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Shear failure behavior of RC beam with corroded shear reinforcement

Ryosuke Takahashi[1]

[1] *University of Yamanashi, Japan*
[*] *Takeda 4-3-11, Kofu 400-8511 Japan, rtakahashi@yamanashi.ac.jp*

ABSTRACT

Because shear reinforcement is located closer to a surface of a concrete member, corrosion of the shear reinforcement develops faster and becomes heavier than the main reinforcement. Therefore it is also important to clarify an influence of the corroded shear reinforcement to the shear capacity and an evaluation method of that capacity. Many studies have investigated the shear capacity of RC beam with the corroded shear reinforcement. However, the effect of corroded shear reinforcement is not clarified enough. In this study, only the shear reinforcement is corroded and static loading experiments are conducted with RC beams having that reinforcement. The effect of corroded shear reinforcement and the evaluation method of the shear capacity of the RC beam with that reinforcement are investigated in this study.

Keywords. Corrosion, Shear capacity, Shear reinforcement

INTRODUCTION

Generally, shear-reinforcing bars are located closer to a surface than tensile main bars in RC members such as the beam, the pier and so on. The corrosion on the shear reinforcement starts faster and grows heavier than that on the main reinforcement. Therefore, it is important to clarify the influence of corroded shear reinforcement to the shear resistance mechanism to establish the evaluation method for the shear capacity of corroded RC beam.

The truss theory or the modified truss theory are now applied to evaluate the shear capacity of a RC beam with the shear reinforcement in design codes. In this theory, the contribution of the shear reinforcement to the shear resisting force is considered as an independent term. Therefore, if the corrosion does not affect to the failure mechanism and does not collapse the truss mechanism, the truss theory with a reduced shear reinforcement ratio can evaluate the shear capacity of RC beam with the corroded shear reinforcement.

Many studies have investigated about the influence of the corrosion to the shear failure behaviour. There are many studies about the influence of corroded tensile main bars or the influence of combination with corroded tensile main bars and shear reinforcing bars and the effect of the corroded shear reinforcement is not investigated enough. In this study, only shear reinforcing bars are corroded and loading experiments of RC beams with those corroded bars are conducted to clarify the effect of the corroded shear reinforcement to the shear resistance of the beam and verify the application of truss theory to RC beam with the corroded shear reinforcement.

OUTLINE OF EXPERIMENT

Two series of specimens that had the different shear reinforcement ratio were prepared. Figure 1 and Table 1 show the outline of test specimens. Each series includes a non-corroded specimen and corroded specimens. Electric corrosion was used to corrode shear-reinforcing bars (Figure 2). Stainless steel plates were used as the electrode and attached on side surfaces of RC beams. Cotton mats containing 10% NaCl solution were located between the specimen and the electrodes to lead electricity. Only shear-reinforcing bars in the target shear span were corroded. All reinforcing bars except the target bars were coated by epoxy resin to avoid corroding. Target corrosion ratios of the shear reinforcement are 10% and 30% as the average weight loss of reinforcing bars. S4010 that is the specimen with 10% corrosion and 80mm spacing of shear-reinforcing bars was also prepared, but this study does not discuss about the result of that specimen because only bottom parts of the shear reinforcement hoops were corroded.

The loading method was the monotonic loading with boundary conditions of the simple beam (Figure 1). Steel plates at loading and supporting points were 80mm wide and 30mm thick. The vertical displacement at the center of span in a beam was measured with displacement transducers.

CORROSION CONDITION

The corrosion ratio of specimens was measured by two ways. A shear reinforcement hoop was cut into 6 pieces and the weight loss of each piece was measured (Figure 1). The corroded cross sectional area was also measured by a vernier caliper at 10 mm intervals. The

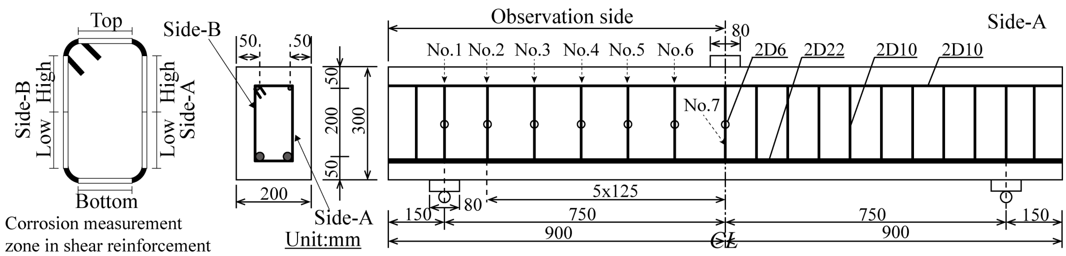

Figure 1. Test specimen and corrosion zone

Table 1. Test specimen

Specimen	a/d	Shear reinforcement			f_c'
		Ratio	Spacing [mm]	Target corrosion ratio [%]	[N/mm^2]
S2400	3.0	0.24	125	-	49.1
S2410				10	46.9
S2430				30	49.3
S4000		0.40	80	-	48.3
S4030				30	50.8

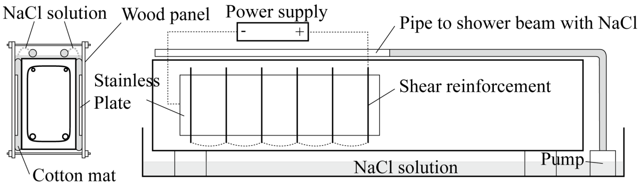

Figure 2. Shape and size of test specimen

Table 2. Weight loss ratio

Specimen	Average [%]	Maximum [%]	Maximum Position
S2410	7.9	15.3	Side-B No.6 Upper
S2430	38.1	47.8	Side-A No.4 Lower
S4030	27.7	48.6	Side-B No.6 Upper

Figure 3. Appearance of rupture in shear reinforcement

Table 3. Maximum loss ratio of cross sectional area

Specimen	Side	Maximum loss ratio of cross sectional area in each shear reinforcing bar [%]									
		No.1	2	3	4	5	6	7	8	9	10
S2410	Side A	-*	15.6	8.5	10.6	9.8	-	-	-	-	-
	Side B	-*	21.2	16.5	15.4	9.8	-	-	-	-	-
S2430	Side A	26.1	100	85.2	91.5	60.8	59.9	35.1	-	-	-
	Side B	27.2	61.0	88.7	66.0	44.2	51.2	23.2	-	-	-
S4030	Side A	23	33.2	44.9	43.6	32.8	33.7	39.7	37.2	18.9	8.0
	Side B	49.4	57.5	100	100	100	67.7	65.9	54.2	31.4	23.3

* not measured

corroded cross sectional area was an average of three different diameters at a section.The rupture was observed in some reinforcing-bars of heavy corroded specimens, S2430 and S4030 (Figure 3). It is difficult to judge whether the corrosion or the loading causes the rapture because the corrosion situation was observed after the loading experiment. In this study the shape of the ruptured cross section was used for that judgment. The round shape of the raptured bar is due to corroding. It was concluded that the rapture of reinforcement No.2 in A-side of S2430, reinforcement No.4, 5 and 6 in B-side of S4030 were caused by the corrosion. In this study, the corrosion ratio given by the weight loss is defined as the weight loss ratio and the ratio given by the cross sectional area loss is defined as the cross sectional area loss ratio.

The weight loss ratio and the minimum cross sectional area measured are shown in Table2, Table 3 and Figure 4. Distributions of the weight loss ratio display that all specimen has relatively uniform corrosion among shear reinforcing bars. The weight loss ratio of the bars

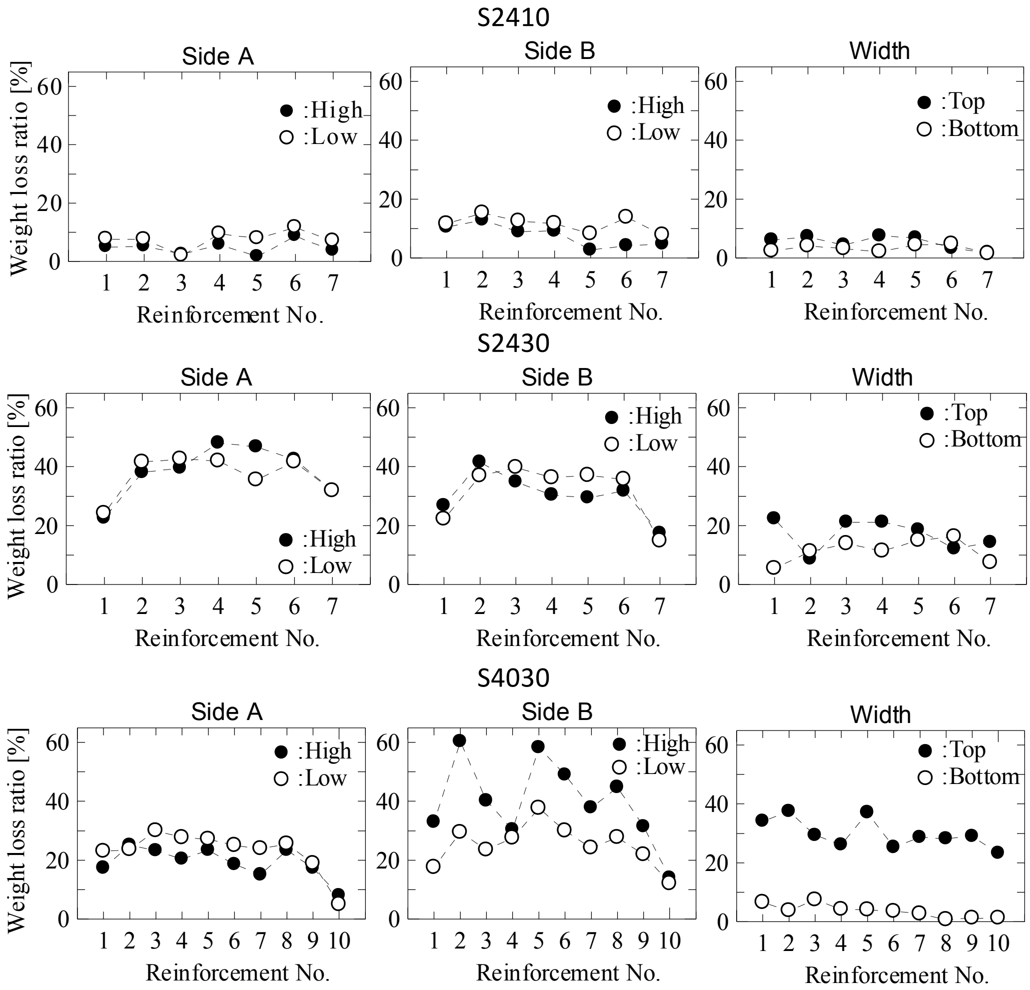

Figure 4. Distribution of weight loss ratio of shear reinforcement

near the support and the loading point is smaller than other bars because the both ends of the electrode plate are located near the loading point and the support point. The maximum cross sectional area loss ratio in a bar shows heavier corrosion than the weight loss ratio. This means that heavy corroded sections exist locally in a reinforcing bar.

Corrosion cracks appearing on a side surface of a specimen (dash lines in Figure 6) are along to the direction of the shear reinforcement in the light corroded specimen, S2410. The crack patterns in the cases of heavy corrosion are different from the case of light corrosion. Long inclined cracks were appeared. Development of crack planes parallel to the side surface of the beam causes a peeling of cover concrete. An out-of-plane deformation of the cover concrete caused by the peeling leads the inclined cracks.

EXPERIMENTAL RESULT

All specimens showed the shear failure in loading experiments. Table 4 shows experimental results and Figure 5 shows load-displacement relationships. Load-displacement relationships of all specimens show the sudden drop of load. Ultimate shear force of the heavy corroded specimens is reduced by the corrosion. On the other hand, the light corroded beam, S2410

Table 4. Loading experiment results

Specimen	Diagonal cracking shear force V_c [kN]	Ultimate shear force V_u [kN]	Degradation ratio of V_u V_{u30}/V_{u00}	Failure mode
S2400	78.4	137.2	1.00	Shear tension
S2410	73.5	137.9	1.01	Shear tension
S2430	80.9	127.3	0.93	Shear compression
S4000	73.5	167.4	1.00	Shear tension
S4030	73.5	107.3	0.64	Shear tension

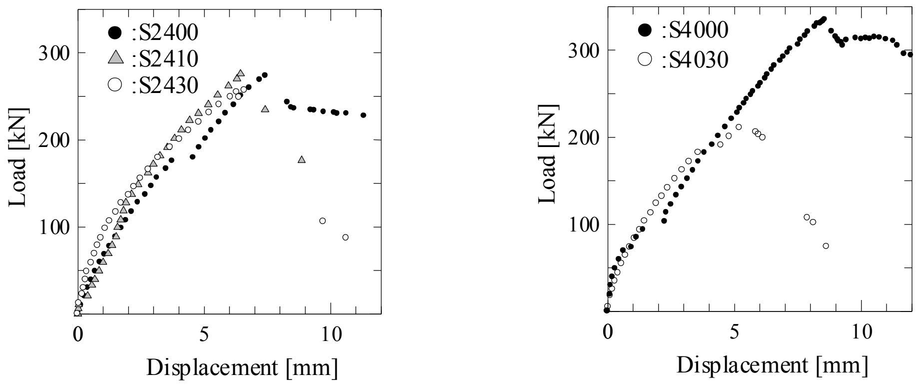

Figure 5. Load displacement relationship of test specimen

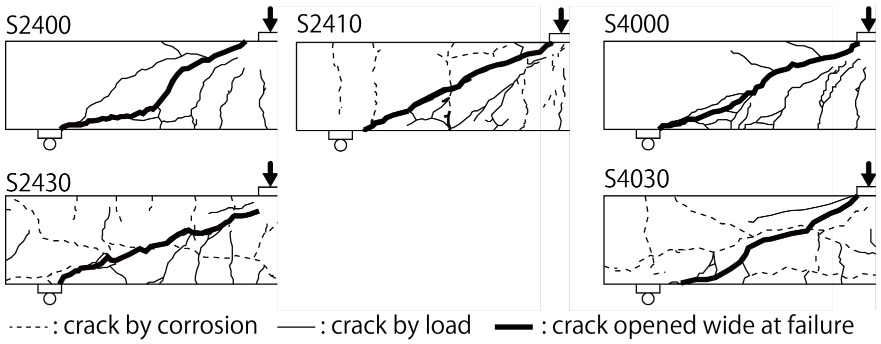

Figure 6. Crack pattern

shows no decrease of the ultimate shear force. The load-displacement relationship also indicates that the corrosion of the shear reinforcement does not affect to the stiffness until the ultimate load.

All specimen displays diagonal cracks (solid line in Figure 6). These cracks did not trace corrosion cracks. Except S2430, one of diagonal cracks opened widely and reached to top surface of the beam at the failure (bold solid line in Figure 6). These cracks are called as the dominant crack in this paper. The dominant crack also appeared in S2430. However, this crack did not reach to the top surface of the beam. At last the failure of S2430 was caused by the compressive failure of concrete below the loading plate. An angle of dominant diagonal crack in S2430 is smaller than the angle in the non-damaged specimen. This decrease of the

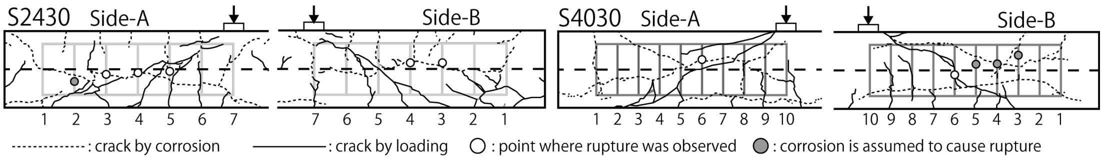

Figure 7. Location of rupture

angle generates a compressive strut connecting to the loading point and the supporting point because the end of the crack reaches just under the loading point and does not reach to the top surface. The corrosion is supposed to have a relation to this reduction of the angle. The clear reduction of the dominant diagonal crack angle is not seen in S4030, whose corrosion is heavier than S2430. The crack condition in this study indicates the corrosion decreases the dominant diagonal crack angle in some cases and that changes the shear failure mode. However, this study does not have evidences enough to clarify the relation between the diagonal crack angle and the corrosion of the shear reinforcement.

Another remarkable change due to the corrosion is shown in the post-peak range in the load-displacement relationships (Figure 5). Share reinforcement of non-damaged beams, S2400 and S4000, causes a ductile behavior after the peak load. That behavior is not seen in the load-displacement relationship of the corroded beams. Figure 7 shows the location of rapture. Some reinforcing bars across the dominant diagonal crack raptured in heavy corroded specimens. The rupture has some relationships with the brittle fracture behavior of corroded beams. However, the rupture is not an assured factor of the brittle behavior because no rupture was observed in S2410.

EVALUATION OF SHEAR CAPACITY

Some design codes like the Japanese code adapt the modified truss theory as an evaluative method for the shear capacity of RC beam. In the theory the shear capacity of the RC beam with the shear reinforcement, the shear capacity V_u is represented as a summation of shear resistances due to shear reinforcement V_s and other factors V_c.

$$V_u = V_s + V_c \qquad (1)$$

If the influence of the corrosion of shear reinforcing-bars to the shear capacity is only the decrease of the cross sectional area, that design formula has a possibility to evaluate the shear capacity of RC beam with the area of the corroded shear reinforcement. To investigate the influence of the corrosion to the shear resistance provided by the shear reinforcement, a relationship between the ultimate shear force and the residual shear reinforcement ratio are displayed in Figure 8. The residual shear reinforcement ratio is the shear reinforcement ratio calculated by using the cross sectional area of corroded reinforcing bars. Hence the residual ratio of the non-corroded specimen agrees with the normal shear reinforcement ratio.

Three different cases are displayed in the Figure 8. Case-A shows the relationship using the residual ratio calculated by an average of the maximum weight loss ratio in each reinforcing bar within the shear span. Case-B uses the residual reinforcement ratio calculated by an average of the maximum weight loss ratio in the each bar across a dominant diagonal crack. An average of the maximum cross sectional area loss ratio in each bar across the dominant crack is used to calculate the residual ratio in case-C. The area of the shear-reinforcing bar ruptured due to corrosion was regarded as 0 in all cases.

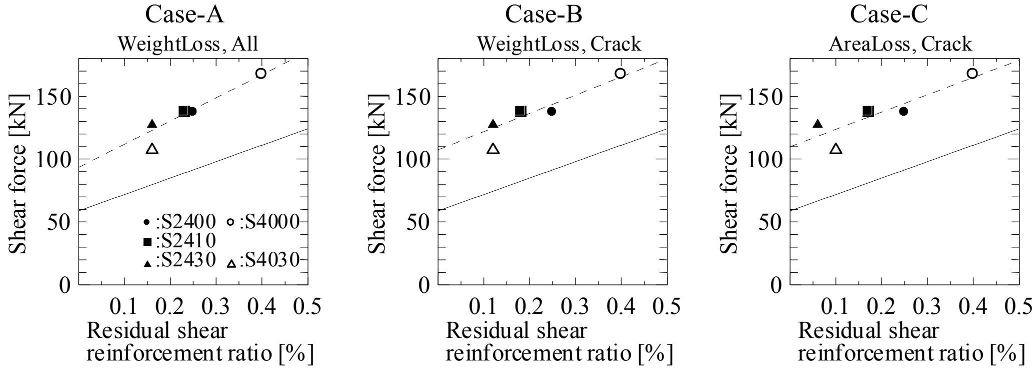

Figure 8. Shear capacity vs. residual shear reinforcement ratio

A solid line in Figure8 is computed by following design formulas.

$$V_s = A_s f_{wy}\left(\sin\alpha + \cos\alpha\right) z/s \tag{2}$$

$$V_c = 0.2 f_c'^{1/3}\left(100 p_w\right)^{1/3}\left(1000/d\right)^{1/4}\left(0.75 + 1.4d/a\right) b_w d \tag{3}$$

where, A_s: cross sectional area of shear reinforcement [mm^2], α: angle of shear reinforcement to a member axis, z: distance between compressive force and tensile force in a section (= d/1.15) [mm], s: spacing of shear-reinforcing bar [mm], f_c': concrete compressive strength [N/mm^2], p_w: reinforcement ratio of tensile main bar, d: effective depth [mm], a: shear span[mm], b: beam width [mm].

JSCE standard specification (JSCE 2008) uses Eq. (2) proposed by the truss theory as the shear resistance provided by the shear reinforcement, V_s and regards V_c as the shear resistance provided by the concrete. The diagonal shear-cracking force used in the JSCE specification. Instead of using the design formula, the experimental formula for the diagonal shear-cracking load, Eq. (3) (Niwa et al, 1986) is used here for accurate investigations. This formula is the base of the design formula in the JSCE specification. The concrete strength averaged among all specimens was used in this calculation.

The formula underestimates the shear capacity of non-corroded specimens because a criterion of the shear failure is the yield of shear reinforcement in the truss theory. Moreover the calculated shear capacities without shear reinforcement, V_c are lower than the experimental diagonal cracking load in the experiments. Most shear-reinforcing bars contributes to the shear capacity in S2410, the light corroded specimen. Therefore, if an approximate line formed by non-corroded specimens and S2410, which is displayed in Figure 8 as a broken line, is considered, the slope of this line almost agrees with the slope of the calculated relationship. This agreement means that the truss theory can evaluate the contribution of the shear reinforcement to the shear capacity in this experiment.

S4030 shows that the shear reinforcement contributes to the shear resistance less than the resistance expected from the residual reinforcement ratio in all cases. Even if the actual cross section resisting shear force is taken into account, that is case- C, the theoretical decrease of the shear resistance does not agree with the experimental result of S4030. In this calculation, reinforcing-bars raptured due to corrosion were assumed and cross sectional area located 5mm from the raptured is used as the assumed cross sectional area of reinforcing-bars raptured by loading. There are possibilities that these assumptions are not correct or the truss mechanism is collapsed by the heavy corrosion.

In case-C S2030 shows the higher contribution of the reinforcement to the shear capacity expected from the residual reinforcement ratio contrary to the result of S4030. The change of the failure mode from the diagonal tension to the compression is an acceptable reason of this disagreement because the mechanism causing the compressive failure is thought to increase the shear resistance except the shear reinforcement. Test results of two heavy corroded specimens show the change of the failure mechanism from the shear failure of non-corroded beam and indicate that further investigations on the failure mechanism are required to evaluate the shear capacity of RC beam with the heavy corroded shear reinforcement.

CONCLUSION

1) The heavy corrosion decreases the shear capacity if the failure mode is diagonal tension.

2) The heavy corrosion changes the failure mode from the diagonal tension failure to the shear compression failure in some cases. In spite of the heavy corrosion, the shear capacity decreases little.

3) In the case of diagonal tension failure, the shear reinforcement in the heavy corroded beam provides less contribution to the shear capacity than the contribution expected from the truss theory even if the minimum cross sectional area in each shear-reinforcing bar crossing the dominant is used to calculate the shear reinforcement ratio.

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