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INTEGRITY EVALUATION OF CORRODED REINFORCUNG BAR USED FOR REINFORCED CONCRETE STRUCTURES

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ABSTRACT

In this paper, integrity evaluation method of deteriorated reinforced concrete structures in nuclear power plant was investigated. Reinforcing bar in concrete structures is subject to the risk of corrosion by carbonation and the effect of chloride-laden air. Corroded reinforcing bar causes cracking in concrete cover, while contributing to further steel corrosion. Since reinforcing bars in concrete members bear tensile forces, their corrosion greatly damages the load-bearing capacity of reinforced concrete members. This study aims to investigate changes in the mechanical properties of deformed reinforcing bars of different types and sizes when they are corroded. As a reinforcing bar is corroded and the cross-sectional area is reduced, the yield point linearly decreases. The rate of such reduction is common to all types, being independent of the strength and diameter of the bar. Also the apparent Young's modulus linearly decreases as corrosion proceeds.

INTRODUCTION

Among concrete structures in nuclear facilities, segments in contact with seawater are particularly prone to reinforcing steel corrosion. Reinforcing steel in general concrete structures is also subject to the risk of corrosion by carbonation, the effect of chloride-laden air, etc. Corroded reinforcement causes cracking in concrete cover, while contributing to further steel corrosion. Since reinforcing bars in concrete members bear tensile forces, their corrosion greatly damages the load-bearing capacity of reinforced concrete members. However, there have not been sufficient data as to losses in the strength of corroded reinforcement.

In this paper, integrity evaluation method of deteriorated reinforcing bar used for reinforced concrete structures in nuclear power plant was investigated. In view of the importance of evaluating the degree of deterioration of reinforced concrete structures, relationships should be formulated among the number of years elapsed, t, the amount of action of a deteriorative factor, F, the degree of material deterioration, D, and the performance of the structure, P. Evaluation by *PDFt* diagrams combining these relationships may be effective. In order to evaluate the performance of the concrete structure caused by reinforcing bar corrosion by using the *PDFt* diagrams. The relationships between the degree of reinforcing bar corrosion and strength performance of reinforcing bar should be indicated.

This study aims to investigate changes in the mechanical properties of deformed reinforcing bars of different types and sizes when they are corroded.

INTEGRITY EVALUATION METHOD BY *PDFt* CURVE

A deterioration evaluation diagram, $V(t)$, expressing time-related changes in an evaluation value, V, is assumed as follows:

$$V(t) = \alpha\, v(t) \quad (1)$$

where α is the coefficient, t is time (years), and $v(t)$ is a basic evaluation equation having no parameters other than t. "$v(t)$" is determined beforehand based on past experiment data and analysis results. Evaluation is carried out by determining the evaluation value, V_{eva}, at a desired year, t_{eva}, using the established deterioration evaluation diagram, $V(t)$, and comparing the result with the predetermined specification values (V_{rg}: regulation value, V_{cr}: critical value, etc.). When V_{eva} exceeds V_{rg}, a necessary step may be taken, such as to proceed to the secondary evaluation.

In order to obtain a rational evaluation, the relationships of the deterioration factor and year (*F-t* diagram), the material deterioration and deterioration factor (*D-F* diagram) and the structural performance and material deterioration (*P-D* diagram) should be cleared. A diagram of the evaluation of the deterioration degree of reinforced concrete structures (hereafter referred to as a *PDFt* diagram, Kitsutaka (2010)) is obtained by integrating the above-mentioned evaluation diagrams as shown in Fig. 1. The diagram in the right lower quadrant (level IV), which is determined by plotting several values of t and P in the right upper (level I) and left lower (level III) quadrants, respectively, forms a *P-t* diagram for assessing the time-related changes in the structural performance. This diagram also clarifies the relationships among the physical quantities. Thorough preliminary investigation of the basic evaluation equation for each diagram is necessary as to whether it can be expressed by coefficients given in Figure 1 as α and b regarding its adequacy and accuracy. Examples of parameters are given in Table 1.

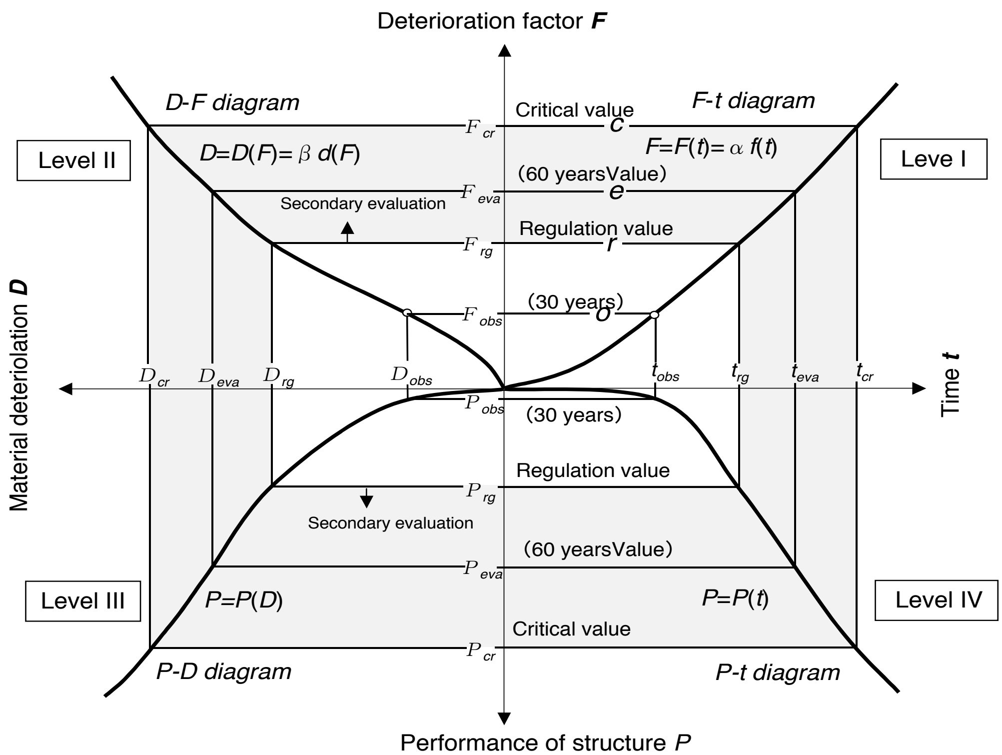

Figure 1: Integrity evaluation diagram of reinforced concrete structures (*PDFt* diagram)

Table 1: Example of parameters

Deterioration factor F		Material deterioration D		Performance of structure P	
F_1	Carbonation(depth)	D_1	Compressive strength	P_1	Stiffness
F_2	Chloride ion	D_2	Young's modulus	P_2	Bearing capacity
F_3	Heating	D_3	Rebar corrosion	P_3	Earthquake response
F_4	Radiation	D_4	Rebar strength	P_4	Constitutive law
F_5	Alcali aggregate reaction	D_5	Tensile strength	P_5	Crack
F_6	Vibration	D_6	Crack resistance	P_6	Bolt strength
F_7	Freeze-thaw	D_7	Bolt corrosion	P_7	Airtightness
F_8	Chemical attack	D_8	Water content	P_8	Permeability
F_9	—	D_9	—	P_9	—
F_0	Others	D_0	Others	P_0	Others

EXPERIMENT OVERVIEW

Specimens

Tables 2 gives the factors and levels of experiments and major mechanical properties of reinforcing bars. Table 3 gives the dimensions and mass of reinforcing bars. The types of reinforcement include the following deformed bars specified in JIS G 3112: SD295A, SD345, SD390, and SD490. D13 bars were tested in regard to SD295A; D13 and D19 in regard to SD 345 and SD390; and D19 in regard to SD 490. Corrosion was induced to a length of 50 mm by electrochemical corrosion. The target losses in the cross-sectional area were in some levels from 0 to 30%. Photo 1 shows a specimen used in the tests. Specimens were threaded bars 600 mm in length. All areas other than the corrosion surface were sealed with silicone and PVC tape.

Table 2: Factors and levels

Factor	Parameters
Strength of the reinforcing bar	SD295A, SD345, SD390, SD490 *1
Diameter of the reinforcing bar	D13, D19, D29, D41 *2
Method of corrosion	Electrolytic corrosion
Length of corrosion (mm)	50
Target of corrosion (%)	0, 2.5, 5, 7.5, 10, 15, 20, 25, 30

*1 Number is a minimum yield strength (N/mm^2), *2 Number is a nominal diameter (mm)

Table 3: Properties of reinforcing bar

Name	Nominal dimension			External diameter (mm)
	Diameter (mm)	Cross sectional area (mm^2)	Unit weight (kg/m)	
D13	12.7	126.7	1.0	14.0
D19	19.1	286.5	2.3	21.5
D29	28.6	642.4	5.0	32.1
D41	41.3	1340.0	10.5	46.3

Center is corroded area

Photo 1: Reinforcing bar specimen

Method of accelerating the corrosion of reinforcement

Reinforcing bars were electrically corroded (Fig. 2) by immersing the test zone in a 3% NaCl solution and applying 30 V constant direct current from a stabilized power supply, with the bar and copper plate serving as the anode and cathode, respectively. Corrosion periods were selected to attain the target cross-sectional losses of reinforcing bars of 2.5, 5, 7.5, 10, 15, 20, 25, and 30%. After the specified corrosion periods, specimens were immersed in a 10% diammonium hydrogen citrate solution to remove rust and subjected to tension tests after measuring the cross-sectional areas.

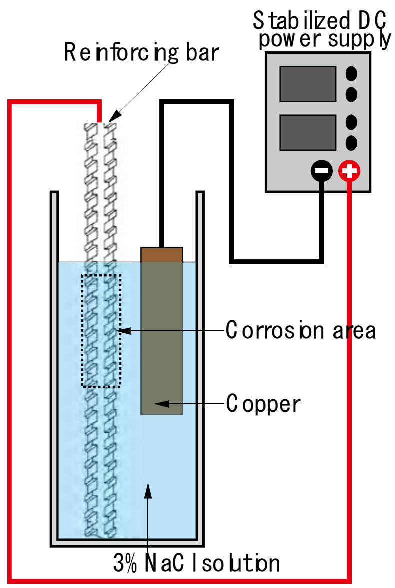

Figure 2: Outline of the corrosion accelerating test

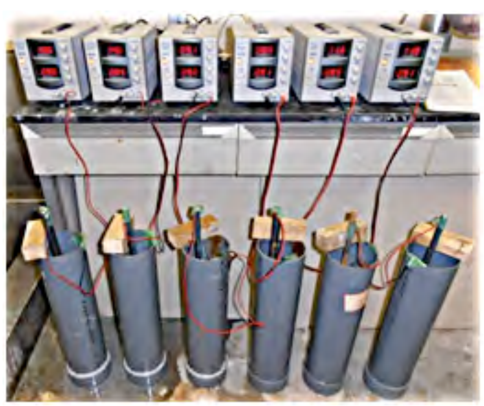

Photo 2: Corrosion accelerating test

Method of measuring cross-sections

Figure 3 shows the equipment for measuring the cross-sections of a specimen. This equipment is capable of measuring the cross-sections of reinforcing bars with a diameter of up to around 50 mm over a span of 100 mm at 0.1 mm intervals using a laser displacement meter. Note that the radial displacement was measured at 0.36° intervals. In this study, the cross-sections were measured at 1 mm intervals in the longitudinal direction.

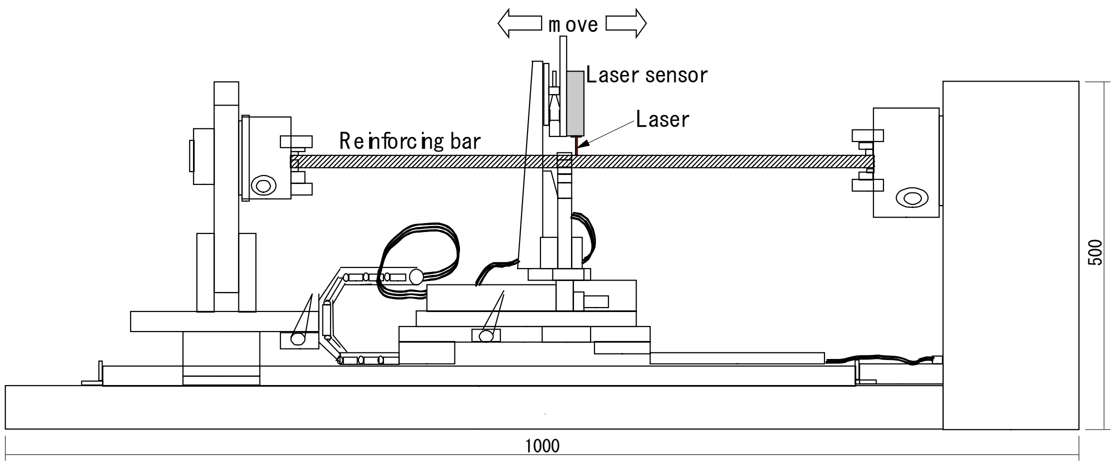

Figure 3: The equipment for measuring the cross-sections of a specimen (unit:mm)

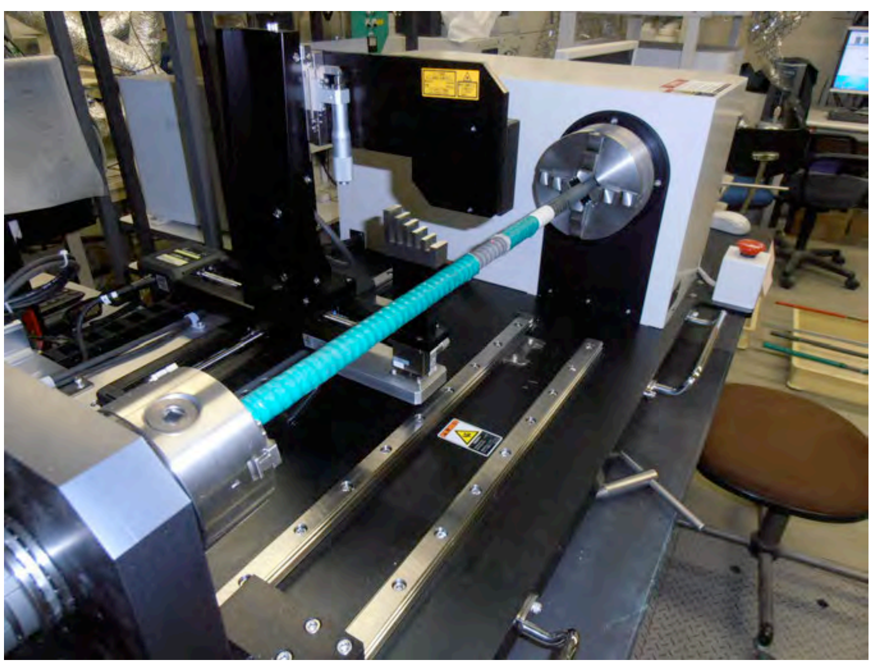

Photo 3: The equipment for measuring the cross-sections of a specimen

Tensile test

After the measurement of cross sections, specimens were subjected to tensile tests using a universal testing machine with a capacity of 1,000 kN. Gauge marks were dented using a punch before testing, with the distance between the gauge marks and longitudinal length of the corrosion test zone being measured using a caliper (Figure 4). The distance between the gauge marks was set at 120 mm. Prior to testing, PVC tape and silicone wound around the specimens for waterproofing were removed to prevent slipping between the chuck of the jig and the bar. Note that the displacement was also measured during testing using a displacement measuring jig and LVDTs as shown in Figure 4.

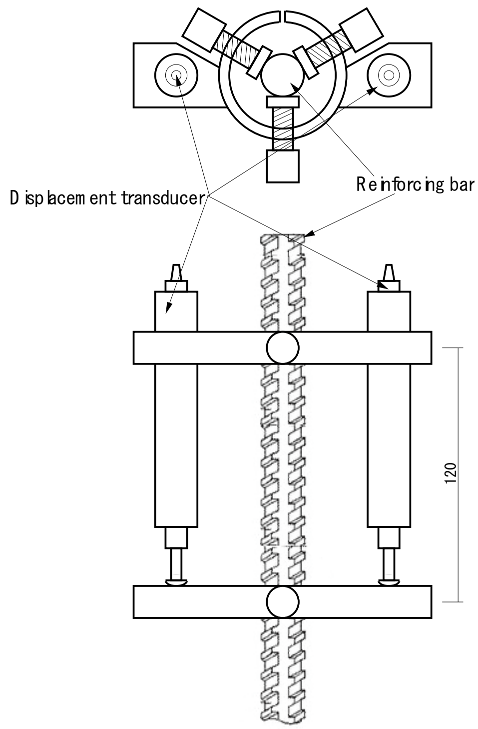

Figure 4: Detail of the jig used for a tensile test

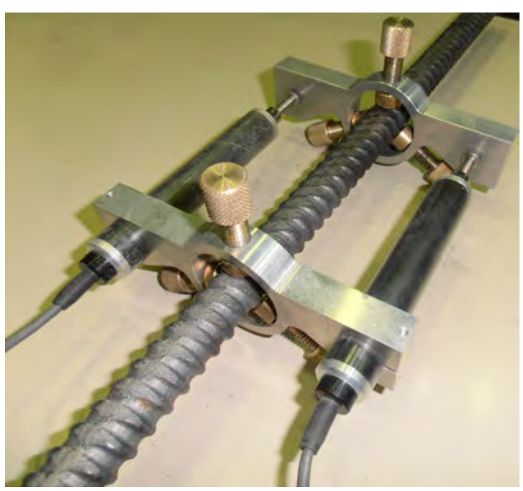

Photo 4: Jig used for a tensile test

RESULTS AND DISCUSSION

Loss in the cross-section due to electrical corrosion

Figure 5 shows a typical result of cross-section measurement. The average cross-sectional area represents the average of the cross-sectional areas measured at 1 mm intervals. The minimum cross-sectional area is the minimum of the measurements. The average corrosion loss ratio is the quotient of the average corroded cross-sectional area divided by the nominal cross-sectional area. The maximum corrosion loss ratio is the quotient of the minimum corroded cross-sectional area divided by the nominal cross-sectional area.

Also, the amount of corrosion per unit area was determined by the equation given below based on the corrosion loss ratio determined from the nominal cross-sectional area and cross-sectional area after corrosion as well as the nominal bar diameter.

$$\Delta C = (D_0/0.51)[(A'/A_0)-1] \quad (2)$$

where, ΔC is an amount of corrosion per unit area (mg/cm^2); D_0 is a nominal diameter; A'/A_0 is a corrosion loss ratio.

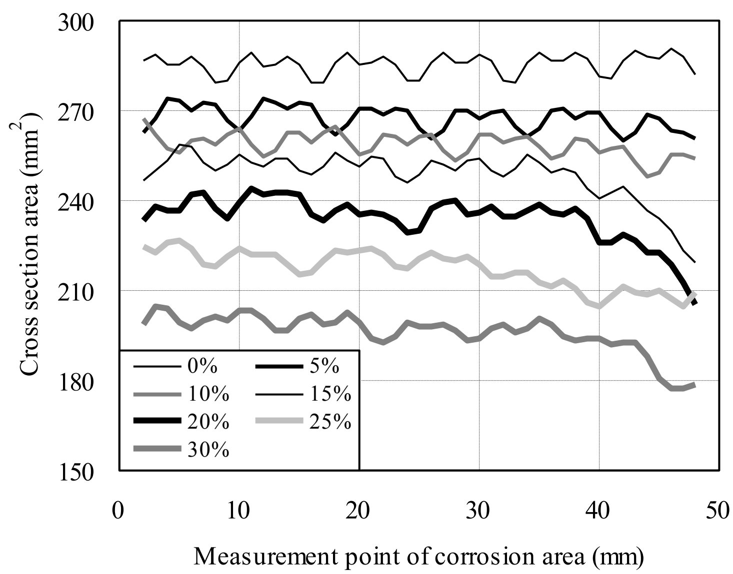

Figure 5: An example of the measurement about the cross section of a reinforcing bar (SD345-D19)

Load-displacement curve

The maximum load and yield point decrease as the corrosion-induced loss in the cross-sectional area of reinforcement increases. The displacement at the maximum load also tends to decrease as corrosion proceeds. Strength is correlated with elongation. Note that the slope toward the yield point of each bar type is nearly constant regardless of the degree of corrosion. The yield strength of reinforcement decreases as the degree of corrosion increases, with the maximum tensile load decreasing as well. Also, the elongation at rupture of bars with a high degree of corrosion is 20 to 40% smaller than that of sound bars, though with a scatter depending on the diameter and yield strength. Therefore, bars with a high degree of corrosion quickly rupture.

Generally speaking, the stress within the cross section of a bar with no corrosion tentatively decreases when the proportional limit is reached, with only the plastic deformation continuing to proceed, while maintaining a constant stress. The amount of deformation during this phase decreased as the corrosion loss ratio increased to nearly 30%. This can be explained as follows: Since corroded cross sections are non-uniformly distributed, the stress is concentrated on the smallest cross section, reducing the total elongation. In response to this, the load necessary for causing the same deformation decreases.

Residual yield stress

Figure 6 shows the relationship between the average corrosion loss ratio and the residual yield stress. Note that the yield points in this figure are apparent values determined by dividing the tensile load by the nominal cross sectional area. A residual yield stress is the value determined by dividing the yield point of corroded reinforcement by the yield point of sound reinforcement. When a reinforcing bar is corroded, with the cross-sectional area being reduced, its yield point linearly decreases regardless of the type and diameter of the bar. Also, the ratio of such reduction is nearly equal to the ratio of cross-sectional loss.

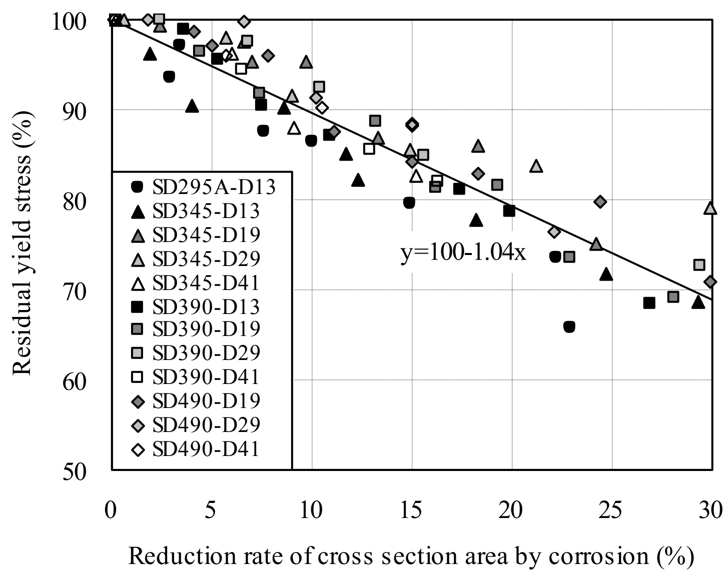

Figure 6. Relationship between the average corrosion loss ratio and the residual yield stress.

Relationship between corrosion loss ratio and Young's modulus

Figure 7 shows the relationship between the average corrosion loss ratio and the residual Young's modulus ratio. In the present tests, the corrosion zone spans 50 mm in the test zone of 120 mm. Therefore, the apparent Young's modulus of the corrosion zone was determined from the equation below based on the load-displacement relationship obtained from the tests. Young's modulus of the sound zones with no corrosion was assumed to be 191.8 kN/mm^2, which is the average of measured Young's moduli.

$$E_2=l_2/(S\times \Delta l/\Delta P-l_1/E_1) \tag{3}$$

where E_1 and E_2 denote Young's modulus of the sound zones and the apparent Young's modulus of the corrosion zone, respectively; l_1 and l_2 denote the lengths of the bars in the sound and corrosion zones, respectively, in the test zone; ΔP denotes the difference between the loads at 1/3 and 2/3 of the yield point; and Δl denotes the difference in the displacements at 1/3 and 2/3 of the yield point.

These figures reveal that the apparent Young's modulus linearly decreases as the corrosion proceeds. Young's modulus of reinforcement is generally assumed to be 20.5 kN/mm^2 regardless of the bar type. However, the total elongation of corroded bars is small due to the non-uniform cross-sectional areas, which cause stress concentration as stated above. It is therefore considered that the load necessary for causing deformation similar to sound bars becomes lower in corroded bars, leading to smaller apparent Young's modulus. Therefore, the greater the corrosion loss ratio, the smaller the Young's modulus, and the lower the bar strength, the greater the rate of reduction in the Young's modulus.

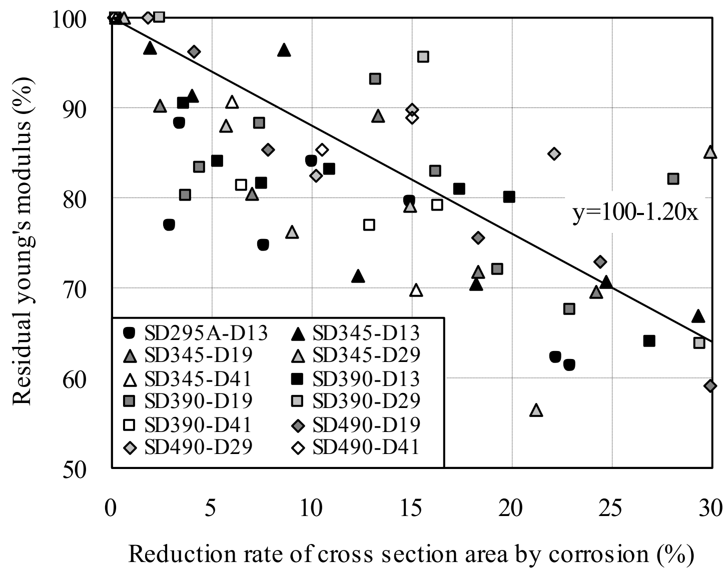

Figure 7. Relationship between the average corrosion loss ratio and the residual Young's modulus

CONCLUSIONS

Findings obtained in this study include the following:

(1) As a reinforcing bar is corroded and the cross-sectional area is reduced, the yield point linearly decreases. The rate of such reduction is common to all types, being independent of the strength and diameter of the bar.

(2) The apparent Young's modulus linearly decreases as corrosion proceeds. The rate of such reduction is common to all types, being independent of the strength and diameter of the bar.

ACKNOWLEDGEMENT

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Kitsutaka, Y. (2010). "Methodology on the Integrity Evaluation in the Aging Management and Evaluation of Reinforced Concrete Structures", AIJ Journal of Technology, NO.32, pp.27-30.