THE EVALUATION OF FLEXURAL STRENGTH OF RC BEAMS DAMAGED BY REBAR CORROSION
Flexural strength of RC beams

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Abstract

This study was carried out to investigate quantitatively the relationship between the degree of rebar corrosion and the flexural strength of RC beams damaged by rebar corrosion. In the experiment, the static loading tests of RC beams were conducted at different degrees of rebar corrosion, which was controlled by an electric supply system. Also, after producing equations for the relationship between both the tensile properties of rebars and bond properties and the corrosion percentage of rebars, finite element analysis was conducted. As a result, it was made clear that the flexural strength of RC beams damaged by rebar corrosion could be practically simulated by FEM using experimentally determined material models representing the bond properties and the mechanical properties of corroded rebars.

Keywords: Rebar corrosion, RC beam, flexural strength, corrosion percentage, FEM

1 Introduction

In order to ensure safety of RC structures whose reinforcing steel has been severely corroded, it is necessary not only to repair the damage appropriately, but also to evaluate strength of RC members according to the degree of rebar corrosion. The effects of rebar corrosion on the strength of RC members reinforced with them can be evaluated by three factors; the losses in the effective cross-sectional area of concrete due to cracking of cover concrete; the losses in the mechanical properties of rebars due to their reduced cross-sectional areas; and the bond strength and rigidity between corroded rebars and concrete. Also, it was confirmed that the strength of RC

members damaged by rebar corrosion can be analyzed by finite element analysis if material models representing the relationships between the degree of rebar corrosion and the bond properties and mechanical properties of corroded rebars can be derived.
The purpose of this study is to investigate quantitatively and experimentally the relationship between the degree of rebar corrosion and the flexural strength of RC beams damaged by rebar corrosion. Also, results of experiment on RC beams damaged by rebar corrosion were compared with the results of finite element analysis.

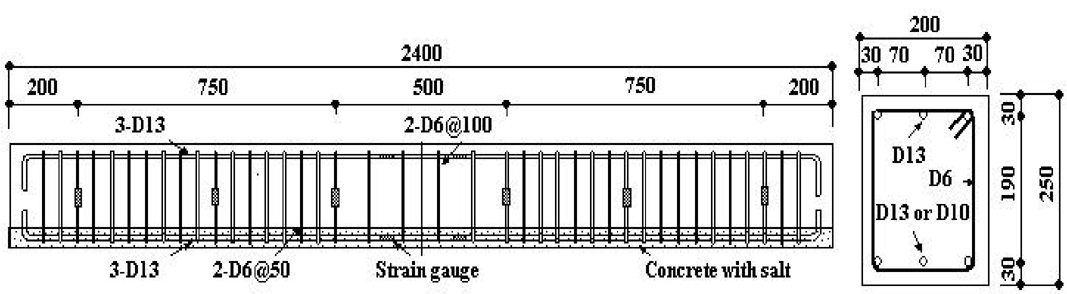
2 Flexural loading tests of RC beams damaged by rebar corrosion

2.1 Experimental procedure

Table 1 shows the types of specimen. In this experiment, three types of specimens were used : sound specimen (BS) ; model specimen with tension rebars of reduced size (BD) ; and corroded specimens which are identical to BS specimen except that their main tension rebars have been corroded in advance by an the electrolytic corrosion method (BCD1-0 corrosion step 1, BCD2-0 corrosion step 2, and BCD3-0 corrosion step 3). The details of RC beams is shown in Fig. 1. The specimens were 200×250×2400 mm in size and the shear span ratio is 3.4.

Table 1: Types of specimen

No.	Symbol	Names of specimen	Tension Main Rebar	Common Data
1	BS	Sound	3-D13 (P_t=0.87%)	Cross section
2	BD	Model	3-D10 (P_t=0.49%)	b x D = 200x250mm
3	BCD1-0	Corrosion 1	3-D13 (P_t=0.87%)	Shear Span Ratio:3.4
4	BCD2-0	Corrosion 2	3-D13 (P_t=0.87%)	Stirrup ratio
5	BCD3-0	Corrosion 3	3-D13 (P_t=0.87%)	D6-@50 (0.64%)



Unit:(mm)

Fig. 1: Details of RC beams

2.2 Materials properties

The mixing proportion and mechanical properties of concrete are shown in table 2. Also, the mechanical properties of rebars are shown in Table 3.

Table 2: Mixing proportion and mechanical properties of concrete

W/C (%)	s/a (%)	Slump (cm)	Unit Weight (kg/m^3) W	C	S	G	σ_c (N/mm^2)	E_c (N/mm^2)	ν
65	45	18	185	285	776	1007	39.2	29419	0.19

Table 3: Mechanical properties of rebars

Type	Yield Strength (N/mm^2)	Tensile Strength (N/mm^2)	Elastic Modulus (Gpa)
D13	343	477	182
D10	289	429	187
D 6	226	415	194

2.3 Corrosion methods of tension main rebars for RC beams

The electrolytic corrosion method is shown in Fig. 2. The level of corrosion was controlled by impressing a direct current of 1A on the specimens for specified periods using a constant electrical current supply. The current was so arranged that the rebar embedded in the specimens and a copper plate, both immersed in water, served as the anode and cathode, respectively. The corrosion percentage was determined by measuring the weight of the rebars after removing the rust with 10% diammonium hydrogen citrate.

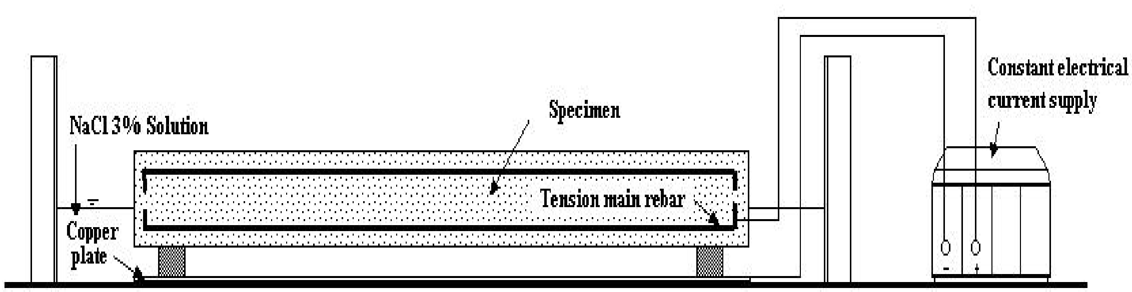


Fig. 2: Electrolytic corrosion method

2.4 Static loading tests and measurement items

In loading the specimen, concentrated loads were applied unidirectionally and monotonically at two points, as shown in Fig. 3. In the tests including sound specimen BS, model specimen BD and corroded specimen BCD1-0, BCD2-0 and BCD3-0, beam deflections at the loading points, strains in the tension main rebar and crack width were measured, and the progress of crack and the condition of crushing failure of concrete were recorded.

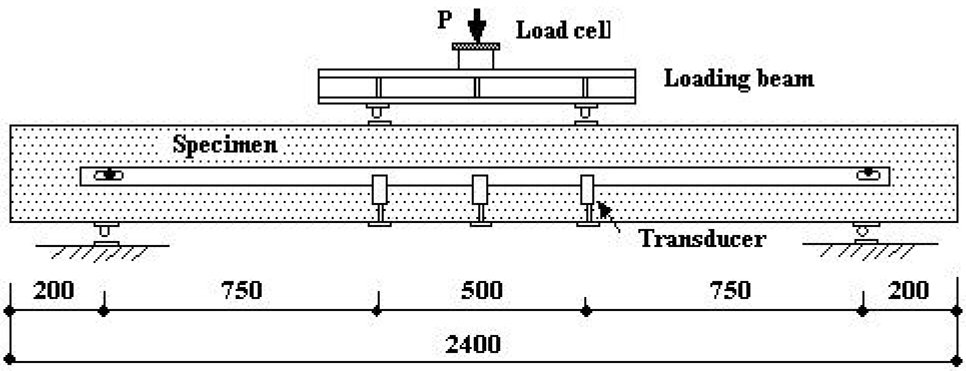


Fig. 3: Static loading test

2.5 Results and discussion

Table 4 is a list of the test results. Fig. 4 gives an overall view of cracking in the specimens observed after carrying out electrolytic corrosion. Mainly cracks alongside the main tension rebar occurred and the corrosion crack width increased with the corrosion level. Also, the rebars had black rust caused by the electrolytic corrosion all over and their surfaces had flake rust and partial losses of the sectional area. Fig. 5 shows cracks observed in the specimens after they failed. The BS and BD specimens collapsed by crushing of concrete after many flexural cracks occurred . The corroded specimens BCD1-0, BCD2-0 and BCD3-0 showed a concentration of flexural cracks in the even bending section. The spalling of concrete at the bottom of the specimen indicated that the bond between tension main rebars and concrete had deteriorated. The load-deflection relationships for specimens are shown in Fig. 6. The maximum strength of BD was 70% that of BS, and the rate of decrease in strength was small for the amount of reduction in the cross-sectional area of rebars. Also, as the corrosion of reinforcing bars progressed, the yield strength and the maximum strength decreased, along with deflection at the maximum strength. Fig. 7 shows the relationship between corrosion percentage (Δw) and the maximum strength ratio (strength of BS / strength of corrosion specimens). As the corrosion percentage increased, the yield strength and maximum strength of the corrosion specimens decreased due to the reduction of sectional area of corrosion rebars, the bond failure of corrosion rebars and the falling of cover concrete.

Table 4: Test results

Symbol	Δw (%)	Cracking Load (kN)	Yield Load (kN)	Maxiumu Load (kN)	Type of Failure
BS	0	22.6 (1.00)	75.5 (1.00)	88.9 (1.00)	Flexure
BD	0	25.5 (1.13)	49.0 (0.65)	62.6 (0.70)	Flexure
BCD1-0	3.8	21.6 (0.96)	71.1 (0.94)	85.4 (0.96)	Bond and flexure
BCD2-0	7.9	20.6 (0.91)	69.6 (0.92)	78.8 (0.89)	Bond of rebar
BCD3-0	25.3	24.5 (1.09)	51.5 (0.68)	67.3 (0.76)	Bond of rebar

Δw : corrosion percentage by weight, (   ) : Strength of specimen / Strength of BS

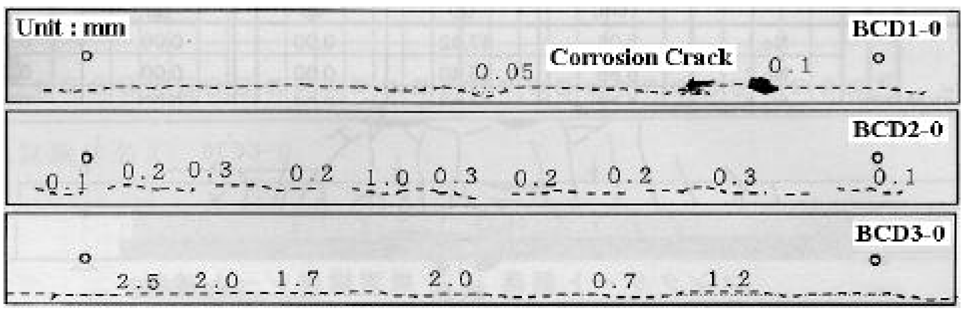


Fig. 4: Cracks in concrete cover due to rebar corrosion

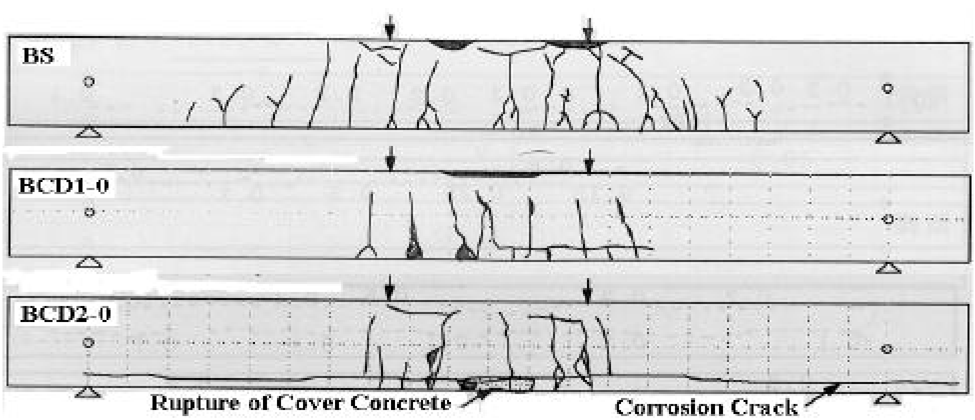


Fig. 5: Cracks patterns of RC beams at failure

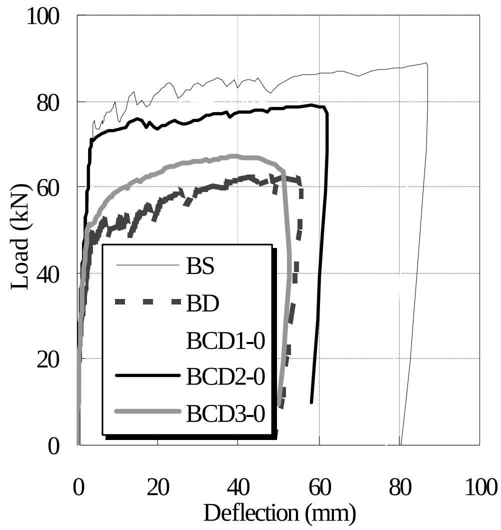


Fig. 6: Load –deflection curves

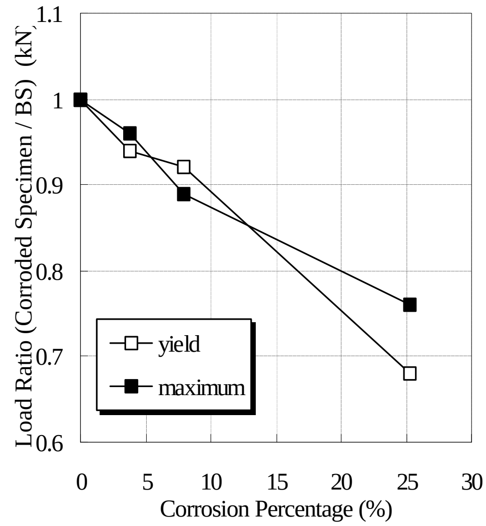
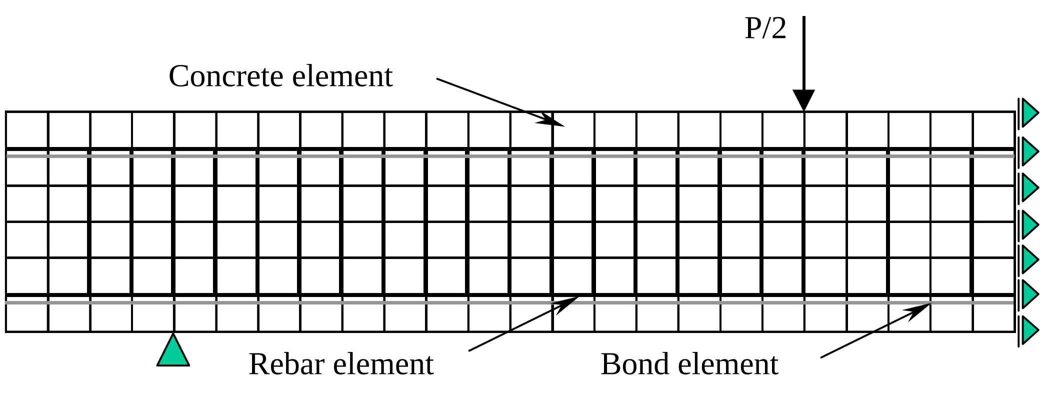


Fig. 7: Relationship between Δw and strength of RC beams

3 FEM analysis of RC beams damaged by rebar corrosion

3.1 Outline of FEM analysis

The specimens analyzed by the finite element method were the sound specimen BS, the model specimen BD and corrosion specimen BCD1-0, BCD2-0 and BCD3-0. Because of the symmetry of the specimens, only the left half of each specimen was analyzed. Each specimen was modeled by dividing the specimen into elements as shown in Fig. 8. The analysis program is a two-dimensional program, which is a type of non-linear analysis program. The displacement-increment method were used for loading.



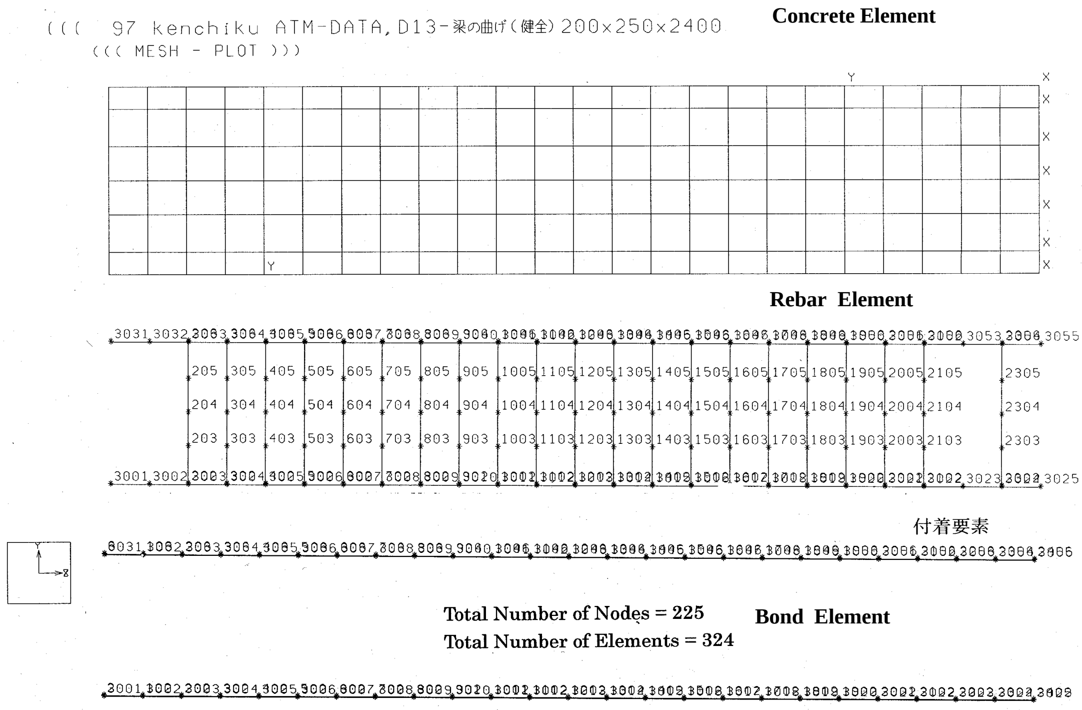
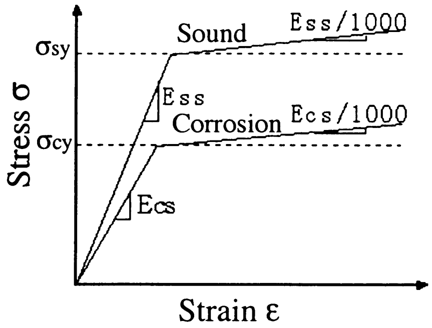


Fig. 8: Finite element meshes for FEM analysis

3.2 Constitutive laws for material elements

1) Concrete elements: Being an isotropic material, 4-node isoparametric plane stress elements were applied. The main input data were compressive strengths, Poisson's ratios and tensile strengths obtained from the experiment.
2) Rebar elements: The bilinear model shown in Fig. 9a is a model available for tension main rebars in an FEM analysis. The main tension rebars and stirrups were expressed by truss elements and the main input data were yield points and elastic modulus of rebars. The mechanical properties of corroded rebars were calculated using the constitutive law based on electrolytic corrosion in Table 5. Accordingly, the constitutive law for rebars can be obtained by determining the yield point and elastic modulus of rebars using the degree of rebar corrosion as a parameter (Δw).
3) Bond elements between rebars and concrete: Bond elements consist of the maximum bond strength (τ_{max}) and bond stiffness (Ds) as shown in Fig. 9b. Accordingly, the constitutive laws for bond elements can be obtained by determining τ_{max} and Ds using the degree of rebar corrosion as a parameter. In the FEM analysis, bond elements were expressed by changing the τ_{max} and Ds. Also, 4-node isoparametric plane bond elements used as the bond elements. Their physical properties were calculated from the corrosion percentage using the equations in Table 6.



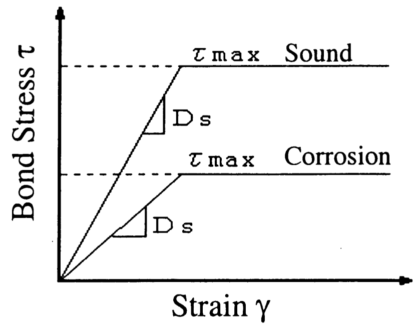


Fig. 9a: Modelling of corrosion rebar **Fig. 9b: Modelling of bond**

Table 5: Equations for mechanical properties of corroded rebar

Properties	Type of Corrosion	Equations
Yield*	Uniform Corrosion	$\sigma_{cy} = (1\text{-}1.24(\Delta w/100))\times \sigma_{sy}$
Strength	Pitting	$\sigma_{cy} = (1\text{-}1.98(\Delta w/100))\times \sigma_{sy}$
Elastic*	Uniform Corrosion	$E_{cs} = (1\text{-}1.24(\Delta w/100))\times E_{ss}$
Modulus	Pitting	$E_{cs} = (1\text{-}1.24(\Delta w/100))\times E_{ss}$

* Nominal values, σ_{sy} : sound rebar, σ_{cy} : corroded rebar

Table 6: Equations for bond properties of corroded rebar

Corrosion percentage (%)	Bond strength (τ_{max}) (Mpa)	Bond rigidity (D_s) (Mpa)
$\Delta w < \Delta w_c$	$\tau_{max} = 0.34\sigma_B\text{-}1.93$	$D_s = 16.5\sigma_B\text{-}160$
$\Delta w \geq \Delta w_c$	$\tau_{max} = 5.21e^{-0.0561\Delta w}$	$D_s = 11600\Delta w^{-1..014}$

σ_B : Strength of concrete, Δw : Corrosion percentage Δw_c : Δw at cracking

3.3 Results of FEM analysis

Fig. 10 shows the measured and analyzed state of cracking after failure. In sound specimen (BS), bending cracks spread over to the shear zone, exhibiting a bending failure mode due to collapse of compressed concrete. In corroded specimen (BCD3-0), however, cracks tended to concentrate on the equal bending moment zone, exhibiting a bonding failure mode associated with widening of axial corrosion cracking due to corrosion expansion of rebars and spalling of cover concrete. Though the FEM analysis results agreed well with the experiment results, a number of cracks appeared along the rebars on the sound beam, while few cracks appeared along the rebars on the beam with corroded rebars. This may be because the bond failure between the rebar and concrete due to rebar corrosion in effect prevented the stress on the rebars from being transferred to concrete.

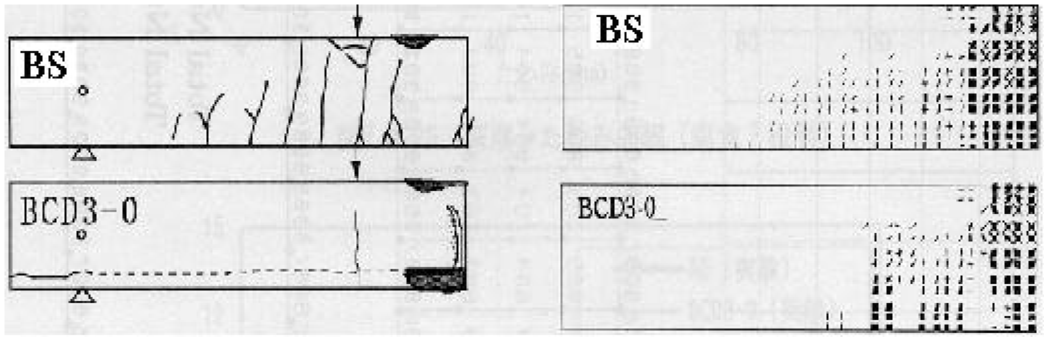


Fig. 10: Crack patterns of RC beams (FEM analysis)

Fig. 11 shows the load-deflection relationships obtained from the loading tests on the reinforced concrete beam and the FEM analysis of sound beam BS and model specimen BD. The analyzed load-deflection relationship agreed well with the static loading test results. Therefore, it can be said that the validity of the input data and the FEM analysis verified. Fig. 12 shows the load-deflection relationships obtained from the loading tests on the reinforced concrete beam and the FEM analysis of corroded beams BCD2-0 and BCD3-0. As a result, the FEM analysis results agreed well with the static loading test results. Accordingly, it is considered that the losses in the structure performance of concrete beams with corroded rebars can be evaluated by an FEM analysis by evaluating the physical properties of rebar elements and bond elements based on the corrosion percentage by weight.

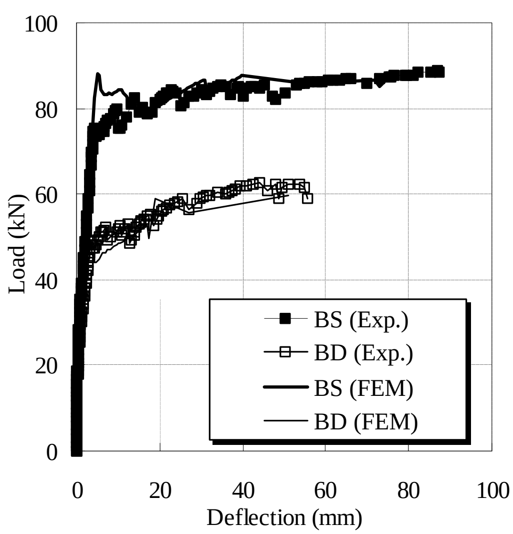


Fig. 11: Load –deflection curves

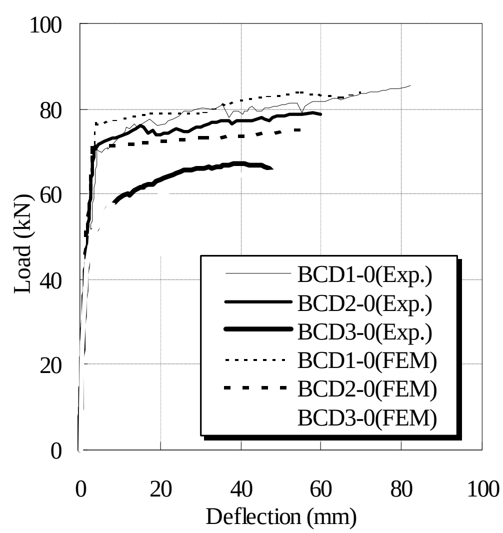


Fig. 12: Load –deflection curves

4 Conclusions

To investigate quantitatively the relationship between the degree of rebar corrosion and the flexural strength of RC beams damaged by rebar corrosion, the static loading test and FEM analysis of RC beams were conducted. The results obtained from these experiments and analysis are summarized as follows :

1) If the main tension rebars of RC beam were corroded, mainly cracks alongside the main tension rebar occurred. Also, the corrosion crack width increased with the corrosion level.
2) As the corrosion of main tension rebars progressed, the yield strength and the maximum strength of RC beams decreased, along with deflection at the maximum strength due to the reduction of sectional area of corrosion rebars, the bond failure of corrosion rebars and the falling of cover concrete.
3) The FEM analysis results of RC beams damaged by tension main rebar corrosion agreed well with the static loading tests results of that. Accordingly, it is considered that the losses in the structure performance of concrete beams with corroded rebars can be evaluated by an FEM analysis, if the mechanical properties of rebar elements and bond elements based on the corrosion percentage by weight can be derived.
4) The subjects to be investigated in the future include the accuracy improvement of the constitutive law for each material changed by corrosion of rebar. Also, the FEM analysis results should be verified with full-scale loading tests not only on RC beams but also on RC column and RC slab.

5 Acknowledgements

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