- Technical Paper -

BONDING AND CRACKING RESPONSES OF CORRODED RC MEMBERS SUBJECTED TO UNI-AXIAL TENSION

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ABSTRACT

This paper investigated the bonding and cracking behavior of eighteen 2.0m long uni-axial RC members, thirteen of which had experienced different levels of impressed current deterioration. Two serviceability-related issues have been focused on for discussion. One is to quantitatively discuss the relationship between the corrosion-induced bond strength decay and the average tension stiffening loss. Another is to discuss corrosion-induced cracks and affected loading cracks, both of which are influenced by the un-uniformity of steel corrosion. It is shown that corrosion-induced bond decay and the resulting-in tension stiffening show significantly different rates in loss with the increase of steel corrosion level. Further analysis indicates that the bond-related tension stiffening loss may be not a major concern for the stiffness degradation in the corroded members even though the mean steel mass loss increases up to 20%. Comparatively, the localized cracking deformations, which are highly related to the un-uniformity of steel corrosion, are more critical for the evaluation of serviceability deterioration in the corroded RC members.

Keywords: bond decay, tension stiffening, cracking, corrosion un-uniformity, serviceability

1. INTRODUCTION

Two major concerns usually are addressed for the corrosion-deteriorated RC members. One is the remained safety in terms of the residual strength and ductility, where the section loss of steel reinforcement and the change of failure mechanisms are primary concerns. Another is to evaluate the remained serviceability in terms of the cracking propagation and stiffness degradation. Since the bond is the most fundamental issue related to the above-mentioned two aspects, extensive tests and theoretical modeling have been conducted to investigate the relationship between the steel corrosion level and the bond strength loss [1, 2]. However, it is noticed that only limited test databases [2] on the corrosion-induced tension stiffening loss are available up to now. Moreover, the quantitative relationships among the corrosion-induced bond loss, average tension stiffening loss, and the global stiffness degradation remain un-clarified.

Another serviceability-related issue is the cracking of concrete in corroded RC members. A lot of models have been developed to predict the corrosion-induced crack widths [1, 2]. Also, lots of experimental studies have been performed to study the crack dispersing properties in corroded RC members under mechanical loading [2]. However, attention shall be paid to that the corrosion-induced or affected cracks are usually much localized phenomena and involved in large variations, which are considerably related to the un-uniformity of steel corrosion. Up to now only a few investigations focused on the correlation between the un-uniformity of steel corrosion and the cracking behavior [3].

Based on uni-axial tension test results on eighteen un-corroded and corroded RC members, this paper aims to discuss the following two topics: (1) the un-uniformity of steel corrosion and its influences on the corrosion cracks and mechanical loading cracks; and (2) corrosion-induced bond strength loss and the way it influences the tension stiffness of the corroded RC members.

2. TEST PROGRAMS

2.1 Test Materials and Specimens

Eighteen RC members with a 150×200mm rectangular section and 2.0m in length were

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prepared for tests. Test variables included the type of rebar (D19-1, D19-2 and D25), transverse confinement ratio (none, D6@150mm, and D6@75mm), and the steel corrosion level (the average steel mass loss varied from 0.0% to 12.26%). The used concrete had a compressive strength of about 40.0MPa at the age of testing. The rebar D19-1 was screwed deformed type, which had a larger rib height than D19-2. All others were normal deformed type. Summaries of all the specimens and all the used reinforcement are provided in Table 1 and Table 2, respectively.

Table 1 Summary of all the tested specimens

Code	Rebar	f_c' (MPa)	Transverse reinforcement	Steel mass loss (%)
T1-1	D19-1	39.3	None	0.00
T1-2				0.66
T1-3				2.85
T1-4				2.48
T1-5				5.55
T1-6				10.60
T1-C1-1		40.7	D6@ 150mm	0.00
T1-C1-2				12.26
T1-C2-1			D6@ 75mm	0.00
T1-C2-2				10.89
T2-1	D19-2	39.6	None	0.00
T2-2				1.79
T2-3				2.84
T2-4				10.83
T3-1	D25		None	0.00
T3-2				1.14
T3-3				2.17
T3-4				10.92

Table 2 Properties of reinforcement

Type	Young's modulus (kN/mm^2)	Yielding strength (N/mm^2)	Fracture strength (N/mm^2)
D19-1(SD345)	190	362	418
D19-2(SD345)	206	378	539
D25(SD345)	206	388	542
D6(SD345)	-	401	474

2.2 Testing System

As listed in Table 1, thirteen specimens were subjected to accelerated impressed current corrosion to certain levels, at which the corrosion-induced crack widths on the four sides of each specimen were carefully recorded along the longitudinal dimension with an interval of 100mm. Two end parts (50mm long) of each specimen remained un-corroded for the purpose of performing loading test. After the inspection of corrosion-induced crack widths, a load-controlled test system shown in Fig.1 was applied to perform tensile tests for all healthy and corroded specimens. During the experiment, load and the corresponding tensile deformation within the testing span (2.0m) were recorded. Also, a line of π gages with an interval of 100mm were attached on the specimen surface to trace the occurrence and propagation of loading cracks. After the loading tests, all the reinforcement was removed from concrete and cut into small pieces of 100mm in length. Then they were measured their mass losses after the surface treatment with sandblasting and a 10% diammonium hydrogen citrate solution. Since the same length 100mm was applied for the evaluation of steel corrosion, corrosion-induced crack, and corrosion-affected loading crack, it is possible to observe their distributing characteristics along the testing span as well as to see the correlations among them from a viewpoint of localization.

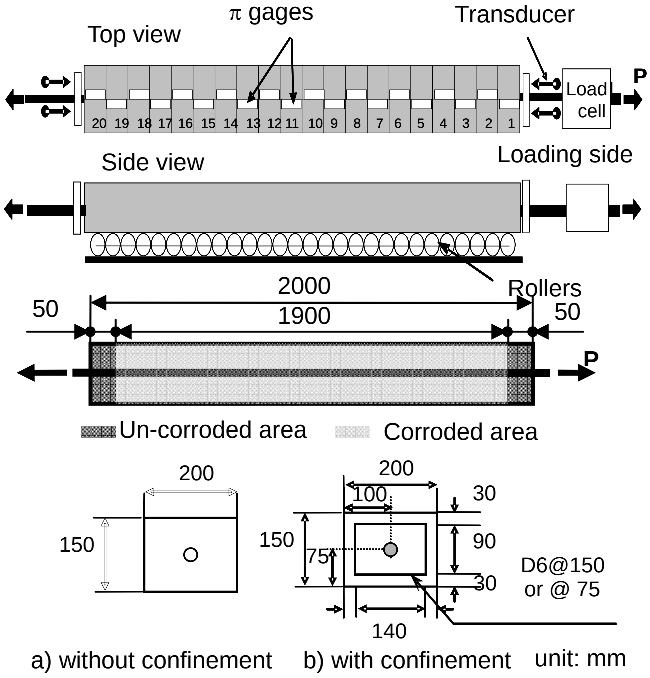

Fig.1 Size of specimens and loading setup

3. TEST RESULTS AND DISCUSSION

3.1 Un-uniformity of the Steel Corrosion

The un-uniformity of steel corrosion is a typical characteristic of corroded RC members and also an important input for both stiffness and strength analysis. Fig.2 shows the distribution of local steel mass losses in all thirteen corroded RC members. Data of nineteen steel segments for each specimen are plotted. All the corroded RC members show significant variations in their local steel mass losses over the whole testing span. In addition, the normal distribution function seems appropriate to describe the un-uniformity as shown in Fig.3. Similar to that reported for the natural corrosion case[4], a larger average steel mass loss is usually accompanied with a greater standard deviation but a smaller coefficient of variation (C.O.V) and vice versa (see Fig.3). Fig.4 compares the un-uniformity of steel corrosion introduced in the laboratory by impressed current method and obtained in the field [4]. The C.O.V of the remained steel section increases with the average corrosion level in both artificial and natural corrosion cases. The statistical distributing properties in two cases are approximately similar. However, the un-uniformity in the natural corrosion case is about 1.7 times of that in the artificial case based on the current database.

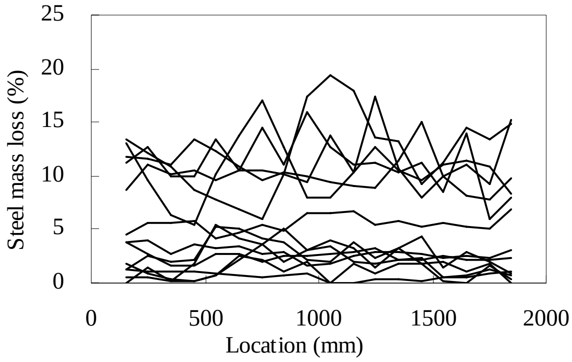

Fig.2. Un-uniformity of steel corrosion

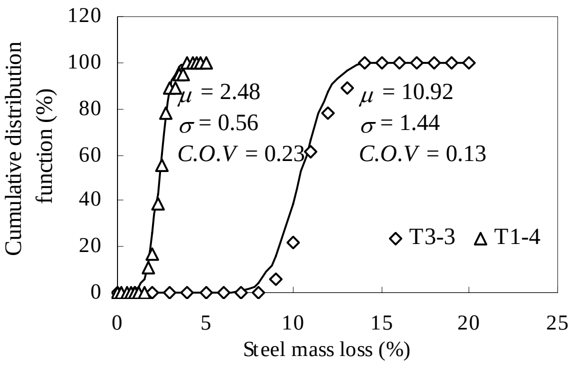

Fig.3. Normal distribution of steel mass loss

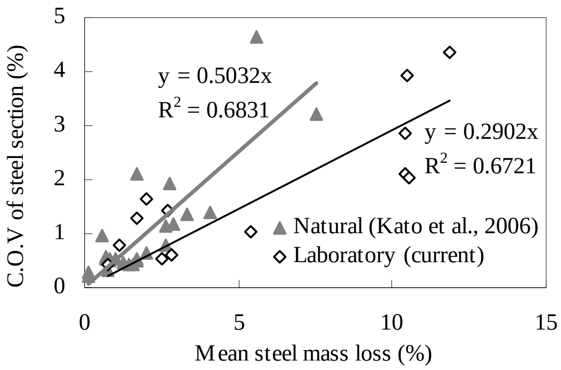

Fig. 4 Comparison of the un-uniformity of corrosion introduced in laboratory and field

3.2 Cracking in the Corroded RC Members

3.2.1 Corrosion-induced cracks

Corrosion-induced crack width is usually treated as an index of deterioration in corroded RC members. Numerous models have been developed to predict the relationship between the corrosion crack width and the mass loss of corroded reinforcement [1]. Most of the existing models show that the relationship behaves like Eq.1:

$$\Delta w = \gamma \Delta d_s \tag{1}$$

where Δw is the increment of corrosion crack width; Δd_s is the loss of rebar diameter; and γ is a constant related to the rebar diameter, concrete cover thickness and type of corrosion products. A simple solution for γ is to assume that increase in volume of cracks equals the volume of the corrosion products produced when the diameter of rebar is decreased by Δd_s. As a result, the following expression can be obtained.

$$(\frac{d_s/2}{d_s/2+c}+1)c\Delta w = (\alpha - 1)\pi d_s \Delta d_s \tag{2}$$

where α is the ratio of the density of the rust product to that of normal steel. The diameter loss Δd_s can be expressed by the steel mass loss C_s using the following equation:

$$\Delta d_s = (1-\sqrt{1-C_s})d_s \tag{3}$$

Fig.5 shows the relationship between the localized steel mass loss and the local corrosion crack width that is the summing up of all crack widths at the four sides of each specimen at any locations. The above-mentioned simple assumption seems able to describe reasonably the linear relationship between the corrosion crack width and the steel mass loss in spite of the scatter. The values of α are 3.0, 3.9, 2.7 for T1, T2, and T3 test series respectively based on linear regression. The different α in the cases of T1 (D19-1) and T2 (D19-2) series indicates that rebar shape may have an influence on the formulation of corrosion cracks. Also, in case of impressed current method, leakage of rust product from the corrosion cracks may occur. As a result, actual volume of corrosion products to cause expansion may be different in cases of different rebar diameters since they cause different corrosion crack widths. That is the possible reason for different α values in T2 (D19-2) and T3 (D25) series. Unfortunately, the correlation of corrosion crack width with the steel mass loss is not clear once the transverse confinement is available (see T1-C series in Fig.5), implying the applicability of the corrosion crack

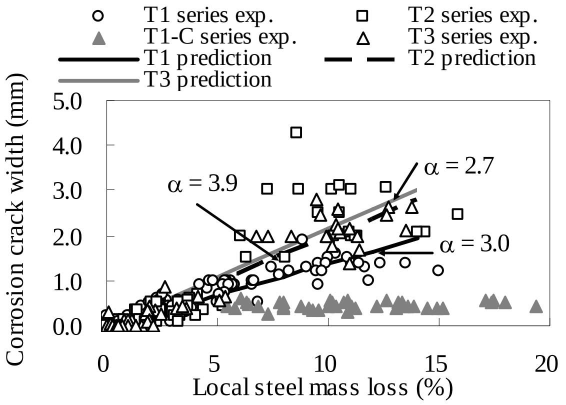

Fig.5 Effects of the steel mass loss on corrosion crack width

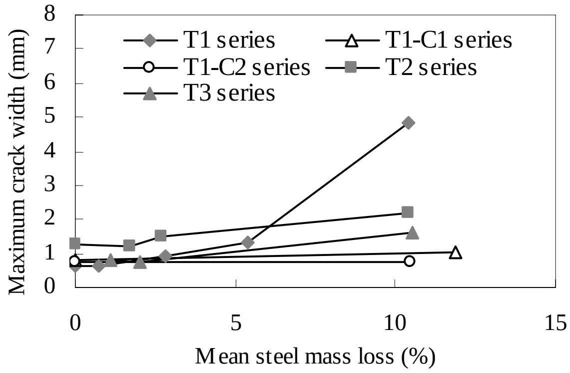

Fig.6. Influence of corrosion on loading crack

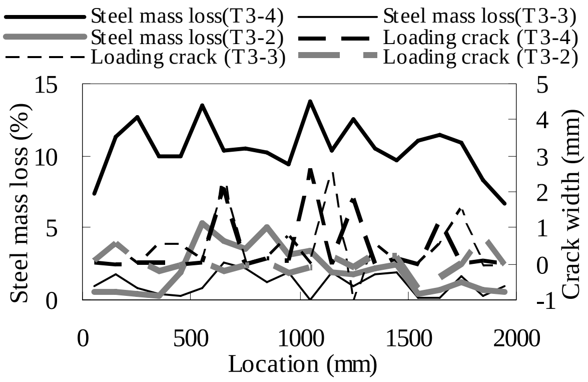

Fig.7. Comparison of loading crack and steel corrosion distribution

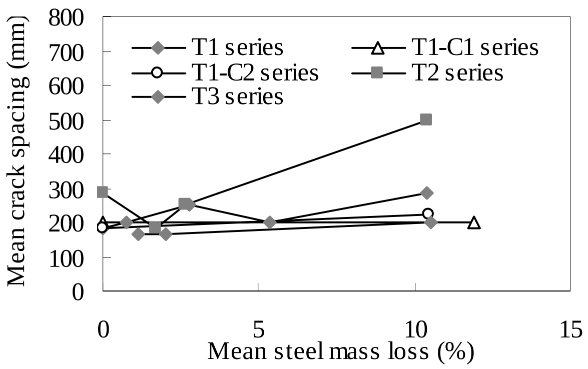

Fig.8. Influence of corrosion on crack spacing

width as a quantitative index to evaluate the steel corrosion is still limited since the confinement conditions in actual corroded RC members are much more complex.

3.2.2 Corrosion-influenced loading cracks

Figure 6 indicates the relationship between the steel corrosion level and the maximum loading crack width, which can be an important index for the remained serviceability. The loading cracks at the same average strain 0.2% of the testing span were chosen for comparing all the specimens together. As expected, the crack width increases with the steel corrosion level obviously except when the transverse confinements are available (see Fig.6). The increase is more significant in cases of T1 and T2 series than that in T3 series. In other words, the effect of corrosion on the loading crack width is less significant in cases of high reinforcing ratios. Comparing the testing series T2 to T1, the latter of which had a larger rib height as presented in Section 2.1, it is shown that the higher rebar rib (T1) suppresses the maximum loading cracks in those un-corroded RC members. On the other hand, its crack-bridging ability loses more rapidly in the higher rib case (T1) once a heavy corrosion occurs (see Fig.6). In addition, the peaks of the loading crack widths generally coincide well with the peak of localized steel mass losses as shown in Fig.7, indicating that these maximum crack widths always occur at the locations where heavier steel mass losses are induced. Therefore, beside the corrosion-induced bond loss, the un-uniformity and localization of steel corrosion is considerably a major factor that influences the loading crack widths in corroded RC members. Fig.8 shows the relationship between the steel mass loss and the mean crack spacing. For both T1 and T2 testing series, the reinforcement ratio of which is about 0.96%, the mean crack spacing increases remarkably with the steel mass loss. However, for T3 test series with a reinforcement ratio of 1.65% and a decreased ratio of steel diameter to the concrete cover thickness, this increase is not very significant even though the steel mass loss increases up to 10.92% (see Fig.8). So the effects of corrosion on the crack spacing probably are more remarkable in cases of a low ratio of reinforcement or a large ratio of steel diameter to concrete cover thickness. On the whole, the loading cracking properties in corroded RC members are more closely correlated to the un-uniformity of steel corrosion.

3.3 Corrosion-Induced Bond and Tension Stiffening Loss

Change of crack widths and crack spacing in the corroded RC members is mainly attributed to the corrosion-induced bond loss. If the bond stress distribution between two adjacent cracks is assumed to be uniform, the relationship between the average bond stress and the mean crack spacing can be expressed as follows:

$$\tau = \frac{d_s f_y}{4l} \quad (4)$$

where τ is the average bond stress between two adjacent cracks, f_y is the yielding strength of rebar, and l is the mean crack spacing. Eq.4 shows that the average bond stress is inversely proportional to the observed average crack spacing. Assuming that τ_0 is the bond strength in cases of un-corroded RC members and using Eq.4, it is possible to plot the relationship between the relative bond strength τ/τ_0 and the mean steel mass loss in Fig.9. It can be seen that almost no bond loss occurs as the result of corrosion if there is transverse reinforcement available. For all the tested RC members except for T2 series, the formulation on corrosion-induced bond loss proposed by JCI-C64 [1] provides a safety margin regardless of the large scatter.

Qualitatively, the corrosion-induced bond decay as shown in Fig.9 is thought to be the main reason to cause tension stiffening deterioration. To know the quantitative relationship between two of them, discrete modeling based on Rigid Body Spring Network (RBSN) method was applied to simulate the test results of series T1 for an example. FIB bond model for the corroded steel/concrete interfaces by introducing a bond decay factor was applied. Details of the modeling are omitted here but can be found in Ref. [5]. The analysis reproduced well the change of crack distributions in concrete when the mean steel mass loss increases (see Fig.10). However, it is interestingly found that the average stress-strain relationship does not degrade monotonically with the increase of steel corrosion (see Fig.11). The considerable reason is that the average tension stiffening behavior reflects the coupled effects of many factors like bond decay, decrease of reinforcement ratio, and the change of crack spacing. Fig.12 indicates the sole effect of bond loss on the tension stiffening deterioration in terms of the tension stiffening factor c, which is employed in the well-known Okamura model. The rates of bond degradation and tension stiffening deterioration seem significantly different. Analytically, the steel mass loss at 20% seems to be a turning point, beyond which the tension stiffening starts to deteriorate rapidly. In practice, this level of steel mass loss may have led to heavy spalling of concrete cover in which case the serviceability may not be a major concern. Therefore, practically the bond loss-caused tension stiffening deterioration may be a marginal factor for the stiffness degradation in corroded RC members concerning the serviceability.

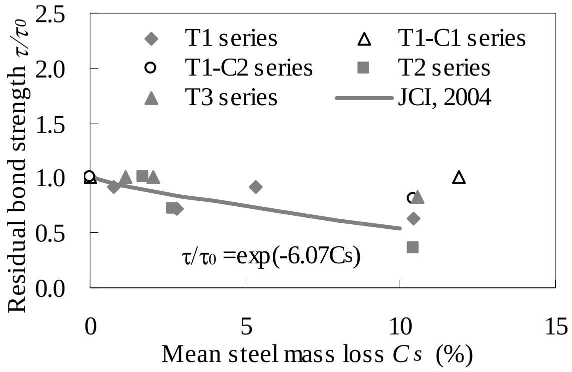

Fig.9. Influence of corrosion on bond strength

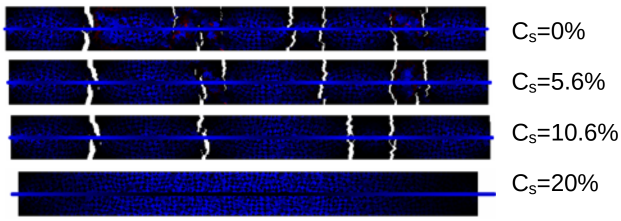

Fig.10 Crack distributions at different corrosion levels

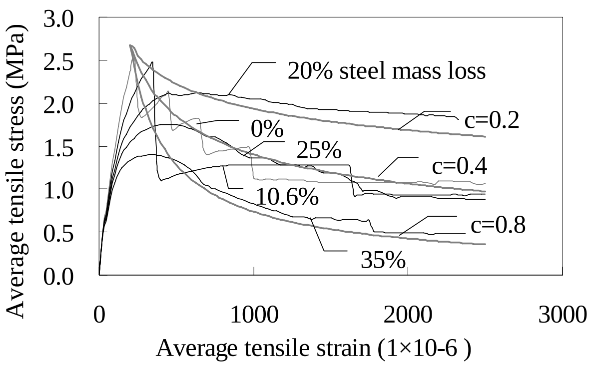

Fig.11. Effects of steel mass loss on the average stress-strain relationships of concrete

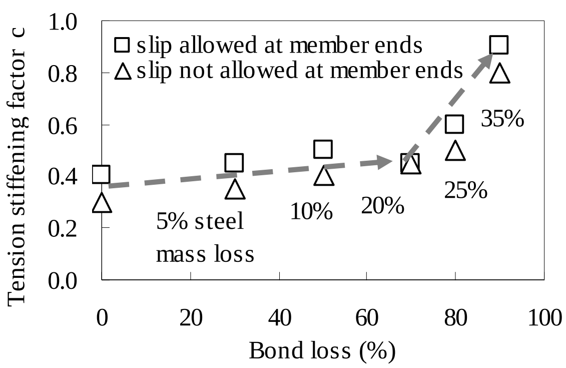

Fig.12. Bond versus tension stiffening loss

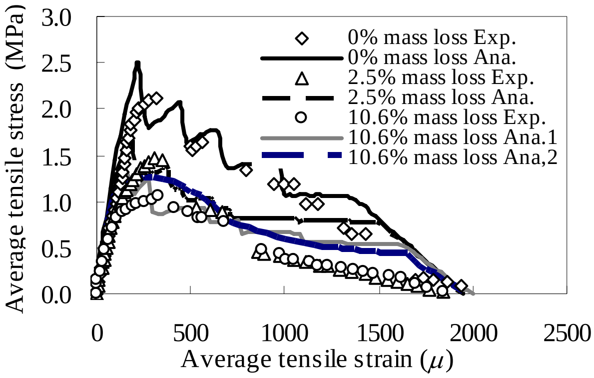

Fig.13. Corrosion-induced tension stiffening: comparison of test and analytical results

Taking test series T1 as an example, Fig.13 shows the typical corrosion-induced tension stiffening loss observed in the experiments using the average stress-strain relationships of concrete. The shrinking of the area enclosed by these curves is clearly seen, indicating a loss of global tension stiffness in the corroded members. However, it is noticed that the peak tensile strength appearing in these curves also decreases with the increase of the corrosion level (see Fig.13). It is hard to reproduce this phenomenon in the analysis if introducing only the bond decay factor as drawn in Fig.9. To introduce very poor bond (90% bond loss of the original) in the analysis seems to be able to approximately simulate the decrease of appeared peak tensile strength (see the thick dotted line in Fig.13). However, the very poor bond usually leads to an anchorage failure at the loaded end without the occurrence of any cracks in the corroded members (refer to the last case in Fig.10). That is different from the failure mechanisms observed in the tests. At final, the solution used in the analysis was to decrease the effective section area of concrete cover to fit the test results (see the thick solid line in Fig.13). The loss of effective section area is considerably related to the geometry of corrosion-induced cracks, which are different from each other in all the test specimens including many uncertainties. In this analysis, the decreasing factor for the effective section area was determined based on back-calculation analysis to fit the current test results. Further three-dimensional analysis is necessary to formulate a general relationship between the remained effective concrete cover and the steel corrosion level, so that the propagation process of corrosion cracks in the concrete cover can be simulated considering the corrosion un-uniformity.

4. CONCLUSIONS

(1) The impressed current method shows its applicability to introduce significant un-uniformity of steel corrosion. The normal distribution seems appropriate to describe the un-uniformity. More severe corrosion corresponds to a greater standard deviation but a smaller coefficient of variation.
(2) The corrosion-induced crack, it-affected loading crack width, and the corrosion-induced bond loss show good correlations with each other. However, this correlation is weak when the transverse confinement is available.
(3) Corrosion-induced bond strength decay and it-induced average tension stiffening loss are different. Analytically, a steel mass loss at 20% (about 70% bond loss of the original), which may not be a status for concerning the serviceability in practice, seems to be a turning point, beyond which the tension stiffening starts to deteriorate rapidly. Therefore, practically the analysis of global stiffness degradation in the corroded RC members may need to merely consider the steel loss-induced stiffness degradation rather than the bond-related stiffening loss. Instead, the localized crack deformations influenced by the corrosion un-uniformity and the local bond loss should be major concerns for serviceability evaluation.
(4) Analysis also shows that introducing corrosion-induced bond decay only can not reproduce the degraded average stress-strain relationships observed in the tests. It is more important to consider the loss of effective section area of concrete cover due to corrosion.

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