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Development of a New Construction Method for Large-Scale Renovation of Concrete Bridges on the Tokaido Shinkansen

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Abstract

This paper reports on the development of a new construction method employing carbon fiber sheets and carbon fiber anchors (CF anchors) for the large-scale renovation of reinforced viaducts and concrete bridges on the Tokaido Shinkansen. This method was developed to improve the construction safety and efficiency of the steel plate cladding method (hereafter referred to as the "initial method"), which has been used since the early stages of the renovation program. A series of performance tests demonstrated that the new carbon fiber reinforced polymer (CFRP) cladding method provides carbonation suppression, weather resistance, punching shear resistance, and load-bearing capacity equal to or greater than those achieved by the initial method. Furthermore, field trials conducted on operating lines confirmed that the lightweight and easily handled carbon fiber materials significantly improve both construction safety and efficiency, while reducing overall costs. In addition, even at sites where buildings are present beneath the viaduct, the use of CF anchors enabled construction without relocation. The new construction method is scheduled to be fully adopted for large-scale renovation work across the entire Tokaido Shinkansen line in fiscal year 2026.

Keywords: Tokaido Shinkansen, concrete bridge, large-scale renovation, carbon fibre sheet, CFRP, CF anchor, carbonation suppression, infrastructure maintenance.

1 Introduction

The Tokaido Shinkansen is a 515-km high-speed railway line connecting Japan's three major metropolitan areas: Tokyo, Nagoya, and Osaka. When operations commenced in 1964, it became the world's first railway to provide commercial service at speeds exceeding 200 km/h. Since its opening, the line has been serving as the main artery of Japan's economy and continues to support national growth. Today, with a maximum operating speed of 285 km/h, the Tokaido Shinkansen carries approximately 460,000 passengers per day, totaling around 168 million passengers annually. The average delay per train is 1.4 minutes, including delays caused by natural disasters, demonstrating a high level of punctuality [1].

The structural composition of civil engineering structures along the Tokaido Shinkansen consists of steel bridges, concrete bridges, tunnels, embankments, and cuttings (Figure 1). Cenral Japan Railway Company (JR Central) has continuously ensured the integrity of these structures through thorough inspection, repair, and reinforcement. However, recognizing that substantial renewal would eventually be required due to aging, JR Central initiated long-term research and development on service-life extension technologies, centered at its in-house research facility established in 2002.

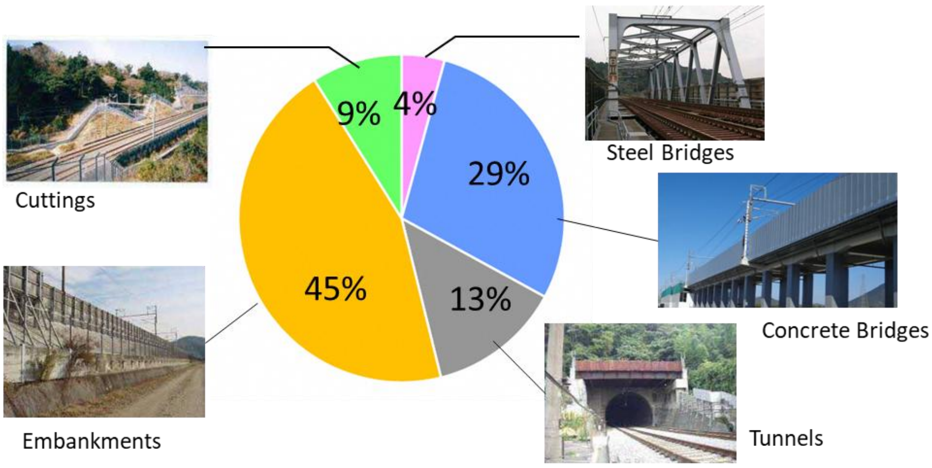


Figure 1: Civil Engineering Structures on Tokaido Shinkansen

Based on the results of this research, JR Central developed new preventive maintenance methods and launched a large-scale renovation program targeting steel bridges, tunnels, and concrete bridges [2]. As of the end of fiscal year 2024, renovations of steel bridges and tunnels have been completed, while more than 70% of concrete bridges have undergone renovation.

In this context, this paper presents an overview of the development of a new construction method for large-scale renovation of concrete bridges.

2 Concept of Preventive Maintenance

Conventional maintenance practices for railway, road, and other infrastructure have generally relied on a "reactive repair and reinforcement" approach, in which repairs are carried out as needed whenever deterioration is detected through inspection. In contrast, because the civil engineering structures along the Tokaido Shinkansen were constructed during the same period based on standard designs, the detection of deterioration at one location suggests that similar deterioration is likely at the same components of similar structures. Therefore, in addition to reactive repairs, JR Central has systematically implemented "proactive repairs and reinforcement" for all components where future deterioration is anticipated.

The large-scale renovation program proposed and implemented by JR Central is based on the concept of preventive maintenance. Under this approach, repairs and reinforcement are carried out on structures that have not yet shown deterioration but are expected to undergo aging-related degradation. Preventive measures are implemented across all applicable structures to effectively delay the initiation of deterioration, followed by continuous monitoring after repair and reinforcement work to determine whether more extensive renovation is necessary.

Because preventive maintenance limits deterioration before it appears, it is more cost-effective than repairing structures only after it has progressed to the point of impairing structural performance. Preventive maintenance is also expected to reduce long-term maintenance costs (Figure 2).

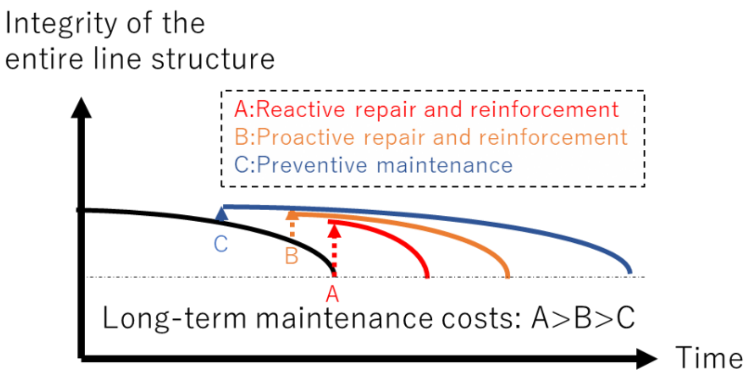


Figure 2: Relationship Between Time and Integrity of the Entire Line Structure for Each Repair/Reinforcement Method

3 Overview of Large-Scale Renovation of Concrete Bridges

When carbon dioxide from the atmosphere penetrates concrete structures, the internal pH decreases, leading to carbonation. Once carbonation reaches the depth of the reinforcing steel, corrosion occurs. Consequently, cracking occurs in the concrete due to the internal pressure generated by corrosion products. To limit the progression of carbonation over time and prevent cracking, JR Central has implemented surface protection treatments—coating concrete surfaces with resin-based materials—since 2000.

In addition, JR Central has continuously monitored the condition of areas where surface protection had been applied since 2002. As a result of this long-term monitoring, no cracking was observed in the surface protection applied to the central slab, beams, or main girders. However, cracking was detected in some parts of the surface protection on the underside of cantilever sections. This cracking is presumed to be caused by repeated loading from passing trains. Once cracks occur in the surface protection layer, carbonation can no longer be effectively suppressed.

In the large-scale renovation program launched in 2013, JR Central adopted optimized surface cladding methods tailored to each structural component (Figure 3). For cantilever sections, a method that clads the concrete surface with steel plates was selected. For the central slab, beams, and main girders, surface protection using resin materials continued to be applied. For columns, different approaches were taken depending on whether seismic reinforcement had been implemented after the 1995 Kobe Earthquake. Columns that had already been reinforced with steel plates were considered adequately protected from carbon dioxide penetration, and no additional measures were necessary. For unreinforced columns, steel jacketing was newly applied as a preventive measure to suppress carbonation [3].

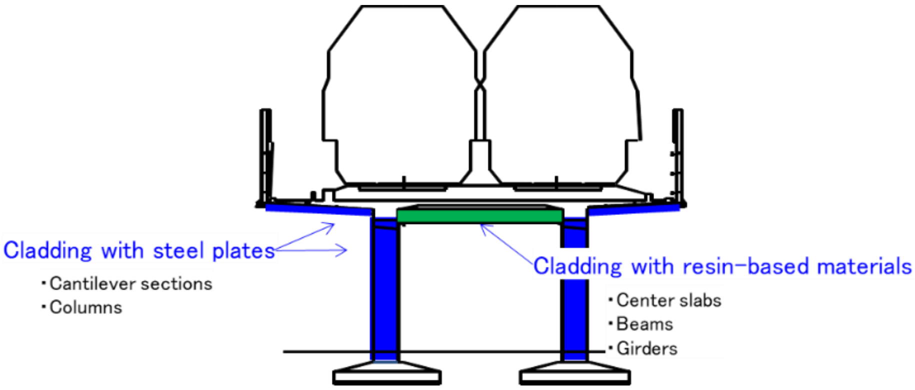


Figure 3: Surface Cladding Methods Applied to Each Structural Component

4 Challenges of the Steel Plate Cladding Method for Cantilever Sections

The steel plate cladding method for cantilever sections is illustrated in Figures 4 and 5. In this method, steel plates are anchored to both the upper and lower surfaces of the cantilever slab, and the gap between the steel plates and the slab surface is filled with resin. The steel plates used in this method weigh up to 60 kg per piece, meaning that safety improvements through the use of lighter materials are another significant challenge. Improving construction processes and reducing manpower requirements through the application of materials with better workability is also an important consideration, as it could help lower labor costs. In addition, due to increases in the prices of raw materials such as iron ore, the impact of the weaker yen, and fluctuations in global supply and demand, the cost of procuring steel in Japan has risen compared with when the large-scale renovation program first began. Reducing material costs has become an important issue.

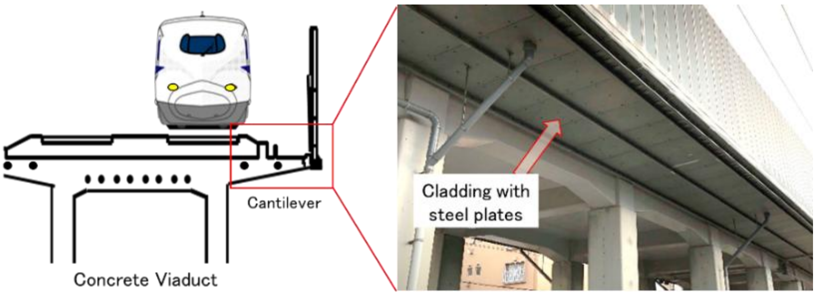


Figure 4: Viaduct After Application of the Steel Plate Cladding Method

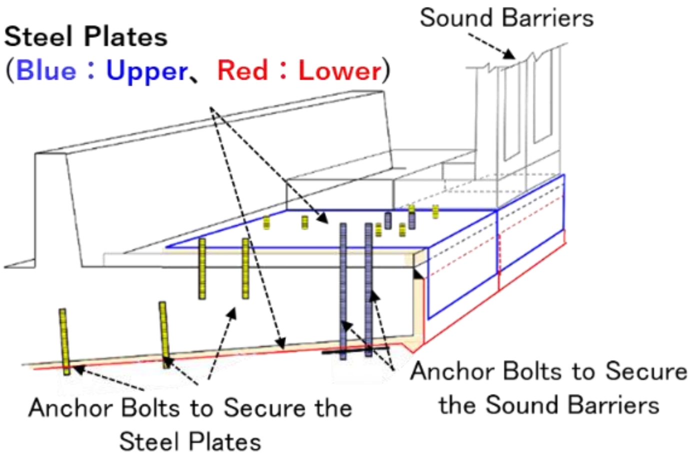


Figure 5: Overview of the Steel Plate Cladding Method

Among the locations subject to large-scale renovation work, there are several cases—such as that shown in Figure 6—where buildings exist beneath the viaduct and exterior walls extend up to the height of the cantilever slab. When the initial method is applied in such locations, installation of steel plates could require removal and restoration of exterior walls, and in some cases, even relocation of the building itself. Therefore, it became necessary to develop a countermeasure method for the underside of cantilever slabs that eliminates, or at least minimizes, the need for such relocation.

Figure 6: Viaduct with Buildings Located Beneath the Viaduct

5 Development of the New Method

5.1 Overview of the New Method

To address the challenges associated with the steel plate cladding method applied to cantilever slabs, a new construction method using lightweight and high-strength carbon fibre sheets was developed (Figure 7). In this method, CFRP layer is formed by bonding and impregnating carbon fibre sheets with an epoxy resin, and this CFRP layer is used to clad the surface of the cantilever slab. A surface protection coating is then applied over the CFRP layer.

Carbon fibres possess approximately ten times the tensile strength of steel, providing sufficient structural performance for reinforcement. The surface protection material serves to prevent the penetration of deterioration factors into the concrete, thereby ensuring adequate suppression of carbonation and crack formation. The preventive maintenance performance of the new method is equal to or greater than that of the steel plate cladding method.

Additionally, because the material cost of carbon fibre sheets is lower than that of steel plates, cost reduction can be expected. The weight of the carbon fibre sheets is less than one-sixtieth that of steel plates, making them significantly easier to handle and contributing to improved workability, labour savings, and enhanced construction safety.

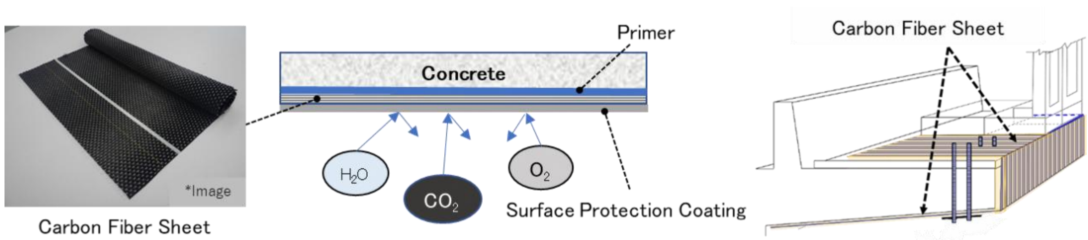


Figure 7: Overview of the CFRP Cladding Method

For locations where buildings exist beneath the viaduct, a new construction method was developed in which the carbon fibre sheets are applied separately to the interior and exterior faces of the building wall and then bonded using carbon fibre anchors (hereafter referred to as CF anchors) (Figure 8). A CF anchor is a rope-like element with a diameter of 10–20 mm, formed by bundling 24,000 carbon fibre filaments made of the same material as the carbon fibre sheets.

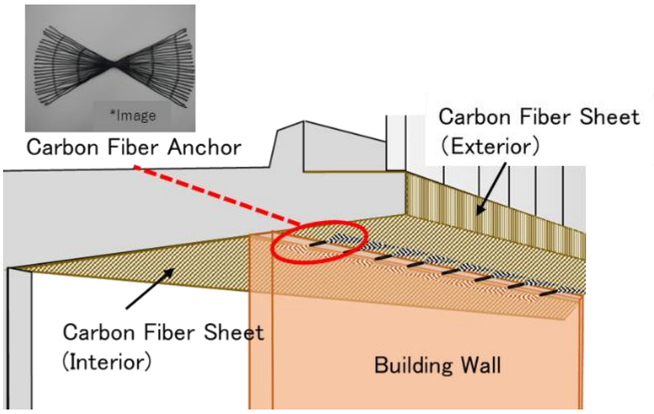


Figure 8: Combination of Interior and Exterior Building Walls Using Carbon Fibre Anchors

When external forces such as strong winds act on the sound barrier and cause the cantilever slab to deform upward, stress tends to concentrate at the boundary where the carbon fibre sheets are divided at the building wall. This concentration of stress can lead to localized cracking. In the new method, CF anchors bond the carbon fibre sheets on both the inside and outside faces of the building wall, thereby reducing stress concentration at the boundary and suppressing crack formation. During the installation of CF anchors, only small holes (approximately 20 mm in diameter) are required in the exterior wall of the building. As a result, large-scale removal or restoration of the building structure is unnecessary, enabling a significant reduction in the construction period. Various verification tests for this method were conducted at JR Central's Komaki Research Centre, and the details of these tests are described in Sections 5.2 and onward [3].

5.2 Carbonation Resistance

The test specimen is shown in Figure 9. Two faces of a cubic concrete specimen—those requiring carbonation resistance and weatherability—were cladded with carbon fibre sheets and then coated with epoxy-based impregnating adhesive resin followed by a fluoropolymer topcoat. The remaining faces were coated with epoxy resin to prevent the ingress of carbon dioxide. The specimen was then placed in an environment with a temperature of 23 ± 3 °C, relative humidity of 60%, and carbon dioxide concentration of 5% for 70 days, equivalent to approximately 20 years of carbon dioxide exposure under natural conditions. After exposure, the specimen was split open, and phenolphthalein solution was sprayed onto the fracture surface. Because the entire cross-section turned pink, the carbonation depth was determined to be 0 mm. The results are shown in Figure 10. These findings confirm that the new method provides sufficient carbonation resistance.

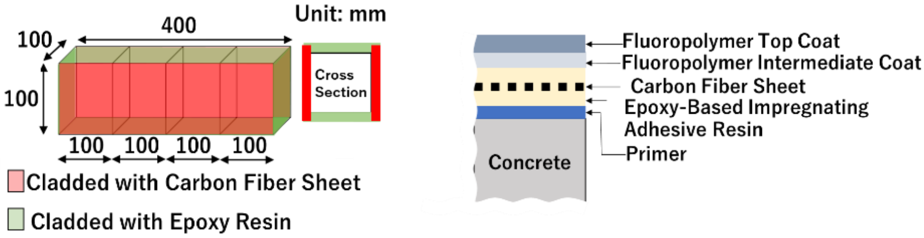


Figure 9: Test Specimen for Carbonation Resistance Test

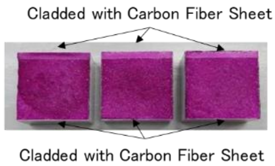


Figure10: Results of the Carbonation Resistance Test

5.3 Punching Resistance

To evaluate the ability of the carbon fibre sheet to prevent the detachment of concrete fragments, tests were conducted. Three specimens were prepared by extracting a core from a concrete slab, reinserting it, temporarily bonding it with cement mortar, and then applying a carbon fibre sheet over the surface. The test configuration is shown in Figure 11. A vertical load was applied to the core portion, and the maximum load was recorded as the punching resistance value. As a result, the average punching resistance of the three specimens was 2.80 kN, exceeding the standard value for punching resistance (1.5 kN) (Table 1).

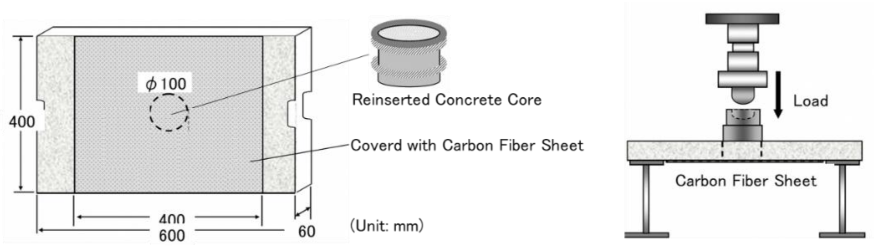


Figure 11: Overview of the Punching Resistance Test

Punching Resistance Values (kN)		
Specimen 1	Specimen 2	Specimen 3
2.72	2.87	2.67
Average Punching Resistance : 2.80kN		

Table 1: Results of the Punching Resistance Test

5.4 Weather Resistance

To verify the weather resistance of the construction method using carbon fiber sheets, an accelerated weathering test was conducted in accordance with JIS K 5600-7-7:2008 Accelerated weathering and exposure to artificial radiation (exposure to filtered xenon-arc radiation), using Method I, Cycle A. In the test, ultraviolet radiation with an irradiance of 75 W/m² was applied for 3,000 hours using a weathering test device. This exposure duration corresponds to approximately 100 years of ultraviolet exposure under natural environmental conditions. The test results are shown in Figure 12. After exposure, no deterioration phenomena—such as cracking, peeling, chalking, or discoloration—were observed. These findings confirm that the new method offers sufficient weather resistance.

(a)Before (b)After

Figure 12: Appearance of Test Specimens Before and After the Weather Resistance Test

5.5 Load-Bearing Capacity

To confirm that the carbon fibre sheets and the CF anchors would not debonded or rupture when subjected to the design wind load acting on the sound barrier (3.0 kN/m ^{2}) [5], a loading test was conducted using a full-scale model constructed with the same dimensions as a standard Tokaido Shinkansen viaduct. The test configuration is shown in Figure 13.

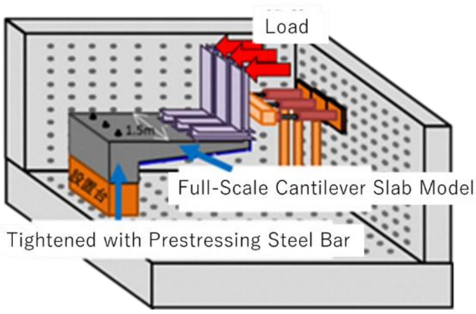


Figure 13: Overview of the Load-Bearing Capacity Test

In the test, a 3.35 m-tall steel sound barrier was installed on the curb section at the tip of the cantilever slab, and a jack and load cell were positioned as illustrated in Figure 14 to apply horizontal loads simulating wind pressure.

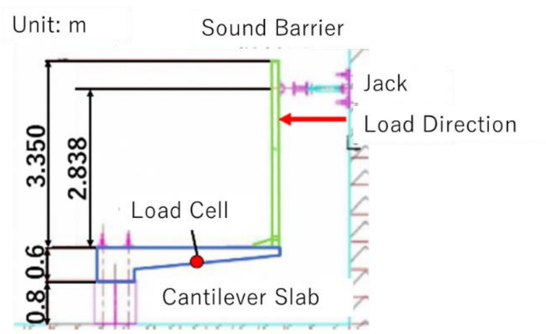


Figure 14: Locations of Jack and Load Cell

The relationship between the strain in the carbon fibre sheet at the centre of the underside of the cantilever slab and the applied load is shown in Figure 15. Even under loads exceeding 3.0 kN/m^2—corresponding to the design extreme wind pressure—the relationship between strain and load remained liner. Yielding occurred at 8.0kN/m^2, and bending cracks were confirmed at 8.5 kN/m^2. These results demonstrate that the load-bearing capacity of the structure significantly exceeds the design wind load.

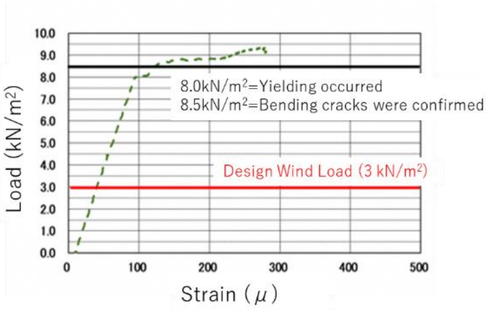
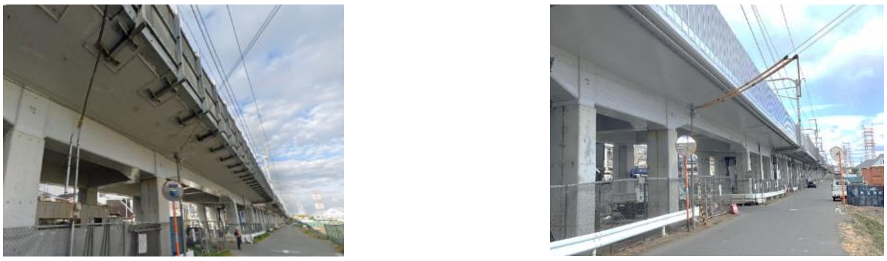


Fig.15 Relationship Between Strain in the Carbon Fibre Sheet and Applied Load

6 Application of the New Method on Operating Lines

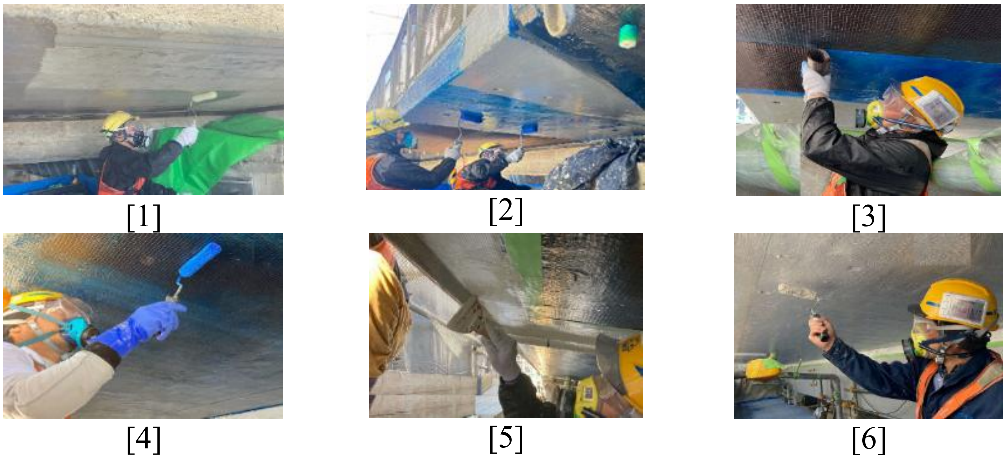
The new construction method using carbon fibre sheets was applied to a viaduct on the operating line. An overall view of the structure before and after construction is shown in Figure 16.



(a)Before (b)After

Fig.16 Viaduct Constructed Using the CFRP Cladding Method

During construction, the carbon fibre sheets adhered well to the cantilever slab with no gaps, and no defects have been observed either during the construction process or more than one year after completion. The initial method required careful handling of steel plates weighing up to 60 kg by at least three workers. Due to the lightweight and easy-to-process nature of the carbon fibre sheets, the new method can be implemented by one or two workers. The new method has achieved improvements in both construction safety and efficiency. The work process for the new method is presented in Figure 17.



[1] Primer Application and Surface Leveling
[2] Application of Impregnating Epoxy Resin (First Coat)
[3] Bonding of Carbon Fiber Sheet
[4] Application of Impregnating Epoxy Resin (Second Coat)
[5] Installation of Drip Edge
[6] Application of Surface Protection Material (Intermediate and Top Coats)

Figure 17: Work Procedure of the CFRP Cladding Method

A comparison of the work procedures for the initial method and the new method is shown in Figure 18. Although the new method requires additional steps—from “primer application and surface levelling” to “top coating with surface protection material”—it eliminates several labour-intensive processes from the initial method, including “fabrication and installation of bottom steel plates,” “sealing and removal of temporary anchors,” “fabrication of top steel plates,” and “installation of top steel plates.” As a result, the construction period for the new method was reduced by approximately 20% compared with the initial method. In addition, the material cost of carbon fibre sheets is lower than that of steel plates, and the number of anchor bolts required was reduced, leading to further cost reductions.

The new method using CF anchors was also applied to a viaduct with buildings located beneath it. The completed structure is shown in Figure 19. Small holes were drilled in the upper portion of the obstructing building wall to insert CF anchors, enabling the carbon fibre sheets to be applied continuously across both the inner and outer surfaces of the wall. This construction process went smoothly, demonstrating that the method can be implemented without requiring relocation or modification of the building. No issues were observed during or after construction.

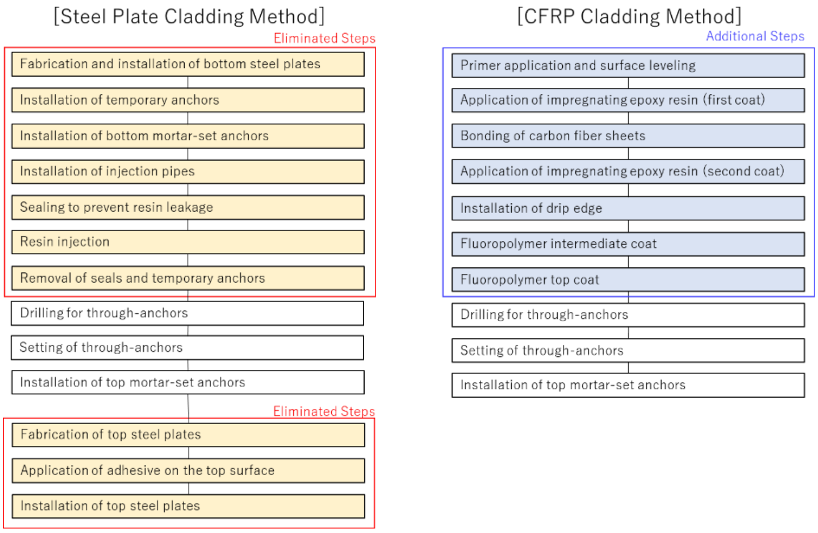


Figure 18: Comparison of Work Processes Between the Steel Plate Cladding Method and the CFRP Cladding Method

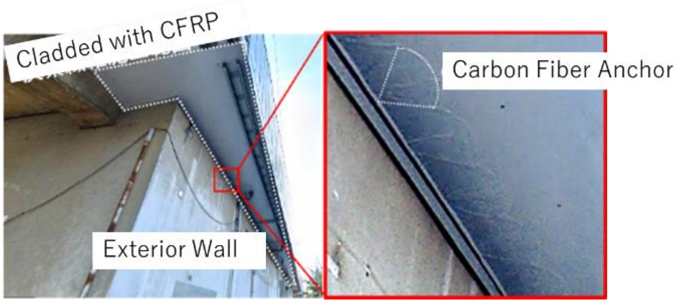


Fig.19 Construction Method Using CF Anchors]

7 Conclusions

A new CFRP cladding method, which uses carbon fibre sheets and CF anchors, was developed to improve the construction safety and efficiency of the steel plate cladding method (the initial method). Various performance tests demonstrated that the new method provides preventive effects equal to or greater than those of the initial method. Field application on viaducts along the operating line confirmed that the lightweight and easily handled carbon fibre materials improve both construction safety and work efficiency, while also reducing overall costs. Furthermore, even at sites where buildings exist directly beneath the viaduct, the use of CF anchors enabled construction without relocation of the building. Beginning in fiscal year 2026, this new method is scheduled to be fully adopted for large-scale renovation work across all concrete bridges on the Tokaido Shinkansen. JR Central will continue to refine construction techniques and develop technologies that contribute to further labour savings and cost reductions, ensuring steady progress of the large-scale renovation work.

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