A SURVEY ON ASR-AFFECTED BRIDGE PIERS WITH FRACTURE OF STEEL BARS ON NOTO EXPRESSWAY

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Abstract

The brittle fracture of steel bars caused by an excessive expansion of concrete due to alkali-silica reaction (ASR) has recently been discovered in large numbers of bridge piers on the Noto expressway. At present, the maintenance and rehabilitation for such severely damaged bridge piers are a great concern especially for bridge engineers in Japan. The authors have been carrying out the series of investigation on both the deterioration of concrete and the fracture of steel bars in ASR-affected bridge piers with reactive andesite stone. The paper describes the investigation in field on seven bridges with the fracture of steel bars and their rehabilitation on the Noto expressway. The asset management for ASR-affected bridges on the Noto expressway is also discussed.

Keywords: ASR, Inspection, Fracture of steel bar, Rehabilitation, Asset management

1 INTRODUCTION

In the Noto expressway of Ishikawa Prefecture, large numbers of bridge piers, which were mostly constructed in the 1980s, are now suffering from serious damages caused by ASR [1]. At the first stage of deterioration in 1980s, these piers were repaired by a combined method of the epoxy-resin injection into cracks and the coating on surface, but it was ineffective in controlling the expansion of concrete, resulting in breaking the coating within 5 years after repairing. In the 2000s, the brittle fracture of steel bars at the corner of stirrups and bent-up steel bars and/or at the weld point of main steel bars due to the excessive expansion of concrete happened in succession in the pillow beam or in the footing of bridge piers on the Noto expressway [2]. Since the fracture of steel bars may lead to the significant loss of structural integrity of element of bridge pier, the Japan Society of Civil Engineers, JSCE, has established the research committee on the mechanisms and countermeasures of damages in ASR-affected bridge piers in 2003 [3]. The seriously damaged bridge piers on the Noto expressway were strengthened and/or partially reconstructed for the last decade according to the classification of damage level decided by the ASR committee of Ishikawa Prefecture [4, 5].

This paper describes both the property of andesite stone and the feature of damages in ASR-affected bridge piers with the fracture of steel bars on the Noto expressway. The rehabilitation and asset management for ASR-affected bridges on the Noto expressway are also discussed.

2 PROPERTIES OF REACTIVE AGGREGATE AND CONCRETE CORE

2.1 Outline of Noto Expressway

Figure 1 shows the location of Noto expressway in Ishikawa Prefecture. The Noto expressway is running from Kanazawa city to Anamizu town on the seashore of the Sea of Japan and through the mountain area in Noto peninsula, where the total length of expressway is some 200 km. There are totally forty three bridges, three tunnels and ninety eight culvert boxes in the Noto expressway, which are classified into the following two areas based on the maintenance of infrastructures; one the seashore area where the chloride induced steel corrosion mainly occurs, and the other the mountain area where ASR mainly occurs. In the mountain area, seventeen bridges of total twenty four ones are severely deteriorated by ASR in various parts of bridge; the pier, abutment, girder, retaining wall and so on. During the winter, a lot of deicing salts, which are mainly composed of the sodium chloride (NaCl), are used on the road surface in order to prevent traffic accidents. The use of de-icing salt appears to intimately influence the deterioration of concrete caused by both ASR and the freezing-thawing action.

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2.2 Noto Peninsula Earthquake in March 2007

Accidentally, in March 2007, the big earthquake of magnitude 6.9, which is named the Noto peninsula earthquake, has occurred over the Noto peninsula. Fortunately, the Noto expressway could be available within one month of a easy repairing work since bridge piers were not significantly damaged by this earthquake, because all severely deteriorated bridge piers had already been strengthened and/or reconstructed until this earthquake occurred. Furthermore, until March 2008, the countermeasure for other bridge piers without strengthening will have similarly been done using the urgent budget by the government. By this earthquake, the embankment and slope near bridges collapsed in many places. Figures 2 and 3 show the damage near the Noto Bridge which is the longest one on the Noto expressway. The wing element of abutment in the Noto Bridge was partially broken by the earthquake, resulting in the settlement of road surface of 50 to 100 mm.

2.3 Properties of Reactive Aggregate

The concrete of bridge piers was made of the non reactive river sand and reactive andesite stone as the fine and coarse aggregate, which are all produced in the Noto peninsula. In this district, the andesite stone has been used for a long period because the river gravel is required to carry a long way from Toyama Prefecture. It is well known that the andesite stone produced in the Noto peninsula is the most reactive aggregate all over Japan. Figures 4 and 5 show the XRD pattern and polarization spectroscopy of typical andesite stone used. This andesite stone contained the cristobalite and volcanic glass as reactive components to a significant extent. The results of alkali-silica reactivity of this andesite stone used in concrete are presented in Table 1. The andesite stone is assessed as "Deleterious" by both the chemical test according to JIS A1145 and the mortar bar tests according to JIS A1146 and ASTM C1260. Furthermore, in the measurement of water soluble alkali content of andesite stone in the saturated calcium hydroxide solution at 38 °C, large amounts of alkalis, mostly Na^+ ion, are released in the process of the reaction of volcanic glasses and/or some altered feldspars. Concerning the ASR mitigation method proposed by JIS A 5308, the total alkali content of concrete is required to be less than 3 kg/m^3, which is the most popular one in Japan. Actually, the alkali content of concrete used in ASR-affected bridge piers ranged from 2.2 kg/m^3 to 2.6kg/m^3, but its mitigation method was ineffective for the andesite stone. It is likely that the alkalis released from the aggregate itself may also play an important role in both the formation of ASR gel and the following successive expansion of concrete due to ASR.

2.4 Mechanical Properties of Concrete Cores

Figure 6 shows the compressive strength and elastic modulus of concrete cores taken from the pillow beam, column and footing of bridge piers on the Noto expressway. The reduction in compressive strength of pillow beam was more significant compared with that of column, in most cases ,which is lower than the designed strength of concrete of 21 or 24 N/mm^2. This is attributable to the lower steel reinforcement ratio of pillow beam. It is also apparent that the reduction in the elastic modulus of concrete is also more remarkable than that in the compressive strength. It is likely that the lower the ratio of elastic modulus to compressive strength (Ec/f'c), the higher the degree of deterioration due to ASR. Figure 7 shows the change in compressive strength of concrete cores with time after construction. It was found out that the compressive strength of concrete gradually decreased with time, and that the compressive strength of about 10 and 20 N/mm^2 is acceptable as the designed one strengthening for the pillow beam and column, respectively, where the lower limit value in variations is adopted. Furthermore, the survey on the deterioration of bridge piers on the Noto expressway indicates that in many cases, the cracks tend to increase every year although the time of thirty years has already passed after construction, and that the residual expansion capacity of concrete remains still high.

3 FRACTURE OF STEEL BARS IN BRIDGE PIER

3.1 Deterioration of Bridge Pier

In ASR-affected bridge piers on the Noto expressway, serious damages such as the reduction in compressive strength, the peeling off of cover concrete, and more importantly, the fracture of steel bars have been observed due to the successive large expansion of concrete for 30 years due to ASR. Concerning the fracture of steel bars, the fracture surface of steel bars is very flat and smooth, which indicates the brittle fracture of steel bar. Presently, it has been pointed out that the fracture of steel bars may be associated with the stress corrosion cracking and/or the hydrogen brittle fracture, but its mechanisms has not fully been understood [3]. Its mechanism and a recent research work are stated in the literature by the authors [6]. In Japan, the electric furnace steel bar is usually used in construction work, which is satisfied with the requirement of SD 295 according to JIS G 3112, while the blast-furnace steel bar is used only in important structures such as atomic power generation plant and high-rise building. Case studies on the fracture of steel bars for seven ASR-affected bridges investigated on the Noto expressway are summarized in Table 2.

3.2 Fracture of Steel Bars in Pillow Beam

The pillow beam of bridge pier, where the water with chlorides can easily penetrate from the joint of deck, is always the most severely deteriorated element of bridge pier. By the inspection at regular intervals, the fracture of steel bars was discovered in the pillow beam of three bridges, Azumi Bridge, Tokuda No.2 Bridge and Kashima Bridge. Figure 8 shows the feature of fracture of steel bars in pillow beam of bridge pier. In these bridges, the large horizontal crack of several milimeters and the gap on the side surface were observed along with the main steel bar, as shown in Figure 9. Surprisingly, when removing the cover concrete, the stirrup steel bars of D 19 or 22 mm of pillow beam fractured at a high probability of fracture of 30 % to 50 %, while some bending-up steel bars of D 32 or 35mm also fractured. It is made clear that the fracture of steel bars occurs mostly at the bending corner of 90 degrees, and that they fracture with no elongation and little corrosion. In some cases, the main steel bars of D 35mm fractured at weld points only in Tokuda No.2 Bridge. This may be attributed to the insufficient melting of attached surfaces in steel bars at the construction work.

3.3 Fracture of Steel Bars in Column

The deterioration of column itself due to ASR is usually not so significant due to a high steel reinforcement ratio even when the residual expansion capacity of concrete is still high. The fracture of steel bars was detected in the column of two bridges, Tsuchikawa Bridge and Tokuda No.2 Bridge. Figure 10 shows the feature of fracture of steel bars in the column of bridge pier. In Tsuchikawa Bridge, which is a rigid frame concrete structure, the hoop reinforcement of D 13 mm fractured along the side corner of bridge pier, and in Tokuda No.2 Bridge, the hoop steel reinforcement of D 19 mm fractured only in the portion of column under the ground, the steel reinforcement ratio by hoop steel reinforcement being very low compared with other portions. In the column, all axial longitudinal steel bars were found to be sound.

3.4 Fracture of Steel Bars in Footing

In the excavation work for strengthening around bridge pier, the serious damage was also detected in the foundation where the ground water level was high. The fracture of steel bars was detected in the footing of three bridges, Tokuda No.2 Bridge, Omatagawa Bridge and Kumakigawa Bridge. Figure 11 shows the feature of fracture of steel bars in the footing of bridge pier. In the most serious case of Tokuda No.2 Bridge, all steel bars of D 19 mm fractured along the upper side corner of footing with a low steel reinforcement ratio, leading to extend large cracks from the side corner to the interior of foundation, and consequently to lose the integrity of a whole footing due to the reduction in the confinement force of internal concrete by steel bars as shown in Figure 12.

3.5 Fracture of Steel Bars in Abutment of Bridge

The deterioration of abutment due to ASR was often accelerated by the water from the joint of deck. The fracture of steel bars was detected in the abutment of three bridges, Azumi Bridge, Toyokawa Bridge and Omatagawa Bridge. Figure 13 shows the feature of fracture of steel bars of abutment. In the case of Toyokawa Bridge, all steel bars of D19 mm fractured along the upper side corner of abutment, resulting in the development of diagonal large cracks towards the interior of abutment.

4 REHABILITATION OF BRIDGE PIER

4.1 Reconstruction of Pillow Beam

In the pillow beam with the fracture of steel bars, the partial or full reconstruction was basically selected according to the existence of weld points of main steel bars. Only the cantilever portion of pillow beam was reconstructed for the pillow beam without weld points of main steel bars, while the whole portion of pillow beam was reconstructed for the one with weld points of main steel bars. In the work of reconstruction, it should be taken into considerations that the Noto expressway is the only main transportation road through the Noto peninsula, for this reason, the reconstruction must be carried out along with making sure the common use of all traffics on road. So, after the decks were supported by the steel frame bent, the deteriorated concrete of pillow beam was demolished by a concrete breaker, followed by installing the new steel reinforcement and then by placing the new concrete of 24 N/mm^2, as shown in Figures 14 and 15.

4.2 Strengthening of Column

In order to increase the load bearing capacity of column against the seismic force, the column of bridge pier on the Noto expressway was usually strengthened by the steel plate bonding method or the PC confined method, where the type of strengthening method was selected depending on the type of foundation; the steel plate bonding method for pile foundation and the PC confined method for spread foundation, as shown in Figure 16 [5]. Furthermore, in the case of Tsuchikawa Bridge, which is a rigid frame concrete bridge, the strengthening by reinforced concrete was only adopted, where the upper and lower part of column was prestressed by prestressing steel rods, as shown in Figure 17.

4.3 Strengthening of Footing

In the strengthening design of footing, the stability against seismic force as well as load bearing capacity was taken into consideration. After removing the weak concrete on surfaces and installing the new steel reinforcement, the original concrete element of footing was vertically prestressed at the stress of 0.3 N/mm^2 by forty eight prestressing steel bars of D 32 mm, SWPD, and horizontally prestressed around the footing by eight prestressing steel wires of D 5 mm, SWPR, as shown in Figures 18 and 19. A monitoring system for the tensile stress induced in prestressing steel bars and prestressing wires is presently set up to monitor the behavior of footing before and after strengthening.

5 CONCLUDING REMARKS

In Japan, a lot of bridge piers have been suffering from serious damage due to ASR. Although some countermeasures in the form of repair were applied, almost none of them could completely mitigate the damage due to ASR. Based on the experience of strengthening and monitoring on the Noto expressway, it can be concluded that the monitoring before and after strengthening is valuable to confirm its effectiveness, and to develop the better strengthening method. At present, the fracture of steel bars in ASR-affected bridge piers also becomes a serious matter all over Japan, because this phenomenon may lead to the fear of the safety of bridge itself. The authors consider that the reconstruction for them is not always the best selection from economical and environmental viewpoints. So, it is urgent to develop the more suitable and economical rehabilitation method for ASR-affected bridge piers especially with the fracture of steel bars. Furthermore, in the maintenance work of ASR–affected bridge piers, it is also important to guarantee the daily safety of bridges by the visual inspection and monitoring. After the Noto peninsula earthquake, it has been decided that all ASR-affected bridge piers in the Noto expressway will be strengthened within one year. At present, the authors are actively proposing to the local government to make the database for all bridges over the Noto peninsula. After that, the bridge asset management including the Noto expressway should be started.

6 ACKNOWLEDGMENTS

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7 REFERENCES

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TABLE 1: Results of alkali-silica reactivity of andesite stone.

Chemical method (JIS A1145)		Sc (mmol/l)	289
		Rc (mmol/l)	109
		Sc/Rc	2.65
		Evaluation	Deleterious
Mortar bar method	JIS A1146	Expansion (%)	0.20
		Evaluation	Deleterious
	ASTM C1260	Expansion (%)	0.55
		Evaluation	Deleterious

TABLE 2: Seven ASR-affected bridges investigated on Noto expressway.

No.	Bridge	Type of structure		Fracture of steel bars				f'c (N/mm²)
				Abutment	Pier			
		Super structure	Pier		Beam	Column	Footing	
1	Azumi Bridge	Steel Girder (4-spans)	RC	×	×	-	-	24
2	Tokuda No.2 Bridge	PC Girder (9-spans)	RC	-	×	×	×	21
3	Toyokawa Bridge	Steel Truss (3-spans)	SRC	×	-	-	-	40
4	Tsuchikawa Bridge	Rigid frame RC		-	-	×	-	27
5	Kumakigawa Bridge	PC Girder (9-spans)	RC	-	-	-	×	21
6	Kashima Bridge	Steel Girder (2-spans)	RC	-	×	-	-	24
7	Omatagawa Bridge	PC Girder (1-span)	RC	×	-	-	×	24

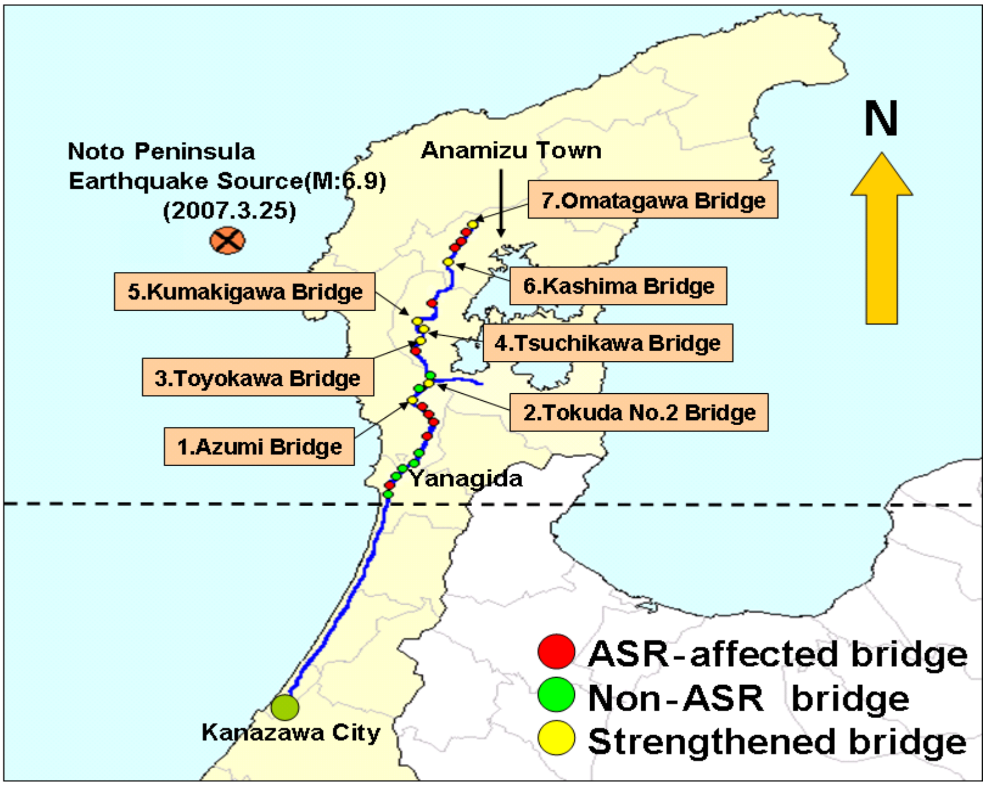

Figure 1: Location of Noto expressway in Ishikawa Prefecture.

Figure 2 :Land slide occurred around Noto Bridge.

Figure 3: Settlement of road surface in Noto Bridge.

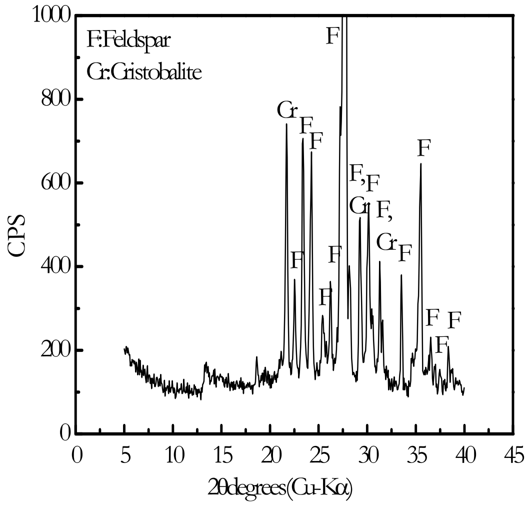

Figure 4: XRD pattern of andesite stone.

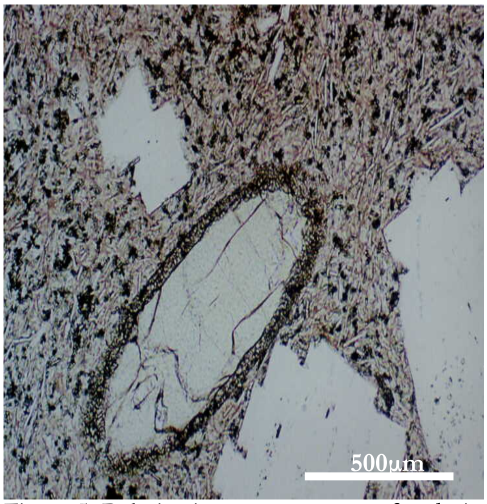

Figure 5: Polarization spectroscopy of andesite stone.

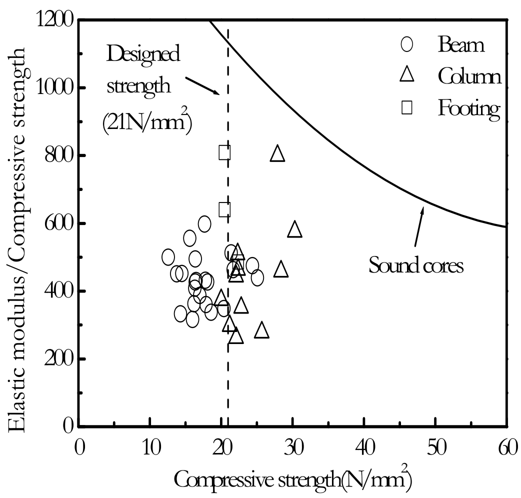

Figure 6: Relations between compressive strength and elastic modulus of cores.

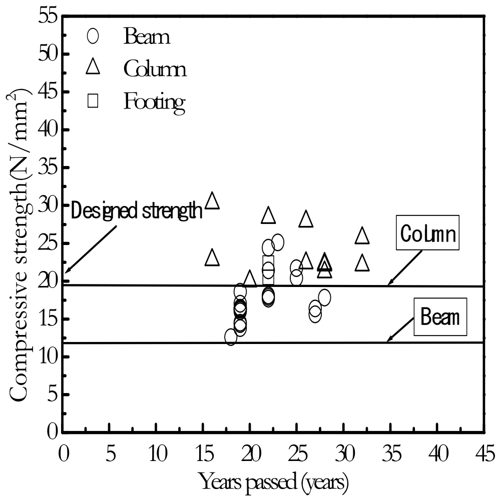

Figure 7: Change in compressive strength of cores with time.

Figure 8: Fracture of steel bars in pillow beam (Azumi Bridge).

Figure 9: Horizontal crack and gap on side of pillow beam (Azumi Bridge).

Figure 11: Fracture of steel bars in footing (Tokuda No.2 Bridge).

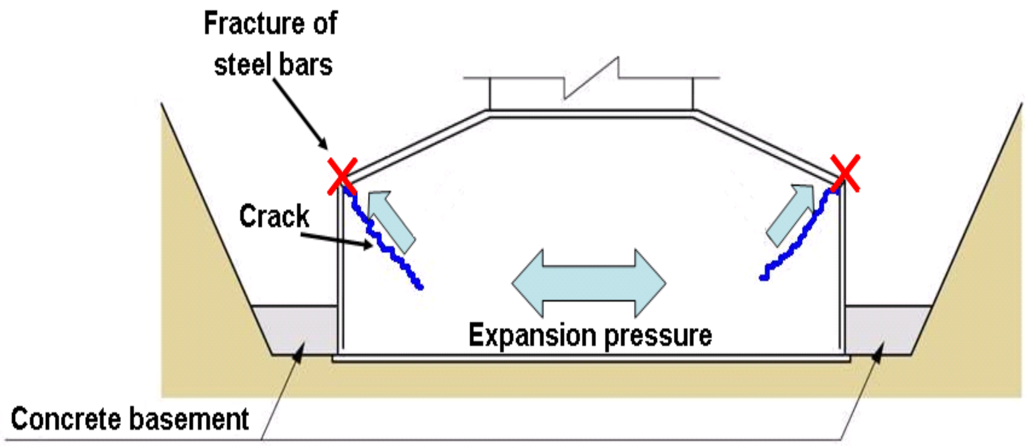

Figure 12: Schematic diagram of ASR expansion in footing.

Figure 13: Fracture of steel bars in abutment (Toyokawa Bridge).

Figure 14: Supporting by steel frame bent (Kashima Bridge).

Figure 15: Demolishing old concrete by breaker (Kashima Bridge).

Figure 16: Strengthening of pier by steel plate bonding (Kashima Bridge).

Figure 17: Strengthening of pier by reinforced concrete (Tsuchikawa Bridge).

Figure 18: Strengthening of footing by prestressing steel wires (Tokuda No.2 Bridge).

Figure 19: Strengthening of footing by prestressing steel rods (Tokuda No.2 Bridge).