Committee Report : JCI- TC112A

Technical Committee on Systematization to Evaluate Structure and Durability Performance in Corroded RC Structure

Tetsuya MISHIMA, Takashi YAMAMOTO, Hideki OHSHITA, Toshiyuki KANAKUBO, Minoru KUNIEDA and Yasuhiko SATO

Abstract

This Technical Committee took up the durability performance relevant to structural performance (structural/durability performance) of concrete structures containing corroded reinforcement, investigated the expression of material deterioration on spatiotemporal axes, and modeled the mechanical behavior of corroded reinforcement and bond between concrete and corroded reinforcement. This was done with the aim of utilizing numerical structural analysis, a technique for numerically expressing such performance on a spatiotemporal scale, and establishing a structural/durability performance index that is capable of evaluating the total system of a structure. The Committee then proposed and formulated a structural/durability performance index and reviewed repair/retrofitting cases of concrete members containing corroded reinforcement to examine the application of this index to the evaluation of repair/retrofitting effects.

Keywords: reinforcement corrosion, structural/debility index, prediction of material deterioration, constitutive model for deteriorated material, repair/retrofitting

1. Introduction

The relationship between the material deterioration of concrete structures, such as reinforcement corrosion, and changes in their performance, or durability performance, has been actively argued over the last decade, with many time-related performance evaluation techniques being proposed. Research into evaluation techniques for structural performance in particular has been conducted with enthusiasm. The development of numerical structural analysis techniques represented by the finite element method has been particularly remarkable. Various models have been under development for use with these techniques. These include mechanical models of corroded reinforcement, models of cracks due to corrosion expansion, and models of interaction between corroded reinforcement and concrete. However, calculation of the currently retained performance of concrete structures containing corroded reinforcement, for which inspection data are available, is not sufficient for establishing a tool for estimating the future performance and residual service life. Modeling of deteriorating materials on the time axis is essential for this purpose. Also, in regard to deterioration phenomena, which rarely proceed in a uniform manner, it has been pointed out that the non-uniformity of corrosion deterioration has a strong adverse effect on the structural performance of concrete structures. Techniques for applying the spatial distribution of corrosion are anticipated for grasping the mechanical behavior of reinforced concrete members containing corroded reinforcement.

Meanwhile, grading techniques, which are said to be semi-quantitative, and techniques based on the above-mentioned numerical analysis have been used for evaluating the durability performance related to structural performance (hereafter referred to as structural/durability performance). While grading is simple and effective for performance evaluation when controlling a number of structures, it tends to depend on the sophisticated engineering judgment of engineers, possibly resulting in inconsistent evaluations. On the other hand, techniques based on numerical analysis enable numerical expression of performance with a mechanical basis, but are yet to be widely utilized depending on the technical level of the owners or administrators of structures.

With this as a background, the present Committee set its goals as follows: to utilize numerical structural analysis as an evaluation technique that is capable of numerically expressing the structural/durability performance of concrete structures containing corroded reinforcement on a spatiotemporal scale, and to establish a structural/durability index for evaluating the total systems of structures. Based on the organization shown in **Table 1**, WG1 investigated models on spatiotemporal axes for material deterioration; WG2 investigated unification of mechanical models for corroded reinforcement and bond between corroded reinforcement and concrete, as well as techniques for using finite element analysis based on these models; WG3 formulated a structural/durability performance index; and WG4 surveyed cases of repair/retrofitting of members containing corroded reinforcement and investigated the application of the structural/durability index to the effect of repair/retrofitting.

2. Evaluation of material deterioration

The Material Deterioration Working Group (WG1) discussed the concept of a framework for not only current but also future performance evaluation of concrete structures over a span of decades in regard to deterioration due to steel corrosion. A related literature search was also conducted. The discussion was premised on the use of sophisticated models involving numerical analysis, instead of macro models, for evaluation of structural performances.

Such evaluation methods have been surveyed in past technical committees of JCI, such as the Technical Committee for Long-term Performance Verification Support Models (2002-2003), with the aim of evaluating environmental forces, systematizing various physicochemical models, and developing from micro to macro models. The Technical Committee for Formulating Recommendations for Performance Evaluation of Existing Concrete Structures has provided information necessary for performance evaluation of deteriorated concrete structures and evaluation procedures.

According to the literature survey carried out by the present Committee, related past studies are roughly classified into three phases: micro-scale studies including those that are based on physicochemical models, such as reinforcement corrosion reaction; mezzo-scale studies including those predicting the crack width associated with corrosion-induced expansion pressure; and macro-scale studies including those focusing on reductions in the bond between concrete and steel reinforcement to predict the load-bearing capacity and deformation of members. In order to seek evaluation of structural performance based on reaction models on a micro-scale, it is necessary to exchange information among the phases. To this end, the spatial scales should be adjusted (averaged) while ensuring consistency among the phenomena. Although it was not possible to reach a decisive conclusion, the discussion of the working group emphasized the need for advances in research on averaging.

Also, the working group conducted discussion assuming two cases: one for performance evaluation at present (t = t1) and the other for performance estimation for the future (t = t1 + ⊿t).

For current performance evaluation, the performance is estimated by such methods as FEM, for which the input values include the cross-sectional area and bond stress-slip relationship of corroded reinforcement. For such members as beams, their longitudinal distributions are also required. In practice, however, information related to longitudinal distributions tends to be discrete, mostly being at intervals of 10 cm or more. It is therefore necessary to convert such discrete information into averaged and continuous information that is usable for FEM, but few studies have realistically provided specific methods of converting information.

For future performance estimation, it is necessary to input data after a period of ⊿t in the tool. Attempts have so far been made to conduct direct performance evaluation by estimating the cross-sectional area and bond stress-slip relationship of reinforcement after a period of ⊿t within the tolerances. However, data have scarcely been fed back to the stage of estimating crack width or the level of estimating the distribution of corrosion using a physicochemical model. Here again, data obtained from inspection (current state quantities) cannot be input on a micro-scale as they are, due to the differences in the amount of spatial information. For instance, even if the amounts of corrosion and chloride ions at multiple points are known, the data are at least 20 to 30 cm apart, with the intervals being too large when compared with the representative size of elements for the analysis of reinforcement corrosion. Future investigation is required regarding the method of inputting data in a model on a micro scale.

As stated above, the survey and discussion by WG1 have clarified the problems when handing over discrete input data obtained from inspection to a different scale system. It is hoped that WG1's achievements further motivate research into these problems.

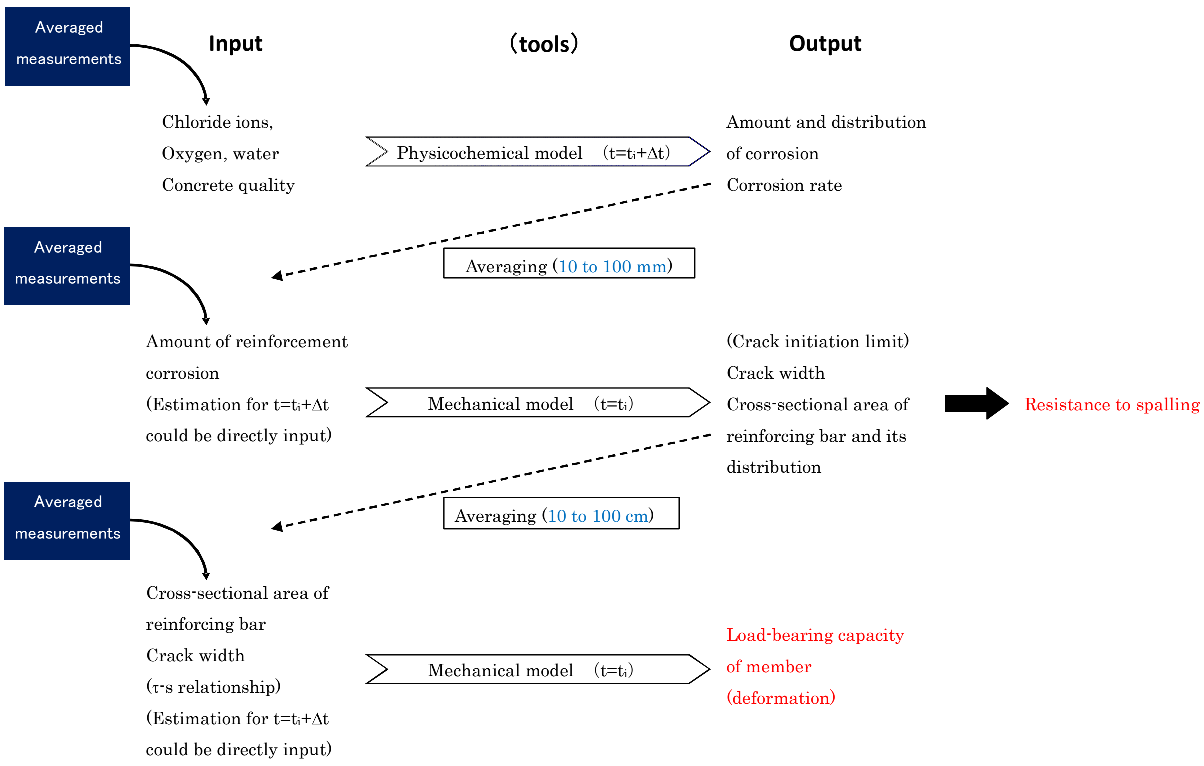


Fig. 1: Data flow and data averaging from micro- to macro-scale

3. Evaluation of constitutive models for FEM

Numerical analysis represented by FEM is a very useful tool for estimating the mechanical behavior of members and structures made of concrete involving reinforcement corrosion and resultant cracking. When applying FEM, it is essential to appropriately select constitutive models for reinforcement and concrete, as well as a bond constitutive model to express their interaction. This chapter briefly introduces the results of the application of FEM to the stress-strain relationship of corroded reinforcement, bond stress-slip relationship between corroded reinforcement and concrete, and the results of tests on members actually having cracks.

3.1 Constitutive models for corroded reinforcement

A number of reports have been published regarding investigation into constitutive models for corroded reinforcement, but these are mostly based on electrically corroded test specimens. In the present Committee, tests were conducted on corroded reinforcement taken from actual structures to emphasize the evaluation of stress-strain relationships based on the degree and distribution of corrosion in actual structures.

Table 1 outlines the subject reinforcing bars. These include deformed and plain bars taken from four different actual structures and molded concrete specimens exposed to the environment. These were subjected to measurement of the cross-sectional area profile using a 3D scanner reported in Reference (1) and the strain using a displacement transducer with a gauge length of 16*d* (*d* = bar diameter).

Figure 2 shows typical stress-strain relationships determined as follows: Divide the reinforcing bar into elements in the longitudinal direction; calculate the total elongation by applying the stress-strain relationship of the material to each element; and divide it with 16*d*, the gauge length, to obtain the average strain, while changing the element size from 1 mm to 16*d*. The stress-strain relationship of the material was determined by measuring a nearly sound specimen with yield and tensile strengths of 368 and 556 N/mm^2, respectively, using a strain gauge. The specimen was a D10 deformed bar (sh 15) with the minimum and mean cross-sectional area of 48.4 and 66.1 mm^2, respectively. The minimum cross-sectional area within each element size was taken as the cross-sectional area of the element for calculation.

A small element size leads to stiffness greater than the test results, causing underestimation of deformation after yielding. This tendency is more evident in deformed bars. Conversely, a large element size tends to overestimate the deformation after yielding, leading to a large difference in the breaking strain. An element size of around 2*d* is therefore considered appropriate for modeling of the stress-strain relationship of reinforcement, including plain bars, from both aspects of strength and deformation.

In consideration of simple application to FEM, approximation was conducted into bilinear models with target ranges of 16*d* and 8*d*. Based on the above-mentioned calculation results with 2*d*, a model was approximated using the same primary slope and breaking point as the calculations. The secondary slope was determined so that the sum of the stress deviations would be zero. **Figure 3** shows example models. Models from Reference (2) are superimposed in the graphs.

Please refer to the Technical Report of the Committee containing the results of all specimens and characteristic values for modeling.

Table 1: Outline of reinforcing bars under analysis

Series	Designation	No. of specimens	Environment	Corrosive factor
sh	D10	6	Splash zone	Chloride attack
to	ϕ22	3	Urban area	Carbonation
sa	ϕ19	3	Shoreline	Chloride attack
ok	D13	2	High initial Cl^- content	Chloride attack

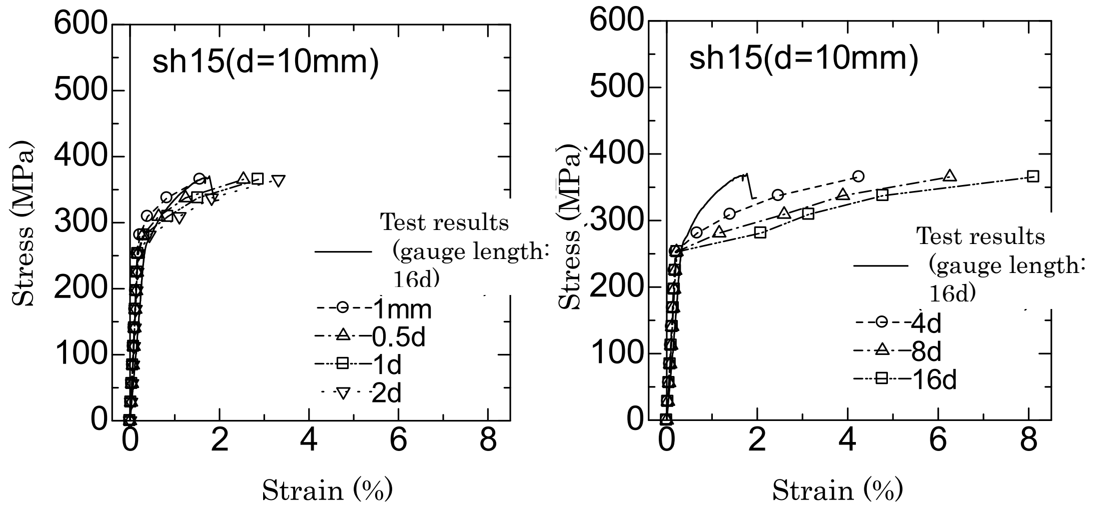


Fig. 2: Effect of element size on stress-strain relationship

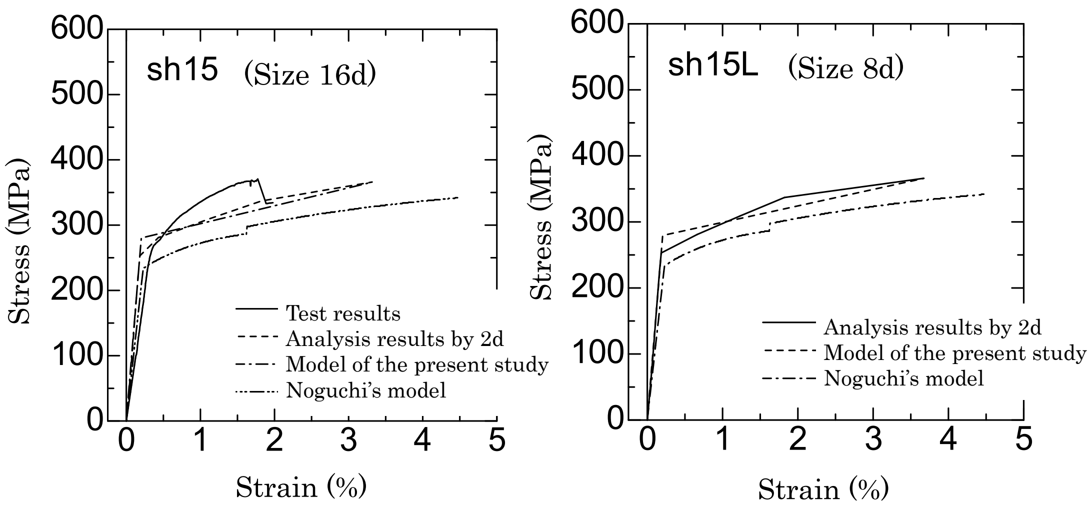


Fig. 3: An example of bilinear modeling

3.2 Bond constitutive model between corroded reinforcement and concrete

Whereas useful findings have been accumulated regarding the effect of reinforcement corrosion on the load-bearing performance of reinforced concrete members, its effect on the deformation performance is yet to be fully elucidated. The major cause of the slow progress of deformation performance evaluation of reinforced concrete members with corroded reinforcement compared with load-bearing performance can be attributed to the mechanical properties of corroded reinforcement (Section **3.1**) and the bond deterioration properties between reinforcement and concrete, which remain unknown. This section surveys past findings on the bond properties between corroded reinforcement and concrete, focusing on bond constitutive models (bond stress-slip relationship) of concrete members containing corroded reinforcement, which are particularly important when conducting FEM analysis.

Factors of reinforcement corrosion affecting the bond properties of reinforced concrete members include cross-sectional losses due to corrosion, formation of weak layers due to corrosion products, reductions in the effective support area due to loss of ribs, and cracking in cover concrete.

A number of studies have been conducted regarding the relationship between bond strength and bond deterioration factors including corrosion cracking and corrosion losses. On the other hand, few reports have been made on the relationship between the bond stress-slip relationship and bond deterioration factors. Systematic surveys have scarcely been conducted. In recent years, however, the bond stress-relationship of reinforced concrete members containing corroded reinforcement has been studied in some cases.

Nagaoka et al., for instance, have proposed a bond constitutive model for reinforced concrete members containing corroded reinforcement that undergo bond splitting failure based on a CEB model as given in Eq (1)[3].

$$
\begin{array}{ll}
0 \le S \le S_{\max} & S_{\max} < S \\
\tau = \tau_{cor} \left(S / S_{\max} \right)^{\gamma} & \tau = -I\left(S - S_{\max}\right) + \tau_{cor} \\
\tau_{cor} = \sigma_n \cdot \cot 54.1^\circ + 2.60 & I = 2.16\,\sigma_n^{0.509} \\
S_{\max} = 1.51\,D/100 & \\
\gamma = 0.431 & \\
I = 2.16\,\sigma_n^{0.509} &
\end{array}
$$

$$\sigma_n = \exp\left(-\alpha \cdot W_{cr}\right) \cdot \sigma_{n-\max}$$

$$\sigma_{n-\max} = 4.05\frac{C_1}{\phi} + 0.103 f_c' - 3.65$$

$$\alpha = \left(-0.407 \ln C_2 + 2.12\right) \cdot f_c'^{2/3}$$

$$\left(\begin{array}{l} 1.32 \le \dfrac{C_1}{\phi} \le 4.19,\ 22.6 \le f_c' \le 55.5 \\ \text{When } \dfrac{C_2 + \phi/2}{C_1 + \phi/2} > 1.50, \quad C_2 = 1.50\,C_1 + \dfrac{\phi}{4} \end{array} \right)$$

where τ: bond stress (N/mm^2); τ_{cor}: bond strength of reinforced concrete member with corroded reinforcement (N/mm^2); S: slip (mm); Smax: slip at the point of bond strength (mm); γ: coefficient for the increasing slope of bond stress; I: softening slope; σ_n: restraining pressure (N/mm^2); Wcr: crack width on the surface of cover concrete with minimum depth (mm); α: coefficient for reduction rate from the maximum restraining pressure; σ_{n-max}: maximum restraining pressure (N/mm^2); C_1: minimum cover depth (mm); C_2: second smallest cover depth (mm); f'_c: compressive strength of concrete (N/mm^2); and $\phi(D)$: bar diameter (m).

In addition to the corrosion crack width along the bar axis, this model incorporates the effects of the cover depth, compressive strength, and bar diameter as part of the restraining pressure of concrete.

Figure 4 shows typical results of applying Eq. (1) to past study results[4]. Dashed and solid lines represent test and evaluation values, respectively. The evaluation model shows relatively good agreement with the test results. In addition to this model, this section of the Committee Report also compares other bond constitutive models proposed in papers overseas with pull-out test results to review the application limits of models and problems left unsolved. Also, Section **3.3** reports on FEM analysis conducted on reinforced concrete beams containing corroded reinforcement using the bond constitutive model proposed in this section.

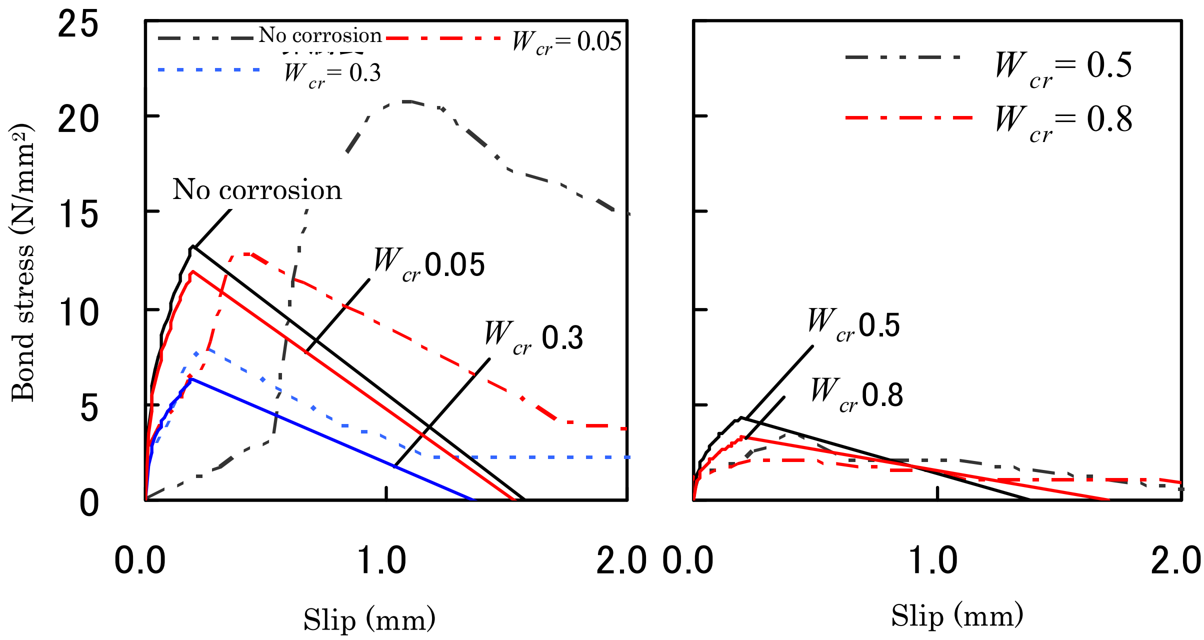


Fig. 4: Results of application of Eq. (1)

3.3 FEM analysis of concrete members containing corroded reinforcement

(1) Analysis overview

A large number of estimations have been published regarding the residual performance of reinforced concrete and prestressed concrete members containing corroded reinforcement. In this light, two of the committee members (Analysts A and B) conducted FEM analysis of the results of round-robin tests, which had been carried out to examine the structural performance of reinforced concrete members containing corroded reinforcement[5)].

(2) Analysis model

Figure 5 shows the constitutive models of the materials used by Analyst A. Similar models were used by Analyst B, but they used different models for the bond stress-slip relationship to apply to the bond springs between the main bar and concrete – Analyst A used the CEB model, whereas Analyst B used the model described in the previous section. As shown in **Fig. 6**, both Analysts used 3D finite element mesh. The main bar was expressed by discretely placed truss elements. Instead of direct modeling, corrosion cracking was modeled as weakening of the bond action between the main bar and concrete in both cases.

(3) Analysis results and discussion

Figure 7 shows typical analysis results. These graphs reveal that the load-central displacement relationships observed in the tests were nearly reproduced by both analysts. This is presumably because, as far as the test results under analysis are concerned, concrete on the compression side tended to crush in the ultimate state without rupture of the main bar. However, the analysis by Analyst A diverged without following the test results to the ultimate state. This can be attributed to the bond stress-slip relationship applied by Analyst A.

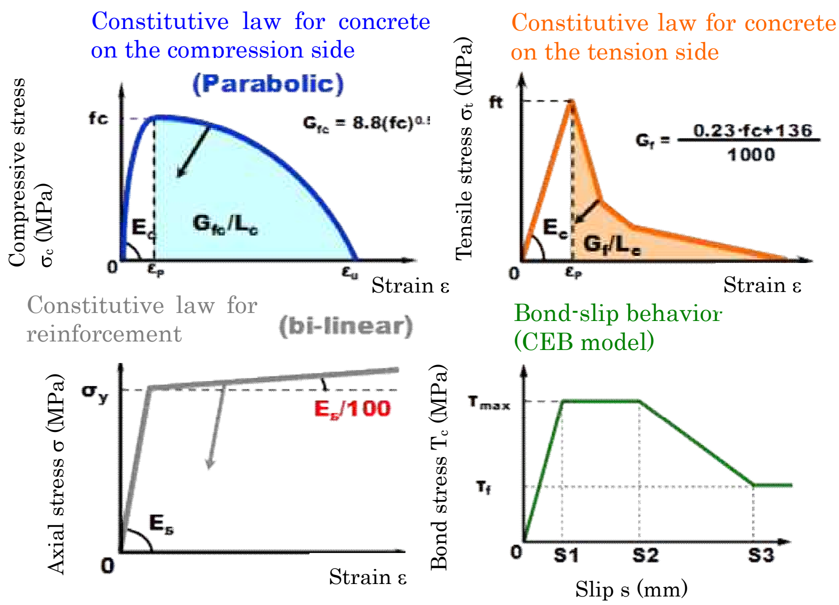


Fig. 5: Constitutive models of materials used by Analysis A

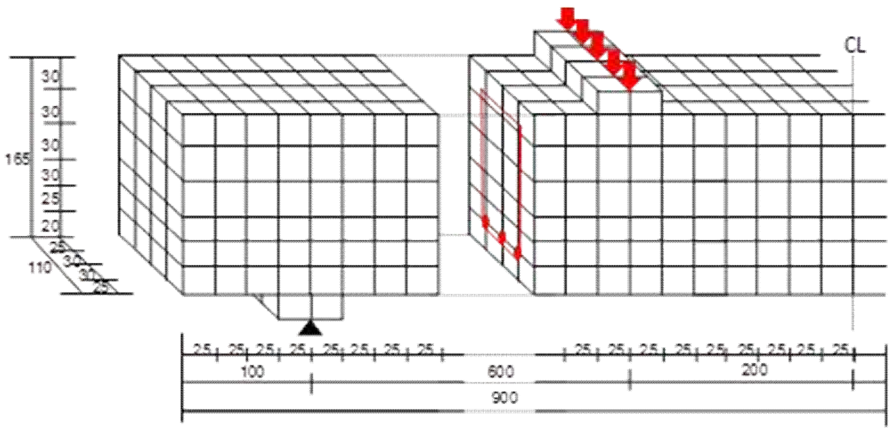
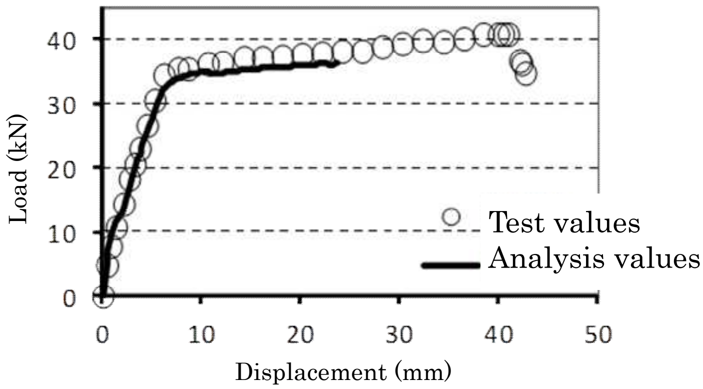
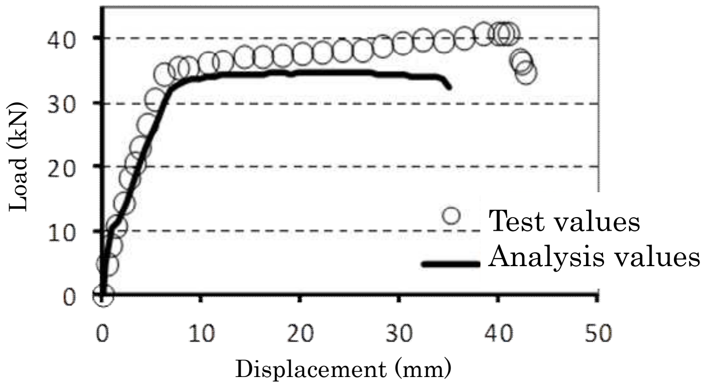


Fig. 6: Analysis model of analyst A



(a) Analyst A



(b) Analyst B

Fig. 7: Examples of analysis results

4. Evaluation of structural/durability performance

Methods of expressing the soundness (degree of deterioration) of concrete structures deteriorated by reinforcement corrosion include grading and the use of FEM mentioned in the previous chapter. Though requiring high proficiency on the part of the engineer in many cases, the grading technique provides performance evaluation relatively easily based on inspection results. It is suitable for screening of structures requiring remedial measures in a situation where a large number of structure groups have to be macroscopically controlled. Nevertheless, evaluation by grading is poorly supported by mechanics, being not always sufficient when identifying the current performance for taking remedial measures and when expressing the effect of such measures. On the other hand, the technique of using numerical analysis provides easy judgment due to direct digitalization utilizing appropriate mechanical models. However, the use of this technique has yet to become common practice in the current situation where large numbers of structure groups are managed by entities and businesses having insufficient numbers of in-house engineers with high technical capacity.

Meanwhile, the structural/durability performance index proposed by the present Committee is positioned between the above-mentioned techniques. It intends to calculate a value that can serve as an index to the soundness of not only members but also structural systems, utilizing, for instance, simple equations that are normally used for design as a mechanical basis for the index. This index was formulated referring to the Is value, the seismic diagnosis standard used in Japan's architectural field.

During the discussion for formulation, two types with different principles of index calculation were investigated: one utilizing the time-related changes in the ratio of resistance to action on the structure (safety factor) and the other utilizing the reduction rate from the initial performance of the structure. There was an argument that the former is more suitable for judging the margin of safety from the engineering aspect. However, an index involving safety factors that vary from one member/structure to another can make it difficult to evaluate the true performance of the structure. For this reason, the latter method based on the reduction ratio was adopted. The index of the sound (initial) state of the total system of a structure was assumed to be 1, and the value was assumed to vary between 1 and 0 depending on the degree of deterioration. It was decided to incorporate the magnitude of external forces as in the former method by applying a factor for external forces on members and segments during evaluation. This was to give consideration, for instance, to sections that are subjected to small external actions, so that their performance index may not be evaluated excessively low even if they are significantly corroded.

4.1 Definitions of structural/durability index

The structural/durability index of a given section, x_i, of a member, j, of a structure at a given time in its service life, t, is put as $id_j(x_i,t)$. The integration of such indexes for all members is put as $ID(t)$ to express the structural/durability index of the total system. Note that only the formulation of safety (flexural and shear) is described in this report due to space limitations, though this framework is applicable to calculation of various performances.

(1) Structural/durability index of a section

The reduction rate from the sound (initial) state of the flexural capacity, $\eta_M(x_i, t)$, is expressed as Eq. (2). Note that the technique of calculating the flexural capacity is not specified in this framework, allowing various evaluation equations. Also, it allows the use of digitized grading, such as 0.25 for Stage IV.

$$\eta_M(x_i, t) = M_u(x_i, t) / M_u(x_i, 0) \quad (2)$$

where $M_u(x_i, t)$ = flexural capacity of section x_i at time t

$M_u(x_i, 0)$ = flexural capacity of section x_i at time t = 0 (initial)

Also, the factor for incorporating the magnitude of the bending moment acting on the section, $\alpha_M(x_i, t)$, is expressed as Eq. (3).

$$\alpha_M(x_i, t) = 1 - W_{corr.} \times M_u(x_i, 0) / M_{max} \quad (3)$$

where W_{corr} = reinforcement corrosion ratio of section x_i at time t (0 – 1)

$M_u(x_i, 0)$ = design bending moment on section x_i (treated as being unaffected by corrosion)

M_{max} = design maximum bending moment of member under analysis

This coefficient is intended to express that a greater bending moment and greater corrosion ratio lead to greater effects, that is, a smaller index of the section. Note that the distribution of acting forces may be changed from that assumed at the time of initial design by corrosion, but it was assumed to remain the same for the sake of simplicity.

The reduction ratio of shear capacity, $\eta_V(x_i, t)$, is similarly defined as follows:

$$\eta_V(x_i, t) = V_u(x_i, t) / V_u(x_i, 0) \quad (4)$$

where $V_u(x_i, t)$ = shear capacity of section x_i at time t

$V_u(x_i, 0)$ = shear capacity of section x_i at time t = 0 (initial)

The coefficient for incorporating the magnitude of the acting shearing force, $\alpha(x_i, t)$, is expressed as Eq. (5).

$$\alpha_V(x_i, t) = 1 - W_{corr.} \times V_u(x_i, 0) / V_{max} \quad (5)$$

where W_{corr} = reinforcement corrosion ratio of section x_i at time t (0-1)

$V_u(x_i, 0)$ = design acting shearing force on section x_i

V_{max} = design maximum shearing force on the member under analysis

A large reduction in one of these section capacities can be a decisive factor for the performance of the section. The structural/durability index of section x_i was therefore expressed in the form of a product as in Eq. (6).

$$id_j(x_i, t) = \{\alpha_M(x_i, t) \cdot \eta_M(x_i, t)\}\{\alpha_V(x_i, t) \cdot \eta_V(x_i, t)\} \qquad (6)$$

(2) Structural/durability performance index of a member

From member j, m sections as mentioned above are selected. In a member, failure of one section can significantly affect the failure of the entire member. It was therefore decided to calculate the structural/durability index of member *j*, $id_j(t)$, by multiplying the indexes of respective sections, $id_j(x_i, t)$, and calculating the geometric mean to eliminate the effect of the number of sections extracted. Note that this index varies depending on the positions of selected sections in a member having a corrosion profile. Though the argument of the Committee did not reach a conclusion on the procedure of selecting sections, it is considered necessary to standardize the procedure, such as to select automatically to a certain extent (at regular intervals along the axis) for structures to be compared.

$$id_j(t) = \left(\prod_{i=1}^{m} id(x_i, t)\right)^{\frac{1}{m}} \qquad (7)$$

(3) Structural/durability performance index of the total system

The presence of significantly deteriorated members may not always have a grave effect on the total system for such reasons as the structural redundancy of a statically indeterminate structure. On the other hand, extraction of critical members and sections is essential from the aspects of the third-party impact performance and repair/retrofitting. For formulating the index, the Committee attempted to select expressions to incorporate the redundancy of the total system, while enabling comparison between the indexes of single members.

When uniting the indexes from members to the total system, coefficients α_{Aj} and α_{Dj} were incorporated. These were adopted respectively to focus on the soundness of structural details including the anchorages of reinforcement and joints of members, and on the proportions of loads borne by members (differences in the magnitudes of action) in the total system. Coefficient α_{Dj} focusing on the load-bearing proportions of members, for instance, is shown in Eq. (8). In other words, this is a coefficient to express that if the load-bearing proportion of member *j* is large in the total system and if its amount of corrosion is large, then its index becomes low to express its strong effect on the performance of the total system.

$$\alpha_{Dj} = 1 - W_{corr.j} \times p_j \qquad (8)$$

Note that there can be a situation where $\alpha_{Dj} < 0$, depending on the load-bearing proportion and corrosion ratio. In this case, α_{Dj} is assumed to be zero, as it means that the member is a key component bearing a large proportion of the loads or its corrosion rate is extremely large.

In this equation, W_{corr} = reinforcement corrosion ratio of member j (0-1)

P_j = proportion of loads borne by member j (when the maximum bending moment acting on member j is 1.2 times that of other members, P_j is 1.2).

Accordingly, the structural/durability performance index of the total system having n members at a given time t in its service life related to safety, $ID(t)$, is expressed as given in Eq. (9).

$$ID(t) = \frac{\sum_j^n \alpha_{Aj} \cdot \alpha_{Dj} \cdot id_j(t)}{\sum_j^n \alpha_{Aj} \cdot \alpha_{Dj} \cdot id_j(0)} = \frac{1}{n} \sum_j^n \alpha_{Aj} \cdot \alpha_{Dj} \cdot id_j(t) \qquad (9)$$

A unified $ID(t)$ incorporating usability and other performances can be obtained by calculating $ID(t)$ for each performance item, multiplying it by a weighting factor (the total of the factors is 1), and adding up all items. The weighting factors can be determined in consideration of the performance items the owner of the structure emphasizes for its control.

4.2 Examples of calculating structural/durability performance index

Figure 8 shows the loading conditions of the structure under analysis. It is a structure having five reinforced concrete simple girders. A concentrated load is assumed to act at the midspan of each girder. The girders from G1 to G5, which are of the same specifications, are connected by a crossbeam located at the midspan of the girders. Note that the crossbeam is assumed to have no defect.

Two cases of calculation were conducted: one where only one of the outermost girders (G1) is deteriorated from the initial sound state ($ID(t)$ = 1) and the other where only the girder in the center (G3) is deteriorated. **Figure 9** shows the corrosion ratio and profile of the deteriorated girder. In this calculation, the reduction ratios of the flexural capacity and shear capacity of each zone are assumed to be equal to the corrosion ratio for the sake of simplicity.

In other words, the capacities of a zone with a corrosion ratio of 20%, for instance, are assumed to be 20% lower than the initial sound state. Also, the proportion of the load borne by the outermost girders is assumed to be 1.2 times those of G2 to G4.

Figure 9 shows the positions of extracted sections for calculating the structural/durability performance index of sections. These are five sections at equal intervals of 3,500 mm along the axis of each girder. **Table 2** gives the results of calculating the structural/durability index of the deteriorated girder. Also, **Tables 3** and **4** give the indexes when G1 and G3, respectively, are deteriorated.

The index of the deteriorated girder, $id_j(t)$, is 0.711. As to the index of sections, that of Section 4 is low, as the action of the bending moment and shearing forces is large on this section and the corrosion ratio is also high. The index of the total system, $ID(t)$, is 0.917 and 0.921 when girders G1 and G3, respectively, are deteriorated, with the difference being not large due to the small difference in the load-bearing ratio of 20%. However, the index is proven to be capable of numerically expressing that corrosion of segments under severe loading conditions adversely affects the structural/durability performance.

Note that the Committee Report describes a series of parametric calculations regarding the effects of load-bearing proportions, corrosion ratios, and positions of selected sections. A number of case studies should be accumulated from now on in regard to the compatibility with actual inspection and the validity of assumption values.

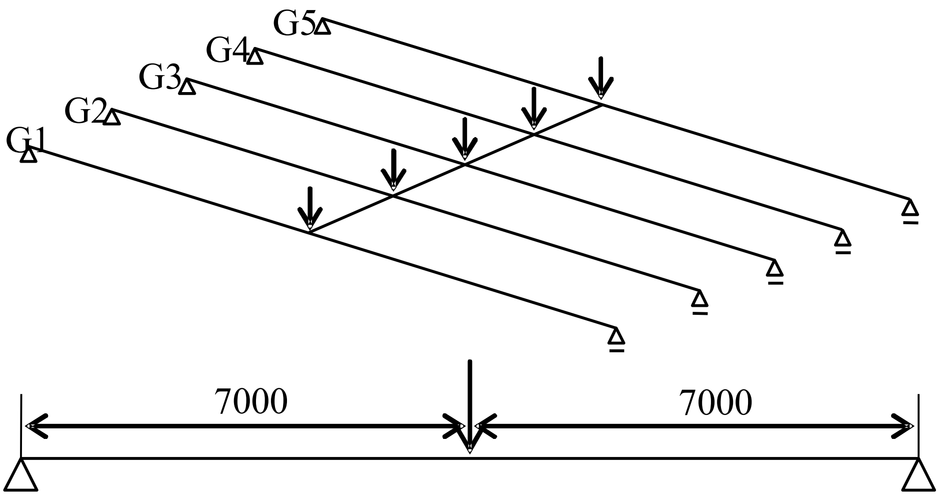


Fig. 9: Arrangement of different corrosion zones in deteriorated girder

Fig. 8: Loading conditions of the structure under analysis (in mm)

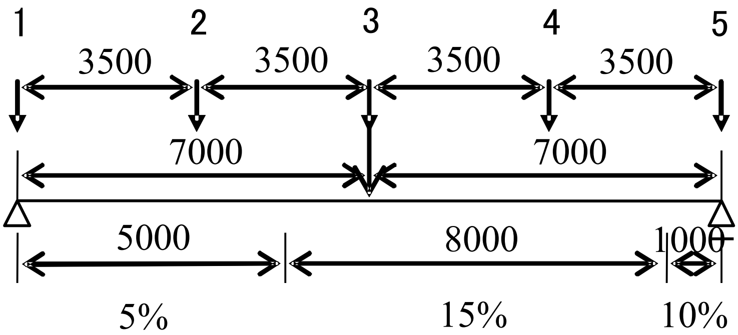


Table 2: Structural/durability index of deteriorated beam

Deteriorated girder	$M(x_i)/M_{max}$	$V(x_i)/V_{max}$	W_{corr}	α_M	η_M	α_V	η_V	$id(x_i)$
Section 1	0.0	1.0	0.05	1.00	0.95	0.95	0.95	0.857
Section 2	0.5	1.0	0.05	0.98	0.95	0.95	0.95	0.836
Section 3	1.0	0.0	0.15	0.85	0.85	1.00	0.85	0.614
Section 4	0.5	1.0	0.15	0.93	0.85	0.85	0.85	0.568
Section 5	0.0	1.0	0.10	1.00	0.90	0.90	0.90	0.729
							$id=$	0.711

Table 3: When G1 is deteriorated

	α_{Aj}	α_{Dj}	id_j	$\alpha_{Aj} \cdot \alpha_{Dj} \cdot id_j$
G1	1.0	0.8	0.711	0.583
G2	1.0	1.0	1.00	1.00
G3	1.0	1.0	1.00	1.00
G4	1.0	1.0	1.00	1.00
G5	1.0	1.0	1.00	1.00
			$ID = \Sigma/n =$	0.917

Table 4: When G3 is deteriorated

Girder	α_{Aj}	α_{Dj}	id_j	$\alpha_{Aj} \cdot \alpha_{Dj} \cdot id_j$
G1	1.0	1.0	1.00	1.00
G2	1.0	1.0	1.00	1.00
G3	1.0	0.9	0.711	0.60
G4	1.0	1.0	1.00	1.00
G5	1.0	1.0	1.00	1.00
			$ID = \Sigma/n =$	0.921

5. Evaluation of repair/retrofitting techniques

The investigation by Working Group 4 included the following: a survey of repair/retrofitting manuals related to steel corrosion; attempts to evaluate the performance of actual structures containing corroded steel and examples of repair/retrofitting; retrofitting effect of members containing corroded steel; and indexes for judging the necessity of retrofitting structures containing corroded steel and selection of repair/retrofitting techniques. Representative results are summarized as follows:

5.1 Attempts to evaluate the performance of actual structures containing corroded steel and examples of repair/retrofitting

The WG conducted a survey of examples of performance evaluation and repair/retrofitting for road structures, port structures, and buildings. As one such example, this section introduces an attempt of new quantitative evaluation for port structures due to spatial limitations.

For reinforced concrete superstructures of piers, repair/retrofitting programs are currently investigated based on visual judgment of the degrees of deterioration (d - a), which are regarded as the evaluations of retained performance. There have been many attempts to numerically evaluate the retained performance of the reinforced concrete superstructures of piers. In most cases, ratings of equal intervals were given to structures under analysis, such as 0, 1, 2, …, by approximately assuming the degrees of deterioration to be an interval scale with assured equality of distance.

Kato et al. collected 40 reinforced concrete members taken from the superstructures of existing piers that were rated as deterioration degrees d, c, b, or a, to investigate the relationship between their deterioration degrees and flexural capacity, thereby grasping the actual reductions in the performance of the pier superstructures[6)]. The results are shown in **Fig. 10**. Though with a significant scatter, there are members with a load-bearing capacity ratio of less than 1.0 among those that were rated as deterioration degrees c to a. In other words, the flexural capacity of reinforced concrete members having visually recognizable defects can be below the initial level by judgment on the safe side. **Figure 11** shows the results of stochastic rearrangement of the above-mentioned relationship for efficient treatment of the scatter of this relationship. This figure can be used to find out the load-bearing capacity ratio of members of each deterioration degree. For instance, 95% of members of deterioration degrees c, b, and a are 0.72, 0.65, and 0.35, respectively.

This simple performance evaluation index is based only on visual deterioration judgment and is no more than a technique for quantifying the ratings of apparent performance expressed as deterioration degrees. However, this index enables numerical comparison among the retained performances of facilities using deterioration degrees, as given in **Table 5** for instance, allowing engineers to determine the priorities of remedial measures for such facilities from the aspect of the progress of deterioration. This is expected to lead to efficient maintenance of the groups of port facilities and structures.

5.2 Effect of retrofitting for members containing corroded reinforcement

Patching, surface overlay, and wrapping with continuous fiber sheets have been widely applied for retrofitting of existing reinforced concrete and prestressed concrete members containing corroded reinforcement. There have been studies in which the effect of transverse restraint by carbon fiber sheets on the flexural deformation properties of beams containing corroded reinforcement was investigated by alternate loading[7),8)]. These studies revealed that certain levels of retrofitting effects can be expected for the purpose of short-term service-life extension, even when corroded reinforcement is used as it is. Points to keep in mind during evaluation have also been gradually clarified.

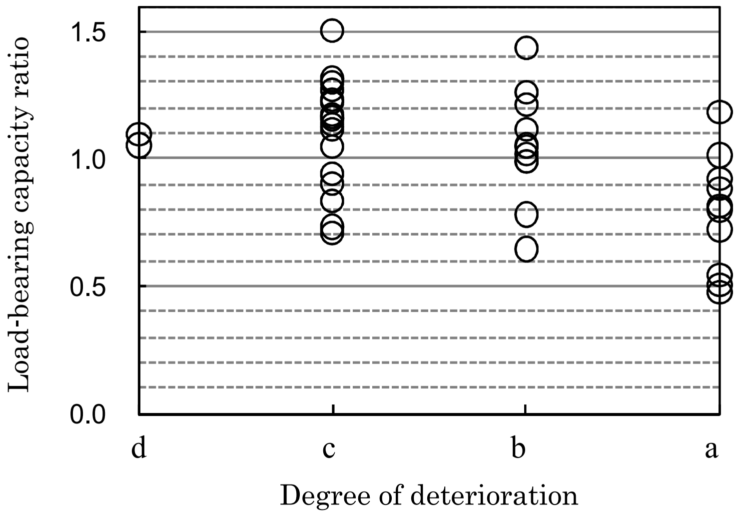


Fig. 10: Deterioration degree related to load-bearing capacity ratio[6)]

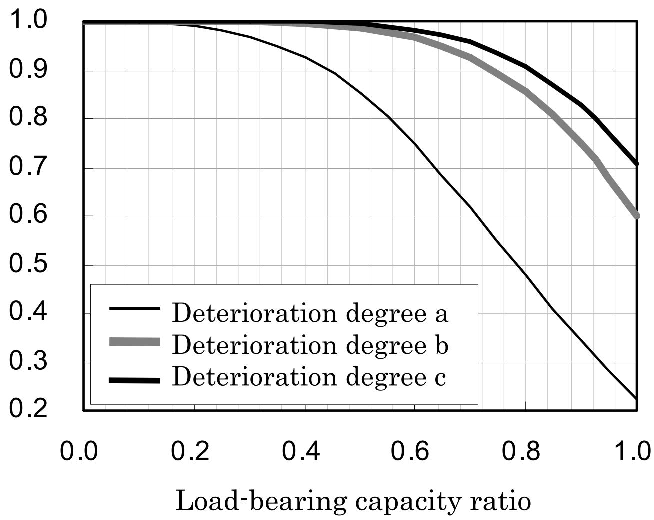


Fig. 11: Probability of load-bearing capacity ratio exceeding x[6)]

Table 5: Minimum expected load-bearing capacity ratio (cumulative probability: 95%)[6)]

Facility	Representative value of deterioration degree		Entire facility		Minimum value in block	
	Beam	Slab	Beam	Slab	Beam	Slab
1	c	c	0.716	0.758	0.709	0.684
2	c	c	0.875	0.885	0.790	0.797
3	c	c	0.697	0.710	0.674	0.696
4	c	c	0.714	0.707	0.703	0.687
5	c	c	0.709	0.705	0.680	0.684
6	c	c	0.695	0.700	0.658	0.678
7	c	c	0.700	0.709	0.663	0.678

6. Conclusions

As a result of its activities over the last 2 years, the present Committee has proposed a technique of utilizing numerical structural analysis as a method of evaluating concrete structures containing corroded reinforcement that is capable of numerically expressing their structural/durability performance on a spatiotemporal scale. It also proposed a framework of a structural/durability performance index. In order to practically use these as estimation techniques, it was found necessary to promote research into problems encountered when passing over discrete input data, which are obtained from inspection, to different spatial scales, while capturing the time-related changes of the scatter. It is also necessary to continue deepening the argument on the quantification of the effect of repair/retrofitting using the structural/durability performance index.

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