Development of Concrete Repair Method Using Thin, Highly Ductile Cement Board (Smooth Board Method)

1. Background of development

The social infrastructure constructed with massive investment during the period of high economic growth (1955-1973) is aging, and accidents are being reported, such as ceiling panels falling in expressway tunnels and concrete fragments falling from side walls on railway viaducts. Due to deterioration, the concrete structures of public transport facilities cannot function as infrastructure (Photos 1 and 2). Moreover, the fall of concrete fragments, typically seen in concrete coverings, is likely to immediately cause third-party damage, possibly leading to fatalities.

Photo 1. Deterioration of tunnel lining concrete

Photo 2. Deterioration of railway side wall (reinforcing steel is corroded and exposed)

Conventional measures to correct deterioration have consisted mainly of plastering work and spray application work using polymer cement. However, these measures are temporary treatments and the quality of the work is dependent on the work crews' skills and experience, weather, and other construction conditions. Furthermore, embedded forms, which are deemed permanent measures, are costly and the forms are thick and heavy, posing challenges in limited spaces.

Under these circumstances, we developed the Smooth Board method that uses a thin, lightweight, highly ductile cement board (Smooth Board) as an embedded form. This board can also be applied to thin reinforced concrete members not only as an embedded form but also as a structural reinforcing material by utilizing its high strength and high ductility characteristics.

2. Overview of technology

2.1 Method of surface protection

This method uses a thin, highly ductile cement board (standard dimensions: 910 x 1820 x 8.5 mm (W x L x D); mass: 24 kgf/piece) as an embedded form. Photo 3 and Figure 1 show tunnel-lining repair work and Photo 4 and Figure 2 show railway side wall repair work.

In this method, the deteriorated concrete is removed. Next, the boards are installed using post-casting concrete anchors and all-screw bolts. The boards are then reinforced by shoring. Next, non-shrinkage mortar is poured between these boards and the placed concrete. After curing, the shoring is removed, and the boards are secured with nuts, etc., to the all-screw bolts. These all-screw bolts will be be used as post-casting concrete anchors, as shown in Figure 1. The heads of the all-screw bolts extend through the wall, as shown in Figure 2.

When used for repairing the lining concrete of a tunnel, the boards are cut in half along the width and installed so as to match the circular shape of the tunnel.

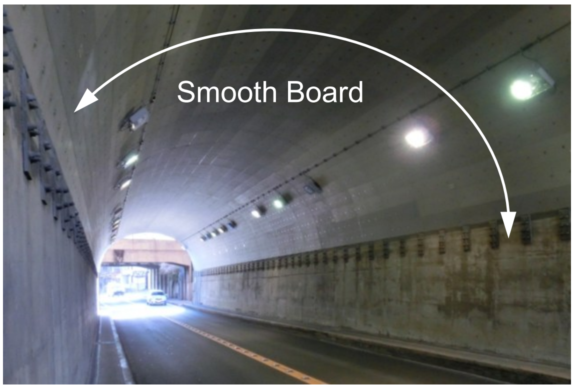

Photo 3. Repair of tunnel lining

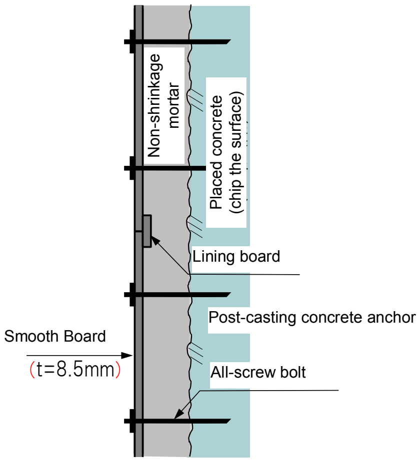

Figure 1. Repaired section (tunnel lining)

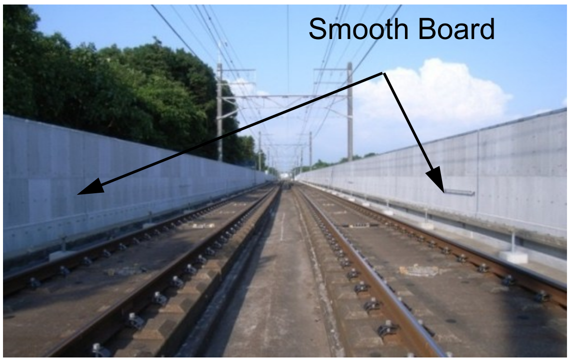

Photo 4. Repair of railway side wall

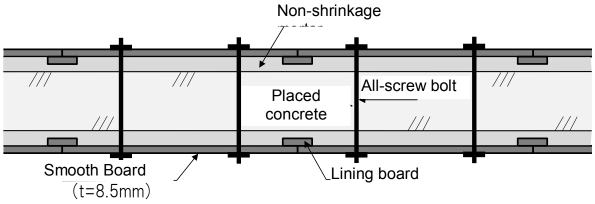

Figure 2. Plane view of repaired section (railway side wall)

2.2 Characteristics of this board

This board is composed of cement reinforced with short vinylon fibers. The board is high in strength and ductility, and has a fiber orientation and a flexural strength of 32 N/mm^2 in the longitudinal direction and $19N/mm^2$ in the lateral direction. Under loading, even after the elastic limit is reached, the board retains its flexural strength by generating several cracks, which increase the amount of deflection.

3. History of development

In 2000, mesh-shaped concavities and convexities were added to one side of the board, which had been plain on both sides. By applying a water-absorption conditioning agent, the board could be bonded to cement-based materials.

From 2001 to 2005, various tests were conducted to verify the strength and deformation characteristics and the physical properties of the board material, as well as the surface protection performance of the board as a concrete composite structure.

In 2008, with the aim of using the board for repairing side walls on railway viaducts and as a structure member, real-size mockup experiments were conducted to verify the flexural reinforcement effect on reinforced concrete beam members. Based on the results, we conducted a joint study with the Railway Technical Research Institute, a public interest corporation, and published the "Guidelines for Designing and Constructing a Repair Work Method for the Side Walls of Existing Railways Using Highly Ductile Cement Board" in March 2013.

This method was adopted for repairing the lining concrete of an old tunnel in 2012, using non-shrinkage mortar together with the board and placing additional concrete to increase the thickness of the lining.

4. Effect of development

4.1 Embedded form (surface protection material)

(1) Type of form shoring

This board has high ductility and use of shoring can provide limited space between the board and the placed concrete with the thickness of only 8.5 mm. To investigate these concerns, experiments on shoring design and construction management were conducted. The space between the placed concrete and the board was set to 8 mm and a mini pressure sensor was attached to the board to measure the pressure exerted by the mortar. At a mortar fill height of 2 m, the sensor registered a pressure of 44 kN/mm^2, which, by assuming that mortar is a fluid, can be considered a fluid pressure. The results confirmed that the external shoring materials that are commonly used for plywood forms, such as vertical and horizontal walling pipes, are sufficient when the mortar fill height per operation is limited to a maximum of 2.0 m.

(2) Bonding performance

To unite the board and the placed concrete, both must bond adequately with the mortar. The board is press-fabricated to form mesh-shaped concavities and convexities on one side of the board. A water-absorption conditioning agent was then applied at the site.

(3) Verification of durability under freezing and thawing, neutralization, and salt penetration conditions

Pressed under a load of 120,000 kN during fabrication, the board is designed to have a tight structure. To verify that the structure can provide surface protection function as a concrete structure, testing under freezing and thawing, neutralization, and salt penetration conditions was conducted. The results demonstrated that the board has adequate durability, as described in Table 1.

Table 1. Surface protection performance test results (concrete composite specimen)

Items	Test method	Test results
Neutralization	JIS A 1153	Outdoor exposure Neutralized depth in terms of 28 years: 1 mm
Salt penetration	JSCE G574-2010	Chloride ion diffusion coefficient: 0.027 cm^2/year
Freezing and thawing	JIS A 1148 A method	Relative dynamic elastic coefficient: 96% Scaling: None

(4) Construction while maintaining the traffic flowing

1) Repair of tunnel lining: one-lane alternate traffic

If the work is carried out in stages using a mortar fill height of up to 2 m per operation, then safety measures can be made very compact, no conventional dedicated protection devices are necessary to block off a vehicular traffic lane, installation of protection sheets using for common frame scaffolding is only necessary (Photo 5). Therefore, one-lane alternate traffic is possible and work can be conducted without blocking the road during the daytime.

2) Repair of railway viaduct side wall: working near railway traffic

Since the board can be fixed to an existing side wall using all-screw bolts during erection, it is safe from the wind pressure created by passing trains, thus enabling operations near active railways (Photo 6).

The work space on the track side needs to be only about 60 cm from the existing side wall, which does not block railway traffic. The nuts fastened from the outside should be locking nuts so that they will not be loosened by vibrations from passing trains.

Photo 5. Tunnel lining (one-way alternate traffic)

Photo 6. Railway side wall (working near railway traffic)

4.2 Reinforcing material (surface protection material + structural reinforcing material)

(1) Verification of flexural strength influenced by decreased bond surface area

With this method, in principle, the board should be attached over the entire surface of the placed concrete and mortar injected between them. However, as Figure 3 shows, aged reinforced concrete structures may contain corroded reinforcing steel where the concrete is detached. This could prevent complete bonding between the board and the reinforced concrete. Quantitative experiments were conducted to reveal how this phenomenon affects the flexural strength. A reinforced concrete specimen 150 mm in thickness was reinforced on both sides with non-shrinkage mortar injected at 8 mm intervals between the specimen and the board.

Figure 4 shows an overview of the experiments. Table 2 lists the experiments. In Figure 4, the areas where polystyrene foam was placed are unbonded areas. Assuming a lack of bonding caused by corrosion of the primary steel bars, 250 mm, the most common interval for reinforcing steel, was set as the interval for the polystyrene foam, and the width (*a* in Figure 4) was set as a parameter.

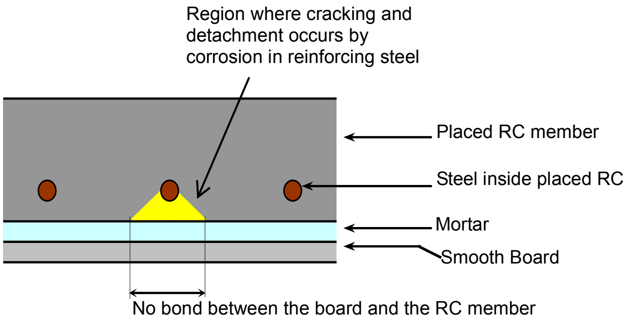

Figure 3. Schematic view of unbonded area

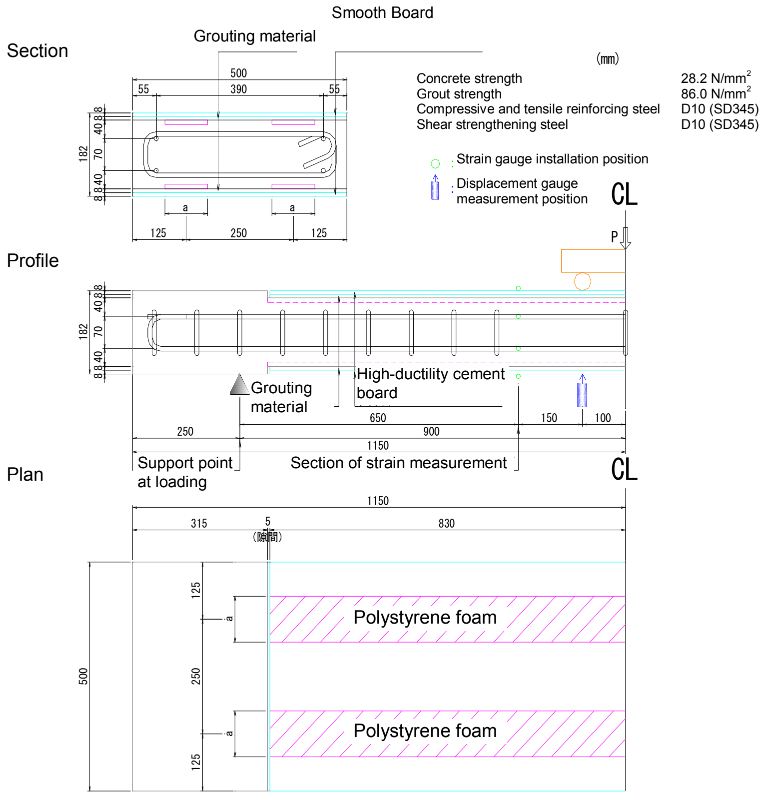

Figure 4. Overview of experiment
(Polystyrene foam: no bonding)

Table 2. List of experiments (bond area decrease ratio)

Experiment	Tensile reinforcing steel ratio	Width of unbonded area[*1]	Bonding area decrease ratio
A-1	0.226% (2-D10)	Completely bonded	0%
A-2		50 mm at 2 places	20%
A-3		100 mm at 2 places	40%
A-4		150 mm at 2 places	60%

*1 50, 100, 150 mm correspond to dimension *a* in Figure 4.

Table 3. Results of experiments

Experiment case	Bonding area decrease ratio	First load peak (at rupture of board)		Second load peak	
		Load (kN)	Displacement (mm)	Load (kN)	Displacement (mm)
A-1	0%	**36.3 (1.00)**	**0.92**	31.8	61.74
A-2	20%	**33.6 (0.93)**	**0.82**	31.4	42.40
A-3	40%	**33.6 (0.93)**	**0.88**	30.9	83.06
A-4	60%	27.0 (0.74)	0.76	**31.6**	**68.04**

Note: Bold type indicates values at maximum load.

[Experiment results and analysis]

Table 3 lists the results of the experiments. The results show that decreasing the bonding area reduces the maximum load. When the bonding area is decreased by the ratio of 20% and 40%, their maximum loads become 93% of that for complete bonding and the maximum load decrease ratio is smaller than the bonding area decrease ratio. On the other hand, when the bonding area is decreased by the ratio of 60%, the maximum load become 74% of that for complete bonding, showing that the influence becomes relatively greater.

However, even when the bonding area was decreased to about half, the reinforcing effect was at least about 70% of the strength of complete bonding. This confirmed that if the corrosion of the reinforcing steel in reinforced concrete structures is minor, this method is applicable even when the deteriorated parts cannot be completely removed.

A bending test was conducted on test specimens without the board. The results showed a yielding load of 17.8 kN. One test specimen (A-1), reinforced with a completely bonded board, produced a yielding load of 36.3 kN, which is approximately twice the yielding load of an unreinforced test specimen. This shows that the board directly increased the flexural strength and can be used as a structural reinforcing material.

(2) Real-size experiment on a railway side wall

To verify the effectiveness and validity of the use of this method for reinforcement, etc., of railway side walls, experiments were conducted using real-size walls. The experimental wall was modelled on a typical structure of concrete blocks and a ground cover on a projecting reinforced concrete floor slab.

The assumed load was wind acting in the horizontal direction. Figure 6 shows the positional relationship between the loading point and the side wall. Four experiments were conducted. In one experiment, a load was applied at P2 at the base of the side wall. For this experiment, the following questions were asked.

[1] In the first cycle, a load 1.2 times the design wind load corresponding to the bending moment generated in the section of the side wall base is applied to loading point P2. Is the side wall in an elastic or non-elastic state?

[2] In the second cycle, a load leading to the fracture of the side wall base is applied to loading point P2. What is the bearing force of the side wall base?

Figure 7 shows the load-displacement relationship at P2. Photo 7 shows the loading at P1.

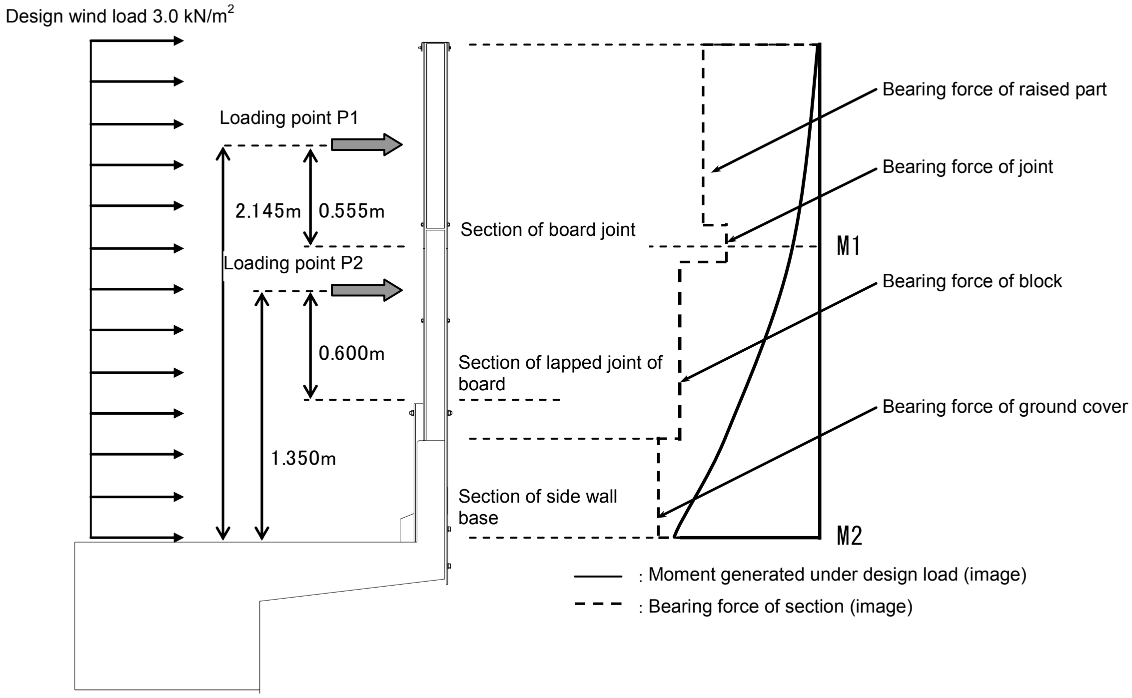

Figure 6. Loading positions and side wall

Photo-7 Loading (opposite the positioning in Figure 6)

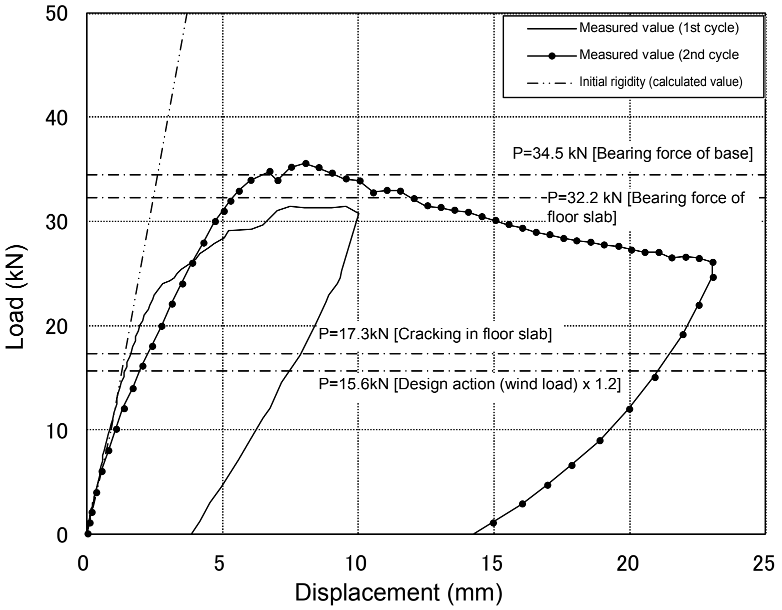

Figure 7. Load-displacement relationship at loading point P2

Evaluation of performance of railway base under design load

In the first cycle, the measured values are consistent with the calculated (pre-analyzed) values) up to 15.6 kN, which is 1.2 times the design load, suggesting that the side wall was in an elastic state. The bearing force on the floor slab was 32.2 kN.

In the second cycle, a load was applied by supporting the underside of the end of the projecting floor slab to measure the bearing force of the side wall base. The bearing force of the side wall base was 34.5 kN (about twice the design bearing force), but no damage to the base at this point was observed, which verified that the method of securing the lower end of the board to the floor slab was valid.

5. Construction record

5.1 Railway viaduct side wall repair work

This method was used for repairing and reinforcing a railway viaduct side water that needed to increase its height as a noise control measure for a new high-speed train services and to rehabilitate age-related deterioration (Photo 8).

Photo 8. Repair of railway viaduct side wall (1.6 m high before construction; 2.5 m after rehabilitation)

5.2 Tunnel lining concrete repair work

At a tunnel that had been protected from concrete detachment using a simple framework of H steel and interior boards, the lining concrete had deteriorated further. This method was used to place additional concrete in order to increase the thickness of the lining.

Photo 9. Repair of tunnel lining (additional concrete cast to increase the thickness)

Conclusion

This method is applied for repairing works in which deteriorated concrete is removed and thin highly ductile cement boards are installed on the concrete surface. Cement-based fillers, such as non-shrinkage mortar, are then injected between the boards and the placed concrete. The board excels in protecting the surface from neutralization, salt penetration, and freezing and thawing, and displays high bond strength with cement-based filling materials. The falling of detached concrete is completely prevented by securing the surface of this board with nuts and bolts and other hardware. Moreover, since the board is thin and lightweight, it can be installed by manpower alone with no need of heavy equipment. This means that the construction work can be conducted in tunnels and other road facilities with traffic and on railway viaducts near passing trains. Side walls of railway viaducts can be repaired by taking advantage of the board’s high strength and adaptability as a structural reinforcement member. The method can also be used to raise railway side walls.

This method is applicable for repairing various concrete structures. The technology is certain to make a great social contribution as a protection measure for aging infrastructure.