformly. For a non-uniform distribution, \( \eta = 1 \). Thus, for \( \eta = 1 \), the corroded section is distributed at the end of the bar, whereas for \( \eta = 0 \), the section is distributed at the beginning of the bar.

Analysis of ductility of corroded reinforcement

As discussed previously, corrosion reduces the ductility of reinforcement, in terms of ultimate strain, ductile area and elongation, much more than strength. The reason is that the reduction of bar strength is caused by a decrease of bar section with local penetration and is dominated by the minimum cross-sectional area of the reinforcement. The reduction of bar ductility, however, is a function of the non-uniform distribution of residual sections along the bar length, as discussed below.

\[ F = \begin{cases} A_s & \text{for} \ 0 \leq x \leq x_{\text{max}}/2 \\ mA_s & \text{for} \ x_{\text{max}}/2 \leq x \leq x_{\text{max}} \\ (2-m)A_s & \text{for} \ x_{\text{max}} \leq x \leq L \\ A_{\text{bar}} & \text{for} \ x = 0 \\ \end{cases} \]

Fig. 11. Analytical model for ductility of corroded concrete. (a) Analytical model; (b) stress–strain curve

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coefficient $\eta$ are constants ($\approx 1.0$) for a given corrosion condition and degree of corrosion.

Furthermore, since corrosion does not change substantially the shape of the stress–strain curve of reinforcement, it is assumed that corroded reinforcement has a similar curve to that of non-corroded bars and has a definite yield plateau, as shown in Fig. 11(b). On the basis of the experimental results given in Table 1, the hardening, ultimate and rupture strains of plain bars are assumed to be 18, 139 and 166 times their yield strain, respectively; those of ribbed bars are assumed to be 7, 41 and 65 times the yield value. Assuming that the hardening strain curve is a parabolic curve, the strain of reinforcement after hardening can be determined by equation (16)

$$\varepsilon = \varepsilon_h + (\varepsilon_u - \varepsilon_h)(\frac{\sigma}{f_y} - 1) \frac{f_u}{f_y}$$

Figure 11(a) shows that, when portion I with an average section yields, portions II and III with minimum and maximum sections must be in stages of strain-hardening and linear elasticity, respectively. In other words, for a particular tensile force, different residual sections have different tensile stresses and strains. Four possible cases of bar rupture are discussed below with the detailed derivations given in the Appendix Table. In each case the bar ruptures within portion II, which has the minimum section, but the states of portions III and I depend on the critical values $1/(f_u/f_y)$ and $2/(1 - f_u/f_y)$ of sectional coefficient $m$. By averaging the test data for non-corroded reinforcement in Table 1, the critical values of $1/(f_u/f_y)$ are 0.72 and 0.83 for tested plain and ribbed bars, respectively. Those of $2/(1 - f_u/f_y)$ are 0.84 and 0.91, respectively.

### Case 1. $m \approx 1/(f_u/f_y)$

Portion I would have just yielded and portion III would still be linear elastic. The total strain can be determined from equations (17) and (18) for plain and ribbed bars, respectively.

$$\varepsilon_u = (0.007 + 0.5\eta)\varepsilon_{a0}$$  \hspace{1cm} (17)

$$\varepsilon_u = (0.024 + 0.5\eta)\varepsilon_{a0}$$  \hspace{1cm} (18)

### Case 2. $m \approx 2/(1 - f_u/f_y)$

Portion I would have strain-hardened and portion III would have just yielded. The total strain can be determined from equations (19) and (20) for plain and ribbed bars, respectively.

$$\varepsilon_u = (0.69 - 0.19\eta)\varepsilon_{a0}$$  \hspace{1cm} (19)

$$\varepsilon_u = (0.73 - 0.21\eta)\varepsilon_{a0}$$  \hspace{1cm} (20)

### Case 3. $m > 2/(1 - f_u/f_y)$

Portion I would have strain hardened and portion III would have just strain hardened. The total strain can be determined from equations (21) and (22) for plain and ribbed bars, respectively.

$$\varepsilon_u = (0.70 - 0.13\eta)\varepsilon_{a0}$$  \hspace{1cm} (21)

$$\varepsilon_u = (0.74 - 0.15\eta)\varepsilon_{a0}$$  \hspace{1cm} (22)

### Case 4. $m \approx 1.0$

Rupture would occur within either portion I or II, when portion III had sufficiently strain hardened. The total strain can be determined from equation (23) for both plain and ribbed bars.

$$\varepsilon_u = (1.0 - 0.12\eta)\varepsilon_{a0}$$  \hspace{1cm} (23)

Equations (15) to (23) indicate that, in addition to the negative influence of the length coefficient $\eta$, a decrease of sectional coefficient $m$ from about 1.0 in Case 4 to 0.72 or 0.84 in Case 1 causes a significant reduction of ultimate strain. As shown in equation (15), the reduction of sectional coefficient $m$ actually is a combined function of increases both of penetration ratio $r$ and corrosion percentage $Q_{cor}$. Equation (15) indicates that, for an assumed penetration ratio $r = 5$, an increase of corrosion from 0 to 10% causes a decrease of sectional coefficient $m$ from 1.0 to 0.93. As a result, for a length coefficient $\eta = 0.5$, the ultimate strains of plain and ribbed bars would theoretically reduce from $\varepsilon_u = 0.94\varepsilon_{a0}$ by using equation (23) to $\varepsilon_u = 0.64\varepsilon_{a0}$ and $\varepsilon_u = 0.67\varepsilon_{a0}$ by equations (21) and (22), respectively.

It is apparent that the substantial reduction of ductility of corroded reinforcement, in terms of ultimate strain, ductile area and elongation, could be the result of small extensions occurring over some lengths of a bar when the smallest residual section ruptures.

The above conclusion is supported by the experimental results of the three plain bars that were mechanically machined to 6.40 mm from their initial diameter of 7.34 mm to simulate a 24% removal of metal from the bar surface by corrosion.
produce different experimental results. If a sensor were attached to portion II, where the residual section is the smallest, a complete force–extension curve with definite yield plateau would be obtained. However, if the sensor were located at portion III, where the residual section is largest, an incomplete force–extension curve without a yield plateau might be obtained, since the bar's yield and rupture would be concentrated within portion II.

Hence, when discussing the characteristics of the stress–strain curve and ultimate strain of corroded bars, it is essential to know the specific testing techniques and details, and care must be taken when interpreting the results from a few test data.

The greater reduction of ductility of bars embedded in concrete, compared with those of bare bars, arises from different corrosion conditions around the bars. As shown in Fig. 2, compared with uniform sodium chloride solution around a single bare bar, the cover concrete surrounding a bar is much less uniform as an electrolyte, because of its non-uniformly distributed material components and pores. As a result, more irregular residual sections are induced along the length of a bar embedded in concrete. Hence, ductility of reinforcements embedded in concrete, in terms of ultimate strain, ductile area and elongation, decrease at a much greater rate than those of bare bars.

Comparison with other researchers

A comparison of the authors' results with those of other researchers is made in Table 3 in terms of residual ductility of reinforcing bars. The authors' data and those of Andrade et al.5, 6, Lee et al.7, Morinaga8, Palsson et al.9, and Zhang et al.10 have been reported. The authors' data are consistent with those of other researchers, except for the strength ratio data of Zhang et al.10, which indicate a 27% decrease in strength ratio for 66% corrosion whereas the data of the authors, Maslehuddin et al.5, Andrade et al.6, Lee et al.7, Morinaga8, and Palsson et al.9, for 66% corrosion indicate a 54% decrease in strength ratio.

The authors' elongation data are also consistent with those of other researchers, except for the strength ratio data of Zhang et al.10, which indicate a 27% decrease in strength ratio for 66% corrosion whereas the data of the authors, Maslehuddin et al.5, Andrade et al.6, Lee et al.7, and Palsson et al.9, for 66% corrosion indicate a 54% decrease in strength ratio.

Table 3. Comparison of authors' results with those of other researchers

<table>
<thead>
<tr>
<th>Researcher</th>
<th>Authors</th>
<th>Bar type</th>
<th>Corrosion condition</th>
<th>Corrosion amount (%)</th>
<th>Elongation $\alpha_\varepsilon$</th>
<th>Strength ratio $\alpha_u$</th>
<th>Elastic modulus $\alpha_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare bars</td>
<td>Maslehuddin et al.5</td>
<td>Plain (8, 16)</td>
<td>Accelerated 0.5–2.0 mA/cm²</td>
<td>0–25%</td>
<td>0.029</td>
<td>No significant change</td>
<td>0.0099</td>
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<td></td>
<td></td>
<td>Ribbed (8, 16, 32)</td>
<td>Marine exposure 10 mA/cm²</td>
<td>0–0.5%</td>
<td>0.024</td>
<td>No significant change</td>
<td>0.0108</td>
</tr>
<tr>
<td>Bars in concrete</td>
<td>Andrade et al.6</td>
<td>Plain (8–32)</td>
<td>Accelerated 10 mA/cm²</td>
<td>0–11%</td>
<td>0.0166</td>
<td>No significant change</td>
<td>Not stated</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ribbed (8–32)</td>
<td>Service chloride 13.0 mA/cm²</td>
<td>0–25%</td>
<td>0.0603</td>
<td>Not stated</td>
<td>0.0123</td>
</tr>
<tr>
<td>Bare bars</td>
<td>Lee et al.7</td>
<td>Plain (8–32)</td>
<td>Service chloride</td>
<td>0–0.5%</td>
<td>0.018</td>
<td>Reduced from 1.50 to 1.10</td>
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<tr>
<td></td>
<td></td>
<td>Ribbed (12)</td>
<td>Service Carbonation</td>
<td>0–11%</td>
<td>0.0137</td>
<td>Not stated</td>
<td>Not stated</td>
</tr>
<tr>
<td>Bars in concrete</td>
<td>Morinaga8</td>
<td>Not stated</td>
<td>Service chloride</td>
<td>0–&gt;30%</td>
<td>0.0123</td>
<td>Not stated</td>
<td>Not stated</td>
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<tr>
<td>Bars in concrete</td>
<td>Palsson et al.9</td>
<td>Plain</td>
<td>Service chloride</td>
<td>0–67%</td>
<td>0.0123</td>
<td>Not stated</td>
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<tr>
<td></td>
<td></td>
<td>Ribbed (10)</td>
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<td>0.0137</td>
<td>Not stated</td>
<td>Not stated</td>
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<tr>
<td>Bars in concrete</td>
<td>Zhang et al.10</td>
<td>Not stated</td>
<td>Service Carbonation</td>
<td>0–67%</td>
<td>0.0123</td>
<td>Not stated</td>
<td>Not stated</td>
</tr>
</tbody>
</table>
Conclusions

(a) The strength ratio, hardening strain and elastic modulus of reinforcement are not significantly affected by corrosion and consequently the corresponding values for non-corroded bars can be adopted in practice.

(b) Corrosion creates a non-uniform distribution of cross-sections along the length of a bar. As result ultimate strain, ductile area and elongation are reduced significantly by corrosion. The reductions in these various measurements of ductility are greater than those of yield and ultimate strength which have been reported previously by the authors.4

(c) The ductility of bars corroded whilst embedded in concrete decreases more significantly than that of bare bars.

(d) Only an average value of about 10% of non-uniform corrosion is sufficient to reduce the ductility of bars embedded in concrete to below the minimum requirement specified in CEB Mode Code 90 for class S reinforcement for use in high ductility situations.

(e) Although the measured reductions in ultimate strain, ductile area and elongation of smaller diameter plain bars were generally greater than those of larger diameter ribbed bars, the observed differences were not significant at the 5% significance level. Hence, the reduction of ductility of corroded reinforcement is primarily a function of the amount of corrosion, rather than the bar type and diameter.

(f) When using laboratory test data or field data obtained from another structure to assist with the prediction of the response of a corroded structure, it is essential that the assessing engineer should have a clear understanding of the corrosion mechanism and environment of the structure under consideration, and of the conditions pertaining to the laboratory and/or field data being used to inform the assessment. However, in this context it is useful to note that the data obtained in the current investigation lie towards the higher end of the range of available laboratory and field data. Hence, it would be conservative to apply them in practice.

Acknowledgements

The senior author would like to express his thanks to the Committee of Vice-Chancellors and Principals of the United Kingdom (CVCP) for the award of an Overseas Research Scholarship, and the British Cement Association and the University of Birmingham for their financial support for the project.

References


9. Palssom R. and Mirza M. S. Mechanical response of corroded bars and one would expect more uniform corrosion under such conditions. However, there is considerable variation in the coefficients for the other sets of data. The coefficients for the authors’ accelerated data are significantly greater than those of the accelerated data of Andrade et al.6 at a comparable corrosion rate, and are within the range of the data from bars in service chloride environments of Morinaga6 and Palssom et al.9. Hence, it appears that the effect of corrosion on ductility is highly dependent on the actual corrosion conditions. As a consequence, when using laboratory test data or field data obtained from another structure to assist with the prediction of the response of a corroded structure, it is essential that the assessing engineer should have a clear understanding of the corrosion mechanism and environment of the structure under consideration, and of the conditions pertaining to the laboratory and/or field data being used to inform the assessment. However, in this context it is useful to note that the data obtained in the current investigation lie towards the higher end of the range of available laboratory and field data. Hence, it would be conservative to apply them in practice.
appendix table. analysis of elongation strain of corroded reinforcements

<table>
<thead>
<tr>
<th>Case</th>
<th>Force (N)</th>
<th>Mean yield and local rupture</th>
<th>Whole yield and local rupture</th>
<th>Elongation ΔL(mm)</th>
<th>Overall strain</th>
<th>Appendix Table. Analysis of elongation strain of corroded reinforcements</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>F = F_y</td>
<td>F_y = f_y</td>
<td>2(−m)F_y = f_u</td>
<td>(1−η)L</td>
<td>ε_u = (1−69%) for plain bars; ε_u = (1+20%) for ribbed bars</td>
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<td></td>
<td>A_a</td>
<td>A_a &lt; f_y</td>
<td>2(−m)A_a = f_u</td>
<td>(2−m)A_a</td>
<td>(0.007 + 0.5%)ε_u for plain bars; (0.024 + 0.48%)ε_u for ribbed bars</td>
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<tr>
<td></td>
<td>F</td>
<td>F = F_y</td>
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<td>(2−m)A_a</td>
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<td>F_y = f_y</td>
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<tr>
<td></td>
<td>(1−η)L</td>
<td>(2−m)L</td>
<td>(2−m)L</td>
<td>(2−m)L</td>
<td>(2−m)L</td>
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<tr>
<td>3</td>
<td>F = mF_u</td>
<td>mF_u &gt; f_y but &lt; f_u</td>
<td>(30.2/968)ε_u</td>
<td>(1−η)L</td>
<td>ε_u = (7/18)ε_u for plain bars; ε_u = (7/18)ε_u for ribbed bars</td>
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<tr>
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<td>A_a</td>
<td>A_a &lt; f_y</td>
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<tr>
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<td>F</td>
<td>F = mF_u</td>
<td>(30.2/968)ε_u</td>
<td>(1−η)L</td>
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<tr>
<td>4</td>
<td>F = F_u</td>
<td>F_u = f_y</td>
<td>(2−m)A_a &gt; f_y</td>
<td>(1−75%)L</td>
<td>ε_u = (31/104)ε_u for plain bars; ε_u = (31/104)ε_u for ribbed bars</td>
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<tr>
<td>5</td>
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<td>(1−75%)L</td>
<td>ε_u = (31/104)ε_u for plain bars; ε_u = (31/104)ε_u for ribbed bars</td>
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<td>A_a &lt; f_y</td>
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<td>(1−75%)L</td>
<td>ε_u = (31/104)ε_u for plain bars; ε_u = (31/104)ε_u for ribbed bars</td>
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<td></td>
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Effect of corrosion on ductility of reinforcing bars


Discussion contributions on this paper should reach the editor by 1 March 2006

Magazine of Concrete Research, 2005, 57, No. 7 419


12. Creanza G. and Russo S. A. New proposal for defining the