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Evaluation Method of Tensile Behavior of Corroded Reinforcing Bars Considering Radius Loss

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Abstract

The tensile behavior of plain round reinforcing bars corroded with various radius losses along their length is investigated experimentally and analytically. In the experiments, various corrosion topographies are simulated through accelerated electric corrosion tests using bare rebar specimens and different cathode arrangements. The tensile performance of the corroded specimens is then studied using a digital image processing method, showing that tensile degradation resulting from corrosion is closely related to radius loss variability. For the analysis, a numerical model based on the rigid body spring method incorporated with a truss network is proposed for the evaluation of tensile behavior in consideration of radius loss. Good agreement with the test data is obtained with the proposed model, which offers an accurate method of estimating the residual tensile capacity of corroded rebars.

1. Introduction

Corrosion of reinforcing steel bars is a principle cause of deterioration of reinforced concrete (RC) structures. The passive film that protects a rebar can be destroyed through the ingress of chloride ions or the carbonation of the cover concrete, triggering the corrosion process. Rebar corrosion may compromise the load bearing capacity of an RC structure by several means: loss of rebar tensile performance due to a reduced cross section, loss of effective concrete section due to concrete cracking and cover spalling and reduced bond strength between corroded rebars and the concrete. In addition to these effects on structural safety, corrosion may also lead to falling concrete, which increases the risk to human safety. Therefore, a reliable means to assess the residual strength and crack development of RC structures damaged by rebar corrosion is essential. Such a method could contribute to optimized and efficient maintenance works, which would extend the service life of RC structures in corrosive environments. This study focuses on a quantitative evaluation method for the tensile behavior of corroded rebars, an important component in the numerical models required to analyze the structural response of corrosion damaged RC structures.

A number of experimental studies have been carried out in the past to investigate the tensile performance degradation of reinforcement caused by corrosion. The corroded rebars used in these studies had been affected by natural corrosion processes, such as the ones removed from real structures (Papadopoulos et al. 2011; Zhang et al. 2012), or by artificial corrosion processes, including the electric method (Almusallam 2001; Cairns et al. 2005; Du et al. 2005; Lee and Cho 2009; Zhang et al. 2012) and salt spray (Apostolopoulos et al. 2007, 2013; Lee and Cho 2009; Papadopoulos et al. 2007, 2011). In spite of the different corrosion methods, the various studies have similarly demonstrated that corrosion may decrease yield and ultimate tensile strengths, and significantly reduce ultimate strain or elongation. By applying regression analysis to the experimental results, some empirical correlations with average corrosion degree η (%) have been proposed to estimate the residual tensile capacity \( F \) from that of non-corroded rebars \( F_0 \). These empirical relationships all have a similar form (Du et al. 2005; Lee and Cho 2009; Zhang et al. 2012):

\[
F = (1.0 - \alpha \cdot \eta)F_0
\]  

Coefficient \( \alpha \) is determined from test data and may change with the corrosion method and rebar type. In a similar way, Cairns et al. (2005) recommended that empirical equations based on the average section loss are suitable for evaluating residual strength and ductility.

Using these empirical equations, satisfactory agreement with test results can be obtained if coefficient \( \alpha \) is appropriately chosen. Lee and Cho (2009) introduced empirical equations into a material constitutive law for reinforcement and suggested that it is possible to numerically analyze the strength of RC structures containing corroded reinforcement with this constitutive law. Dekoster et al. (2003) and Kallias and Rafiq (2010) have adopted these empirical equations in a rebar material model to investigate the flexural behavior of corroded RC beams using the finite element method (FEM).

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Although the applicability of the empirical equations has been confirmed, there is variability in the recommended values of coefficient $\alpha$. This might result from the varied corrosion states produced by different corrosion methods. The electric method yields a more uniform corrosion while the natural corrosion process is more localized. Comparing these different corrosion states, Zhang et al. (2012) indicated that natural corrosion has a greater impact on tensile degradation than corrosion caused by the electric method due to the greater cross-sectional loss at certain locations. Moreover, the coefficients needed to evaluate yield and ultimate strengths, as well as elongation, may also differ, which makes the selection for a numerical model difficult. A better option may be using corrosion topography or profile, as suggested by Cairns et al. (2005) and the authors.

Aiming at this problem, the present paper reports an attempt to evaluate the tensile behavior of corroded rebars in consideration of corrosion profile, which is represented by radius losses along the rebar. Initially, an experimental study based on the corroded rebars with different corrosion profiles is carried out, in which corrosion was obtained by the electric method. Then a numerical model based on the rigid body spring method and a truss network is developed to simulate the corrosion profiles using the Laplace equation and Faraday’s law, and thereby evaluate the residual tensile performance. The applicability of the proposed model is verified by comparisons to the experimental results.

2. Experimental study

Plain steel reinforcement bars SR235 (JIS 2010) with yield strength greater than 235MPa and ultimate tensile strength greater than 380MPa were artificially corroded using a micro-cell corrosion circuit. A range of average corrosion degrees over the test area from 3% to 15% was considered. Simultaneously, in electric corrosion tests, various corrosion profiles were simulated using different cathode arrangements. Then uniaxial tensile tests were carried out with both corroded and non-corroded rebars to investigate the effects of corrosion on the mechanical properties of the rebars.

2.1 Artificial corrosion process

The corroded rebar specimens were prepared through an accelerated corrosion process, in which they were straightly exposed to salty water and subjected to a direct current. In reported experimental investigations, corrosion tests of bare rebars have been performed by exposing the specimens to the natural atmosphere (Allam et al. 1994; Maslehuddin et al. 1990) or a stainless steel tube filled with salty water and connected to a direct current (Du et al. 2005). The residual cross-sectional areas of the corroded specimens prepared by these two methods varied irregularly along the rebar length, which causes difficulty in clarifying the effects of different corrosion states and also in numerical model validation. Hence, different cathode arrangements were used in this study to obtain various and comparable corrosion profiles.

The experimental unit is illustrated in Fig. 1. To build each unit, one 600mm long rebar with a diameter of 16mm was partly embedded in a 250mm long PVC pipe. The rebar extended 175mm beyond the pipe at each end. The pipe, with an inner diameter of 68mm, was fully filled with 3% sodium chloride solution. A complete or only one-quarter tubular copper plate was placed around the rebar as the cathode. The cathode varied in length to simulate different corrosion profiles. The authors presumed that the varying distance from a point on the rebar surface to the cathode would lead to different corrosion currents at various points on the rebar surface. More distant points would be subjected to lower corrosion currents, so corrosion should be concentrated at the center part of the rebar. The measured radius losses along the rebar specimens after the corrosion tests proved this point. A tube was used in the experimental device to assist in the transfer of gases generated by the cathode reaction. The hydrogen embrittlement effect is ignored in this experiment, since the tested rebars, which have an ultimate strength of less than 1000MPa, are not generally considered susceptible (Kirby 1996) and the test results show no appreciable effect either.

The laser meter used to measure radius loss has a limited scanning length of 200mm. Hence, the length of corroded part was confined to 180mm by coating the other parts with anti-corrosion paint, waterproof tape and insulating tape in sequence to prevent from corrosion. In order to implement micro-cell corrosion, the mill scale of the part exposed to corrosion was carefully removed using a grinder before corrosion testing.

Table 1 presents a list of test variables. Specimens were named in the form U10-3%, which means a uniform case with a cathode length of 10mm and an objective average corrosion degree of 3% over 180mm test area. Three specimens were used for each test case. To ensure the same objective corrosion degree, all units were connected in series to DC power and then supplied with a constant current, as shown in Fig. 2. Various degrees of corrosion can be achieved by supplying current for dif-
The corrosion degree $\eta$ is quantified as the ratio of the gravimetric mass loss of the tested specimen to the original mass of the corroded part:

$$\eta = \frac{m_c - m_0}{180w}$$  \hspace{1cm} (2)

where $m_c$ is the mass of the cleaned specimen, $m_0$ is the initial mass, and $w$ is the unit mass.

The corrosion profiles of corroded specimens were measured using a laser meter with a precision of $0.1\mu m$. Four measurement lines located at four different circumferential positions around the corroded specimens were tested, as shown in Fig. 3. The non-corroded parts at the sides of the corroded area with a length of $10\text{mm}$ were used as reference levels, using which the measured values were transformed into relative heights. Each corroded specimen was measured before the corrosion test to obtain the initial level. The difference between the initial level and the measured level after the corrosion test was treated as the radius loss.

### 2.3 Uniaxial tensile tests and digital image processing

Tensile tests of non-corroded and corroded specimens were carried out with a universal testing machine. The tensile testing length from the upper chucked point of a test specimen to the lower one was $400\text{mm}$, within which the $180\text{mm}$ long corroded zone was included. Five strain gauges were attached to the corroded zone with a spacing of $40\text{mm}$ along the length of the specimen to investigate the developments of local strains. The applied load with a speed of $250\text{N/s}$ and the corresponding strains were automatically recorded with a data collecting and processing system. However, using this technique, it is difficult to obtain a complete strain history up to specimen fracture due to the limited measurement range of strain gauges. The strain gauges are also likely to debond from the specimens because the corroded surface is not smooth. Thus, a digital image processing method was also used in the tensile tests.

The image processing method usually used in such cases, called the digital correlation method (Sutton et al. 1983; Wang et al. 2010), provides data on the in-plane deformation of an object. In this method, images are continuously recorded during deformation and are correlated with the initial image by matching intensity patterns. A speckle pattern is painted on the surface being studied and, using bilinear interpolation, displacements as small as $0.10$ pixels can be measured (Sutton et al. 1983). However, a different image processing method was used in this case, whereby the correlation is established using distinguishable marks instead of an interpolated intensity distribution. Since no complicated algorithm is involved in this proposed method, processing time and memory can be saved.

To make the distinguishable marks, the side of the specimen opposite the one with strain gauges was fitted with eight round red spots of diameter $5\text{mm}$. Two additional spots located at the bottom were used to compensate for extra displacements caused by vibrations. During the tensile tests, a digital camera aimed perpendicularly at the face with spots were used to capture sequential images with a resolution of $4000 \times 6016$ pixels at an...
interval of 5 seconds, resulting in about three hundred images for each test specimen. The experimental setup is shown in Fig. 4.

The proposed digital image processing method was used to acquire displacements of the red spots and thereby calculate engineering strains. This process is explained in detail below.

Firstly, the captured images were transformed into binary images to identify all the spots: i.e. the color value of pixels composing the spots was set to 0 and other pixels to 255, as shown in Fig. 4. Then a plane coordinate system based on a pixel scale was defined for the binary images, where the bottom left was set as the origin. By comparing the coordinates of the spot centers in each binary image, displacements of the spots can be determined. Finally, the engineering strain can be calculated as the ratio of the extension between two adjacent spots to the initial spacing.

The precision of this image processing method depends on the pixel size (the length represented by a pixel in practice), which varies with the area of the image occupied by the object under study. The spot diameter of 5mm and the spacing of 40mm were confirmed in the experiment to be able to obtain an accurate strain distribution, by which the detectable displacement can be as small as 0.068mm. The stress-strain relationships obtained separately by the strain gauges and the image processing method are compared in Fig. 5, in which the U10-9% series is taken as an example and the measuring positions are explained in Fig. 4. The stress was derived by dividing the tensile load by the nominal cross-sectional area. As we can see, the results from the image processing method are similar to those from strain gauges. The image processing method is able to provide a complete strain history until specimen fracture.

3. Experimental results

3.1 Corrosion degree and profile

Figure 6 presents the measured corrosion degree, demonstrating that the actual corrosion degree follows Faraday’s law accurately. Fig. 7 shows the measured loss of radius along the corroded part for the uniform cases. For clarity, the U180 and U10 series are taken as typical examples. Most of the specimens show that the radius losses along the four measurement lines are similar, which indicates that the specimens are uniformly corroded in the circumferential direction. Comparing the series with different cathode lengths, it can be found that the corrosion profiles of the U180 series are linear, while
in the U10 series the radius loss at the center is about 3-4 times that at the ends of the corroded part. Hence, the use of a small cathode in the electric method concentrates the corrosion in the center to a certain extent. When the corrosion degree reaches 15%, the corrosion profiles become asymmetrical, i.e. one end is more corroded than the other end. During the corrosion tests, it was noticed that some corrosion products adhered to the specimen surface as shown in Fig. 8, a phenomenon only found in the cases with 15% corrosion. These adhered corrosion products may affect the distribution of corrosion current along the specimen surface and result in the asymmetrical corrosion profile. Related effects on the corrosion process will be discussed in the following analytical section.

Corrosion profiles of the quarter cases are shown in Fig. 9, where radially non-uniform corrosion can be confirmed. The radius loss along the bottom line, which is closer to the cathode, is evidently larger than those along other measurement lines. Radius losses along the left and right lines are almost the same due to their symmetric location away from the cathode, while the top line shows the least loss since the distance from the cathode is the largest.

### 3.2 Tensile test results

The stress-strain relationships for non-corroded and corroded specimens show the same pattern. The ultimate strains corresponding to the rebar specimen fracture at three different measuring positions as shown in Fig. 4 are 0.12, 0.5 and 0.19 respectively for non-corroded specimens, while their values are 0.1, 0.37 and 0.14 respectively for the corroded specimen U10-15%. They both show that the strain differs along the rebar length and only at the center that is the fracture part does the strain continue to increase in the post-peak stage, as shown in Fig. 5. It appears that the properties of the steel may not be affected by corrosion, which is in agreement with the views of Palsson and Mirza (2002) as well as Cairns et al. (2005). However, the ultimate strain at the specimen center decreases significantly. For the U10 series, its value falls from 0.44 to 0.37 as the average corrosion degree increases from 3% to 15%.

In order to evaluate the effects of different corrosion profiles on the degradation of tensile performance, the yield and ultimate load were investigated in detail. The residual tensile capacity of corroded specimens, in terms of the yield and ultimate loads, and their elongation were determined as a ratio by dividing the test results by the results for the non-corroded specimens. Elongation was calculated based on deformation of the fracture zone, which had an original length of 128mm, i.e. 8 times the
diameter of the non-corroded specimen (JIS, 2011). A comparison of the various studied series is shown in Fig. 10.

As we can see, the tensile performance of the corroded specimens decreases significantly with an increase of corrosion degree. In the case of 15% corrosion, the yield and ultimate load may be reduced by up to 18% and 23.5% respectively. It seems that the ultimate load decreases at a higher rate than the yield load, and elongation is the most affected property, which may result in a higher risk of brittle failure. This test result is similar to those found by Morinaga (1996) and Zhang et al. (2012).

Comparing the different series, it is clear that when corrosion is concentrated on the center part (see U10 and Q10), performance degradation becomes more severe even for the same corrosion degree. Empirical equations that are recommended based on average corrosion degree in other experimental studies (Lee and Cho 2009; Zhang et al. 2012) are employed to predict the residual strengths of the studied specimens, as also shown in Fig. 10. It appears that the empirical equations only work well with specimens corroded uniformly in the length direction, which implies that the accuracy of the empirical equations is sensitive to coefficient $\alpha$ as expressed in Equation (1).

A comparison of the quarter cases to the uniform cases demonstrates that different radius losses in the circumferential direction presented in Q180 hardly change the residual tensile capacity. This can be ascribed to the similar residual cross-sectional areas along the length of the specimens to that in the case of U180. However, there is still an obvious reduction in tensile performance in the quarter cases when concentrated corrosion occurs (see Q10). Hence, it can be deduced that the tensile capacity of corroded rebars depends on the minimum cross-sectional area along the length of the rebar.

4. Evaluation method

The experimental results presented above suggest that the residual tensile performance of corroded rebars is closely related to the corrosion profile: that is, to radius losses along the length of the rebar. Here, an analytical approach based on a numerical model that takes into account the corrosion profile is developed to accurately evaluate the tensile degradation. The rigid body spring method (RBSM) is combined with a truss network to compute the radius losses of corroded rebars and then evaluate their tensile behavior. Since the expansion pressure caused by corrosion products in concrete can be predicted well from rebar radius loss (Lundgren 2002), this model can be integrated into a comprehensive model (Tran et al. 2011) considering both concrete crack propagation and the loss of rebar tensile capacity to assess RC structures damaged by corrosion.

4.1 Three-dimensional RBSM

RBSM represents a continuum material as an assemblage of rigid particle elements interconnected by zero-length springs along their boundaries, as shown in Fig. 11. Each of the elements has six degrees of freedom at its nucleus. At the center point of every triangle formed by the center of gravity and the vertices of the boundary between two elements, three springs, one normal and two shear, are defined. The response of the spring model provides an
understanding of the interaction between particle elements instead of the internal behavior of each element based on continuum mechanics. (Yamamoto et al. 2008)

4.2 Truss network

Field-type problems and mass transfer situations that are governed by partial differential equations are usually analyzed with a continuum model, whereas RBSM does not require continuity. Hence a truss network (Nakamura et al. 2006) is combined with RBSM to cope with the analysis implemented here. The rigid particle elements are linked by truss elements with a node at each nucleus and at intermediate points on each particle boundary, as shown in Fig. 12. A simplified one-dimensional partial differential equation is applied to the truss elements to carry the potential flow or mass transfer.

4.3 Rebar material model

Figure 13 shows the stress-strain relationship applied for non-corroded rebars. Since the mesh model of the rebar specimen developed for the analysis consists of regular hexahedral elements, shear behavior was neglected in the tensile analysis. The stress-strain relationship is introduced into normal springs to model the tensile behavior, where \( \sigma \) represents tensile stress, \( E \) is Young modulus, \( \varepsilon \) is strain, \( \varepsilon_y \) is strain until the yield stage, \( \varepsilon_{sh} \) is strain until the hardening stage, \( f_y \) is yield strength, \( f_u \) is ultimate tensile strength and \( k \) is a constant dependent on the yield strength.

The stress-strain relationships used by Cairns et al. (2005), and Lee and Cho (2009) are simply bilinear models. Although their models can approximate actual rebar tensile behavior, it is difficult to accurately calculate the yield and tensile strengths. In this study, the stress-strain relationship described previously is used. The simulated result for a non-corroded specimen is compared to the experimental results in Fig. 14. As we can see, the rebar material model shows good agreement with test data.

4.4 Analytical process flow

Figure 15 shows the analytical process flow of the developed numerical model, which is composed of potential distribution analysis using a truss network and tensile simulation by RBSM. In the first part of the analysis, a three-phase material model consisting of salty water, corrosion products and the rebar is set up with an average element size of 5mm, as shown in Fig. 16. This model has the same dimensions as the experimental units. In the simulation, considering the continuous corrosion profile along the rebar length and the computation efficiency, the length of a divided rebar element was set as 5mm, which is reduced for a more complex corrosion profile, such as that of pitting corrosion. During the corrosion tests, it was observed that the potential difference between the anode and cathode was about 1V. Hence, in the simulation, the potential of the red node (representing the anode) is simply assumed to be 1V, while the boundaries marked in green that represent the cathode are fixed as zero. A zero influx condition is applied on the other boundaries. The analysis is controlled by ensuring the calculated current flow consistent with the test condition listed in Table 1.

The potential distribution inside the pipe is calculated based on the Laplace equation (Moliton 2007), which is expressed as a matrix (Segerlind 1984):

\[
\frac{\partial}{\partial x} \left( \varepsilon_x \cdot \frac{\partial \phi}{\partial x} \right) = 0
\]

\[
\begin{bmatrix}
I_1 & A \varepsilon_x & 1 & 1 & -1 & 0 \\
I_2 & -1 & 1 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
\phi_1 \\
\phi_2
\end{bmatrix}
= \begin{bmatrix}
0 \\
0
\end{bmatrix}
\]
where $\Phi_1$ and $\Phi_2$ represent the potential at each node of a truss element, respectively, $A$ is the cross-sectional area of the truss element (and is equal to the area of the corresponding facet of a rigid particle element), $l$ is the length of the truss element, $\varepsilon_r$ is relative electric permittivity, and $I_1$ and $I_2$ are the interelement terms that are depleted in the calculation unless derivative boundary conditions are specified at these nodes (Segerlind 1984).

Since only a micro-cell corrosion circuit is involved in the corrosion method used, the corrosion current $I_j$ flowing through each truss element connecting the rebar layer and corrosion products layer can be simply determined with Ohm’s law:

$$I_j = \frac{\Delta \Phi_A}{\rho_l}$$  \hspace{1cm} (5)

Where $\Delta \Phi_A$ is the potential difference between the two nodes of the truss element and $\rho_l$ is the electrical resistivity.

Accordingly, the mass loss $m_i$ for each corroded rebar element $i$ is calculated using Faraday’s law:

$$m_i = \frac{I_j \cdot \rho \cdot M}{nF}$$  \hspace{1cm} (6)

Where $t$ represents conduction time, $M$ is the molar mass of iron, $n$ is the valency, and $F$ is Faraday’s constant.

The local radius loss is determined as a height reduction $h_i$ in the cross-section of each corroded rebar element:

$$h_i = \frac{m_i}{\rho_s \cdot A_s}$$  \hspace{1cm} (7)

where $\rho_s$ is the density of iron and $A_s$ is the area of the corroded surface of the rebar element, as illustrated in Fig. 17.

As geometric reductions of the mesh model are not allowed in the simulation, degradation factors derived from local radius losses are introduced into the rebar material model, which is calculated as follows:

$$\alpha_i = \frac{A_{s,t}}{A_{s,t} \cdot h_i} = \frac{(h - h_i) \cdot (l_2 + l_1)}{h \cdot (l_1 + l_2)}$$  \hspace{1cm} (8)

where $A_{s,t}$ is the original cross-sectional area of each corroded rebar element, $A_{s,t} \cdot h_i$ is the residual cross-sectional area, $h$ is the original height of the rebar element (2mm), $l_1$ is the initial length of the corroded surface (3.14mm), $l_2$ is the length of the inner surface (2.36mm), and $l_3$ is the residual length of corroded surface. An illustration of the method used to calculate degradation factors is presented in Fig. 17.

In the tensile simulation, the material properties of the corroded rebar elements are reduced based on degradation factors:

$$E_{i,\text{corr}} = E_i \cdot \alpha_i, f_{y,i,\text{corr}} = f_{y,i} \cdot \alpha_i, f_{u,i,\text{corr}} = f_{u,i} \cdot \alpha_i$$  \hspace{1cm} (9)

where $E_{i,\text{corr}}, f_{y,i,\text{corr}}$ and $f_{u,i,\text{corr}}$ are the residual Young
modulus, yield strength and ultimate strength for each corroded rebar element, respectively.

Regarding the boundary conditions for the tensile simulation, the bottom surface is constrained, while the top surface is applied with a fixed vertical displacement in each analysis step. The parameters used in the simulation are listed in Table 2.

5. Analytical results

5.1 Corrosion profiles

5.1.1 Uniform cases

It was mentioned previously that in the 15% corrosion cases, some corrosion products adhered to the rebar surface, possibly affecting the distribution of corrosion current along the rebar. To account for this in the simulation, a simple varied distribution of relative permittivity in the corrosion products layer was assumed in the case of 15% corrosion, instead of the constant value used in the 3% and 9% cases. From the right end of the rebar, a section with a length of 72.5 mm was assumed to have a relative permittivity of 264 to represent adhered corrosion products, while the relative permittivity of the left part falls linearly to 88 to represent direct contact with the salty water. The potential distributions in the corrosion products layer under this assumption are compared to those in the case of a constant relative permittivity in Fig. 18. This makes clear that the potential difference between the rebar layer and the corrosion products layer becomes larger at the left part, which results in a larger corrosion current.

The simulated corrosion profiles of the U180 and U10 series for corrosion levels of 3% and 9% are compared to the experimental results in Fig. 19(a). Since most of the tested specimens are uniformly corroded in the circumferential direction, the averaged radius loss based on the four measurement lines for each specimen is used in this comparison. The simulated results show good agreement with the test results, not only in the shape of the distribution but also in absolute values.

When corrosion reaches 15%, corrosion profiles based on the assumed relative permittivity distribution are closer to the test results, as shown in Fig. 19(b).

![Fig. 18 Influence of adhered corrosion products on the potential distribution.](image)

![Fig. 19 Comparison of simulated corrosion profiles to test results (uniform cases).](image)
5.1.2 Quarter cases

Figure 20 compares the modeled potential distributions at the center section of the experimental units between the uniform and quarter cases. It shows that the potential gradient for uniform cases is the same for all points in the circumferential direction, according with uniform corrosion, whereas for quarter cases the potential gradient at the bottom, i.e. the side nearest to the cathode is greater than that on the other sides, representing radially non-uniform corrosion.

The calculated corrosion profiles for the quarter cases are compared to the test results in Fig. 21. These simulations are also consistent with the measured results, indicating that the truss network model used for analysis is effective for predicting the corrosion profiles of rebars exposed to a micro-cell corrosion circuit.

5.2 Evaluation of tensile performance

Following the successful prediction of radius losses, the load-deformation relationships of corroded specimens with various corrosion profiles were simulated. The results for the U180 and U10 series are compared to the test results (obtained as explained by digital image processing) in Fig. 22. The numerical predictions agree well with the test results, which confirms the applicability of the proposed numerical model to the evaluation of tensile performance of corroded rebars.

The estimated residual tensile strengths and elongations for the U180 and U10 series are compared to the test data in Fig. 23. This demonstrates that the proposed model, which considers the varying radius losses along the length of corroded rebars, can successfully deal with the effects of different corrosion states on rebar tensile
strength. Since the rebar material model described in section 4.3 does not include the necking behavior that occurs before rebar fracture, the elongations computed by the numerical model are smaller than the test results. However, the degradation trend can be properly evaluated. The establishment of a complete tensile stress-strain relationship is a task for the future.

The proposed numerical model is also able to simulate local strains well. Taking U10-9% and U180-9% as examples, local strains corresponding to two different load states in the strain hardening stage are compared to the test data in Fig. 24. The predicted strain distributions are similar to those obtained in the tensile tests, which indicates that the numerical model can be beneficial to the assessment of the deformation of corroded RC structures.

The generally excellent conformity with the results of tensile tests in terms of the load-deformation relationship, residual tensile strengths and local strain profiles confirms that the proposed numerical method can accurately predict the tensile behavior of corroded rebars. The use of a truss network in this study to calculate radius losses along the rebar ensures that model integrity will be retained in future studies of concrete corrosion. The proposed model can also make the use of corrosion profiles measured in laboratory tests or from field observations.

6. Conclusions

The purpose of this study is to propose a numerical model for evaluating the tensile behavior of corroded rebars in consideration of radius losses along the rebar, and to accurately estimate residual tensile capacity. An experiment on bare rebar specimens was carried out to study the effects of different corrosion profiles on tensile degradation, and to obtain data with which to verify the applicability of the proposed model. The following conclusions can be derived from this study:

(1) The electric corrosion method with various cathode arrangements is capable of simulating various corrosion profiles. The use of a small cathode concentrates the resulting corrosion to a certain extent.

(2) A proposed digital image processing method of recording the development of local strain and obtaining a complete strain history, which was applied to the rebar tensile tests, yields satisfactory accuracy.

(3) Tensile tests of corroded rebar specimens show that, with corrosion, the ultimate load decreases more than the yield load and that elongation is most affected. This may increase the risk of brittle failure when rebar corrosion is severe.

(4) The residual tensile capacity of corroded rebars depends on the minimum residual cross-sectional area along the rebar. Concentrated corrosion would lead to a more tensile degradation.

(5) The tensile behavior of corroded rebars can be well simulated by the proposed model, in which degradation factors based on corrosion profiles are introduced into the rebar material model. Residual tensile strengths can also be accurately estimated with the proposed model. Although the numerical model was developed using RBSM, it could also be implemented using FEM.

This study considered bare rebar specimens only. In
future work, we will extend the method to corrosion in concrete and build a model that can simulate corrosion current flows using a truss network model and concrete crack propagation using RBSM.

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