Development of inner lining for deteriorating reinforced lining of mountain tunnels

Yoshinori Nagayama i) and Masahiro Kondo ii)

i) Deputy General Manager, Structural Engineering Office, West Japan Railway Company, 4-20, Nishinakajima 5, Osaka, 532-0011, Japan.
ii) Deputy Director, Structural Engineering Office, West Japan Railway Company, 4-20, Nishinakajima 5, Osaka, 532-0011, Japan.

ABSTRACT

Long-term stability of mountain tunnels is disrupted by natural causes such as ground pressure and earthquakes. In some cases, their serviceability is disturbed by deterioration of lining concrete. There are 280.5 kilometers of tunnels in Sanyo Shinkansen. Among them, 16.8 kilometers are reinforced concrete structures. Rock pockets and cold joints are main causes of loose parts of lining concrete. They are mainly defects at the time of construction, and once they are removed, further deterioration is limited. However, the cause of loose parts of reinforced lining is carbonation combined with deficiency in the depth of cover of rebars, and carbonation continues into the future. In order to ensure long-term performance of tunnels with reinforced lining, the authors have developed a new technology of inner lining. Members of the new lining were tested in laboratory, and confirmed they will withstand grouting pressure, wind pressure caused by train operation, and weight of loose parts of concrete. A mock tunnel was constructed and test executions were carried out to verify execution time before actual construction.

Keywords: mountain tunnel, RC lining, carbonation, FRP lining, mock tunnel

1 INTRODUCTION

Some of reinforced concrete linings of Sanyo Shinkansen tunnels have loose parts due to corrosion of rebars caused mainly by carbonation of concrete. The progress of deterioration is being monitored and new loose parts are being removed at frequent intervals. Conventional repair methods for existing concrete lining employ bonding sheets, attachment plates, mounting angels, wire mesh, shotcrete, etc. But all these materials and/or anchor bolts which are used to fasten them require regular inspections. Furthermore, they cannot withstand by themselves, so they have to be supported by existing linings. Thus, drastic measures are required and a new technology of inner lining has been developed. This paper describes necessary conditions for mitigation measures, and details of the developed method.

2 BACKGROUND OF THE PROBLEM

2.1 Delamination of plane concrete lining

Pieces of concrete lining came loose and fell in 1999, which damaged the safety reputation of the Sanyo Shinkansen. The first fallen pieces of concrete were blocks of concrete adjacent to a cold joint, and the second ones were surplus concrete at side walls that had been added during inverted construction of the lining. They are mainly defects at the time of construction, and once removed, further deterioration is limited. After these accidents, all concrete surfaces of the 142 tunnels on the Sanyo Shinkansen line, a total length of 280.5 km, were examined during 52 days of comprehensive inspections.

2.2 Delamination of reinforced concrete lining

Pieces of concrete fell from reinforced concrete lining seven years later from the comprehensive inspection. After the incident, chloride ion content, depth of carbonation (neutralization), and cover of rebars were measured. Figure 1 shows chloride ion contents of 13 tunnels, which were well over the corrosion threshold of 1.1 kg/m².
It was assumed that little attention was paid to chloride ion content at the time of construction, because most of the linings were made of plane concrete.

Figure 2 shows carbonation depths of these 13 tunnels, compared to design cover of rebars. The carbonation depths were relatively smaller than the design cover of rebars. The actual depths of cover were measured at exposed rebars using adjacent sound surfaces as a base line. Figure 3 shows cover of rebars and depths of carbonation of the Higuchiya tunnel (No. 7). In this figure, measured depths of cover were less than the design values and as small as carbonation depths. When non-carbonated cover is less than 10 mm, formation of rust starts at reinforcement. Therefore, it was concluded that corrosion of rebars due to carbonation, combined with deficiency in the depth of cover and high content of chloride ions had caused delamination of the cover. Since carbonation continues into the future, corrosion of rebars is inevitable. Thus, drastic measures were necessary.

Sanyo Shinkansen has five-hour time windows for inspection and works. Therefore, the inner lining under construction should be structurally robust at the end of each time window. For this purpose, arch supports with insertion panels were adopted. In order to make the circumferential structure robust after each time window, the gap between the panel and existing lining is grouted immediately after the panels are installed.

Available clearance between the construction limit and interior surface of the lining is about 150 mm in design. Based on detailed surveying, the thickness of inner lining was decided to be 100 mm (Fig. 4). In order to secure the construction limit, a H-shaped arch support of 100 mm in height was adopted, and every parts of the new lining were kept within this thickness with some exceptions near the spring line.

No bolts and nuts should appear on the surface because those parts require regular inspections and replacement when necessary. For this reason, joints of supports do not use them and those of panels are covered by the lining itself.

It also has to conform to irregular surfaces of existing tunnels, because loose parts of linings have been removed. For this reason, adhesive joining was excluded and grouting was adopted.

3 OUTLINE OF THE DEVELOPMENT

3.1 Requirements for preventive measures

In addition to the operational safety of Shinkansen, long-term stability and minimal maintenance are given top priorities. The followings are the requirements and adopted methods:

Fig. 2. Depth of carbonation.

Fig. 3. Depth of carbonation and cover of rebars at Higuchiya tunnel.
After the completion, the inner lining acts as a concrete arch reinforced both circumferentially and orthogonally by FRP members.

### 3.3 Execution procedures of the adopted method

The execution process is as follows:

**Step 1:** Brackets and footing beams are installed as shown in Fig. 5, and FRP support is constructed circumferentially using socket joints. The support is fixed to the existing concrete by anchor bolts.

**Step 2:** FRP panel is inserted between the supports through insertion slot, where flanges are cut off (Fig.6). The panel is guided by the flanges.

**Step 3:** The gap between the panel and existing concrete is grouted through inlets at the web.

Steps 2 and 3 should be completed within the same time window.

**Fig. 5.** Detail of foundation of the inner lining.

**Fig. 6.** Insertion of a panel between arch supports.

### 4 LABORATORY TESTS

Glass-fiber-reinforced polyester is made of layers of glass cloths and/or glass mats hardened by polyester resin. So strength of it varies with specification. Therefore, flexural capacity of the members were tested at laboratory and confirmed they would withstand grouting pressure, air pressure variation caused by trains, and loading from loose parts of concrete. Figure 7 shows rupture of the H-shape beam, and figure 8 shows rupture of a rib of the panel. In these figures, FRP members were delaminated both at a tension flange of a beam and at a compression rib of a panel, leading to brittle failure. This means careful attention is necessary in setting design safety factors for these members.

**Fig. 7.** Rupture at a tensile flange of an H-shape beam.

**Fig. 8.** Rupture at a compressed rib of a panel.

### 5 EXECUTION PRACTICE USING A MOCK TUNNEL

A mock tunnel of the size of Shinkansen tunnel was constructed to confirm the erection of supports, insertion of the panels, and grouting (Fig.9). The pressure of injected grout was measured and it was well below the capacity. Leakage of the grout was prevented by sealants between the support and the panel, the support and uneven surface of existing concrete, and/or from insertion slot. The gelation time of the grout was 60-90 seconds, so when leakages happen, they were stopped in a few minutes by disposable cloth.

**Fig. 9.** A full-size mock tunnel.

Here are some of the improvements made during execution practices:

A guide angle was attached to the support and the panel is guided by the gap between the flanges of the angle and the support. This angle also acts as a reaction for sealant when sponge rubber is filled between the
panel and the flange of the support (Fig. 10).

In order to enhance bending strength and flexural rigidity of the panels, the number and size of air release holes at a panel rib were reduced to two 25 mm holes from the original six 30 mm holes.

6 LOADING TEST FOR COMPLETED LINING

Loading tests were conducted at the completed lining through holes in lining of the mock tunnel. Horizontal and vertical strains were measured at 100 and 200 mm distance from the loading point on the surface of the panel. Figure 11 shows loading equipment and figures 12 and 13 are horizontal distribution of horizontal strain and circumferential distribution of vertical strain, respectively. The later shows arching behavior of the new lining as it was compressed circumferentially at 200 mm distance from the load.

7 EXECUTION AT A REAL TUNNEL

The major target is Higuchiyama tunnel where over 300 meters long section is to be lined and a grout plant should be loaded on a carrier. But the developed method of inner lining was first applied to Ohirayama tunnel, where deteriorating lining was located near the portal. So a mixing plant of grout was placed outside of the tunnel portal. Three meters have completed within the time window, but grouting of the first lining was interrupted at the crown due to poorly prepared outlet of the air, leaving another day to complete. Figure 14 shows the completed FRP lining.

8 CONCLUSIONS

A method to improve lifetime of deteriorating reinforced lining of Sanyo Shinkansen was developed. Laboratory tests, design calculations, field tests and construction practices on a mock tunnel, improvements of details, all contributed to the successful execution within the narrow time window of Shinkansen. But further improvements are necessary to curb the costs.