- Technical Paper -

INFLUENCE OF SHEAR REINFORCEMENT ON RESIDUAL LOAD CAPACITY OF RC BEAMS WITH CORROSION

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ABSTRACT

The requirements of forming arch action are that the bond stress in shear span is removed, and the anchorage performance well to restrain arch support from slipping. Two methods are adopted to remove the bond stress. One is applying wax between ridges and then wrapping it with tape and finally applying lubricant on the surface of the tape (series BN), the other is the method of electrolysis test. About the contact surface between tensile reinforcement and stirrups, in the former specimens, there is no contact force; while in the latter beams there is residual bond stress more or less.

Keywords: load-carrying capacity, bond stress, arch action, flexural failure, stirrup

1. INTRODUCTION

Many built infrastructure facilities are deteriorating and literally crumbling. One major cause is the corrosion which most often affects reinforced concrete (RC) structures. With the period of establishing new civil engineering infrastructures shifting to the period of maintenance at present, the method for inspection of materials degradation, and estimating the residual strength in present environment in future are become more and more important in the maintenance of established civil engineering infrastructures. Because the load-carrying capacity of the corroded structures drops gradually with the corrosion of materials, so it is important to clarify the fracture mechanism and to accurately predict the residual ultimate load carrying capacity of corroded (RC) beams, which are basic structure elements having rectangular cross sections. It is generally considered that there are two failure modes of RC beams that are flexural and shear failure modes for along time, but now arch action is being researched. This kind of type makes good use of the compression resistance of concrete, so when design a beam subjected to a certain load, arch action can abate the size and the gravity of itself, and it can save cost. Therefore much attention is paid to arch failure mode recently, which must be researched in order to form a system of predict the residual ultimate load carrying capacity of corroded RC beams.

Based on this background, the objectives of this study are to investigate the relationship between stirrup and arch action. In this study, an experimental program was conducted. Failure modes are different when there are differences in corrosion rate, the number of stirrup and bond stress. The experimental results showed that when there is no bond stress between reinforcement and concrete, the stirrups in shear span don not contribute to load-carrying capacity.

2. EXPERIMENTAL PROGRAMS

2.1 Specimens and Parameter

In order to investigate the ultimate load carrying capacity of reinforced concrete beams which are designed to performance shear failure, an experimental program is conducted. The dimensions of beams and the arrangement of reinforcements are shown in Fig. 1, the specimens are rectangular RC beams having width 240mm, height 340mm and length 2400mm or 2950mm. The tensile reinforcements are 3D16(SD295A) deformed bars at 60mm intervals, and shear reinforcements are D6(SD295A) deformed bars. In order to identify the reinforcements (Consulting Fig. 1), two outside tensile reinforcements are named L and R, and middle reinforcement is named M. The characteristics of reinforcements are shown in Table 1, and the mix proportion is given in Table 2, (The design strength of concrete is 30MPa), and 5% NaCl solution is used as mixing water, to accelerate the electrolysis test. Moreover, the specimens are cast in ordinary general purpose cement, whereas beam L10-10F is cast in early strength cement. It is well known that the load capacity of arch action is higher, so a higher bond force in anchor is needed to keep balance. Fixing plates on the ends of beam is an effective method to gain a higher reacting force, which is important for the formation of arch action. Therefore, plates are used in some beams.

2.2 Details of corrosion

In this study, in order to short the time spent on corrosion, and control the corrosion process easily, the

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method of electrolysis test is adopted [1]. Tensile reinforcements are anodes electrode, and copper mesh is a cathode electrode, with 18.9A current flows across the two electrodes, till the electric charge in coulombs transferred meets the demands. The whole beams of series S (S4 and S150) are deposited in water trough which is filled with 5% NaCl solution, whereas in the beams of series L10 and L150, only shear span are deposited in the solution. Furthermore, the tensile reinforcement in anchorage region and the shear reinforcement of this series are coated with epoxy to keep them away from corrosion. Take partly corrosion for example and show it in Fig. 2.

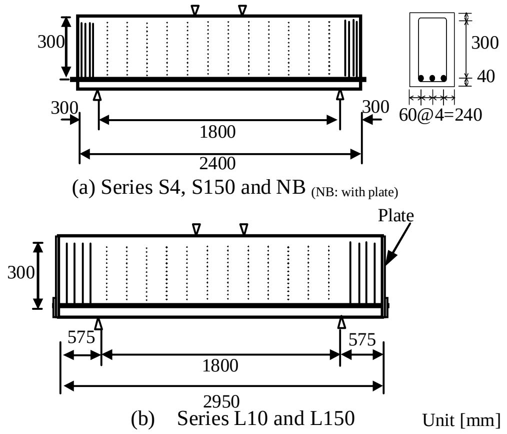


Fig.1 Layout of specimens

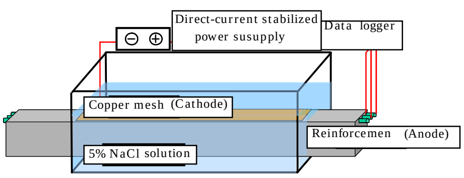


Fig. 2 Setup of partly corrosion

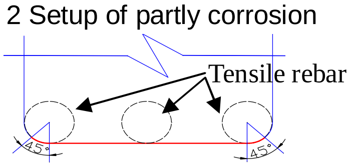


Fig. 3 Bottom part of stirrup

About tensile reinforcements, the local corrosion rate is defined as the rate of mass reduction, first, measure the mass and length of reinforcements, before cast. So the mass of per millimeter m_{unit} can be calculated. Then taken them out after load test, and immerse them in 10% $(NH_4)_2HC_6H_5O_7$ solution for 24 hours to dissolve rust. Next cut them into parts with spacing of 50mm, and measure the mass m_{local} and length l_{local} of each part respectively. Finally the local corrosion rate equals the value of m_{local} divided by the product of m_{unit} and l_{local}. And the local corrosion rate of beam is the average local corrosion rate of three tensile reinforcements. About stirrups, the rate of mass reduction is calculate both in whole stirrup and the bottom part of stirrup which is marked with red line in Fig. 3

2.3 The Test Variables

The Parameters are shown in Table 3. They are corrosion rate, whether there are shear reinforcement (if there are, the spacing), steel plate and bond stress or not. First, in series S4, there are three tensile reinforcements and four stirrups in anchorage having the length of 300mm. Then, in series S150, the size is the same with series S4, but the shear reinforcements are set with spacing 150mm based upon standard specifications for concrete structures. Next, the series L are the same with series S, but the length of anchorage is 575mm, in which there are ten stirrups. The whole beams of series S are corroded, while the beams of series L are only corroded in shear span, in order to restrict bond deterioration in anchorage. Finally, series NB have the same size with series S, but the bond stress of which between supports is removed entirely, by applying wax between ridges and then wrapping it with tape, then applying lubricant on the tape. So the tensile reinforcements are separate from concrete and stirrups, additionally, the stiffness of wax is typically much lower than reinforcements. Therefore the tensile reinforcements are unbonded, and which is also proved by the distribution of strain.

Table 1 Reinforcement properties

Nominal diameter	D6	D22
Specifications	SD345	SD345
Nominal Area(mm^2)	31.7	387.1
Yield stress (N/mm^2)	438	400
Tensile strength(N/mm^2)	557	579
Elasticmodulus(N/mm^2)	2.0×10^5	

Table 2 Mix proportion of concrete

Gmax (mm)	W/C (%)	SL (cm)	Air (%)	Unit weight (kg/m3)					
				W	C	S	G	Admixture	NaCl
20	60	10	5	168	280	826	996	2.8	8.8

Table 3 Parameters

Series	Specimens	Aimed corrosion Rate (%)	stirrup Spacing (mm)	Number of stirrup in anchorage	anchor Length mm	Steel plate	Experimental Load (kN)	Shear capacity kN	Flexural Capacity kN
S4	S4-0	0	-	4	300	No	174.3	184	332
	S4-10	10					209.5		
	S4-20A	20					236.5		
	S4-21B	20					213.8		
S150	S150-0	0	150				276	257	
	S150-10	10					302.7		
	S150-20	20					221.7		
L10	L10-10F	10	-	10	575	Have	251.7	184	
	L10-20F	20					296.2		
L150	L150-10F	10	150				245	257	
NB	S4-0NF	0	-	4	300		360.4	184	
	S150-0NF	0	150				369.6	257	

Table 4 Average corrosion rate of reinforcements

Series	Specimen	Tensile rebar Average (%)	Sturrup (%)							
			Left anchorage		Shear span		Right anchorage		Average	
			Whole	Bottom	Whole	Bottom	Whole	Bottom	Whole	Bottom
S4	S4-10	6	36.5	32.6	-	-	33.4	13.3	34.9	23
	S4-20A	12	45.7	50.8	-	-	45.1	26.4	45.4	38.6
	S4-20B	15	69.9	48.7	-	-	64.4	26.6	67.2	37.7
S150	S150-10	4	34.8	15.3	36.2	12.4	32.6	9.1	34	12.2
	S150-20	10.5	35.1	72.8	36.7	37.8	33	22	34.3	46.4
L10	L10--10F	9	-	-	-	-	-	-	-	-
	L10--20F	13.3	-	-	-	-	-	-	-	-
L150	L150-10F	7	-	-	-	-	-	-	-	-

2.4 Flexural Loading Test and Measurement

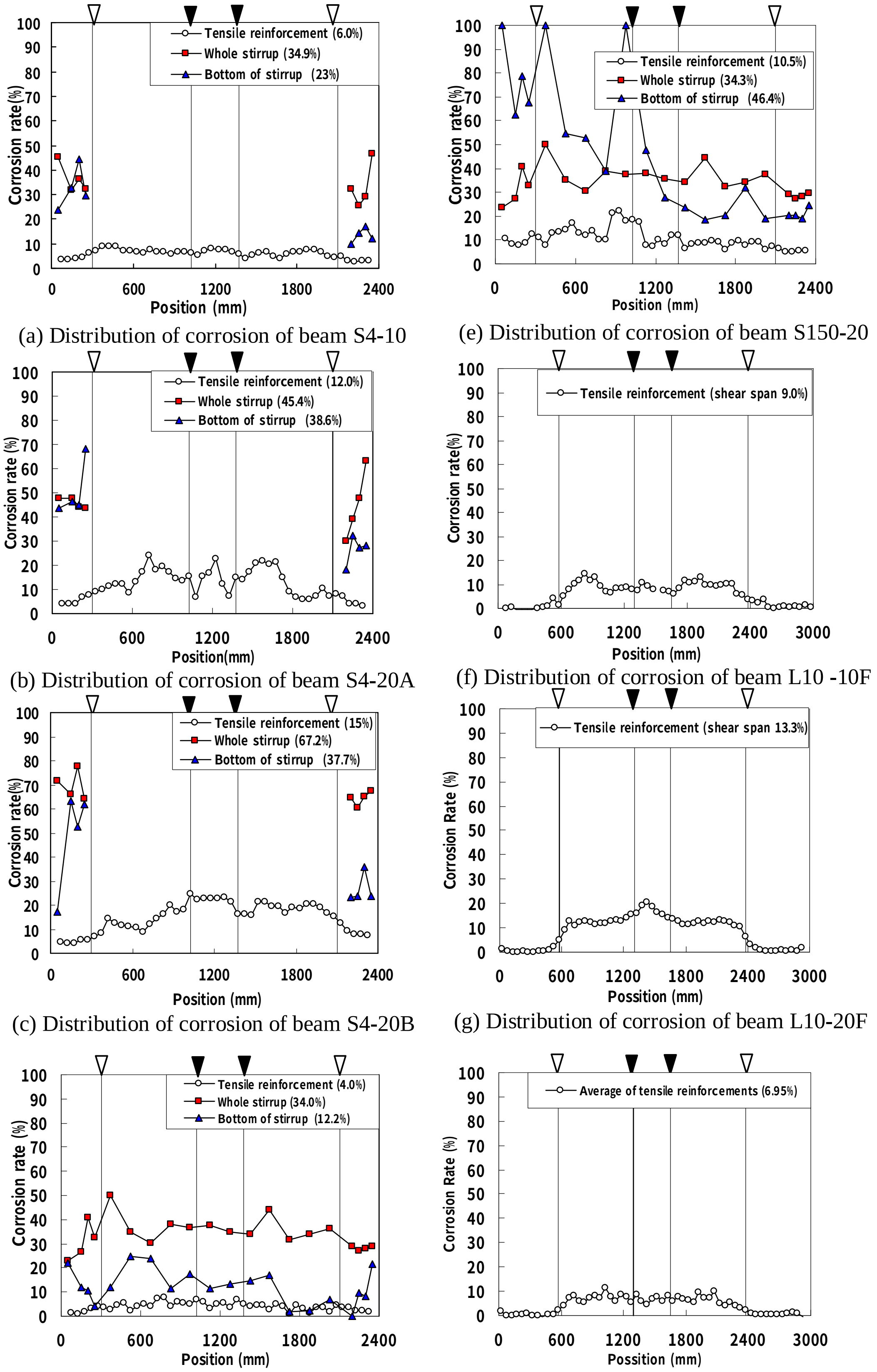
All the specimens are monotonically tested till failure with four-point flexural loading. The loading span and support span are 350mm and 1800mm respectively. Load is applied at the speed of 0.5mm per minute. The items measured are load, beam deflection in the constant moment region, and the axial strain of tensile reinforcement M. In order to prevent strain gauges from damage due to corrosion, the gauges are set inside the tensile reinforcement, with spacing of

48mm, whereas there are no gauges in beam S4-20B.

3. CORROSION PATTERN

The average corrosion rate of tensile reinforcements and the stirrups including the corrosion rate of bottom part is shown in Table 4, and the distribution of them is shown in Fig.4.

Concerning to the corrosion rate of tensile reinforcements, they are near to the aim corrosion rate, and performance uniformly corroded. About the



(a) Distribution of corrosion of beam S4-10

(b) Distribution of corrosion of beam S4-20A

(c) Distribution of corrosion of beam S4-20B

(d) Distribution of corrosion of beam S150-10

(e) Distribution of corrosion of beam S150-20

(f) Distribution of corrosion of beam L10 -10F

(g) Distribution of corrosion of beam L10-20F

(h) Distribution of corrosion of beam L150-10F

Fig. 4 Distribution of corrosion rate

reinforcement of beams of series L10 and L150, which is partly corroded, only the stirrups near support are corroded, generally speaking are almost not being corroded in anchorage. Therefore, the bond stress is kept in good condition.

About the shear reinforcement, the corrosion rate is higher than that of tensile reinforcement, but the corrosion rate of bottom part of shear reinforcements is more higher, and performance non-uniformly corroded.

4. RESULTS OF TEST

The load deflection curves and final stage cracks are shown in Fig. 5 and 6, respectively.

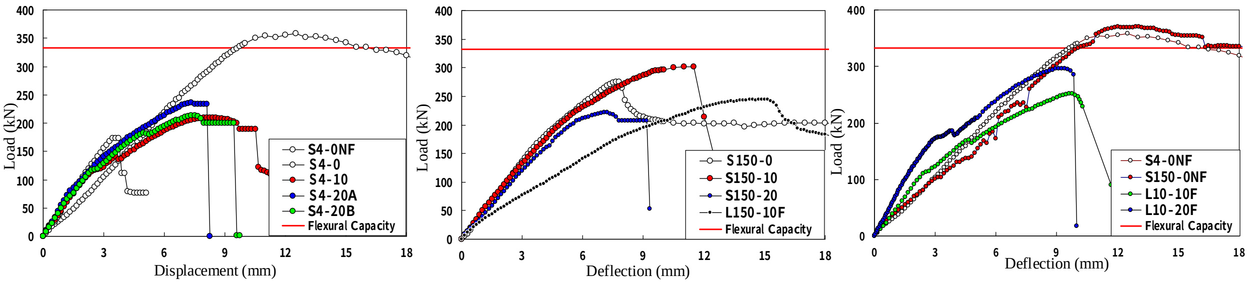
4.1 Load deflection

(1)Series S4

The plot of load versus mid-span deflection for series S4 is shown in Fig. 5(a).The ultimate loads of three corroded beams are all higher than uncorroded beam S4-0. It is because that arch action is formed in corroded beams. The load of beamS4-20A is higher than beam S4-10, it indicates that the higher the corrosion rate is, the higher the load is. But the load of beam S4-20B is not the largest, because of a higher corrosion rate.

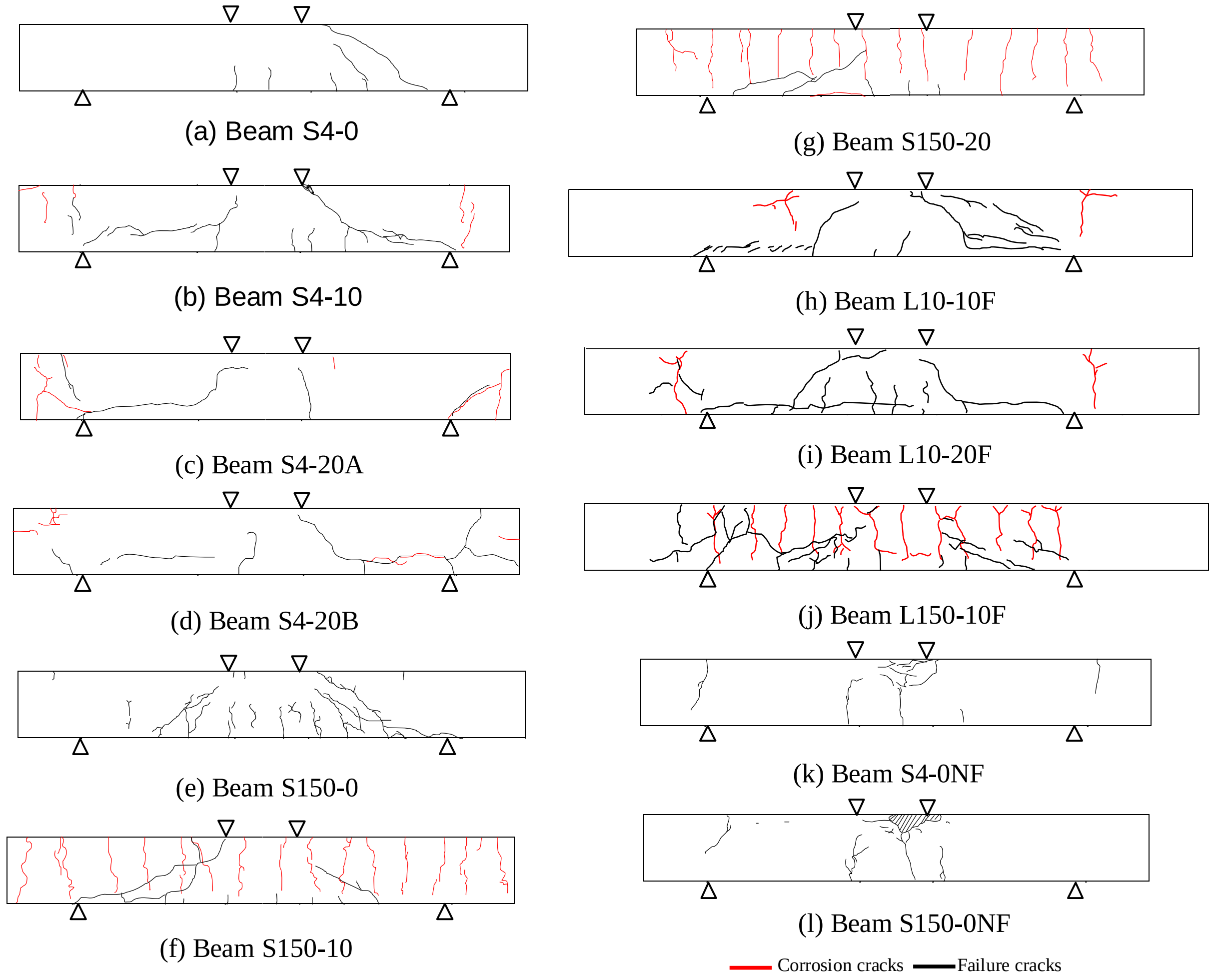
(2)Series S150

The plot of load versus mid-span deflection for series S150 is shown in Fig. 5(b), and the corrosion rate of the bottom of stirrups are shown in Fig. 4(d) and (e). The ultimate load of beam S150-10 is higher than uncrroded beam S150-0; it means arch action forms in



(a) Series S4 (b) Series S150 (c) Series L and NB

Fig.5 Load- deflection curves



(a) Beam S4-0

(b) Beam S4-10

(c) Beam S4-20A

(d) Beam S4-20B

(e) Beam S150-0

(f) Beam S150-10

(g) Beam S150-20

(h) Beam L10-10F

(i) Beam L10-20F

(j) Beam L150-10F

(k) Beam S4-0NF

(l) Beam S150-0NF

Fig.6 Cracks pattern of all beams

corroded beam. About the beam S150-20, it performs bond failure, for the minimum corrosion rate of bottom stirrups in one side is extremely heavy (72.8%, consulting Fig. 4(e)). So it confirms that the load is lower if anchorage performs badly.

(3)Series L10

The plot of load versus mid-span deflection for seriesL10 is shown in Fig. 5(c). Both the two beams of series L10 perform compressive failure of concrete in the upper constant moment region. The load of beam L10-20F, with higher corrosion rate, is higher relatively, and the ultimate loads of the two beams are higher than corroded beams of series S4, for the steel plate can restrict tensile reinforcement from pulling out. So it can be concluded that firm arch action forms, when the tension reinforcements are fixed in anchorage well.

(4)Series L150

The plot of load versus mid-span deflection is shown in Fig. 5(b). The ultimate load is less than that of beam S150-10, because the crack along shear reinforcement appears in anchorage near support point, and develops during loading, finally, beam fails in anchorage failure.

(5)Series NB

In order to make uncorroded beam performance firm arch action, the beam S4-0NF, of which the bond stress between supports is removed, is cast, and in order to investigate the influence of stirrups when there is no bond stress in support span, the beam S150-0NF is cast too. The plot of load versus mid-span deflection for the two beams is shown in Fig. 5(c), the failure stage cracks of both beams are shown in Fig. 6(k) and (l), and the photo of cracks is shown in Fig. 7. Because there is no bond

(a)Beam S4-0NF

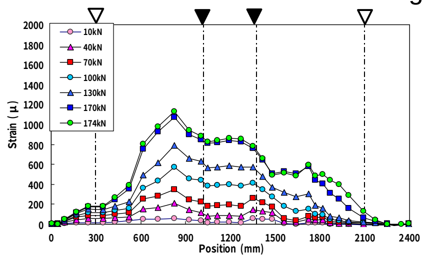
(b)Beam S150-0NF

Fig.7 Failure stage cracks

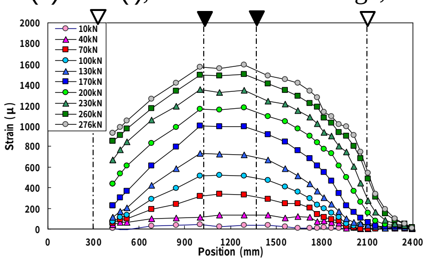
stress between concrete and tensile reinforcement in support span, the ultimate load is higher than flexural capacity calculated by bending theory. The flexural cracks only appear in constant moment region, and there is no flexural cracks in shear span.

4.2 Distribution of strain

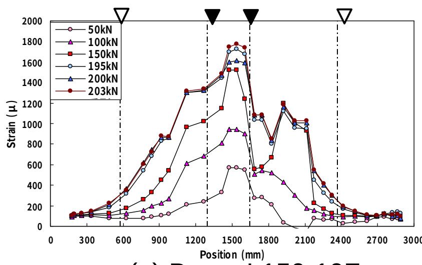
The distribution of strain is shown in Fig. 8. The distribution of strain of uncorroded Beam S4-0 shows that the gradient of strain is heavy in shear span. It shows there is bond stress in shear span, so the uncorroded beams present truss mode, Whereas the distribution of strain of corroded Beams is different, such as the beam S4-10, of which the strain is almost the same in shear span, but the gradient of strain in anchorage is larger. It indicates that load is transferred to anchorage, and arch action forms in corroded beam.



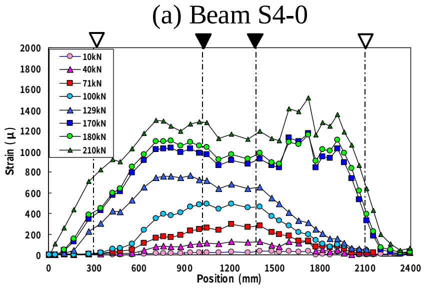
(a) Beam S4-0



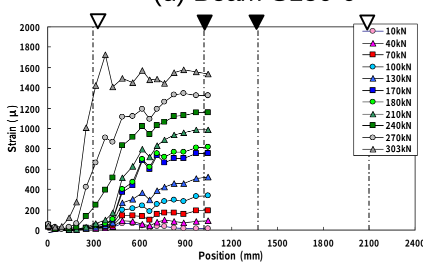
(d) Beam S150-0



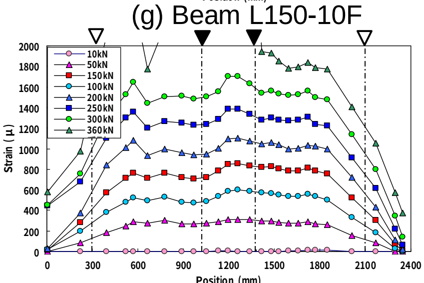
(g) Beam L150-10F



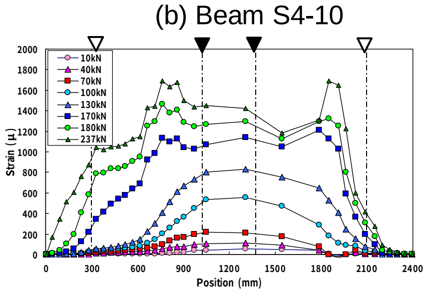
(b) Beam S4-10



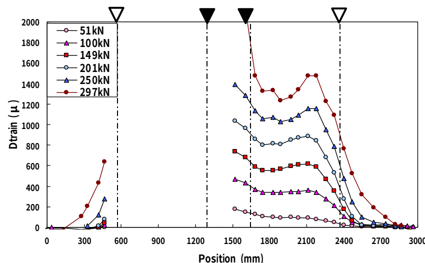
(e) Beam S150-10



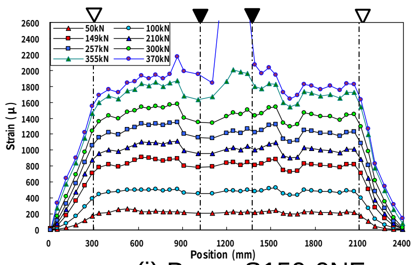
(h) Beam S4-0NF



(c) Beam S4-20A



(f) Beam L10-20F



(i) Beam S150-0NF

Fig.8 Distribution of strain

The beam performs bond failure, for there is no adequate bond force to balance with load. The distribution of strain of series S150 is similar to that of series S4. Therefore it can be drawn that weak arch action forms in corroded beams when there is no or less shear reinforcement.

Concerning to the series NB, the distribution of strain shown in Fig.8(h) and (i), show that the tensile reinforcements yield at the stage of failure, for the strain at yield point is 1840μ. About the beam L10-20F, yield point is 1720μ, so that the tension reinforcements yield too, at the stage of failure. Therefore, in beams with steel plate, arch action fails for the extension of tensile reinforcements, and in this failure mode, the compressive stress will reach a critical level at the smallest cross-section. In this situation, critical section lies in the up fiber of constant moment region.

4.3Arch action with stirrup in corroded beams

(1) Stirrups in anchorage

The corrosion rate of reinforcements is shown in Table. 4. The bond stress in anchorage region degrades along with corrosion. In series S4, weak arch action forms in all corroded beams, of which the average corrosion rates of tensile reinforcements vary from 6% to 15%. However, in series S150, beam S150-10, corrosion rate of tensile reinforcement is near to S4-10, performs shear compression failure. The main reason is that the bottom stirrups in anchorage are lightly corroded (15.3% and 9.1%), so the bond stress decrease lightly too. On the contrast, when the arch support is weakened by corrosion, weak arch action forms.

(2) Stirrups in shear span

Compare with beam S150-0, the anchorage of beam S150-10 performs well relatively, when the shear reinforcements are corroded, the restriction of shear reinforcements is weakened, so that the load can be transferred to anchorage easily and the strain of reinforcement become almost the same. Therefore, it is easy for the beam shift from truss mode to arch mode. But the ultimate load capacity of beam S150-20 is less than uncorroded beam S150-0. It is because that the corrosion rate of stirrups on left anchorage is corroded heavily, so the arch support can not be restrained effectively.

4.4 Arch action with stirrup when there is no bond stress

In series BN, there is no any bond stress in shear span. The load-carrying capacity is almost the same shown in Fig.5(c). Load capacities of both are higher than flexural capacity, and there is nearly no difference in load, cracks and the distribution of strain. So it can be drawn a conclusion that when there is no bond stress in shear span, the shear reinforcements do not contribute to load capacity.

4.5Failure mode shift

As shown in Fig.9, two diagonal cracks appear in L10-10F, when the load reaches the number expressed in graph. The load increase linearly. With the crack with green line appears, the load decreases a little transitorily, and then rise again. It indicates that truss action shift to arch action. (In the corroded beams without shear reinforcement (L10-20F and S4), the same phenomenon appears.) And then bond failure crack appears, by which the residual bond stress is removed, and then crack with red line appears, therefore compressive zone of arch action forms.

When there are stirrups, there is no phenomenon of shift moment. Because when cracks appear, the stirrups can connect concrete, and prevent load from dropping suddenly. Consequently, the truss mode shift to arch mode smoothly.

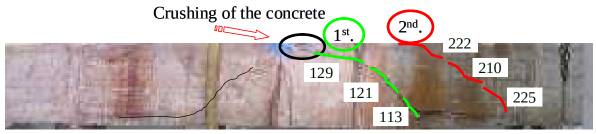


Fig.9 Final stage cracks of beam L10-10F

5. CONCLUSIONS

(1) When the beam corroded, the ultimate load increase, and the load of which is higher than uncorroded beams.
(2) The beam performs arch action when the corrosion rate is higher; while performs truss action when the corroded rate is light.
(3) The load-carrying capacity of corroded beams can be increased when stirrups performs well,
(4) When there is bond stress between tensile reinforcement and shear reinforcement, the shear reinforcement is to the disadvantage of load capacity.
(5) When there is no bond stress between tensile reinforcement and shear reinforcement, the shear reinforcement is independent of load capacity.
(6) When there is no shear reinforcement, the load decrease transitorily, during truss mode shift to arch mode
(7) In arch action, the load is resolved into compressive stress and transmitted to the supports, so the load-carrying capacity of this kind mode is higher than other mode for the concrete has relatively high compressive strength.
(8) When tension reinforcement is fixed well in anchorage, corroded beams perform ductility failure.

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