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Residual capacity of corroded reinforcing bars

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This paper presents an experimental investigation into the residual capacity of corroded reinforcing bars. By performing both accelerated and simulated corrosion tests on bare bars and on bars embedded in concrete, the mechanism of the reduction of the capacity of corroded reinforcement was investigated. The influence of type and diameter of reinforcement on its residual capacity is discussed. The experimental results show that, due to local attack penetration, the residual cross-section of a corroded bar is no longer round and varies considerably along its circumference and its length. Although the force–extension curves of corroded bars are similar to those of non-corroded bars for up to 16% corrosion, their residual yield and ultimate forces decrease more rapidly than their average cross-sectional area and, therefore, their residual strength decreases significantly. Even though the residual capacity of corroded small diameter and/or plain bars reduces more than that of large diameter or ribbed ones, differences are not significant and can be neglected. Finally, a simple equation is proposed to predict the residual capacity of corroded reinforcing bars in practice.

Notation

A_{corr}	actual minimum cross-sectional area of corroded reinforcement
A_s	average cross-sectional area of corroded reinforcement
A_{s0}	initial cross-sectional area of non-corroded reinforcement
d	diameter of non-corroded reinforcement
d_s	diameter of corroded reinforcement
F	force of corroded reinforcement
F_0	force of non-corroded reinforcement
F_y	yield force of corroded reinforcement
F_{y0}	yield force of non-corroded reinforcement
F_u	ultimate force of corroded reinforcement
F_{u0}	ultimate force of non-corroded reinforcement
f	strength of corroded reinforcement
f_0	strength of non-corroded reinforcement
f_y	yield strength of corroded reinforcement
f_{y0}	yield strength of non-corroded reinforcement
f_u	ultimate strength of corroded reinforcements
f_{u0}	ultimate strength of non-corroded reinforcement
Q_{corr}	amount of corrosion of reinforcement (%) in terms of weight loss
W_0	weight of reinforcement prior to its corrosion (g)
W_1	weight of corroded reinforcement after it was cleaned in acid solution (g)
W_{n0}	weight of a non-corroded reinforcement before it was cleaned in acid solution (g)
W_{n1}	weight of non-corroded reinforcement after it was cleaned in acid solution (g)
x_{max}	maximum local attack penetration of corroded reinforcement
x_s	average attack penetration of corroded reinforcement
α	force factor
β	strength factor
κ	ratio of maximum penetration to average penetration
Δw	weight of water displaced from a glass tube by corroded reinforcement
Δl	length of each portion of reinforcement immersed into water

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Introduction

Reinforcement corrosion is a principal cause of the deterioration of reinforced concrete structures. Due to the carbonation of concrete cover and/or intrusion of chloride ions, the protective passive layer around the

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reinforcement surface is destroyed and consequently the corrosion of reinforcement can initiate. When corrosion of reinforcement develops significantly, it not only affects structural serviceability by cracking, or even spalling the concrete cover, but can also impact on structural safety by decreasing the load-bearing capacity of reinforced concrete members, which is of great concern to both owners and users of the actual structures.

The corrosion of reinforcement in concrete is an electrochemical process that involves both chemical reaction and current flow with anode and cathode occurring simultaneously on the reinforcement surface.[1,2] At anodic sites, the iron is first dissolved into positive ferrous ions and negative free electrons: $Fe \rightarrow Fe^{2+} + 2e^-$. At cathodic sites, the free electrons from anodes react with water and oxygen in concrete pores to produce hydroxyl ions: $2e^- + H_2O + \frac{1}{2}O_2 \rightarrow 2OH^-$. During diffusion through the pore solution, the ferrous ions Fe^{2+} from anodes react with the hydroxyl ions $(OH)^-$ from cathodes to produce a ferrous hydroxide: $Fe^{2+} + 2(OH)^- \rightarrow Fe(OH)_2$. A series of subsequent oxidisation reactions converts the ferrous hydroxide into hydrated ferric oxide (i.e. rust). It is clear that, since the corrosion of reinforcement starts with the removal of the iron from its surface and transforms the iron into rust, it must affect the residual capacity of corroded reinforcement.

There is a large amount of literature on the corrosion of reinforcement in concrete. However, the majority of publications focus on the mechanism of corrosion, and its prevention, rather than its effects on the mechanical properties of reinforcement and on structural performance. Only a very small number of studies have been devoted to the residual capacity of corroded reinforcement.[3–9] In all reported experimental investigations, either single bare bars[3,4] or bars embedded in concrete[5–9] were adopted as test specimens. They were subjected to conditioning corrosion by outdoor atmospheric exposure,[3] indoor electro-chemical acceleration[4–6] or were removed from actual structures which had corroded due to chloride intrusion[7,8] or concrete carbonation.[9] On the basis of experimental results from tension tests, Maslehuddin *et al*.[3] reported that up to 1·1% corrosion in air hardly changed bar strength. By using the measured smallest sectional area of corroded bars, Palssom and Mirza[8] also reported that the average nominal yield and ultimate stresses of reinforcement with less than 10% loss of cross-sectional area were similar to those with more than 30% sectional loss, and that even a slight increase in the yield strength was noted in pitted specimens.

In contrast to Maslehuddin *et al*. and Palssom and Mirza, Andrade *et al*.[4] argued that corrosion decreased bar strength significantly. By using the average cross-sectional area determined by the measured weight loss, it was noted that 10% corrosion decreased the yield and ultimate strengths by 4·5 and 3·3%, respectively. Although the conclusions of Andrade *et al*. were obtained from single bare bars, they were still well supported by the experimental results of Lee *et al*.,[5] Saifullah,[6] Morinaga[7] and Zhang *et al*.,[9] whose test specimens were corroded reinforcement embedded in concrete.

There is no doubt that all of the above results are very useful. However, some important data are still lacking, and, in addition, different researchers reported contradictory results. A particular area in which there is still a lack of data is the influence of bar type and diameter on residual capacity of corroded reinforcement.

This paper presents the results of an experimental investigation into the residual capacity of corroded reinforcement of different types and different diameters, in addition to the identification of the source and mechanism of such a reduction of capacity.

Experimental programme

The variables investigated were specimen type, reinforcement type, reinforcement diameter, and corrosion times with expected amount of corrosion of 5, 10, 15 and 20%, as summarised in Table 1. Three nominally identical specimens were made for each combination of variables. The techniques of both accelerated and simulated corrosion were employed.

Test specimens

A total of 108 reinforcement specimens with the same length of 450 mm were manufactured, as shown in Fig. 1. They consisted of 87 corroded and 21 non-corroded control specimens. There were 78 single bare bars and 30 bars embedded in concrete. For the latter bars, in order to avoid crevice corrosion and to prevent the bare reinforcement outside the concrete from corroding, a primer coating and an epoxy coating were used to cover the cleaned surface of the bare reinforcement and the end surface of the concrete cylinder shown in Fig. 1.

The concrete mix had a water to cement (w/c) ratio of 0·65 and a fine to coarse aggregate ratio of 1·6. The Ordinary Portland Cement content was 270 kg/m^3 and 10 mm maximum size gravel was used. In addition, 4% calcium chloride by mass of cement was added to improve the electrical conductivity of the concrete. The average concrete cube strength was 46·4 N/mm^2 when the reinforcement commenced corrosion. It is acknowledged that concrete with a w/c ratio of 0·65 should not be used in a chloride environment or where corrosion is like to occur. It was used in the experiments to accelerate corrosion damage. In real engineering practice, a dense concrete with a smaller w/c ratio is commonly employed, which may delay the initiation of corrosion and possibly induce more uniform corrosion on the reinforcement surface, provided that such concrete is well placed and compacted. Hence, the test

Table 1. Experimental programme

Specimen type	Reinforcement type	Bar diameter: mm	Current intensity: mA/cm^2	Specimen number	Corrosion period: days	Corrosion methodology
Single bare bars	Plain bar	8	NA	R08MC	NA	Simulated
			0·5	R0807	7	Accelerated
				R0814	14	
				R0821	21	
				R0828	28	
		16	1·0	R1607	7	
				R1614	14	
				R1621	21	
				R1628	28	
	Ribbed bar	8	0·5	T0807	7	
				T0814	14	
				T0821	21	
				T0828	28	
		16	1·0	T1607	7	
				T1614	14	
				T1621	21	
				T1628	28	
		32	2·0	T3207	7	
				T3214	14	
				T3221	21	
				T3228	28	
Bars embedded in concrete	Plain bar	16	1·0	RC1607	7	
				RC1614	14	
				RC1621	21	
				RC1628	28	
	Ribbed bar	16	1·0	TC1607	7	
				TC1614	14	
				TC1621	21	
				TC1628	28	

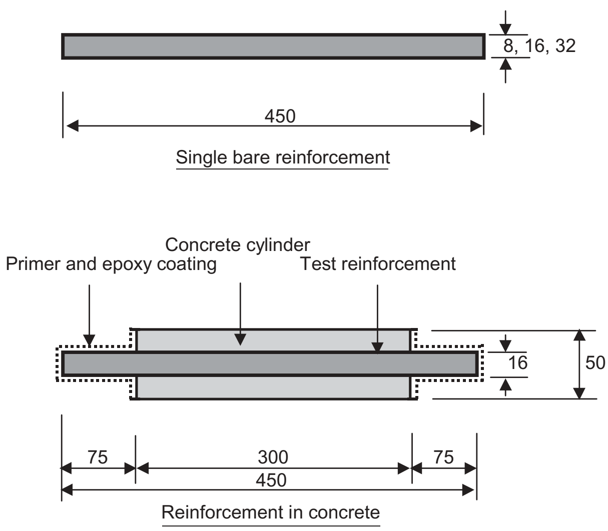

Fig. 1. Specimen of test reinforcements

conditions were more onerous than those that should be present under actual field conditions.

Corrosion methodology

There are three types of techniques that can be used to corrode reinforcement, namely, natural corrosion, accelerated corrosion and simulated corrosion. The natural corrosion technique exposes a specimen to marine or aggressive environments to activate corrosion of reinforcement[1] or uses corroded reinforcement taken from existing deteriorated structures as test specimens.[7–9] The main features of natural corrosion tests are that the reinforcement corrodes naturally with a relatively low corrosion rate, and the test results represent the actual corrosion-induced properties in real structures. However, natural corrosion may take many years for corrosion to have any significant influence on its mechanical properties, and actual corroded structures are not always available for the removal of reinforcement specimens. Hence, an electrochemical technique was adopted to accelerate the corrosion process of reinforcement in order to achieve a significant amount of corrosion of reinforcement within a reasonable time.

As shown in Fig. 2, a direct current from the positive terminal of a potentiostat was impressed onto the reinforcement. The current flowed to a surrounding stainless steel tube either through 3·5% sodium chloride solution (for single bare bars) or concrete saturated with sodium chloride solution (for reinforcement in concrete), and eventually reached the negative terminal of the potentiostat. In the resulting circuit, the test reinforcement and stainless steel tube acted as an anode

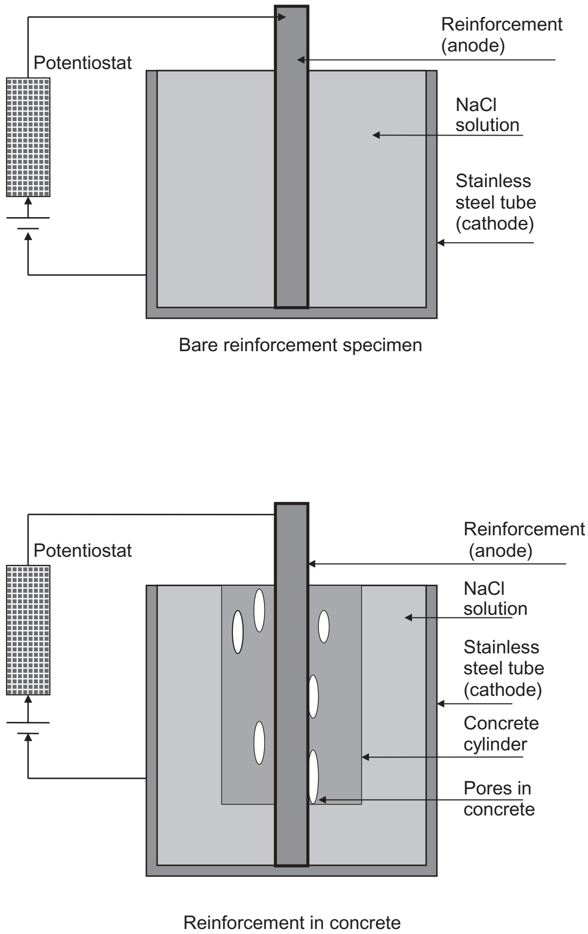

Fig. 2. Corrosion arrangement of reinforcement specimen

and external cathode, respectively, while the saturated concrete and sodium chloride solution behaved as the electrolyte. The test bars were positioned at the centre of the stainless steel tube. Corrosion currents of 0·5, 1·0 and 2·0 mA/cm^2 were impressed onto the 8, 16 and 32 mm diameter reinforcements, respectively.

In addition, in order to identify the mechanism of variation of residual capacity of corroded bars, three reinforcement specimens were machined mechanically to simulate the removal of iron from the reinforcement surface by corrosion attack penetration.

Measurement of amount of corrosion of reinforcement

On basis of the assumption that weight loss of corroded reinforcements took place only within the length covered by sodium chloride solution, the amount of corrosion was measured by weight loss and determined by equation (1)

$$Q_{\text{corr}} = \frac{W_0 - W_1 + (W_{n0} - W_{n1})}{W_0} \times 100\% \qquad (1)$$

where Q_{corr} is the amount of corrosion of reinforcement (%), W_0 is the weight of reinforcement prior to its corrosion, W_1 is the weight of the same reinforcement after it was corroded and cleaned in acid solution, W_{n0} is the weight of the non-corroded reinforcement before it was cleaned in acid solution, and W_{n1} is the weight of the same non-corroded reinforcement after it was cleaned in acid solution

Measurement of residual section of corroded of reinforcement

Assuming that the volume of water displaced from a glass tube was equal to the volume of bar immersed in the water in the tube,[9] the residual section of corroded reinforcement was measured by water volume and determined by equation (2)

$$d_s = \sqrt{\frac{4(\Delta w)}{\pi \gamma_w (\Delta l)}} \qquad (2)$$

where d_s is the average residual diameter of each portion of corroded reinforcement (mm), Δl is the length of each 10 mm portion of reinforcement incrementally immersed into water, $\gamma_w = 0{\cdot}001 \text{g/mm}^3$ is the density of tap water, and Δw is the weight of water displaced from a glass tube by corroded reinforcement as measured by the apparatus shown in Fig. 3. The apparatus consisted of a scale with a precision of 1·0 mm, a balance with a precision of 0·01 g, a glass tube with a

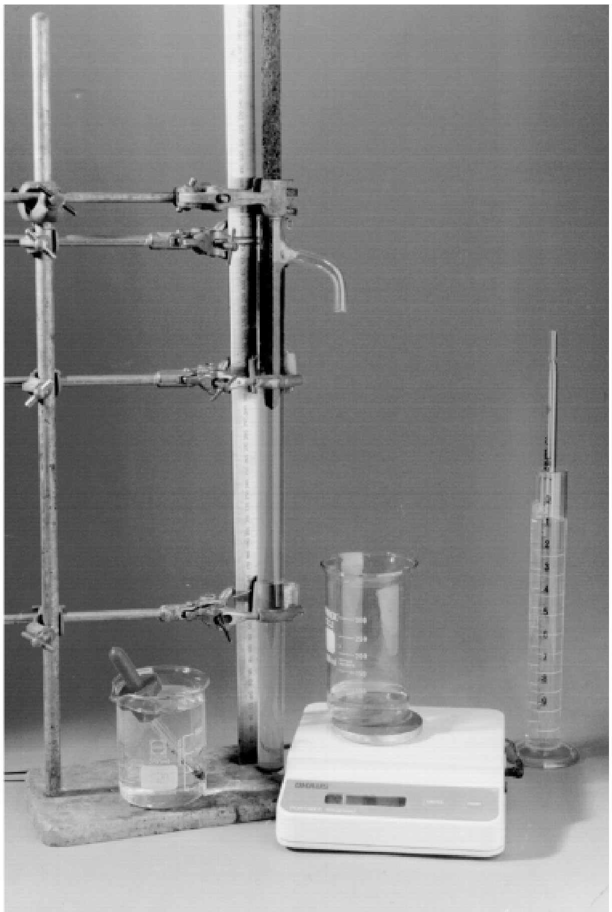

Fig. 3. Apparatus for measuring residual section of corroded reinforcements

hole at its top, a steel frame and a glass beaker. By moving the reinforcement specimen downwards inside the glass tube and recording the reading on the balance of the weight of the displaced water in the beaker, the residual section of corroded reinforcement was estimated.

Uniaxial tension tests of reinforcement

Uniaxial tension tests of the reinforcement specimens were performed on a Denision Testing Machine, which was equipped with a data-processing computer, an electrical extensometer and a linear variable displacement transducer (LVDT). The computer was programmed to control the test under displacement and to record the applied load and reinforcement elongation. The electrical extensometer with a maximum stroke of 0·3 mm over its 50 mm gauge length was used to measure the linear elongation of reinforcement to determine its elasticity, prior to the yielding of the reinforcement. The LVDT with a maximum stroke of 35 mm over its 43 mm gauge length was then employed to record the elongation of the reinforcement until its fracture. In addition, two marks with initial distance of 200 mm were made on the reinforcement surface. After reinforcement fracture, the extension between these two marks was measured and was taken as the reinforcement elongation.

Results and analysis

External surface and residual section of corroded reinforcement

Taking 8 mm diameter plain and ribbed reinforcements R08 and T08 as typical examples, the external surface and residual section of corroded reinforcement are shown in Figs 4 and 5, respectively. In these and subsequent figures the last two digits in the bar notation refer to the corrosion time in days. Hence R0821 is a plain (R), 8 mm diameter (08) bar corroded for 21 days (21).

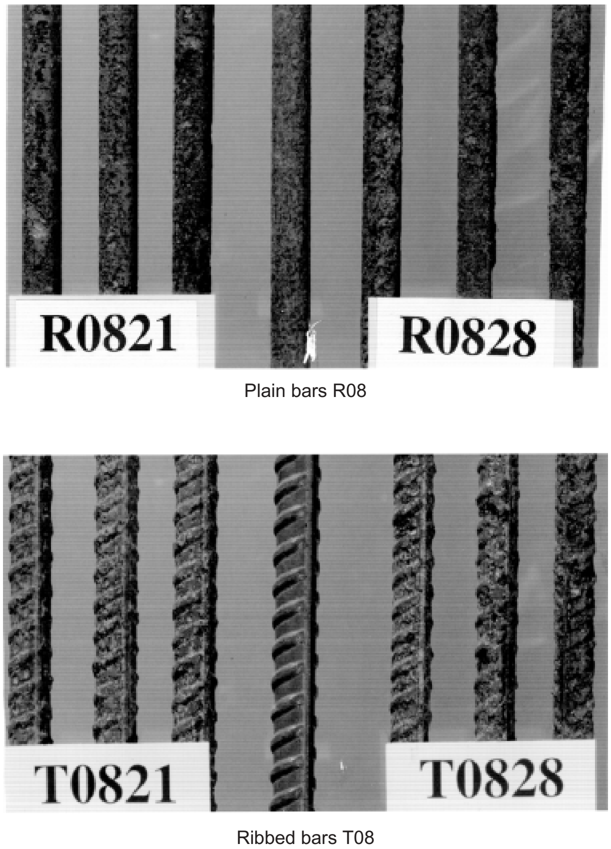

Fig. 4. The external surface of corroded reinforcements

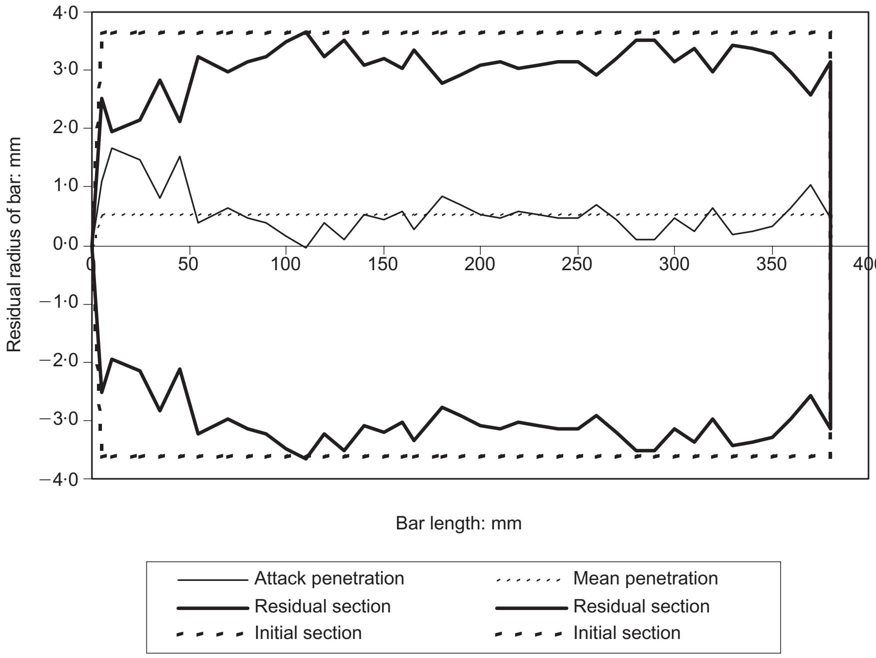

Fig. 5. Residual section of corroded plain bar R0828

Figure 4 indicates that, compared with the non-corroded reinforcement located in the middle of each photograph, the external surface of the corroded reinforcement has been altered. With an increase of corrosion time from 21days to 28 days, the corrosion pits on the reinforcement surface: increased in number; expanded in size; joined up with each other; and finally formed general corrosion. It is clear that corrosion of the reinforcement not only reduced its cross-section irregularly, but also altered the rib shape on a ribbed bar surface. Furthermore, since the actual corrosion penetration of reinforcement varied considerably over its surface as well as around its circumference, an approximately round cross-section of reinforcement prior to corrosion was changed into a section with a very irregular shape after corrosion.

Figure 5 shows that, due to the differential removal of iron from the reinforcement surface, the actual residual section of corroded reinforcement measured by the water volume method varied greatly and irregularly along its length. This agrees with the observation of the surface appearance of corroded reinforcement, as shown in Fig. 4. The so called 'corrosion amount' by the weight loss method only represents an average reduction of the cross-sectional area of reinforcement, which underestimates the reduction of some cross-sections. Hence, it is unreasonable and unsafe to evaluate the residual capacity of corroded reinforcement only by considering a reduction of its average cross-section, as determined by the method of weight loss.

Force–extension curve of corroded reinforcement

Taking 16 mm dia. plain reinforcement as a typical example for all reinforcements, the force–extension curves of corroded reinforcement are shown in Fig. 6.

It is clear that, for up to 16% corrosion, the shape of the force–extension curve of reinforcement does not change substantially. The force–extension curves of all corroded reinforcements, which had an obvious yield plateau before corrosion, still exhibited large plastic strains.

It is emphasised that, as far as the stress–strain curve of corroded reinforcement is concerned, different researchers have reported contradictory results. The results of Andrade *et al*.[4] and Palssom and Mirza[8] show that corrosion hardly alters the shape of the load–elongation curves of test reinforcement. However, Zhang *et al*.[9] reported that up to 21% corrosion shortened and even caused the disappearance of the yield plateaux on the load–elongation curves of corroded reinforcement.

It is the authors' view that the above contradictions result mainly from different experimental techniques. Andrade *et al*. and Palssom and Mirza used an electrical extensometer to record the load–elongation curve, whereas Zhang *et al*. utilised a tensile machine. The elongation measured by Andrade *et al*. and Palssom and Mirza using extensometers with a gauge length of 25 to 60 mm was a local tensile deformation, which represents the local yielding elongation of corroded reinforcement. However, the elongation measured by Zhang *et al*. using their testing machine was total tensile deformation along the reinforcement over a length of about 200 to 400 mm. Local yielding elongation may be too small relatively to significantly affect the total elongation.

Residual capacity of corroded reinforcement

As mentioned previously, three nominally identical specimens were made for each combination of variables. The experimental results of all specimens were plotted against the percentage amount of corrosion.

In the following discussion, strength refers to bar resistance expressed as a stress. The test data were first considered as a single population and then the effects of individual variables were considered. In terms of yield and ultimate forces/strengths, the residual capacity of corroded reinforcement is shown in Figs 7 to 10. The ratios of F_y/F_{y0}, f_y/f_{y0}, F_u/F_{u0}, f_u/f_{u0} and A_s/A_{s0} of the yield force F_y, yield strength f_y, ultimate force F_u, ultimate strength f_u and cross-sectional area A_s of corroded bars to those of non-corroded ones with the additional subscript 0 are shown in Figs 7 and 8 for bare bars, and in Figs 9 and 10 for bars embedded in concrete. The yield and ultimate strengths of corroded

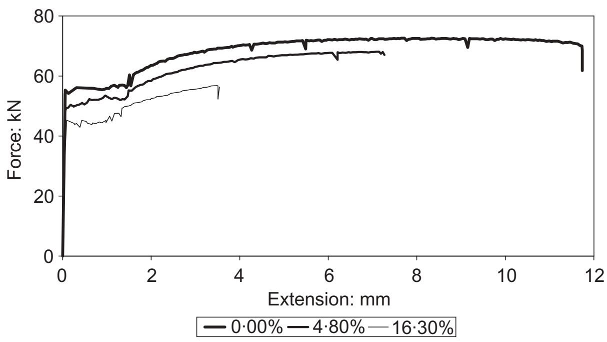

Fig. 6. Force–extension curve of corroded bars

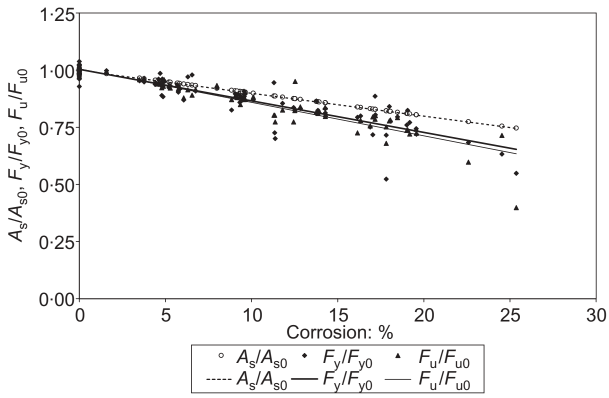

Fig. 7. Residual forces of corroded bare bars

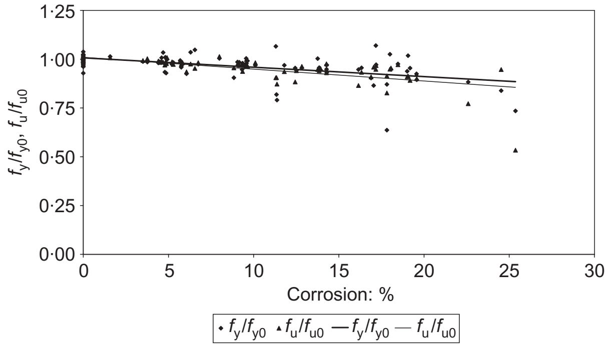

Fig. 8. Residual strength of corroded bare reinforcements

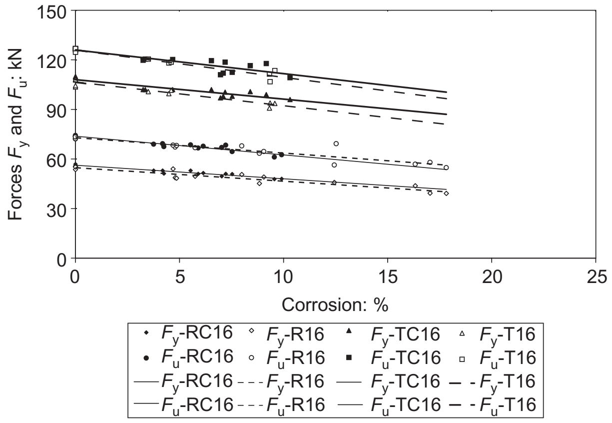

Fig. 9. Residual forces of corroded bars in concrete

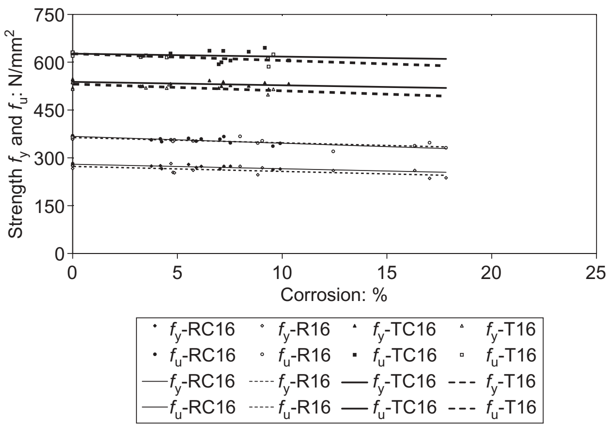

Fig. 10. Residual strength of corroded bars in concrete

and non-corroded reinforcements were determined by dividing the reinforcement forces by their average corroded or initial cross-sectional area, respectively, as shown in equations (3) to (5)

$$f_y = F_y/A_s \quad f_u = F_u/A_s \tag{3}$$

$$f_{y0} = F_{y0}/A_{s0} \quad f_{u0} = F_{u0}/A_{s0} \tag{4}$$

$$A_s = A_{s0}(1{\cdot}0 - 0{\cdot}01Q_{corr}) \tag{5}$$

where A_s is the average cross-sectional area of corroded reinforcement, A_{s0} is the initial cross-sectional area of non-corroded reinforcement, and Q_{corr} is the amount of corrosion of reinforcement (%).

Figure 7 indicates that, with an increase of corrosion amount, the yield and ultimate forces of bare reinforcement decrease more rapidly than does its average cross-sectional area. On the basis of a linear statistical regression, 10% corrosion reduces yield and ultimate forces of bare bars by about 14 and 15%, respectively. It is clear that, in addition to the expected reduction caused by a decrease of the average cross-sectional area, an extra reduction of the residual capacity of corroded bare reinforcement was caused by the local attack penetration on the reinforcement surface and stress concentration at these pitting points. As a result, the yield and ultimate strengths of bare reinforcement also decrease with corrosion, as shown in Fig. 8. Ten percent corrosion reduced them by 5 and 6%, respectively. Hence, the residual capacity of corroded bare reinforcement decreases significantly.

Figures 7 and 8 also show that, due to corrosion, the reductions of yield force and strength of corroded bare reinforcement are similar to those of ultimate force and strength, respectively. As examined by significance tests,[10] at the 5% significance level, the reductions of yield force and strength are statistically equal to those of ultimate force and strength. Hence, the further regression analyses performed on both sets of test data suggested that the residual capacity of corroded bare reinforcement could be determined by equations (6) and (7)

$$F = (1{\cdot}0 - 0{\cdot}014Q_{corr})F_0 \tag{6}$$

$$f = (1{\cdot}0 - 0{\cdot}005Q_{corr})f_0 \tag{7}$$

where F and F_0 are yield or ultimate forces of corroded and non-corroded reinforcement, respectively. f and f_0 are yield or ultimate strengths of corroded and non-corroded reinforcement, respectively.

Figures 9 and 10 show that the residual capacity of corroded reinforcement embedded in concrete also decreased with an increase of the amount of corrosion. Furthermore, the reductions of yield and ultimate forces and strengths of corroded reinforcement (RC16 and TC16) in concrete were almost identical to those of corroded bare reinforcement (R16 and T16), respectively. Their regression lines almost coincided with each other. At the 5% significance level, the reductions of residual forces and strengths of bars RC16 and TC16 in concrete are equal to those of bare bars R16 and T16 for the same amount of corrosion, respectively.[10] Hence, the residual forces and strengths of reinforcements in concrete can also be determined by equations (6) and (7).

The experimental results show that the residual capacity of corroded reinforcement not only decreases with the amount of corrosion, but also varies with the diameter and type of reinforcement. Hence, taking the yield strength of bare reinforcement as a typical example, the influence of bar type and diameter on residual capacity of corroded reinforcement is discussed below.

Influence of bar type on residual capacity of corroded reinforcement

The influence of bar type on the residual capacity of corroded reinforcement is shown in Figs 11 and 12 for 8 and 16 mm diameter bars, respectively.

As illustrated in Figs 11 and 12, 10% corrosion decreases the yield strength of 8 and 16 mm plain bars by 7·9 and 5·8%, respectively, whereas it reduces those of 8 and 16 mm ribbed bars only by 2·0 and 1·6%, respectively. The reason for this is that, as shown in Fig. 4, the weight loss of corroded plain reinforcement entirely comes from the reduction of its cross-sectional area, whereas that of ribbed reinforcement is from the reduction of its sectional area and from the diminished ribs. For the same corrosion, the residual sectional area of plain reinforcement becomes less than that of ribbed reinforcement. Hence, for the same diameter and same corrosion, the residual capacity of corroded plain reinforcement decreases more than that of corroded ribbed reinforcement.

Influence of bar diameter on residual capacity of corroded reinforcement

The influence of bar diameter on the residual capacity of corroded reinforcement is shown in Figs 13 and 14 for plain and ribbed reinforcement, respectively.

Figures 13 and 14 show that, for 10% corrosion, the yield strength of 8 mm diameter bars R08 and T08 decreased by 7·9 and 2·0%, respectively, whereas that of 16 mm bars R16 and T16 reduced only by 5·8 and 1·6%, respectively. The reason for these different reductions is the different ratio $x_{\max}/A_s$ of the maximum attack penetration to the average sectional area for different diameter bars, as presented by equation (8)

$$\frac{x_{\max}}{A_s} = \frac{\kappa Q_{\text{corr}}}{\pi d(1 - 0 \cdot 01 Q_{\text{corr}})} \tag{8}$$

where $x_{\max} = \kappa x_s$ is maximum local attack penetration of corroded reinforcement, $x_s = Q_{\text{corr}} d/4$ is the average attack penetration of corroded reinforcement, A_s is the average sectional area of corroded reinforcement (as determined in equation (5)), d is the diameter of non-corroded reinforcement, $\kappa = x_{\max}/x_s$ is the ratio of maximum penetration to average penetration and is dependent on bar type and corrosion condition, and Q_{corr} is the amount of corrosion of reinforcement.

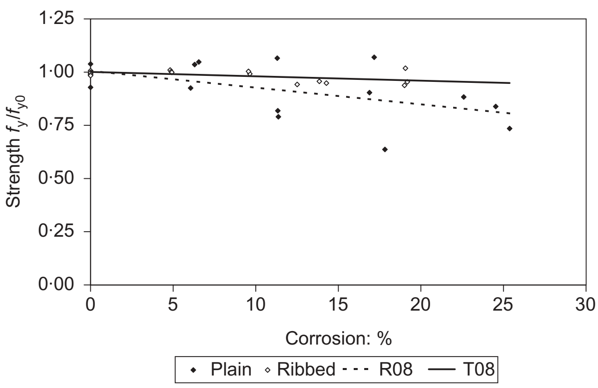

Fig. 11. Effect of bar type on strength of 8 mm corroded bars

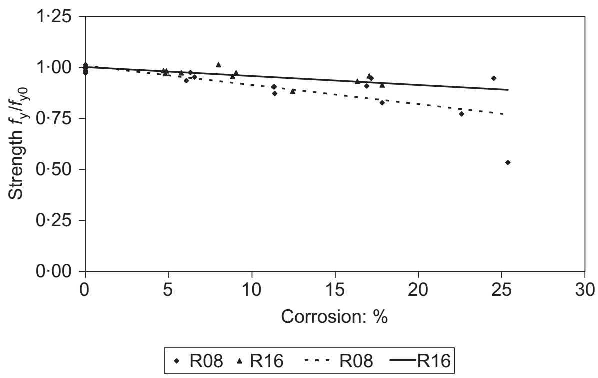

Fig. 13. Effect of diameter on strength of corroded plain bars

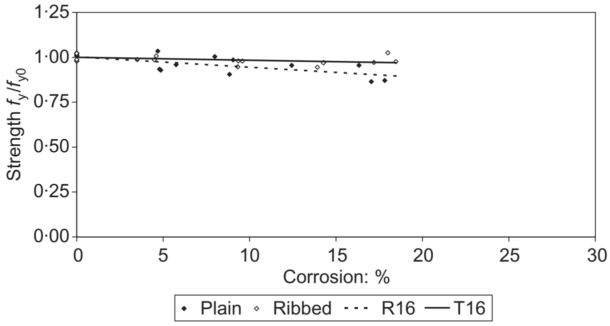

Fig. 12. Effect of bar type on strength of 16 mm corroded bars

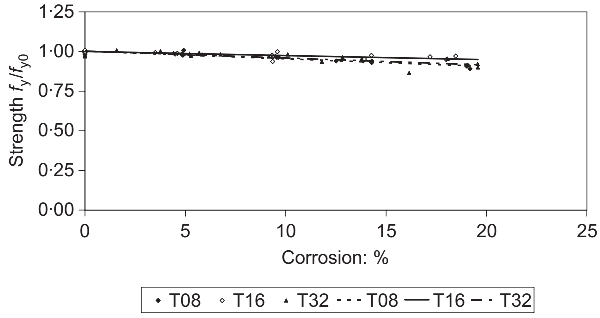

Fig. 14. Effect of diameter on strength of corroded ribbed bars

Equation (8) indicates that, for identical values of the ratio κ, and for the same corrosion Q_{corr}, the smaller is the bar diameter d, the greater is the ratio $x_{\max}/A_s$, and the more severe is the influence of local attack penetration and stress concentration on reinforcement capacity. Hence, due to corrosion, the residual capacity of small diameter reinforcement decreases much more than that of large diameter reinforcement.

An exceptional result was caused by too high an impressed current of 2·0 mA/cm^2 for the 32 mm ribbed bar T32. This high current induced a more severe local attack penetration and a rougher surface. Ten percent corrosion reduced the yield strength of 32 mm ribbed reinforcement by 3·6%, which is greater than those of 2·0 and 1·6% for 8 and 16 mm ribbed reinforcement, as shown in Fig. 14. However, this would not be the case in practice, where the highest rate of corrosion recorded in service typically is of the order of 0·01 to 0·025 mA/cm^2 in chloride-contaminated concrete, as reported by Rodriguez *et al.*[11]

Significance tests of influence of bar type and diameter on reinforcement capacity

Although both bar type and bar diameter do indeed affect reinforcement capacity, the significance of their influences on the residual forces and strengths of corroded reinforcement is different.

At the 5% significance level, the means of yield force ratio F_y/F_{y0} and ultimate force ratio F_u/F_{u0} of corroded reinforcement with different diameters and types are not significantly different from each other.[10] In other words, although the residual forces of small diameter or plain bars decrease more than those of large diameter or ribbed bars, their differences are insignificant and can be neglected. Hence, it is suggested that, in practice, equation (6) can be employed to predict the residual forces of all corroded plain and ribbed reinforcement with different diameters.

In contrast to residual forces, there were significant differences at the 5% significance level between the mean of the strength ratios f_y/f_{y0} and f_u/f_{u0} for each individual kind of reinforcement.[10] Hence, the influence of bar type and diameter on the residual strength of corroded reinforcement is significant in some cases.

The reason for the significant effect of bar diameter and type on residual strength is that the attack penetration of corroded reinforcement not only decreases the residual forces, but also reduces the actual residual sectional area A_{corr}, which deviates around the average sectional area A_s.

Although bar diameter and bar types do affect the residual strengths of corroded reinforcement, there is no consistent trend for their influence. Hence, it is suggested that, for practical purposes, equation (7) can be used to estimate the residual strengths for all corroded plain and ribbed reinforcement with different diameters. However, it should be noted that using equation (7) for residual strengths is less reliable than using equation (6) for residual forces.

Analysis of reduction of residual capacity of corroded reinforcement

In accordance with equations (6) and (7), the force and strength of corroded reinforcement can be expressed generally as

$$F = [1{\cdot}0 - (0{\cdot}01 + \alpha)Q_{\text{corr}}]F_0 \qquad (9)$$

$$f = (1{\cdot}0 - \beta Q_{\text{corr}})f_0 \qquad (10)$$

where α is a force factor and β is a strength factor, which are used to represent the effects of local attack penetration on the residual force and strength of corroded reinforcements, respectively. Their relationship can be obtained from equations (2) to (10) and follows below

$$\beta = \frac{\alpha}{1 - 0{\cdot}01Q_{\text{corr}}} = \alpha\frac{A_{s0}}{A_s} \qquad (11)$$

Equation (11) shows that, for a corroded bar, since its initial sectional area A_{s0} is always greater than its average cross-sectional area A_s, the strength factor β should analytically be always larger than the force factor α. This is in complete agreement with the regression parameters obtained from the test results experimentally, as shown in Tables 2 and 3. Hence, the influence of local attack penetration of corroded reinforcement on its residual strength is much more severe than that on its residual force.

Equations (9) and (10) indicate that the residual strength of corroded reinforcement is primarily dependent upon the amount of corrosion. For an assumed constant factor α and linear reduction of residual forces with corrosion, the residual strength of corroded reinforcement reduces more rapidly with an increase of its corrosion.

Equations (9) and (10) also show that, for a given amount Q_{corr} of corrosion, the residual strength of corroded reinforcement is affected by the force factor α due to local attack penetration. The more severe is the local penetration, the larger is the force factor α, and consequently the smaller is the residual strength of corroded reinforcement. If there were no local penetration, the factor α should be equal to zero and consequently the residual strength of corroded reinforcement should be equal to that of non-corroded reinforcement for any amount of corrosion.

In order to verify the above deduction from equation (10), three plain bars were mechanically machined to 6·40 mm from their actual initial diameter of 7·34 mm to simulate a 24% removal of metal from the bar surface by corrosion, but with negligible local penetration. After machining, the bars were tensioned to failure.

The experimental results indicated that, due to negligible local attack penetration on the external surface of the machined reinforcement, 24% reduction of sec-

Table 2. Force factor α regressed from the test results

Bar	All bars			R08		R16		T08		T16		T32	
Force	F/F_0	F_y/F_{y0}	F_u/F_{u0}	F_y/F_{y0}	F_u/F_{u0}	F_y/F_{y0}	F_u/F_{u0}	F_y/F_{y0}	F_u/F_{u0}	F_y/F_{y0}	F_u/F_{u0}	F_y/F_{y0}	F_u/F_{u0}
Regression parameter α	0·0043	0·0038	0·0046	0·0060	0·0071	0·0048	0·0026	0·0017	0·0039	0·0014	0·0022	0·0028	0·0035
Correlation coefficient R	0·919	0·894	0·936	0·841	0·926	0·941	0·908	0·975	0·995	0·969	0·987	0·977	0·975

Note the residual force of corroded reinforcements, $F = [1{\cdot}0 - (0{\cdot}01 + \alpha)Q_{\text{corr}}]F_0$.

Table 3. Strength factor β regressed from the test results

Bar	All bars			R08		R16		T08		T16		T32	
Strength	f/f_0	f_y/f_{y0}	f_u/f_{u0}	f_y/f_{y0}	f_u/f_{u0}	f_y/f_{y0}	f_u/f_{u0}	f_y/f_{y0}	f_u/f_{u0}	f_y/f_{y0}	f_u/f_{u0}	f_y/f_{y0}	f_u/f_{u0}
Regression parameter β	0·0054	0·0048	0·0061	0·0079	0·0094	0·0058	0·0044	0·0020	0·0048	0·0016	0·0026	0·0036	0·0044
Correlation coefficient R	0·587	0·508	0·672	0·549	0·713	0·705	0·754	0·546	0·949	0·452	0·767	0·748	0·775

Note the residual strength of corroded reinforcements, $f = (1{\cdot}0 - \beta Q_{\text{corr}})f_0$.

tional area had little effect on strength. The average yield and ultimate strengths of three non-machined bars were 260 and 386 N/mm^2, respectively, which are almost equal to those of 263 and 387 N/mm^2 of three machined bars, respectively. Hence, the reduction of residual strength of corroded reinforcement is, indeed, induced by the local attack penetration.

Comparison with results of other researchers

Equation (10) was used to calculate the strength reduction factor β from the data of various researchers as shown in Table 4.

It is clear that, except for the results of Maslehuddin *et al.*[3] and Palssom and Mirza,[8] there is a consistent trend between the authors' results and those of other researchers for bars in a chloride environment whether accelerated or under service conditions. Positive coefficients β for bar strengths indicate a reduction of residual capacity of corroded reinforcement. Furthermore, results of Saifullah[6] show that the residual strength of corroded plain reinforcement decreases more than that of ribbed reinforcement. The coefficients for yield strength of ribbed bars obtained by Andrade *et al.*,[4] Lee *et al.*[5] and Saifullah range from 0·0016 to 0·0045. All of these agreed well with the authors' results.

The amount of corrosion in tests performed by Maslehuddin *et al.* did not exceed 0·5%. Hence, one would not expect, from equation (7), a strength reduction greater than about 0·3%, which is negligible.

Palssom and Mirza[8] calculated their strengths using the minimum, rather than the average, cross-section. Hence, one would not expect a strength reduction from their test results.

Table 4 also shows that the coefficients from the results obtained by Zhang *et al.*[9] are much less than the other positive values discussed above. This is because the corroded bars used by Zhang *et al.* were removed from an actual structure damaged by concrete carbonation rather than chloride attack. The corrosion due to concrete carbonation is much more uniform than that caused by chloride attack, and hence there is less local attack. Consequently these results are consistent with the predictions from equations (10) and (11) and the results for the authors' machined bars.

Implication in practice

It is emphasised that the conditions under which either the accelerated or simulated corrosion of reinforcement was achieved in this experimental investigation are very different to those that occur naturally. In particular, the corrosion rates of 0·5, 1·0 and 2·0 mA/cm^2 are significantly higher than those of the order of 0·01 to 0·025 mA/cm^2, which have been reported in chloride-

Table 4. Comparison of authors' results with other studies

Researchers and dates	Du (2001)		Maslehuddin *et al.* (1990)		Andrade *et al.* (1991)	Lee *et al.* (1996)	Saifullah (1994)		Moringa (1996)	Palssom and Mirza (2002)	Zhang *et al.* (1995)	
Testing specimen	Bare bars Bars in concrete		Single bare bars		Single bare bars	Bars in concrete	Bars in concrete		Bars in concrete	Bars in concrete	Bars in concrete	
Reinforcement type (diameter)	Plain (8, 16)	Ribbed (8, 16, 32)	Plain (8–32)	Ribbed (8–32)	Ribbed (12)	Ribbed (10)	Plain (8)	Ribbed (8)	Not stated	Not stated	Plain (8–14)	Ribbed (10—25)
Corrosion condition	Accelerated 0·5–2·0 mA/cm^2		Marine exposure		Accelerated 1·0 mA/cm^2	Accelerated 13·0 mA/cm^2	Accelerated 0·5 mA/cm^2		Service chloride	Service chloride	Service carbonation	
Amount (%)	0–25%		0–0·5%		0–11%	0–25%	0–28%		0–25%	0–> 30%*	0–67%	
Yield strength β_y	0·0049	0·0012	0·00		0·0045	0·0021	0·0028	0·0016	0·006	0·000	0·0004	
Ultimate strength β_u	0·0065	0·0015	0·00		0·0033	Not stated	0·0068	0·0044	0·0063	0·000	0·0005	

Note: 1. Yield strength of corroded reinforcements: $f_y = F_y/A_s = (1{\cdot}0 - \beta_y Q_{corr}) f_{y0}$
Ultimate strength corroded reinforcements: $f_u = F_u/A_s = (1{\cdot}0 - \beta_u Q_{corr}) f_{u0}$
Sectional area of corroded reinforcements: $A_s = (1{\cdot}0 - 0{\cdot}01 Q_{corr}) A_{s0}$
Initial area of non-corroded reinforcements: $A_{s0} = \pi d^2/4$
2. Corrosion levels were determined by the method of weight loss in all studies except that of Palssom and Mirza,[8] in which corrosion of reinforcement was determined by measuring the area of its smallest section with vernier caliper.

contaminated concrete,[11] and the stress in the reinforcement caused by service loads in real structures were not induced before corrosion of reinforcement in the tests. However, very few laboratory studies have been performed on the corrosion of reinforcement while under stress.[12] The different conditions may affect the nature of the corrosion products, the amount of corrosion to cause concrete cracking, and the bond between the corroded reinforcement and the concrete, in addition to the intensity and distribution of the corrosion penetration at the reinforcement surface.

A full understanding of reinforcement corrosion in real concrete structures and the determination of the important factor $\kappa = x_{\max}/x_s$ need significantly more site data than are currently available. Hence, the structural concrete community has to rely largely on laboratory data interpreted with site conditions in mind. In this respect, it should be noted that the authors' results agree reasonably well with those obtained under natural corrosion conditions. This suggests that the results can be applied in practice with reasonable confidence.

It should be noted that, in practice, both residual diameter and corrosion rate are often measured to assess the corrosion of reinforcement. The amount of corrosion used in equations (6) and (7) can be determined from such measured values by using equations (12) and (13):

$$Q_{\text{corr}} = 1 - (d_s/d)^2 \tag{12}$$

$$Q_{\text{corr}} = 4\frac{x_{\text{corr}}}{d} = 0 \cdot 046\frac{I_{\text{corr}}}{d}t \tag{13}$$

where d is the diameter of non-corroded reinforcement (mm), d_s is the diameter of corroded reinforcement, $x_{\text{corr}} = 0{\cdot}0115 I_{\text{corr}} t$ is the corrosion attack penetration at the reinforcement surface,[13] I_{corr} is the corrosion rate of reinforcement in the real structure (μA/cm^2), and t is the time elapsed since the initiation of corrosion (years).

As an example, taking a $d = 16$ mm bar, if the measured diameter is $d_s = 14$ mm, the amount of corrosion is $Q_{\text{corr}} = 23{\cdot}4\%$. In addition, if the measured average corrosion rate $I_{\text{corr}} = 10\ \mu\text{A/cm}^2$ over the 10 years since it is estimated that the corrosion started, the amount of corrosion is $Q_{\text{corr}} = 28{\cdot}8\%$. Once the amount of corrosion is known, the residual capacity of corroded reinforcement can be estimated using equations (6) and (7).

Conclusions

(*a*) Corrosion alters the external surface of reinforcement because of very irregular attack penetration. The residual section of corroded reinforcement is no longer round and varies considerably along its circumference and its length.

(*b*) Up to 16% corrosion does not substantially alter the shape of the force–extension curve of corroded reinforcement, which still has a significant yield plateau.

(*c*) Due to local attack penetration and stress concentrations, the residual forces of corroded reinforcement decrease more rapidly than does their average cross-sectional area. As a result, the residual strength, measured in terms of stress which can be resisted, of corroded reinforcement also reduces significantly.

(*d*) For the same corrosion, the residual capacity of bare reinforcement and that corroded whilst embedded in concrete are similar.

(*e*) Although the residual capacity of smaller diameter and/or plain reinforcement decreases more rapidly than that of larger diameter or ribbed reinforcement, the influences of type and diameter of reinforcement are insignificant at the 5% significance level in most cases and can be neglected in practical engineering.

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