EVALUATION OF DAMAGE TO REINFORCING BARS IN ASR-AFFECTED CONCRETE STRUCTURES

Kenji Kosa [1], Hiroki Goda [2], and Hiroyuki Igarashi [3]

Abstract

This paper is aimed at clarifying the causes and mechanism of fracturing at the bending area of reinforcing bars arranged in the concrete structures affected by Alkali-Silica Reaction (ASR). Specimens imitating ASR-affected beams constructed of expansive concrete were used for this investigation. Under the expansion pressure of the concrete, the bending area of reinforcing bars of the former rib type (produced before 1980) fractured. The fracturing behavior was roughly identical to that of reinforcing bars fractured in actual structures. Therefore, we investigated the fracturing mechanism of reinforcing bars by changing experimental conditions.

1. Introduction

Early deterioration of structures due to ASR has been a concern these years. ASR is a chemical reaction between alkalis in the cement and silica components in the aggregate. In the structures seriously affected by ASR, damage such as fracturing has been found at the bending area of reinforcing bars, which raised a concern due to a decrease in the strength of structures.

In this study, we focused on the fracturing of reinforcing bars because it is a serious damage among the damages related to ASR. Using ASR-imitating specimens constructed of expansive concrete, propagation of damage to reinforcing bar which occurs as the concrete expands was investigated.

2. Background of Research

From existing studies, the following four factors have been pointed out as the major factors contributing to the fracturing of reinforcing bars in ASR-affected concrete structures: (1) Use of former rib type reinforcing bars (steep-angled rib, produced before 1980), (2) Initial cracks generated by bending process of the bar, (3) Propagation of cracks due to concrete expansion, and (4) Effect of a corrosive environment. Among the four factors, our investigation paid attention to Factors (3) and (4) whose effects are not yet clearly elucidated. Fig. 1 shows the flow of study. In our experiments, roughly two types of specimens were constructed: one used the present rib type reinforcing bars and the other used the former rib type reinforcing bars. The rib angle is gradual in the present

1) Professor, Dept. of Civil Eng., Kyushu Institute of Technology, Kitakyushu, JP
2) Assistant Professor, Kyushu Institute of Technology, Kitakyushu, JP
3) Researcher, Development Department, Shinko Wire Company

type and steep in the former type. According to the bending tests, damage to reinforcing bars was more serious in the specimens containing the former rib type bars, with the occurrence of fracturing [1, 2, 3] . Therefore, focusing on the specimens containing the former rib type reinforcing bars, we investigated the mechanism which causes the fracturing of reinforcing bars arranged in ASR-affected concrete structures.

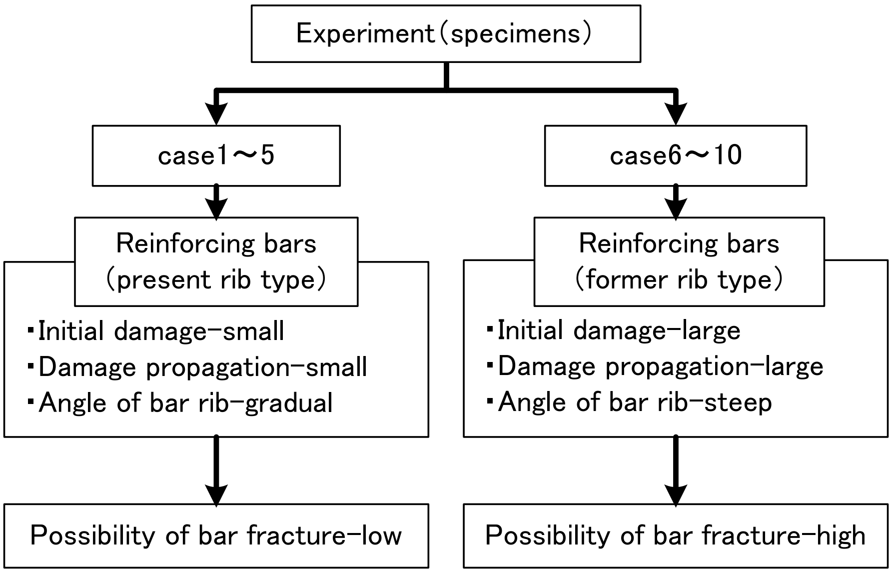


Fig.1 Flow of study

3. Experimental Program

3.1 Specimens

(1) Parameters

Table 1 shows the attributes of specimens. Of the 10 cases experimented, attention was paid to Cases 6 through10 containing former rib type reinforcing bars which have a high possibility of fracturing. To compare the damage which would differ by rib type, corrosion was used as the parameter. Also, to measure propagation of cracks, the bending area of the reinforcing bar placed at the end portion of the specimen in Cases 9 and 10 was cut in half and cover concrete was removed for continuous monitoring (Fig. 2).

(2) Specimen configuration

Fig. 3 shows the configuration of specimens. To reproduce expansion pressure due to ASR, expansive mortar was placed in the center of the normal concrete of the specimen. The expansion behavior of the specimen due to expansive mortar ended in about two weeks after construction. The cross section of the specimen was constructed to 1/8 scale of that of actual pier beams which sustained ASR damage and fracturing of reinforcing bars. As to the shape of hoop ties, the present rib type D10 bar arranged in the center of the specimen was bent to circle the entire cross section, but the former rib type D16 bar arranged at both ends of the specimens in Cases 9 and 10 was made up of two L-shaped bars with both ends hooked, because the available bar was limited in length. The present rib type D16 bar arranged in the specimens of Cases 6 through 8 was also constructed in a similar manner.

Table1 Attributes of specimens

	Cover (Y/N)	Bending radius	Hoop tie ratio	Bar type	Half-cut bar(Y/N)	Environ. Conditions
case1	Y	1.00d	0.147%	Present D10	N	Normal
case2	N					
case3	Y		0.290%			
case4		1.25d	0.147%			
case5		0.75d				
case6	Y	1.00d	0.410%	Present D16,D10, Former D16	N	Normal
case7						
case8						Corrosion 10%
case9				Present D10, Former D16	Y	Normal
case10						Corrosion 4%

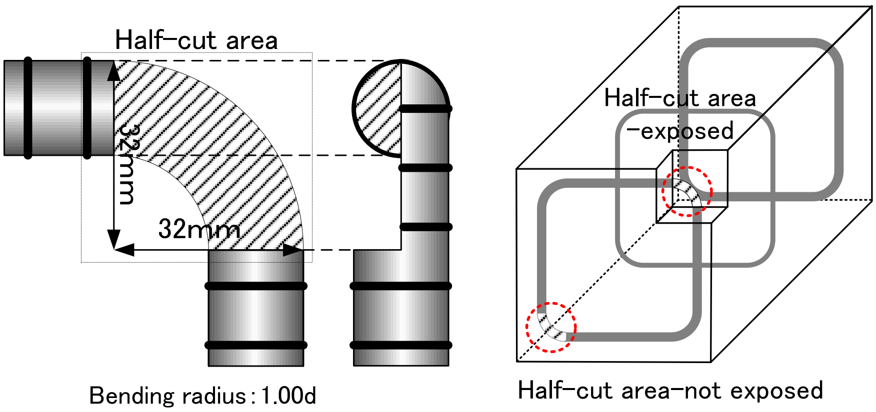


Fig.2 Half-cut area

(3) Specimen construction and materials used

Tables 2 and 3 show mix proportions of the concrete and expansive mortar used for the construction of specimens in Cases 6 through 10. Normal concrete in the outer side of the specimen was wet-cured for two weeks before the expansive mortar was placed in the center area [4]. The observed expansion due to expansive mortar during the experiment was 24%. As shown in the analysis results in Table 4, mechanical and chemical properties of the reinforcing bars used for this experiment satisfied the requirements of JIS standards. The former rib type reinforcing bar had no deficiencies in quality, as known from the fact that the value of nitrogen (N) likely to influence strain aging was roughly similar to that of the present rib type reinforcing bars. To accelerate strains to reflect aging deterioration, reinforcing bars were heat-treated at 12℃ for 10 hours using an electric furnace.

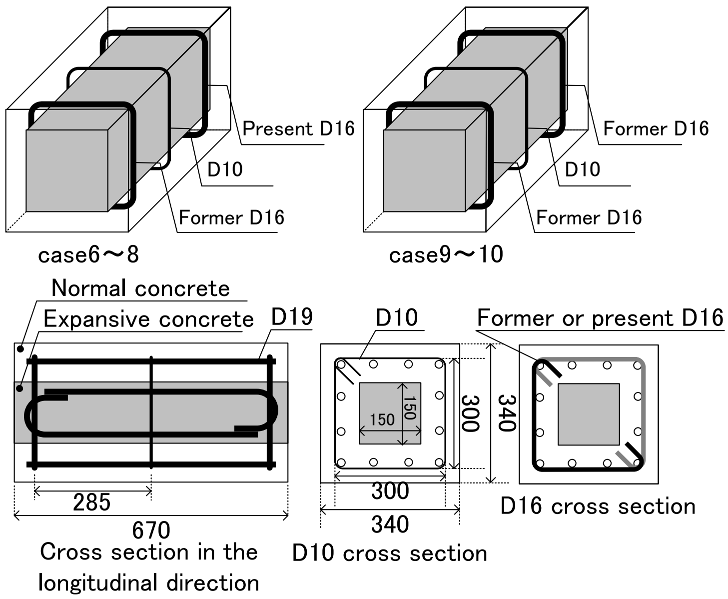


Fig.3 Specimen configuration

Table2 Mix proportion of normal

Gmax (mm)	Water/cement ratio:W/C(%)	Fine aggregate ratio:s/a(%)	·Unit volume(kg/m^3)				Admixture (g/m^3)
			Water W	Cement C	Fine aggregate S	Coarse aggregate G	
20	46	43	175	381	718	1018	1.142

Table3 Mix proportion of expansive mortar

Water/cement ratio:W/C(%)	Unit volume(kg/m^3)				
	Water W	Cement C	Fine aggregate S	Coarse aggregate G	Expansive admix E
40	230	575	1150	–	200

3.2 Measurement items

(1) Deformation

To evaluate the relationship between deformation and reinforcing bar damage, deformation on the cross section of the specimen was measured. The measuring method is shown in Fig. 4. Using a digital camera (pixels: 4 million), the cross section was pictured by placing a fixed point in the center of the cross section. To evaluate the deformation mode, the entire cross section was measured with an accuracy of 1.0 mm. When more detailed measurements were necessary, the distance between reference points was measured with an accuracy of 0.1 mm in the focused 75mm x 75mm range.

(2) Crack Depth

Fig. 5 shows the measuring method of cracks. Like observations in former investigations, the 1/2 cross section of the bending area of the reinforcing bar was magnified to 50 to 200 times to measure the cracks [2, 3]. However, in the current study, propagation of crack depth and width with time was also measured by placing half-cut reinforcing bars at the end portion of the specimen in Cases 9 and 10.

Table4 Comparison of experimental bars and JIS standard

	Yield load (N/mm^2)	Tensile strength (N/mm^2)	Elongation (%)
Former bar	345	508	30
Present bar	352～380	515～550	23～29
JIS	295 or over	440～600	16 or over
	Chemical composition		
	N	P	S
Former bar	0.0092	0.018	0.03
Present bar	0.013	0.037	0.042
JIS	−	<0.05	<0.05

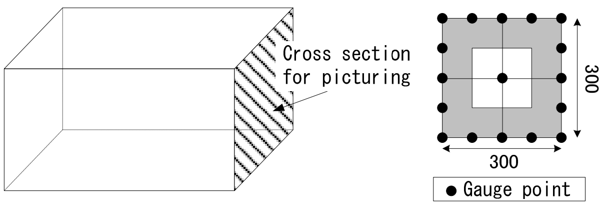


Fig.4 Positions of gauging points

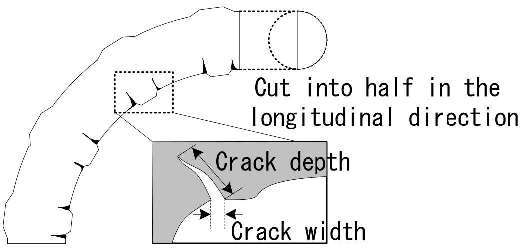
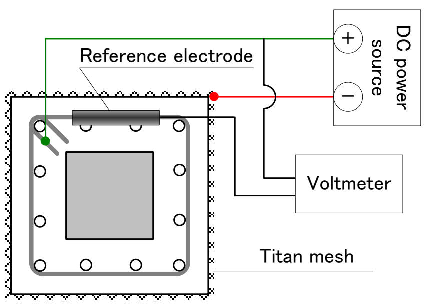


Fig.5 Measuring method of cracks



	Current	Hours	Electrolyte aqueous solution
	A	hr	NaCl
case8	0.15	504	5.00%
case10		197	

Fig.6 Circuit diagram and energizing conditions

(3) Corrosion

The effect of a corrosive environment on the damage to reinforcing bars was investigated. Fig. 6 shows the circuit for inducing forced corrosion. A Titan mesh was fixed on the specimen surface and direct current was applied in the manner to make the Titan mesh to be a cathode and reinforcing bars an anode. To observe the effect of a corrosive environment while the expansion pressure was being imposed on reinforcing bars, the forced corrosion test was made after cracking started in the concrete. Also, to make reinforcing bars susceptible to corrosion, the concrete was kept in a wet condition using 5% NaCl water solution as an electrolyte. As the target of forced corrosion for reinforcing bars, corrosion level (10% weight loss of reinforcing bars) in which a sectional loss is found in the entire circumference was set for Case 8, and corrosion level (4% weight loss of reinforcing bars) in which corrosion is visible on the most part of the bar surfaces was set for Case 10 [5].

4. Experimental Results and Discussions

4.1 Relationship between Expansion Force and Bar Damage

Considering that the effect of expansion force is most visible in the form of deformation, the relationship between expansion force and damage to reinforcing bars was investigated using the total deformation of the specimen.

(1) Deformation Mode

Fig. 7 shows the typical deformation mode of the cross section of specimens. In Case 7, fracturing of the reinforcing bar occurred at the anchoring area of the bar which was bent to 135 degrees. In Case 9, fracturing occurred at the reinforcing bar which was cut in half and placed at the inner side of the concrete. Large bar damage was also observed in other specimens constructed of former rib type reinforcing bars.

In Fig. 7, it is seen that large deformation, about 20 mm, occurred around the area of bar fracturing. In the case of past experiments, deformation became conspicuous after the bending area of reinforcing bar had yielded [3]. Therefore, it is considered that the expansion force is concentrated around the area where serious bar damage occurs.

Fig. 8 shows a typical deformation observed on the fractured cross section of the reinforcing bar in Case 7. In the current experiment, fractured cross sections generally sustained brittle fracture. But, detailed observation showed that a ductile fracture occurred in a very narrow range between the two brittle fracture areas, which is similar to a fracturing behavior typically seen in ASR-affected reinforcing bars. This means that fracturing of bars in the current experiment successfully reproduced the fracturing of ASR-affected reinforcing bars qualitatively.

(2) Relationship between Deformation and Bar Damage

The relationship between specimen deformation and reinforcing bar damage was investigated using the results of deformation and crack propagation. However, it is difficult to evaluate the effect of deformation on reinforcing bars using the moved distance between gauging points. Therefore, comparison was made considering that deformation in the diagonal direction between the gauging points, because diagonal direction gave most significant effect on crack propagation (Fig. 9). Crack propagation was evaluated with a focus on the largest crack which was seen in the reinforcing bar of the former rib type. In the case of the half-cut bar whose crack propagation was measured with time, multiple initial cracks of less than 4.5% loss were observed at the rib bottom.

The relationship between cracks and deformation is shown in Fig. 10. Cracks on the reinforcing bar propagated significantly by the time the diagonal deformation became 20 mm, and fracturing occurred when the deformation slightly exceeded 20 mm. This indicates that the range up to 20 mm deformation is the crack propagation range where cracks propagate largely while the reinforcing bar provides resistance to expansion force. After a deformation of over 20 mm, the deformation-progress rapidly due to occurrence of the fracturing of reinforcing bar. But, as shown in Fig. 10, the relationship between cracks and deformation at the half-cut bar area at the exposed outer corner was slightly different from that at the inner side of the concrete. This is because the confinement of concrete at the former position differed from that at the latter position because of the removal of concrete for monitoring.

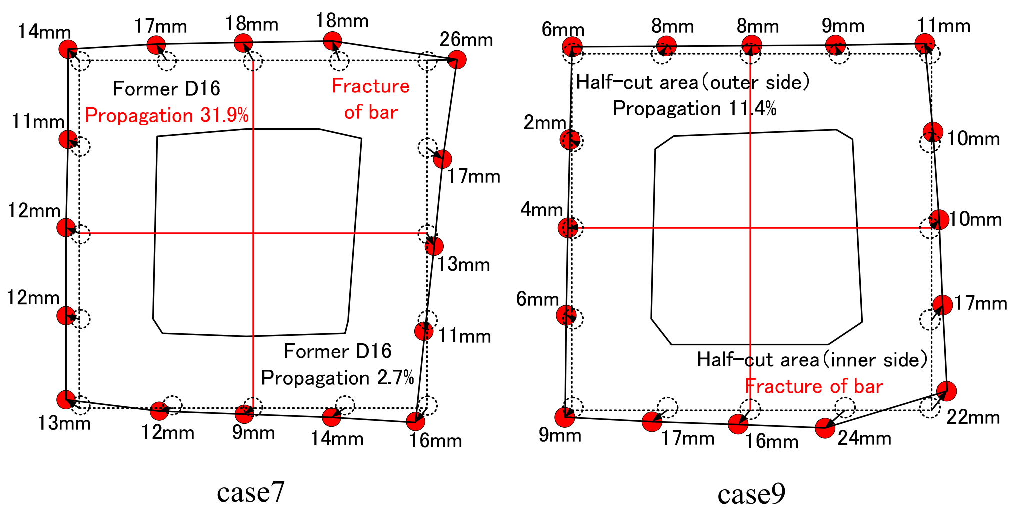


Fig.7 Comparison of deformation modes

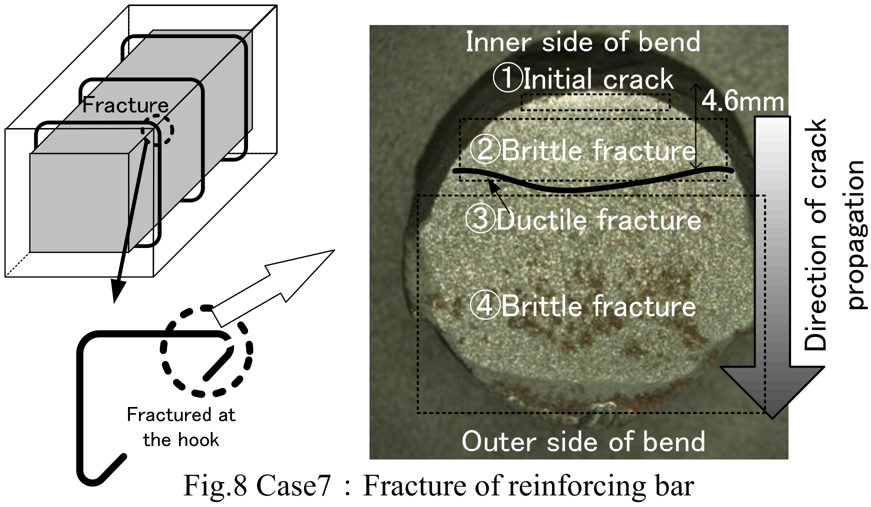


Fig.8 Case7 : Fracture of reinforcing bar

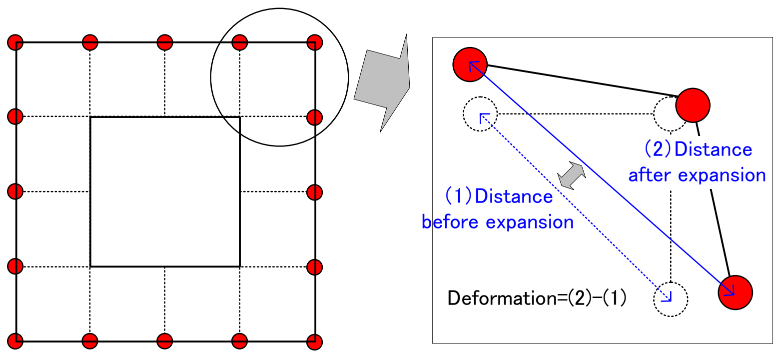


Fig.9 Measuring method of deformation at the corner

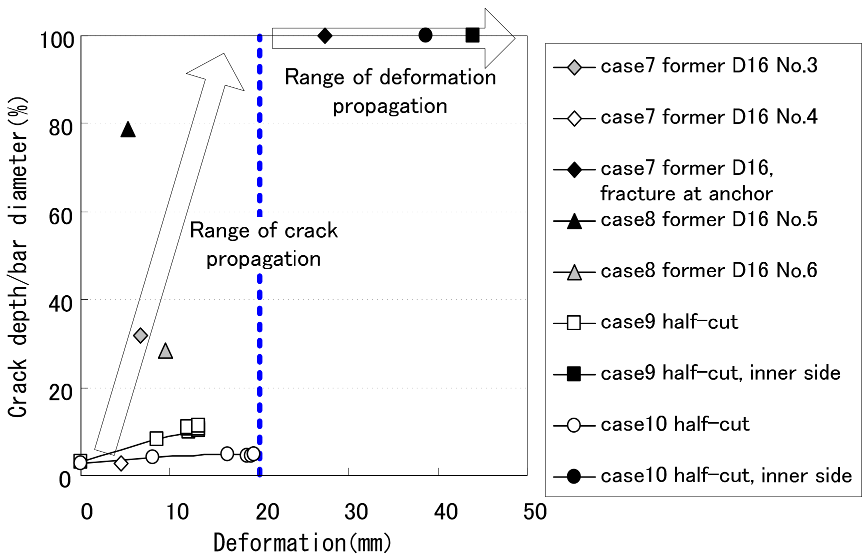


Fig.10 Relationship between cracks and deformation

(3) Effects of concrete confinement

Because the relationship between specimen deformation and bar damage was not correlated in the case of the half-cut bar at the exposed outer side of the specimen as seen in Fig. 10, deformation of the bar in Case 9 before and after the expansion started was compared. The results are shown in Fig. 11. Because a peculiar feature was seen at the bending area having large deformation, we focused on the bending area and compared damage to the former rib type D16, half-cut bar at the inner side, and half-cut bar at the exposed outer side of the concrete.

Fig. 12 shows the results of comparison obtained from the bending area of reinforcing bars. As a tendency, it is seen that the former rib type D16 bar and the half-cut bar covered with concrete sustained deformation at the straight line area and the bending area under the effect of expansion pressure. To be specific, D16 bar deformed toward the outer side by 4.3 mm on average, and the half-cut bar placed at the inner side deformed significantly after expanding toward the outer side and fracturing.

In contrast, the half-cut bar which was not covered with concrete deformed by 3.2 mm on average in the straight line area only and virtually no conspicuous deformation occurred at the bending area.

The mechanism of damage which is inferred from these phenomena is shown in Fig. 13. From the results in Fig. 12, the damage mechanism is considered to differ in cases with or without confinement of concrete.

When the concrete is confined, it is considered that the expansion force of concrete acts on the entire bending area of reinforcing bar from the inside and strengthens a bond between concrete and bar. But, if a concrete crack occurs at the bending area of reinforcing bar, a localized force acts on the bending area whose bond strength has been lost due to cracking, which enlarges bar damage. In contrast, in the case of no confinement of concrete, damage behavior becomes like bending-back of the bar using the bending area as the support point, and disperses the force acting on the bar.

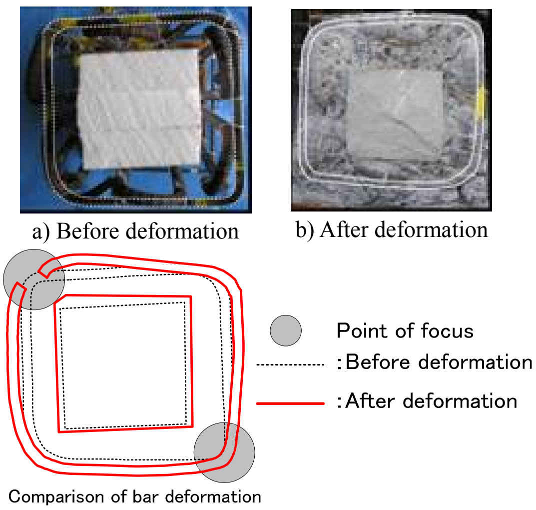


Fig.11 Comparison of bar deformation

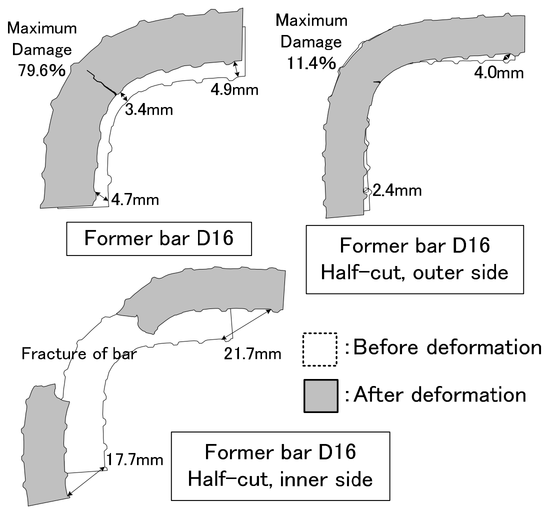
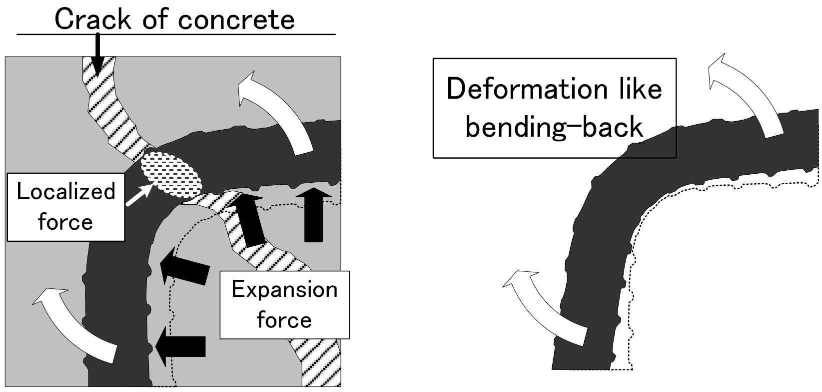


Fig.12 Case9 : deformation at bend



Confined by concrete　　No confinement by concrete

Fig.13 Effect of concrete confinement

4.2 Effect of Corrosion

It is considered that corrosion and hydrogen are principle causes of ASR damage to reinforcing bars. In this experiment, to evaluate the effect of corrosion, forced corrosion was induced. The target reduction amount and the attained reduction amount are shown in Table 5. It is seen that the target reduction amount of force corrosion was roughly attained.

Fig. 14 compares the strains of reinforcing bars between Case 6 with no corrosion and Cases 8 and 10 with forced corrosion. Regardless of the presence/absence of corrosion, only the bending area yielded and the straight line area did not yield. Propagation of strain also showed a similar tendency. Namely, the bending area abruptly yielded and the strain in the straight line area remained around 1500 μ .

Then, the difference in the damage level of reinforcing bars was evaluated. Table 6 shows the maximum damage to the 90-degree bending area of reinforcing bars of the former rib type in each case. As shown in Table 6, the maximum damage was 40.8% when the loss of weight was 4.0%, and 78.8% when the loss of weight was 10%. However, 79.6% damage was also observed even in the case of no corrosion. This means that the damage similar to corrosion cases could occur even in the environment having expansion pressure only and no corrosion.

Picture 1 shows the cross sections of reinforcing bars taken from specimens experimented with forced corrosion. Occurrence of a corrosion pit like (a) was observed, but the occurrence of corrosion was not found at the crack as shown in (b). So, it was not possible to confirm that cracking was accelerated by forced corrosion.
From this comparison, it can be said that the possibility is low that corrosion has a major effect on the propagation of cracks.

Table5 Average reduction by corrosion

case8 (Target：10%)	Average reduction (%)	case10 (Target：4.0%)	Average reduction (%)
Present D16	7.9	Former D16,half-cut	2.3
Former D16	10.7	Former D16	2.9
Present D10	13.4	Present D10	5.5

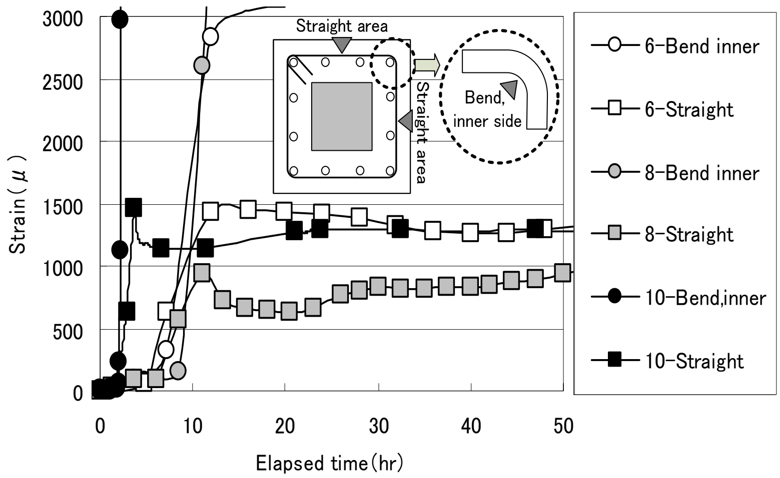
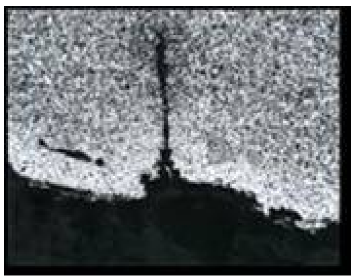


Fig.14 Comparison of bar strains

Table6 Damage to bars (former D16)

	Former D16, maximum damage		
Normal	4.8%	31.9%	79.6%
Corrosion 4.0%	40.8%	—	—
Corrosion 10%	78.8%	—	—

a) Cavitation



b) Crack

Picture1 Damage under forced corrosion

5. Conclusions

(1) From the relationship between bar damage and specimen deformation, it may be said that reinforcing bars might have been fractured if 20 mm diagonal deformation is found in the corner area of the concrete.
(2) When the confinement of reinforcing bar by concrete is intact, the bar damage may be expanded significantly if cracking occurs around the bending area of the bar.
(3) No clear difference was found in the damage level of reinforcing bars placed in the ordinary environment and the forced corrosion environment. Therefore, it is unlikely that only the corrosion has a predominant effect on the propagation of cracks.

References

1) JSCE: Report of the Sub-committee on the Measures against ASR – Fracturing of Reinforcing Bars and New Responses - Concrete Library No. 124, pp. I-2 - I- 77, 2005 (in Japanese).
2) Kosa, K. et al.: Materials Tests to Find the Mechanism of ASR-Affected Fracturing of Reinforcing Bars, Journal of Structural Engineering, Vol. 52A, pp. 951-958, 2006 (in Japanese).
3) Kourogi, N. et al.: Effect of Rib Shape and Concrete Expansion on Fracturing of Reinforcing Bars, Proceedings of Japan Concrete Institute, Vol. 28, No. 1, pp. 719-724, 2006 (in Japanese)
4) Kawashima, K. et al.: Quantitative Evaluation of ASR-Affected Damage in Actual Structures, Proceedings of Japan Concrete Institute, Vol. 28, No. 1, pp. 737-742, 2006 (in Japanese)
5) Tottori, S. et al.: Durability of Elevated Railway Bridges valuated from Corrosion of Reinforcing Bars, Proceedings of Symposium on Rehabilitation of Concrete Structures, pp.45-54, 1998 (in Japanese).