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UNIAXIAL COMPRESSIVE PERFORMANCE OF RC COLUMNS WITH SIMULATED CRACKS DUE TO CORROSION

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ABSTRACT: The purpose of this study is to evaluate the influence of cover concrete cracks due to bar corrosion on the compressive performance of RC columns. The uniaxial compressive test was conducted using RC column specimens with slits simulating the corrosion cracks. From the test results, it was confirmed that the stress – strain curves after the maximum stress were influenced by the total length of cover concrete cracks and the length of concrete fracture zone. The model of the stress – strain curves for concrete with cracks is proposed based on the test results considering the ratio of the length of cracks and concrete fracture zone to the test length.

1 INTRODUCTION

Recently, the number of RC structures which has passed years from construction has been increasing. Corrosion of the reinforcing bar due to salt injury or carbonization has caused performance degradation of existing RC structures. To manage the maintenance of RC structures in the long term, it is necessary to accurately assess the effects of deterioraion. Corrosion of the reinforcing bars does not only deteriorate themselves performance but also causes concrete cracks due to volume expansion by the corrosion products. Cracks along reinforcing bars have a possibility to lead the degradation of RC structures. Many researches on tensile performance of corroded reinforcing bars have been conducted, but there are few reseaches in which the compression performance is studied. In previous studies (Suzuki et al., 2013), the bending loading test of RC beams with corroded reinforcing bars in compression side was conducted. As a result, compressive performance of RC beams was influenced by cracking of cover concrete due to corrosion of reinforcing bar and buckling of corroded reinforcing bars. The purpose of this study is to evaluate the influence of cover concrete cracks due to bar corrosion on the compressive performance of RC columns. In this study, the uniaxial compressive test is conducted using RC column specimens with slits simulating the corrosion cracks and scraped reinforcing bars.

2 TEST OUTLINE

2.1 Test specimen

The column specimens are shown in Figure 1. The specimens list is shown in Table 1. The cross sectional size of the specimens is 150mm × 235mm. Hoops (D6@30) are arranged in both ends to avoid the failure in these regions. Deformed bar (D10) is used for main reinforcing bars. Concrete cracks are simulated by inserting slits around main reinforcing bars. The polypropylene sheets with thickness of 0.5mm are set in the test region. Variation factors are simulation method of concrete cracks, main reinforcing bars scraping to express the sectional area reduction due to corrosion, and the test length. The variation of the slits is shown in Figure 2. The ratio of total length of slits (L_{cr}) to the test length (L) is varied in each test length specimen. The scraping reinforcing bar simulates the sectional area reduction due to corrosion. The bars are scraped using a disc sander as shown in Figure 1. Scraping is carried out by controlling a scraped depth in the section that regards the minimum diameter direction between lugs of reinforcing bar. The sectional area reduction is set to be 30%. Only specimens with the test length of 150mm have the scraped bars because the reinforcing bars with test length of 400mm are little affected by scraping due to elastic buckling (Kanakubo et al., 2014). The scraped position is varied as central part only, and the parts from the center to 37.5mm upper and lower. Mechanical properties of materials used in test are shown in Table 2 and Table 3.

Table 1. Specimens list

Specimen name	Test length(mm)	Sectional area reduction(%)	Slit direction (perpendicular to)	L_{cr}/L
SN-N0.00	150	-	-	0.00
SN-L0.33	150	-	Long side	0.33
SN-L0.67	150	-	Long side	0.67
SN-L1.00	150	-	Long side	1.00
SN-B1.00	150	-	Both side	1.00
SN-B1.33	150	-	Both side	1.33
SN-B1.67	150	-	Both side	1.67
SN-B2.00	150	-	Both side	2.00
SR-N0.00	150	30	-	0.00
SR-L0.33	150	30	Long side	0.33
SR-L0.67	150	30	Long side	0.67
SR-L1.00	150	30	Long side	1.00
SR-B1.00	150	30	Both side	1.00
SR-B1.33	150	30	Both side	1.33
SR-B1.67	150	30	Both side	1.67
SR-B2.00	150	30	Both side	2.00
MN-N0.00	235	-	-	0.00
MN-L1.00	235	-	Long side	1.00
MN-B2.00	235	-	Both side	2.00
LN-N0.00	400	-	-	0.00
LN-L0.50	400	-	Long side	0.50
LN-L1.00	400	-	Long side	1.00
LN-B1.00	400	-	Both side	1.00
LN-B1.50	400	-	Both side	1.50
LN-B2.00	400	-	Both side	2.00

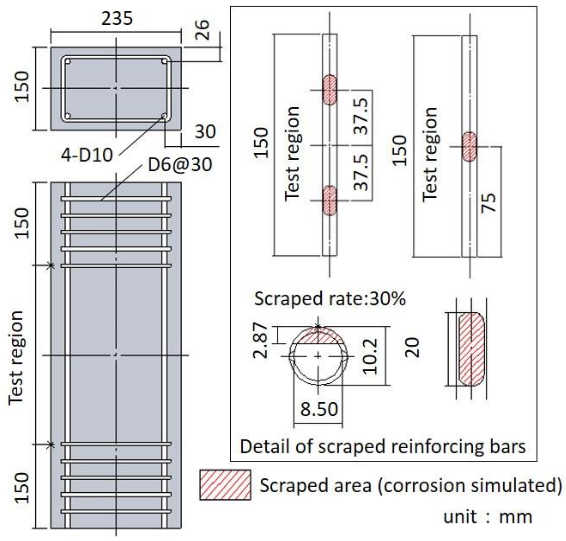

Figure 1. Detail of specimens

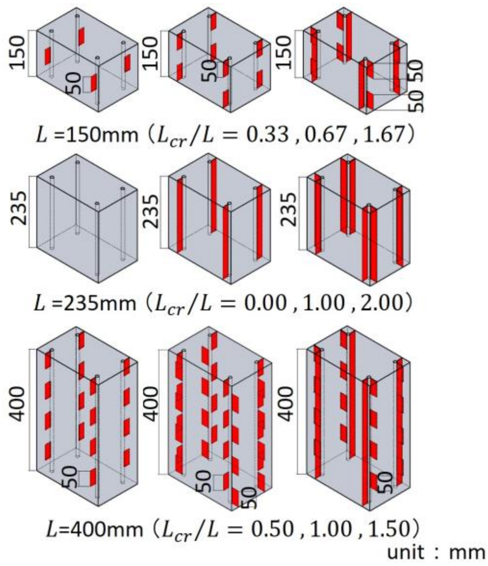

Figure 2. The variation of slits

Table 2. Mechanical property of concrete

Compressive strength (MPa)	Elastic modulus (GPa)	Splitting strength (MPa)
14.1	17.1	1.44

Table 3. Mechanical property of reinforcing bar

Tensile strength (MPa)	Elastic modulus (GPa)	Yield strength (MPa)
468	192	346

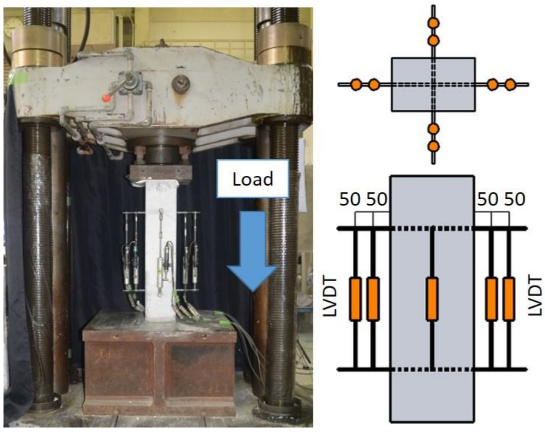

Figure 3. Loading and measurement

2.2 Loading and measurement

Loading and measurement methods are shown in Figure 3. Monotonic compression loading was carried out using a universal testing machine of 2,000kN capacity. Measurement items were compressive force and axial deformations using LVDTs for four surfaces.

3 TEST RESULT

3.1 Failure modes

The examples of the specimens after loading are shown in Figure 4. The maximum load was reached after occurring cover concrete cracks in all of the specimens. The specimens failed after the remarkable load decrement with cover concrete falling. The fracture zone of the specimens with the test length of 150mm and 235mm was mostly the whole of test region of the specimen, while those of 400mm showed a tendency to be fractured in a limited zone. The buckling of reinforcing bars occurred at the position of cover concrete falling.

Table 4. The list of test results

Specimen name	Test length (mm)	Maximum stress (MPa)	Strain at maximum stress (%)
SN-N0.00	150	13.5	0.37
SN-L0.33	150	14.0	0.54
SN-L0.67	150	13.9	0.39
SN-L1.00	150	13.4	0.49
SN-B1.00	150	13.6	0.50
SN-B1.33	150	14.1	0.51
SN-B1.67	150	13.7	0.76
SN-B2.00	150	13.9	0.64
SR-N0.00	150	13.1	0.54
SR-L0.33	150	13.5	0.55
SR-L0.67	150	13.4	0.39
SR-L1.00	150	13.1	0.56
SR-B1.00	150	13.4	0.54
SR-B1.33	150	13.8	0.62
SR-B1.67	150	13.9	0.52
SR-B2.00	150	13.9	0.59
MN-N0.00	235	13.2	0.40
MN-L1.00	235	12.6	0.43
MN-B2.00	235	12.7	0.47
LN-N0.00	400	12.9	0.33
LN-L0.50	400	12.6	0.29
LN-L1.00	400	13.1	0.31
LN-B1.00	400	12.4	0.31
LN-B1.50	400	11.2	0.34
LN-B2.00	400	13.0	0.39

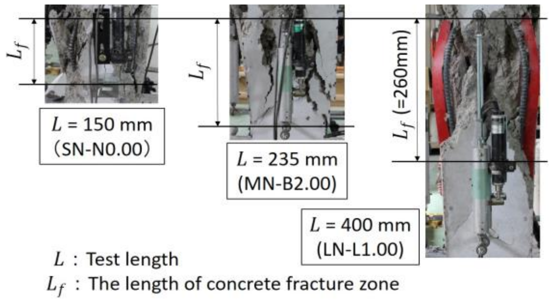

Figure 4. Specimens after loading

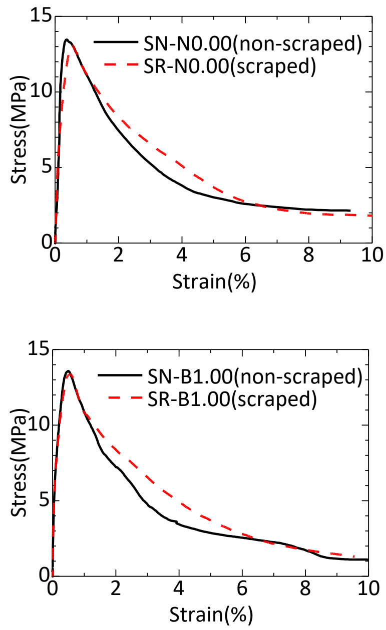

Figure 5. Stress – strain curve compared with scraped or non-scraped reinforcing bar

3.2 Stress – strain curves

The list of test results is shown in Table 4. Stress is determined by dividing compressive force by cross sectional area of the specimens. Strain is calculated by dividing axial deformation in test region by test length.

3.2.1 Influence of scraped reinforcing bar

Examples of stress – strain curves compared with the specimens which have scraped or non-scraped reinforcing bars are shown in Figure 5. Maximum stress is not affected by cross sectional area reduction of scraping reinforcing bars. The stress – strain curves after the maximum stress of the specimens with scraped reinforcing bars show more gradual declivity than those with non-scraped reinforcing bars. It is considered that this shows similar behavior as the buckling of scraped reinforcing bar (Suminokura et al., 2015).

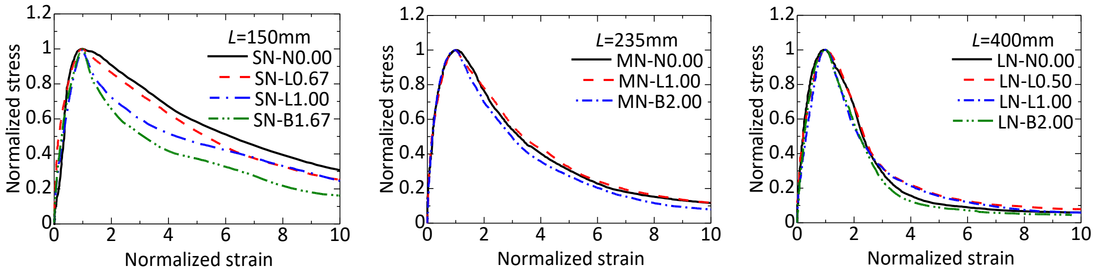

Figure 6. Examples of normalized stress – strain curve compared with variation of slits

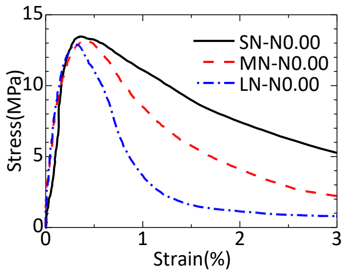

Figure 7. Stress – strain curve compared with test length

Table 4. The list of variables used in modeling of reinforcing bar

L (mm)	L_f (mm)	σ_s (MPa)	ε_s (%)	β
150	150	346	0.85	0.74
235	200	346	0.59	0.98
400	260	307	0.42	1.40

Where, L: test length, L_f: length of fracture zone,

σ_s: buckling strength, ε_s: buckling strain

3.2.2 Influence of slits

Maximum stress is not affected by variation of slits in contrast to a slight difference by test length is recognized as shown in Table 4. Examples of stress – strain curves compared with variation of slits are shown in Figure 6. Stress and strain are normalized by maximum stress and strain at maximum stress, respectively. As the ratio of the total length of the slit to the test length increases, the stress – strain curves after maximum stress become steeper.

3.2.3 Influence of test region

The stress – strain curves of the specimens without slits compared with test length variance are shown in Figure 7. As the test length of the specimen becomes longer, the stress – strain curves after the maximum stress shows steep declivity. It is considered that the localization of concrete fracture zone as shown in Figure 4.

4 MODELLING OF STRESS – STRAIN CURVES

4.1 Modelling of reinforcing bar

The stress – strain model of buckled reinforcing bar after the maximum stress is described by Equations (1), (2) and (3) based on previous study (Suminokura, et al., 2015). The list of variables used in modeling of reinforcing bar is shown in Table 4. In this study, the buckling length of reinforcing bar is assumed to be equal to the length of concrete fracture zone as shown in Figure 4. The length of the concrete fracture zone (L_f) in Table 4 is based on the previous study (Nakamura, et al., 1999). Equation (2) and (3) cannot be applied for the specimens with the test length of 400mm (260mm of fracture zone length) because of elastic buckling. The buckling test was carried out to obtain stress – strain curve of reinforcing bar with the test length of 260mm in the same method in previous study (Kanakubo et al., 2014). The post peak curve of the reinforcing bar with the buckling length of 260mm is also expressed by Equation (1) with the modification of the experimental coefficient β as 1.40.

$$\sigma/\sigma_s = \begin{cases} \text{Non-scraped reinforcing bar} \\ (\varepsilon/\varepsilon_s)^{\beta} \\ \text{Scraped reinforcing bar} \\ (\varepsilon/\varepsilon_s)^{\beta\sqrt{1-\alpha/100}} \end{cases} \tag{1}$$

$$\beta = 0.049(L/D) \tag{2}$$

$$\varepsilon_s = \varepsilon_y e^{21.7/(L/D)} \tag{3}$$

Where, α: reduction ratio of the minimum cross sectional area, D: bar diameter, ε_y: yield strain in tensile test.

4.2 Modelling of concrete

The stress – strain model of concrete is described by Equation (4) based on previous study (Popovics, 1973).

$$\frac{\sigma}{\sigma_c} = \frac{n(\varepsilon/\varepsilon_c)}{n-1+(\varepsilon/\varepsilon_c)^n} \tag{4}$$

Where, σ_c: maximum stress of concrete, ε_c: strain at the maximum stress.

Figure 8 shows the stress – strain curves comparing the influence of coefficient n in Popovics models. It is confirmed that the stress – strain curves after the maximum stress become steeper as coefficient n increases. From the test results, it is considered that coefficient n is varied by increasing the total length of slits and that of concrete fracture zone. Coefficient n of each specimen is calculated by least square method using stress - strain curves of concrete which are obtained by subtracting the stress – strain model of reinforcing bar from the test results of each specimens. Figure 9 shows the relationship between coefficient n and the ratio of the total length of slits to the test length. It is confirmed that coefficient n increases as the test length and the ratio of the total length of slits to the test length increases. To evaluate the influence of localizing concrete fracture, Figure 10 shows the relationship between coefficient n_0 (without slits) and the ratio of the length of the concrete fracture zone (L_f) to the test length. It is confirmed that coefficient n_0 increases as the ratio of the length of concrete fracture zone to the test length decreases. As a result, Equation (5) is derived.

$$n_0 = 1.81(L_f/L)^{-0.84} \tag{5}$$

Where, L_f: length of the concrete fracture zone.

To evaluate the influence of slits, Figure 11 shows the relationship between coefficient n of each specimens normalized by Equation (5) and the ratio of the total length of slits (L_{cr}) to the test length. It is confirmed that n/n_0 increases as the ratio of the total length of slits to the test length increases. As a result, Equation (6) is derived.

$$n/n_0 = 0.071(L_{cr}/L)+1 \tag{6}$$

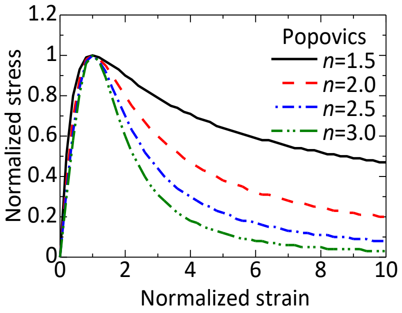

Figure 8. Stress – strain curves comparing the variation of coefficient *n*

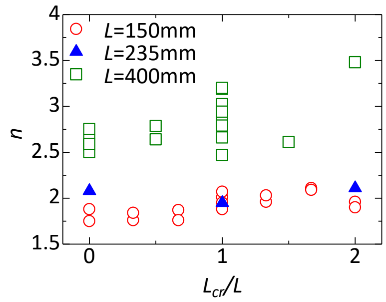

Figure 9. Relationship between coefficient *n* and the ratio of the total length of slits to the test length

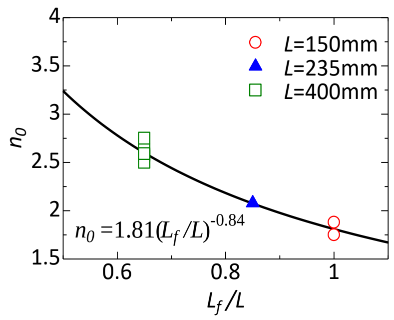

Figure 10. Relationship between coefficient n_0 and the ratio of the length of concrete fracture zone to the test length

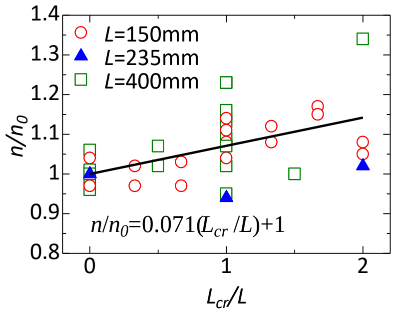

Figure 11. Relationship between n/n_0 and the ratio of the total length of slits to the test length

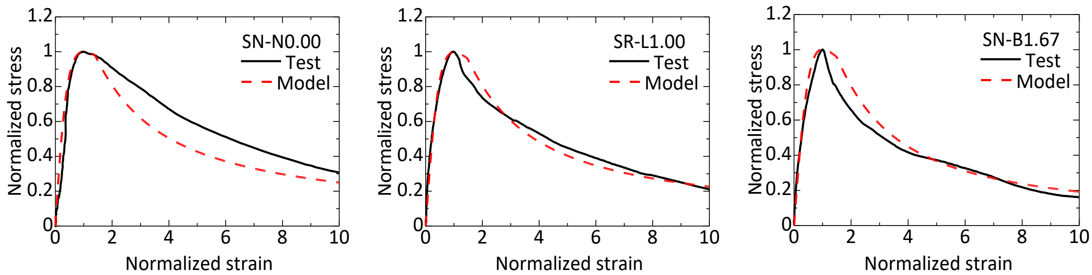

Figure 12. Comparisons of the test results and proposed model (*L*=150mm)

Where, L_{cr}: total length of slits simulating concrete cracks.

Thus, Equation (7) is obtained from Equations (5) and (6).

$$n = \frac{0.13\left(L_{cr}/L\right)+1.81}{\left(L_f/L\right)^{0.84}} \tag{7}$$

4.3 Comparison of test results and model

The stress – strain model of RC column is calculated by summation of the stress – strain models both of reinforcing bars and concrete. Comparisons of the test results and proposed model are shown in Figure 12 and Figure 13. Stress and strain is normalized by the maximum stress and strain at maximum stress of each specimen, respectively. The proposed models can express the test results for simulating the stress – strain curves.

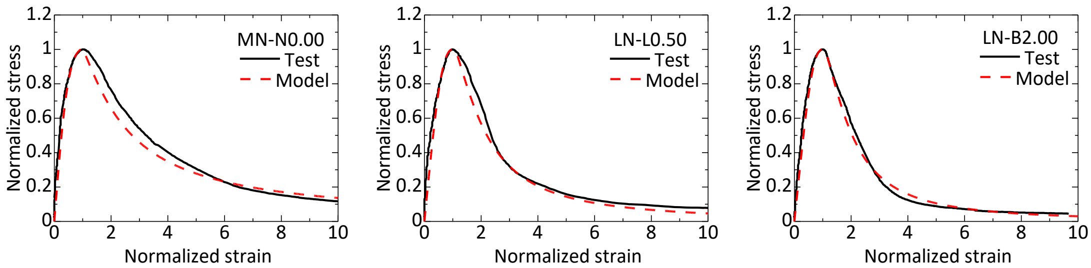

Figure 13. Comparisons of the test results and proposed model (*L*=235mm, 400mm)

5 CONCLUSION

The uniaxial compressive test was conducted using RC column specimens with slits simulating the corrosion cracks. The stress – strain curves were modeled based on the test results. The followings are concluded.

(1) The maximum stress is not affected by the slit simulating concrete cracks and scraped reinforcing bars which simulate corroded bars.
(2) The stress – strain curves after the maximum stress show steeper declivity caused by slits and localizing of concrete fracture.
(3) The proposed model using the ratio of the total length of slits and that of concrete fracture zone to the test length can express the test results for simulating the stress – strain curves after maximum stress.

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