Structural Performance of Corroded RC Column under Uniaxial Compression Load

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Abstract
It is important to confirm the safety performance of existing reinforced concrete (RC) structures against the seismic load, especially when they are damaged by corrosion. It is considered that strength and deformation capacity of RC column decreases due to the corrosion of main bars and hoops. Until now, many evaluation methods have been proposed for calculating structural performance of non-corroded RC structures. However, no calculation formula or assessment procedure has been proposed to the corroded RC member because of the lack of experimental data and related information. This paper aims to present the fundamental properties of strength and deformation capacity of the corroded RC column subjected to uniaxial compression loading.

In this study, twenty two short column specimens are subjected to axial compression load. The parameters are the corrosion part of reinforcements, simulation method of corrosion and corrosion level. From the test results, it is confirmed that corrosion of the main bars has the influence to reduction of maximum load, and corrosion of the hoops has the influence to deformation capacity after the maximum load. The compressive stress-strain model is proposed using sectional area of corroded reinforcing bars considering the relationship between minimum sectional area and the yield ratio.

Keywords: Corrosion of reinforcement, Electrolytic corrosion, Scraped, axial compression, Confine effect.

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1.0 Introduction

It is important to confirm the safety performance of existing reinforced concrete (RC) structures against the seismic load, especially when they are damaged by corrosion. It is considered that strength and deformation capacity of RC column decreases due to the corrosion of main bars and hoops. Until now, many evaluation methods have been proposed for calculating structural performance of non-corroded RC structures. However, no calculation formula or assessment procedure has been proposed to the corroded RC member because of the lack of experimental data and related information.

For coexistence of maintenance and to reduce a life cycle cost for reinforced concrete structures, research of a decline in structure performance caused by reinforcing bar corrosion has been developed. However, it is difficult to control the quantity of corrosion and a corrosion position caused by a conventional electrolytic corrosion or natural exposure, so it is difficult to evaluate a decline in structure performance quantitatively. To control quantity of corrosion and a corrosion position, authors have tested cyclic loading RC column that simulated corrosion by using a scraped bar and small size round-bar, and evaluated structure performance [1]. In this study, the influence of a corrosion of reinforcing bar on the uniaxial compression property examined using electrolytic corrosion and corrosion simulated scraped reinforcing bar and small size round-bar.

2.0 Outline of Loading Test

2.1 Specimen

An example of specimen and measurement position of axial deformations is shown in Figure 1. List of specimen is shown in Table 1. The cross section of a specimen is 180mm x 180 mm. Height is 660 mm and test region is 360 mm (assumed corrosion region is 200 mm). In addition, the corrosion of hoops is assumed to be occurred in four of the assumed corrosion region. Covered concrete of all specimens are planed to be excluded to get a relationship between stresses and strains of confining concrete in a core section. Parameters of the experiment are a position of reinforcing bar with corrosion being assumed (1 side, 2 sides and entire side), corrosion level (20%, 40%, 60% and 80%) and method of simulated corrosion (electrolytic corrosion, scraped and small size round-bar). The main reinforcing bar is D16, and hoop is D6, however, if corrosion position of hoops occurred in whole section, small size round-bars (ϕ 6, 5, 4, 3) are used depending on the corrosion level of hoops at a corrosion assumed region. The corrosion level is defined as the ratio of minimum sectional size to the maximum one.

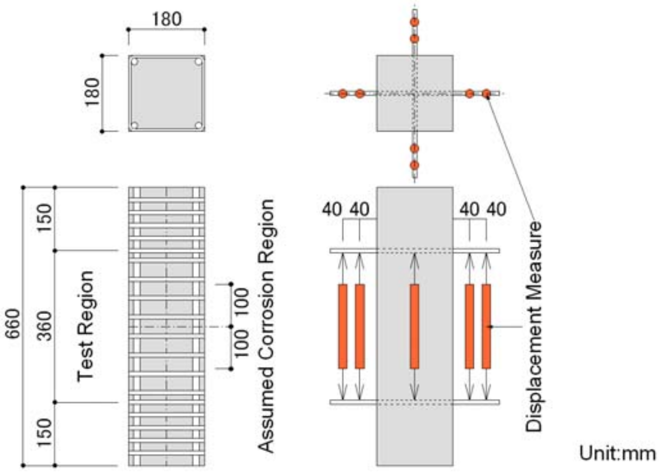
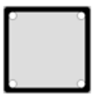


Figure 1. Example of specimen and measurement position of axial deformations

Table 1. List of specimen

Specimen No.	Corrosion of reinforcing bar			
	Main bar	Hoop bar		
	Method (level)	Position	Method	level
1	Non-corroded			
2	Electrolytic (5%)			
3	Electrolytic (15%)			
4	Electrolytic (30%)			
5	None*	Non-corroded		
6	None*	Entire 	ϕ6@49.5	20%
7			ϕ5@46	40%
8			ϕ4@44.5	60%
9			ϕ3@50	80%
10	None*	1 side 	Scraped	20%
11				40%
12				60%
13				80%
14	None*	2 side 	Scraped	20%
15				40%
16				60%
17				80%
18	Scraped (30%)	Entire 	ϕ6@49.5	20%
19			ϕ5@46	40%
20			ϕ4@44.5	60%
21			ϕ3@50	80%
22	None*	Non-corroded		

*ϕ3 bar for assembling are arranged

2.2 The Method of Loading

The monotonic compression loading tests are performed by displacement control using 2MN universal testing machine. Measurement items are axial compression load and axial deformation in four sides of the test region as shown in Figure 1.

3.0 The simulating Method of Corroded Reinforcing Bar

3.1 Electrolytic Corrosion

The electrolytic corrosion method is shown in Figure 2. An external tank is attached at corrosion assumption region and filled with electrolytic solution, which contains 3% sodium chloride (NaCl) by the weight of water. The copper plate is set around specimens in the tank. The current generator is arranged so that four of the reinforcing bar embedded in the specimen serves as anode and the copper plate serves as cathode. The current is controlled with the decrease rate of reinforcing bar to be corrosion level of 5, 15 and 30 percent as a target. After axial loading test, the rust is removed and weight of corroded bar is measured. The actual corrosion showed higher level rather than the target level at main reinforcing bars and hoops in No.2. and two times of the target level in No.3 and 4 in hoops and around half of the target in main reinforcing bar.

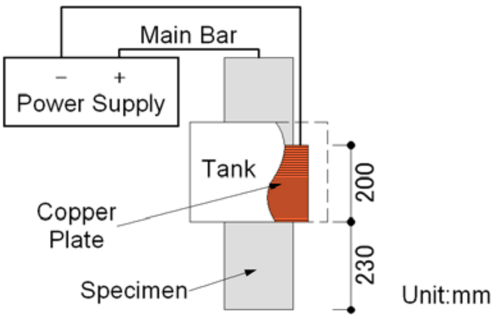


Figure 2. The electrolytic corrosion method

3.2 Small Size Round-Bar

The pitch length of small size round-bars simulates that corrosion on hoops occurred on the entire section, and is adjusted so that hoop ratio for the corrosion level is about the same. In addition, vinyl tapes were used to prevent bonding for the round-bar.

3.2 Scraped Bar

The detail of scraped bar [2], simulating the real corrosion reinforcing bar, is shown in Figure 3. Assumed length of corrosion of D16 scraped bar is 200 mm. The first scraped region is defined as scraping around 15% of whole cutting section in entire assumed corrosion region, and second scraped region is defined as scraping 30% decrease of cross section area locally. In addition, the second scraped area of D16 scraped bar is made every 15mm with 2 places. Assumed length of corrosion of D6 scraped bar is 100 mm, and the corrosion level of the first scraped section area is cut to be as half as the second scraped area. Moreover, vinyl tape is used to prevent bonding.

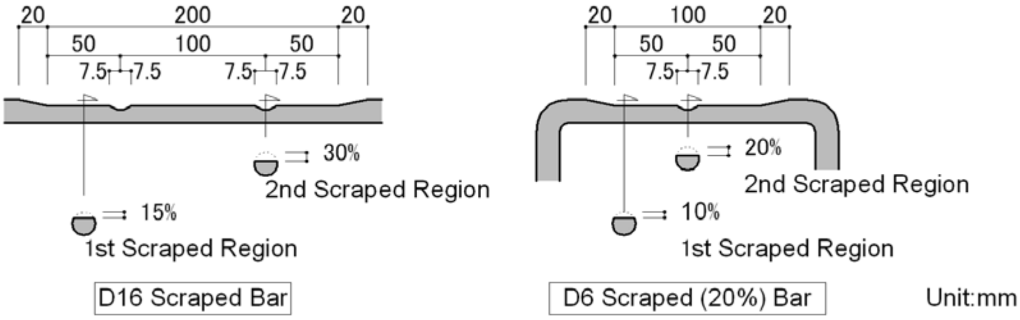


Figure 3. Detail of scraped bar

4.0 Experimental Result

Figure 4. shows the measurement method of strain for tensile tests on the scraped bar. Assumed length of corrosion is 100mm for both D16 and D6's scraped bar. Strain is measured using displacement 1, having test length of 16*d* (*d*: diameter) for D16 scraped bar or 24*d* for D6 scraped bar, displacement 2, having contact length of 50 mm, and strain gage stuck on both sides of the second scraped region (ε_1 and ε_2) and the first scraped region (ε_3 and ε_4) and the scraping starting region (ε_5). Stress is calculated from the tensile load divided by the cross sectional area of nominal value. Displacement 1 strain (D1 strain) is calculated from displacement 1 (Δ_1) divided by the contact length (G_1), displacement 2 strain (D2 strain) is calculated from displacement 2 (Δ_2) divided by the contact length (G_2), and the average strain is calculated from strain gage 1 and 2. Pseudo yield stress and elastic modulus are calculated for each measured region.

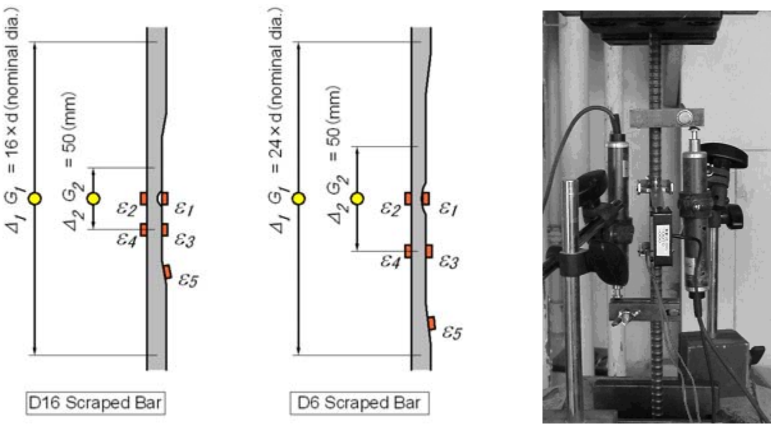


Figure 4. Measurement method of strain for tensile tests on the scraped bar

Table 2 shows the tensile test results for normal reinforcing bar and scraped bar. The mechanical properties of concrete are shown in Table 3. Figure 5. shows the stress-strain relationship of scraped bar measured by displacement 1strain. Mechanical properties of corroded bar such as decrease in strength and elongation with increase in corrosion can be simulated adequately.

For D16 scraped bar, ε_1 at second scraped region yields earlier and lost linearity. ε_2 yields with delay due to bending and the stiffness decreases after yielding. It can be considered to have the strain-hardening behavior at the secondary scrapping region immediately. As the load increases, ε_3 and ε_4 at the first scraped region yields. The first scraped region also reaches strain-hardening after a little yielding stage. ε_5 at scraping starting region yields followed by the previous progress.

For D6 scraped bar with 20% corrosion, similar behavior as D16 scraped bar until yielding at the first scraped region is observed. It is presented that the strain-hardening at the first scraped region is reached after yielding, with no clear yielding stage. ε_5 at scraping starting region yields followed. For D6 scraped bar with 40% corrosion, similar behavior as D16 until yielding at the first scraped region is observed. It ruptured without yielding of ε_5 at scraping starting region after the first scraped region yielding.

For D6 with 60% and 80% corrosion, similar behavior as D16 until yielding at the second scraping region is observed. It ruptured without yielding of ε_3 and ε_4 at the first scraped region after the yielding at the second scraped section. As the yield ratio of non-corroded bar of D6 is 0.69. It ruptures before yielding reaches the non-scraping region.

Table 2. The tensile test results for normal reinforcing bar and scraped bar

Kind of reinforcing bar		Specimen No.	Pseudo yield stress (MPa)			Pseudo elastic modulus (GPa)		
			D1 strain	D2 strain	ε_1,ε_2 average	D1 strain	D2 strain	ε_1,ε_2 average
D16	Non-corroded	1	383			180		
	Scraped (30%)	18～21	314*	290*	214*	147	237	100
D6	Non-corroded	1, 5	419*			171		
		22	378*			162		
	Scraped (20%)	10, 14	404*	400*	349*	165	204	151
	Scraped (40%)	11, 15	317*	299*	240*	136	190	117
	Scraped (60%)	12, 16	240*	212*	143*	74	95	86
	Scraped (80%)	13, 17	51*	-	46*	8	-	60
ϕ6	Non-corroded	6, 18	348*			213		
ϕ5	Non-corroded	7, 19	481*			204		
ϕ4	Non-corroded	8, 20	565*			208		
ϕ3	Non-corroded	9, 21	683*			214		

*0.2% offset strength

Table 3. Mechanical Properties of Concrete

Specimen No.	Compressive strength (MPa)	Eastic modulus (GPa)	Tensile splitting strength (MPa)
1～5	24.2	22.1	2.26
6～22	27.9	23.1	-

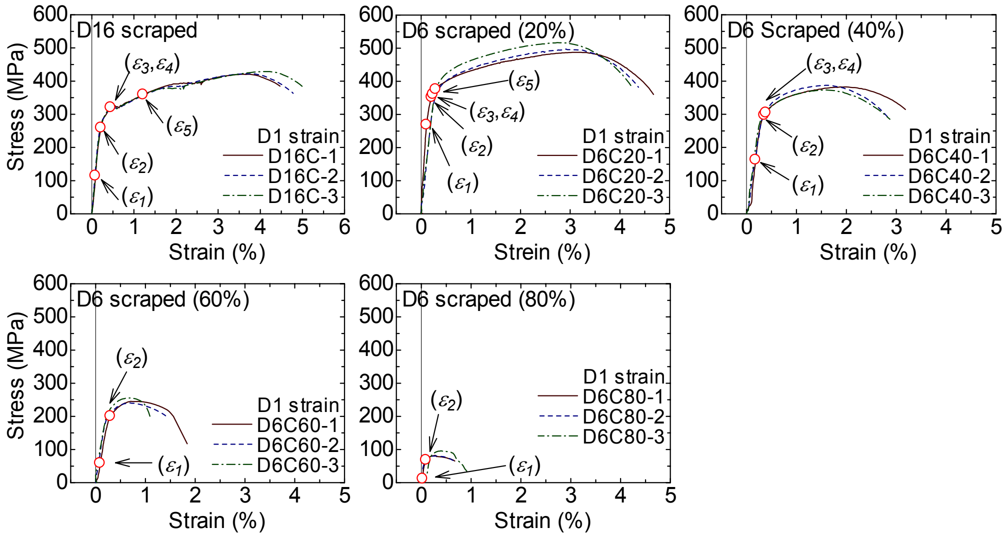


Figure 5. Mechanical properties of scraped bar

5.0 Teat Results

The comparison of relationships between the axial stress and strain for every parameter is shown in Figure 6. The axial stress is divided by compressive strength of concrete.

From specimens, assuming the corrosion in hoops only, some differences are seen in the maximum proof stress depending on corrosion methods. On the other hand, no difference is seen in the maximum stress if corrosion method is the same. However, a significant difference is seen in stress softening area after the maximum stress. Moreover, the strength decline of specimens (No.6-9) being simulating corrosion using small size round-bar with assumed positions of the corrosion being in the entire section increases in proportion to the corrosion level. On other hand, the strength decline of specimens (No.10-17) showed a sudden increase when the corrosion level is over 60%. From the tensile test result of scraped bar, the bar ruptures only by yielding of second scraped region if the corrosion level is over 60%. Therefore, it is considered that enough confining effect can not exhibit without entire yielding of hoop.

For specimens (No.2-4), with main reinforcing bars and hoops corroded by electrolytic corrosion, maximum stress decrease with increase of corrosion. The corrosion of the main reinforcing bar has an influence on the maximum stress, and corrosion of hoops has an influence on stress softening behavior after maximum stress.

In the corrosion level in main reinforcing bar as 30% (No.18-21), and corrosion of hoops using small size round-bar, no difference on the maximum stress is observed regardless of the corrosion level in hoops.

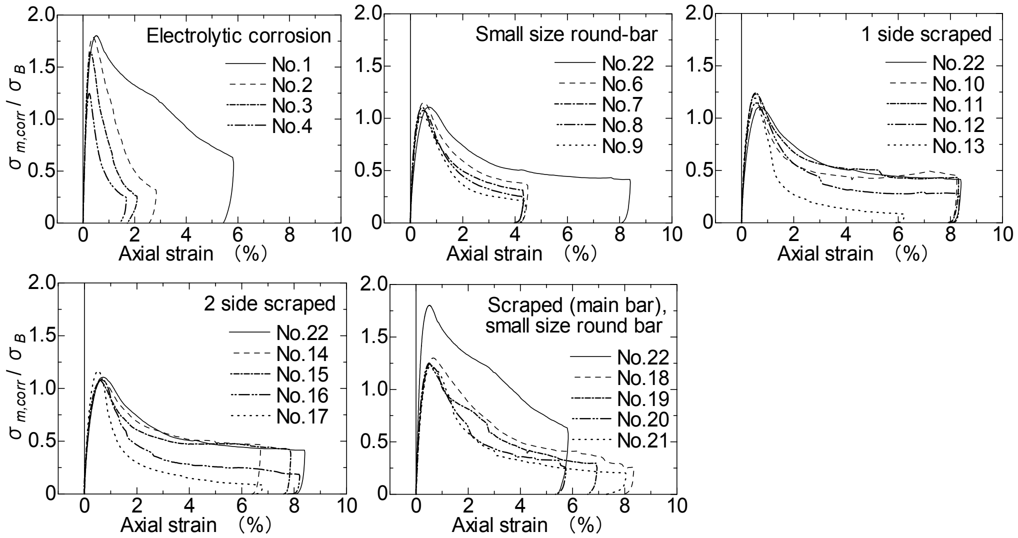


Figure 6. Comparison of relationships between the axial stress and strain

6.0 Modeling of The Relationship Between Axial Stress and Axial Strain

The relationship between stress and strain of specimens (No.6-17) which hoops have corrosion is modeled. The model refers to the past study [3], and is followed Eq. 1 before maximum axis stress. From the relation in figure 7, axial stress is evaluated using Eq. 2 when the axial strain is 2% and axial stress is evaluated using Eq. 3 after 4%, connecting each other with a straight line. Moreover, α in Eq. 2 and 3 can be calculated from the relationships between the yielding ratio and corrosion level in non-damaged bar when assuming corrosion using scraped bar. However, if α is negative or calculating of small size round-bar, let α is 0. Moreover, p_{wc} is calculated using cross-sectioned area of first scraped region. Maximum axial stress is calculated using Eq. 4, 5 and 6 depending on corrosion methods.

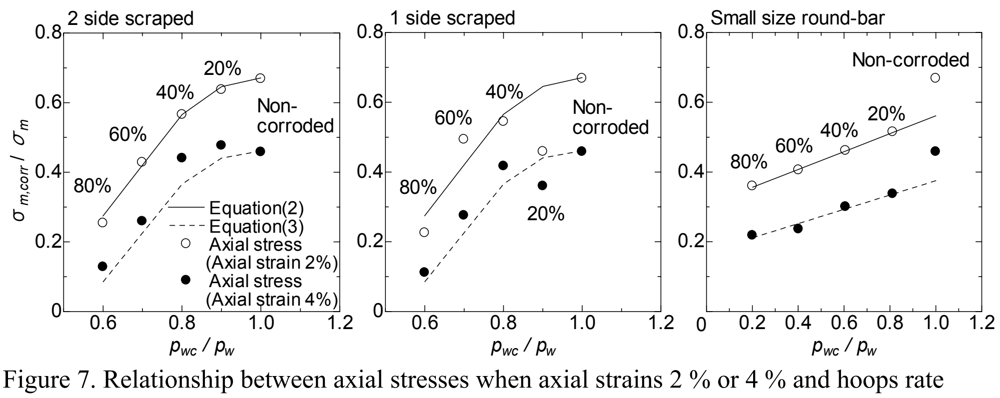


Figure 7. Relationship between axial stresses when axial strains 2 % or 4 % and hoops rate

$$\frac{\sigma}{\sigma_m} = 0.2\left(\frac{\varepsilon}{\varepsilon_m}\right) - \left(\frac{\varepsilon}{\varepsilon_m}\right)^2 \quad (1)$$

$$\frac{\sigma}{\sigma_m} = 0.256\left(\frac{p_w}{p_{wc}}\right) + b_2 - 0.6\alpha \quad (2)$$

$$\frac{\sigma}{\sigma_m} = 0.205\left(\frac{p_w}{p_{wc}}\right) + b_4 - 0.6\alpha \quad (3)$$

where,

ε_m	: axial strain when maximum axial stress (=0.5%)		
σ_m	: maximum axial stress (MPa)		
p_w	: hoop ratio of non-corroded section (%)		
p_{wc}	: hoop ratio of assuming corrosion section (%)		
	$b_2 = 0.305$	$b_4 = 0.17$	(small size round-bar)
	$b_2 = 0.415$	$b_4 = 0.256$	(1 side or 2 side scraped)

$$\alpha = \gamma - \left(1 - \frac{c}{100}\right) \quad (\alpha \text{ is always more than } 0)$$

γ	: yield ratio			
c	: corrosion level (%)			
$\alpha = 0$	(scraped 20%)	$\alpha = 0.09$	(scraped 40%)	
$\alpha = 0.29$	(scraped 60%)	$\alpha = 0.49$	(scraped 80%)	

$$\frac{\sigma_m}{\sigma_B} = 0.24 p_{wc} + 0.99 \quad (4)$$

$$\frac{\sigma_m}{\sigma_B} = 0.12 p_{wc} + 1.15 \quad (5)$$

$$\frac{\sigma_m}{\sigma_B} = 0.12 p_{wc} + 0.99 \quad (6)$$

where,

σ_B : Compressive strength of concrete (MPa)

The comparison of test result with the model prediction is shown in figure 8. Model prediction showed a good agreement with the experimental result with a great degree of accuracy in the stress-softening area after the maximum axis stress.

The applicability of the proposed model will be evaluated with a close investigation on the relation between the actual corroded concrete structure and the property of the assumed corrosion-reinforcing bar used in the experience.

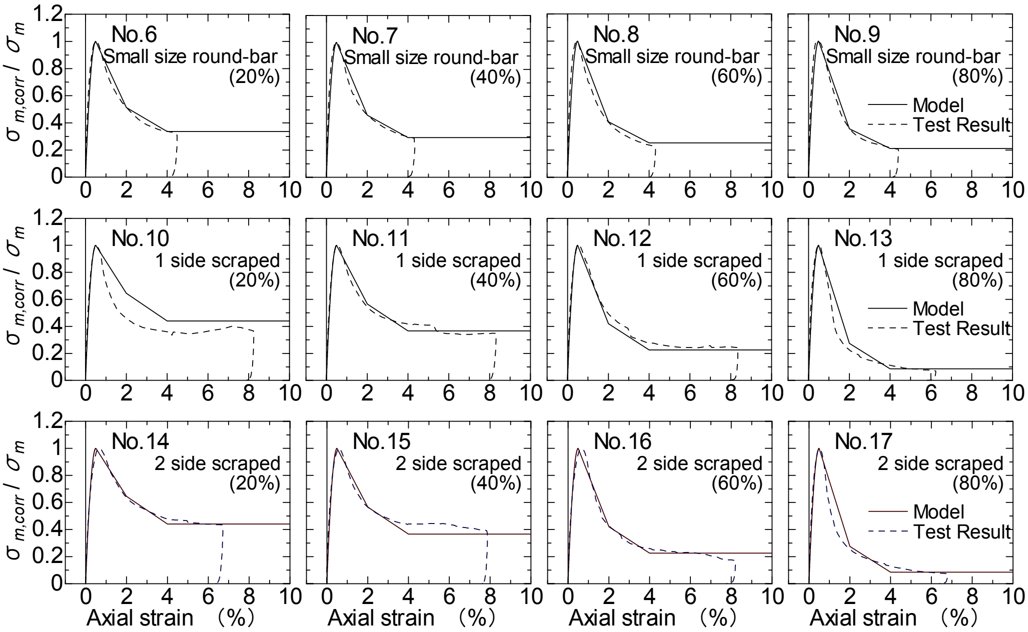


Figure 8. Comparison of test result with the model prediction

7.0 Conclusions

In this study, twenty two short column specimens are subjected to axial compression load. The parameters are the corrosion part of reinforcements, simulation method of corrosion and corrosion level. From the test results, the followings are summarized.

(1) It is confirmed that corrosion of the main bars has the influence to reduction of maximum load, and corrosion of the hoops has the influence to strain softening behavior after the maximum load.

(2) The compressive stress-strain model is proposed using sectional area of corroded reinforcing bars considering the relationship between minimum sectional area and the yield ratio.

8.0 References

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