Maintenance of Railway Infrastructure

Large-scale Renovations of the Civil Engineering Structures along the Tokaido Shinkansen

Masaki Seki

Introduction

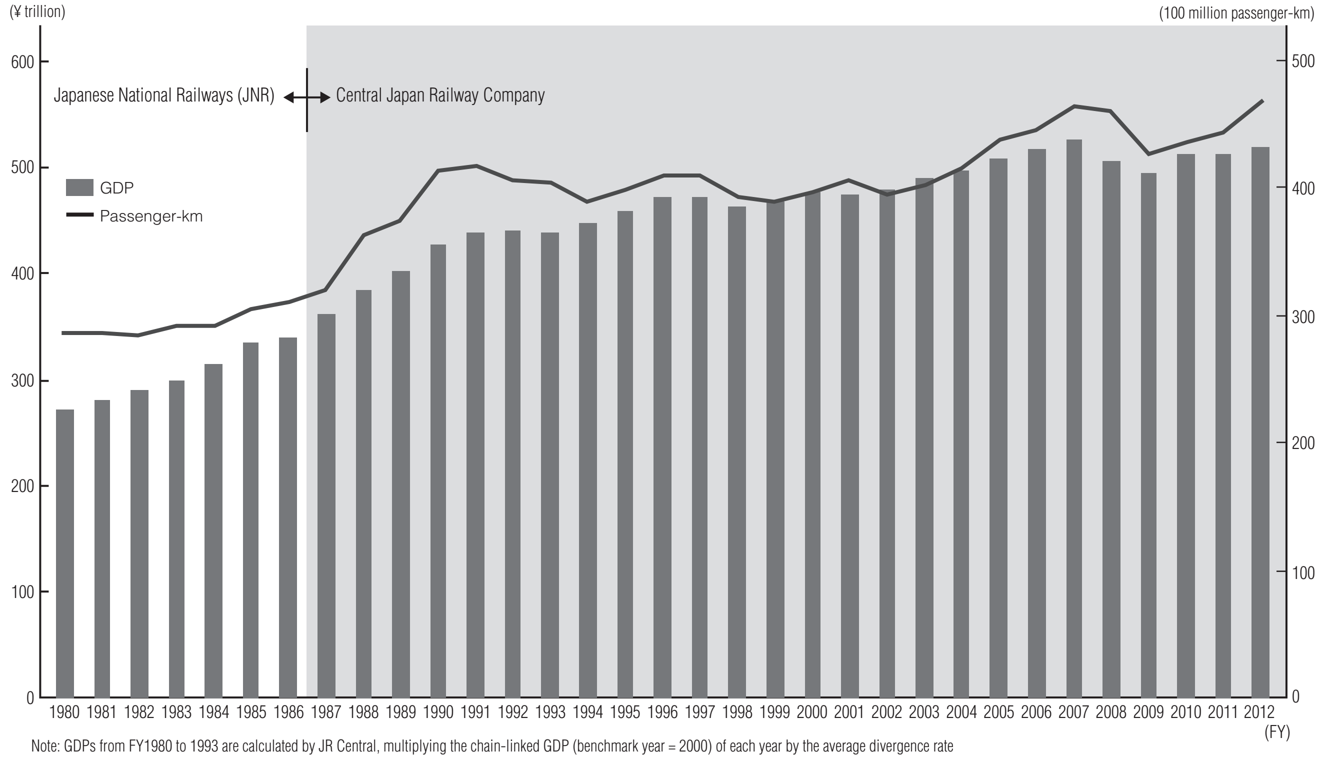
The Tokaido Shinkansen opened in 1964 as the world's first high-speed railway, operating at speeds of greater than 200 km/h. Since then, it has supported Japan's economic growth as a key artery connecting the conurbations of Tokyo, Nagoya, and Osaka. The service area is about 24% of Japan's total land, but it is home to about 60% of the population and accounts for 64% of GDP, making it the centre of Japan's economy. The Tokaido Shinkansen is used by about 390,000 people each day or 150 million annually, providing high-frequency and high-volume transport unparalleled in the world (Figure 1).

The Tokaido Shinkansen has also maintained a safety record of zero passenger fatalities in railway accidents since the start of operations. In addition, average delay per train is 30 seconds (FY2012), even including delays due to natural disasters, severe weather, and similar occurrences, demonstrating its capacity to offer very stable transport (Figure 2). This shinkansen safety and stability record is revered worldwide.

One aspect supporting the Tokaido Shinkansen operations safety and stability is continuous implementation of appropriate maintenance and management of civil engineering structures, making it imperative for the operator Central Japan Railway Company (JR Central) to secure both maintenance and management funding as well as personnel to perform the work.

JR Central has been making the necessary investment in safety continuously since the April 1987 Japanese National Railways (JNR) division and privatization. Approximately ¥150 billion has been invested annually for

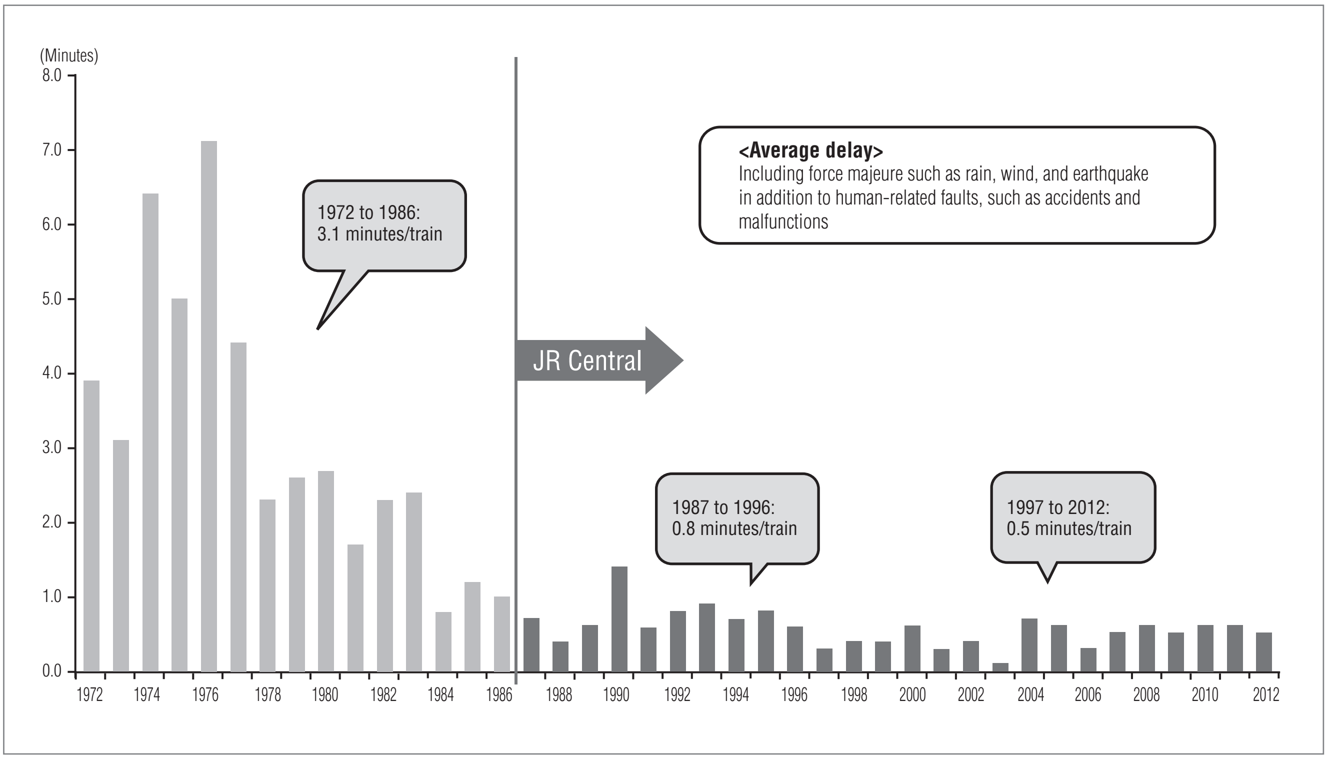
Figure 1 Changes in Passenger-km and GDP



Note: GDPs from FY1980 to 1993 are calculated by JR Central, multiplying the chain-linked GDP (benchmark year = 2000) of each year by the average divergence rate between the GDP (benchmark year = 2000) and the GDP (benchmark year = 2005). GDPs from FY1994 to FY2011 are the chain-linked GDPs (benchmark year = 2005)
Source: GDP — Annual Report on National Accounts, Cabinet Office, Government of Japan

a total of ¥2.7 trillion from FY1987 to FY2012. In addition to investment in structures, investment has also been made in countermeasures to natural disasters, such as earthquakes and typhoons, replacement of worn rolling stock, update of infrastructure such as signals, electrical equipment and tracks, and introduction of new systems (Figure 3).

Figure 2 Tokaido Shinkansen Delay Times



<Average delay>
Including force majeure such as rain, wind, and earthquake in addition to human-related faults, such as accidents and malfunctions

1972 to 1986:
3.1 minutes/train

1987 to 1996:
0.8 minutes/train

1997 to 2012:
0.5 minutes/train

Figure 3 JR Central Investment in Safety

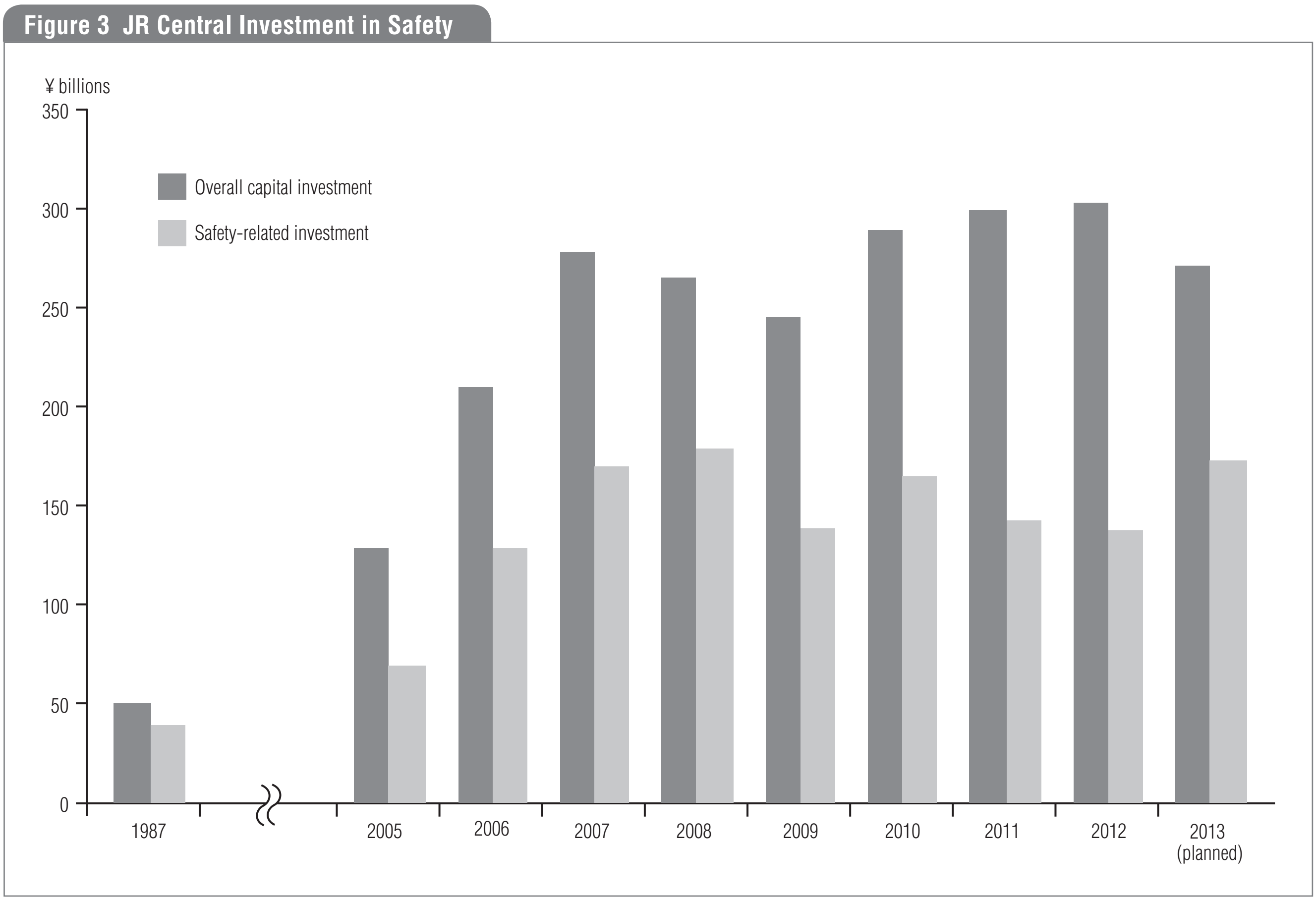


Table 1 Maintenance/Management and Division of Duties

Structure	Inspection	Handled
Steel structures	General inspections (2-year cycle)	Track maintenance depots (civil engineering)
	Individual inspections	
	Special inspections (8-year cycle)	Shinkansen structure inspection centres
Concrete structures	General inspections (2-year cycle)	Track maintenance depots (civil engineering)
	Individual inspections	
Tunnels	General inspections (2-year cycle)	Track maintenance depots (civil engineering)
	Individual inspections	
	Special overall inspections (10-year cycle)	Track maintenance depots (civil engineering) Shinkansen structure inspection centres

Concern about infrastructure safety is rising in Japan since the Great East Japan Earthquake on 11 March 2011. The soundness of civil engineering structures of the nearly 50-year-old Tokaido Shinkansen is assured by careful daily inspections, followed-up by repair and reinforcement wherever necessary. However, since major update of old equipment is inevitable at some time in the future, JR Central had planned for large-scale renovations to start in 2018. Funding the work by reserving part of the operating profits (free of tax liability) was approved by the Minister of Land, Infrastructure, Transport and Tourism (MLIT) in 2002 and reserves have been accumulating since that date.

Research and development into construction methods for these planned large-scale renovations has been on-going for years headed by JR Central's Komaki Research Centre in Aichi Prefecture, which opened in 2002, where new construction methods for extending the life of civil engineering structures have been established. From the perspective of using new construction methods for preventive maintenance, a decision was made to bring forward large-scale renovations on the Tokaido Shinkansen by 5 years. Consequently, a request to MLIT was made in January 2013 to change the reserves plan and was approved in February. As a result, large-scale renovation work started from April 2013. This article describes key aspects of the ongoing work.

Organization for Maintaining and Managing Civil Engineering Structures on Tokaido Shinkansen

General inspections of civil engineering structures on the Tokaido Shinkansen are conducted by eye in 2-year cycles by 20 track maintenance depots in charge of day-to-day routine maintenance and management. Locations needing detailed confirmation after a general inspection are subjected to detailed individual inspections using specialist equipment.

Shinkansen structure inspection centres were also established in 1993 in Tokyo, Shizuoka, Nagoya and Osaka to specialize in identification of ageing fatigue and deterioration of civil engineering structures. Table 1 shows the main inspections implemented by track maintenance depots and these centres, and the division of duties.

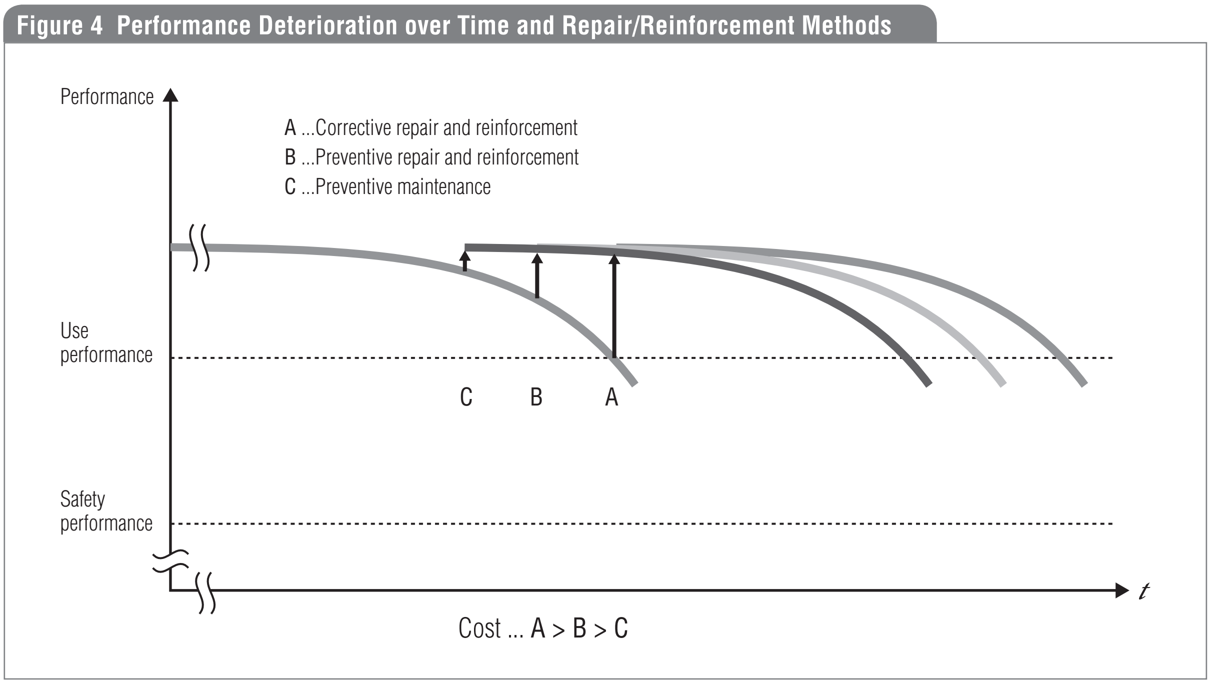
Allowance Reserve Plan for Large-scale Renovations

Although the soundness of civil engineering structures on the Tokaido Shinkansen is maintained by appropriate day-to-day maintenance and management, the progress of ageing deterioration is an issue, especially weld fatigue on steel bridges, carbonation of reinforced concrete (RC) structures, and the effects of vibration and air pressure changes in tunnels.

For these reasons, fundamental measures—replacement of equipment or large-scale renovations with the same effect—are necessary. In particular, the Tokaido Shinkansen was built as a whole system in a short time frame under severe constraints to meet the 1964 opening deadline, so there are concerns that widespread ageing deterioration may occur suddenly in a similarly short time frame. Accordingly, preparations for future large-scale renovations are needed.

At the same time, although the Tokaido Shinkansen was built by JNR, the now-private railway operators have

Figure 4 Performance Deterioration over Time and Repair/Reinforcement Methods



full responsibility for carrying out large-scale renovations on their inherited infrastructure requiring large funds. Therefore, to help conduct large-scale renovation smoothly, the Nationwide Shinkansen Railway Development Act was revised in June 2002 in line with the full privatization of the three JR operators on Honshu (JR Central, JR East, JR West), and the system of funding reserves described above was created by the government. MLIT subsequently approved a plan to reserve ¥33.3 billion annually from operating profits (total reserves of ¥500 billion, construction expenses of approximately ¥1.1 trillion, construction period of 10 years from FY2018 to FY2027).

Large-Scale Renovations by Preventive Maintenance

The 2002 plan anticipated starting renovations in 2018 with specific measures to replace steel bridges and to steel-clad the surfaces of some RC structures and tunnel linings. Such work would inevitably disrupt train service through cancellations and speed restrictions, but would have to be minimized due to the important role the Tokaido Shinkansen plays in Japan's economy and society.

The Komaki Research Centre played a key role in R&D for more than 10 years to overcome these issues using its structural-analysis equipment, full-size models, and large testing equipment to predict deformation over time and develop maintenance and reinforcement construction methods that reduce service disruptions and cut construction costs. The construction methods were examined by the 'Committee for surveying Tokaido Shinkansen civil engineering structures'. It was composed of outside experts and headed by Professor Kazuo Konagai of Yokohama National University. Test construction and other work was implemented based on advice from the committee, and the new construction methods were put into practical use.

Corrective repair and reinforcement is the normal method for maintaining railways, roads, and other infrastructure. In other words, repairs and reinforcements are done only when deformation is discovered by inspection. However, the Tokaido Shinkansen civil engineering structures have a standardized design and were all built at nearly the same time, so deformation at one place is likely to occur simultaneously at other similar locations. Consequently, preventive repair and reinforcement have been conducted systematically at all locations where future deformation is predicted.

The huge damage caused by the 2011 Great East Japan Earthquake was a wake-up call about the importance of infrastructure, so studies on starting the eventual large-scale renovations were brought forward. An application was made in January 2013 to change the reserve (total reserves of ¥350 billion, construction expenses of about ¥730 billion, construction period of 10 years from FY2013 to FY2022) and the application was approved in February. The revised plan calls for a 5-year earlier start of large-scale renovations on the Tokaido Shinkansen using new construction methods from the perspective of preventive maintenance, which inhibits the occurrence of cracks and other deformations while the structure is still sound, keeping overall costs down (Figure 4).

The civil engineering structures on the 515.4-km Tokaido Shinkansen comprise 22.1 km of steel bridges (4%), 148.0

Figure 5 Civil Engineering Structures on Tokaido Shinkansen

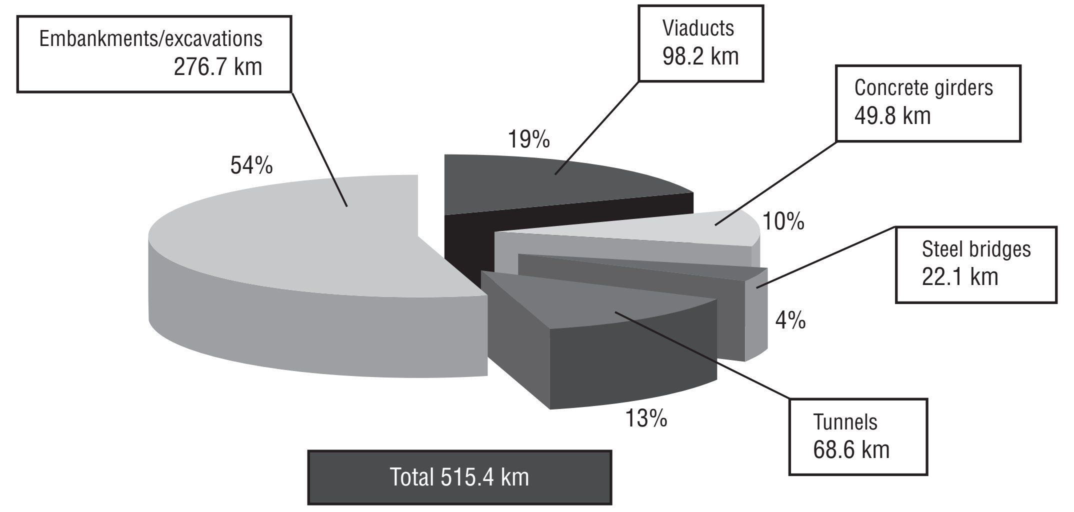


Figure 6 Longitudinal Beads

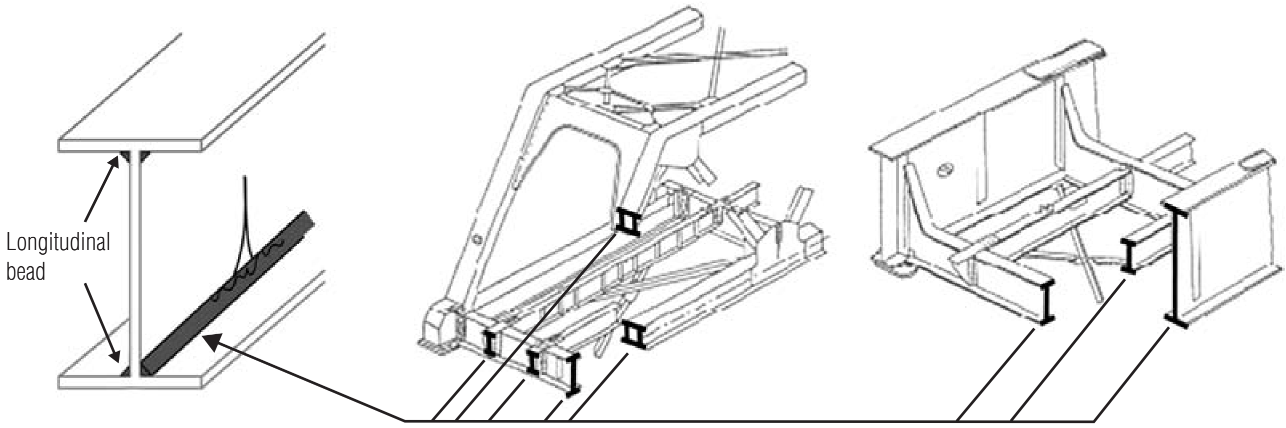


Figure 7 Overview of Large-Scale Steel Bridge Renovation

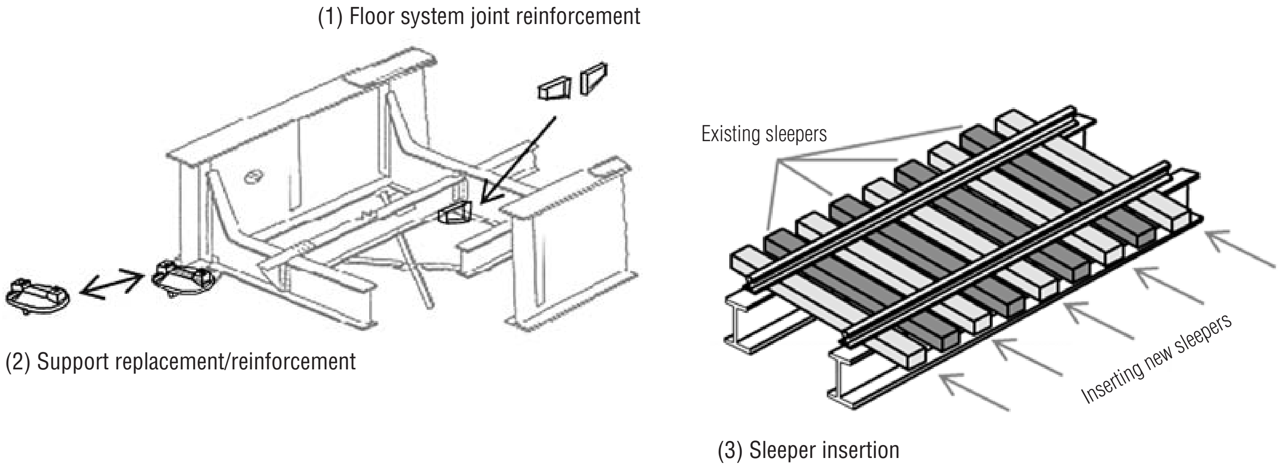
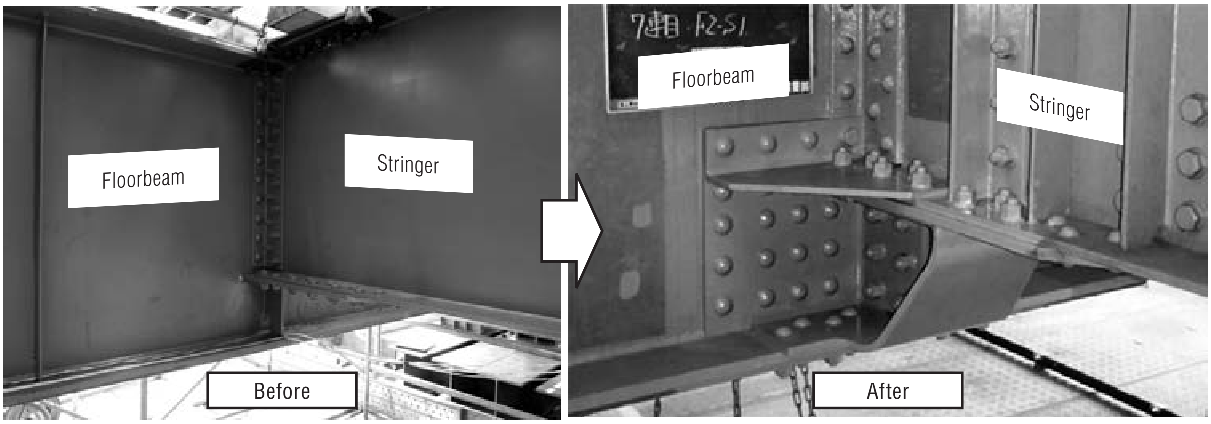


Figure 8 Floor System Joint Before/After Reinforcement



km of concrete bridges (viaducts and concrete girders) (29%), 68.6 km of tunnels (13%) and 276.7 km of earthworks (54%) (Figure 5). Of these, large-scale renovation work is to be conducted on steel bridges, concrete bridges, and tunnels, where there are worries about ageing deterioration. The basic method for each type of structure is to implement preventive maintenance at all applicable locations to prevent deterioration and then to continue observation and overall renovation at locations as required.

Maintenance and Reinforcement of Steel Bridges

Issues with steel bridges

Issues with steel bridges are accumulated fatigue at weld joints as trains run across as well as durability performance. The long fillet welds (longitudinal beads) on major members make it difficult to focus inspection efforts. Fillet weld cracks grow rapidly and can be difficult to handle at general and special inspections (Figure 6). As a result, a large-scale renovation plan was devised in 2002 to prioritize replacement of all 22.1 km of steel bridges to assure safe operations. Under this plan, most of the three-span truss bridges on the Tokaido Shinkansen would each require suspension of train operations for 2 days to complete the work. There are 135 spans making up 37 bridges, so services would have to be suspended 8 days a year for 10 years to replace all the bridges. To ensure safety during preparatory work, speeds would have to be reduced all day, causing major disruptions to transport. Consequently, R&D was needed on new countermeasures to cracks in long fillet welds, thereby increasing bridge lifespan, minimizing disrupted train operations, and having the same effect as replacement.

Overview of construction measures

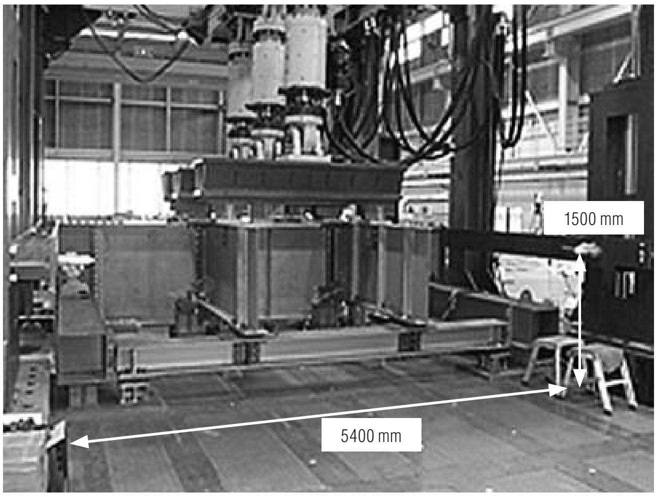
So far, there have been no cracks in fillet welds of major members of steel bridges. However, if the structural system at individual locations changes due either to damage at other locations or to very heavy impact loads from train axles according to track irregularity, the resultant stress can exceed the fillet weld fatigue limit. 3D FEM analysis and stress measurements on actual bridges showed that stress at fillet welds of major members is increased by cracks in the joints of the floor system (floorbeams and stringers) and by damage to supports. Therefore, reinforcing these parts reduces the risk of cracks in fillet welds.

To prevent deformation of fillet welds caused by such stresses, new methods have been developed to reinforce floor system joints, and replace and reinforce supports. The occurrence of heavy axle loads was identified from load measurements using actual wheels. Heavy axle loads tend to occur at rail expansion joints on steel bridges, but have also been confirmed at general rail sections such as welded rail joints and loose sleepers. To prevent heavy axle loads, new sleepers are being inserted between existing sleepers as a means to increase the rail support area. Figure 7 shows an overview of these construction methods.

Details of specific measures

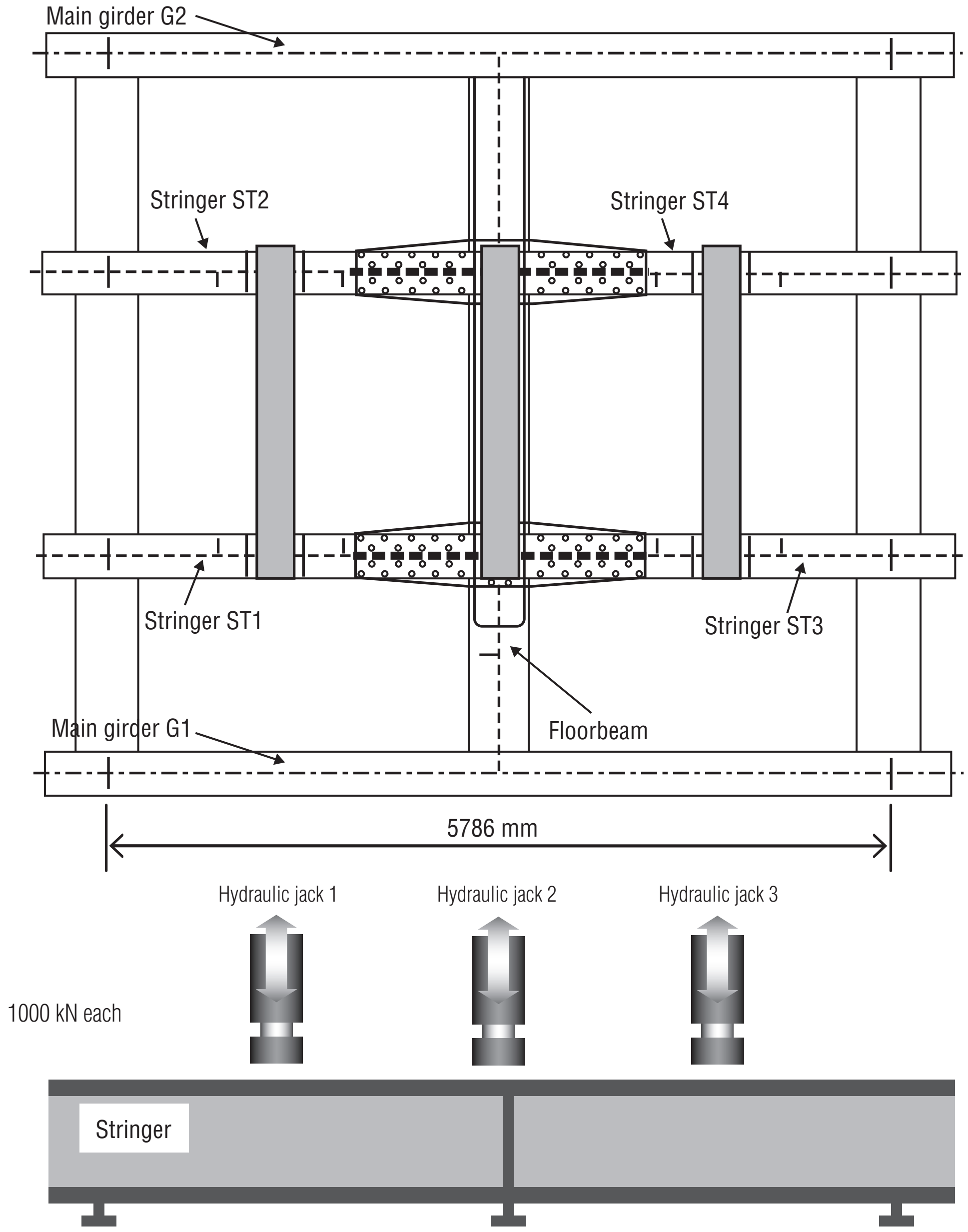
Damage to joints in through-truss and open-floor through-plate-girder floor systems increases stress in fillet welds and can cause cracks. Two types of fatigue cracks have been identified in these areas: at welds in the stringer support and top end of the vertical stiffener, and at the boxing in the floorbeam web slit. Reinforcement was proposed to prevent these cracks (Figure 8) and a full-scale truss model was built at the Komaki Research Centre based on designs

Full-scale truss model (Komaki Research Centre) (JR Central)



Railway structure loading test system (JR Central)

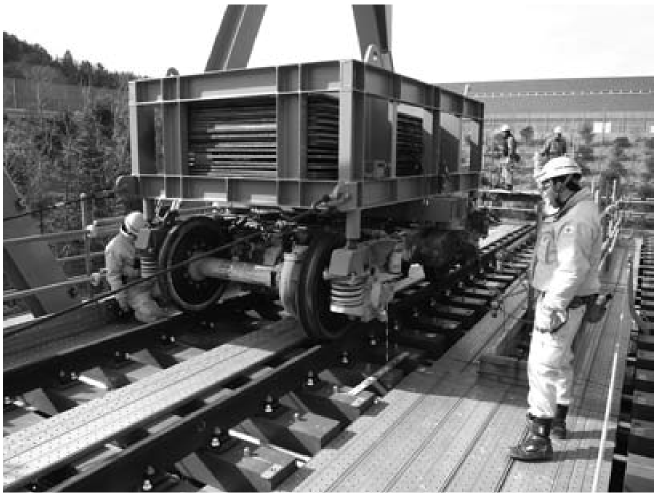
Figure 9 Fatigue Test Specimen of Through-Truss Floor System in Railway structure loading system



from 1964. The proposed remediation was validated by specimen fatigue tests (Figure 9), 3D dynamic running analysis, and dynamic load tests using shinkansen bogies on the full-scale truss model (see photo on p22). The effectiveness of the countermeasures was also confirmed by test construction on an actual shinkansen track.

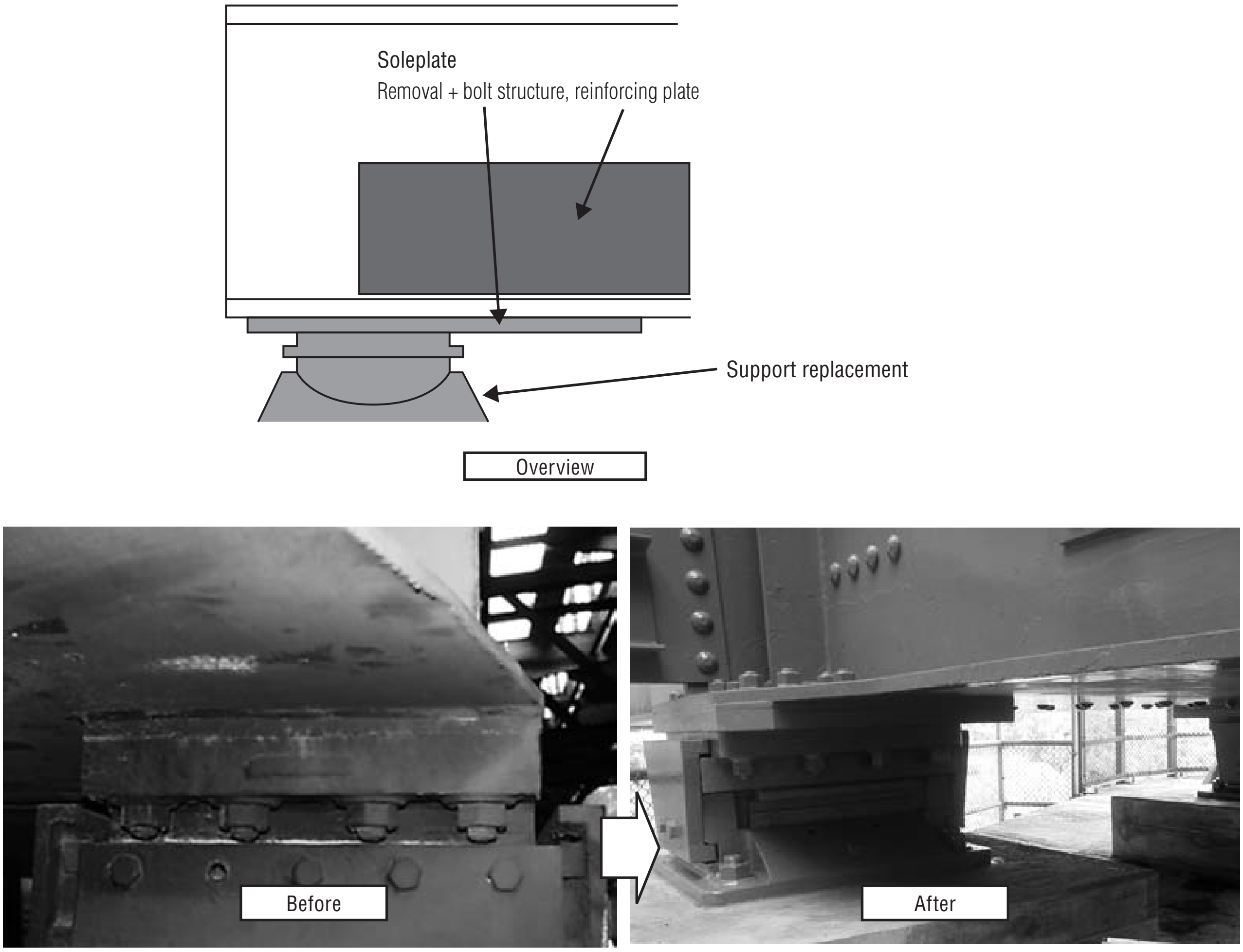
Stress measurements on actual bridges showed that a drop in support function can greatly increase stress on fillet welds. In particular, when a soleplate is welded to a girder, fatigue cracking occurs from the soleplate weld, progressing to the girder flange and web. Maintaining the support in sound condition is critical in preventing such cracking. However, removing the welded part and changing to a bolted structure is also a reasonable countermeasure.

Such replacement work used to require slowing trains. To prevent slowing trains, temporary support structures and construction procedures were revised. Support replacement without slowing trains was possible by building a temporary support with the same load-bearing capacity as the main structure, taking into consideration the effect of the lift of girder contact on track condition, and managing track irregularities. Testing on two actual bridges last fiscal year proved it was possible to work without slowing trains (Figure 10).



Dynamic load testing with shinkansen bogie (JR Central)

Figure 10 Overview of Support Replacement/Reinforcement



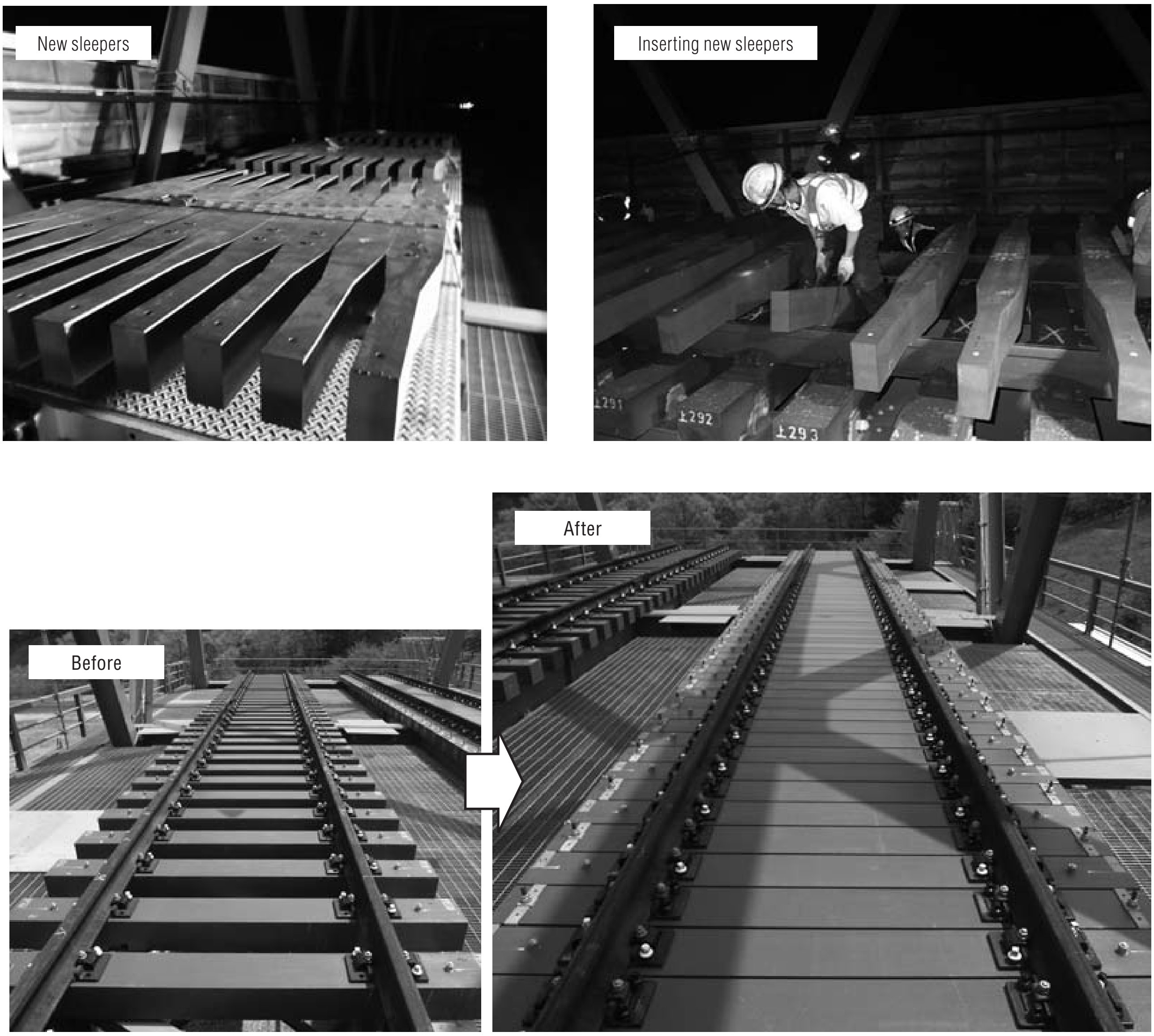


Figure 11 Inserting Sleepers

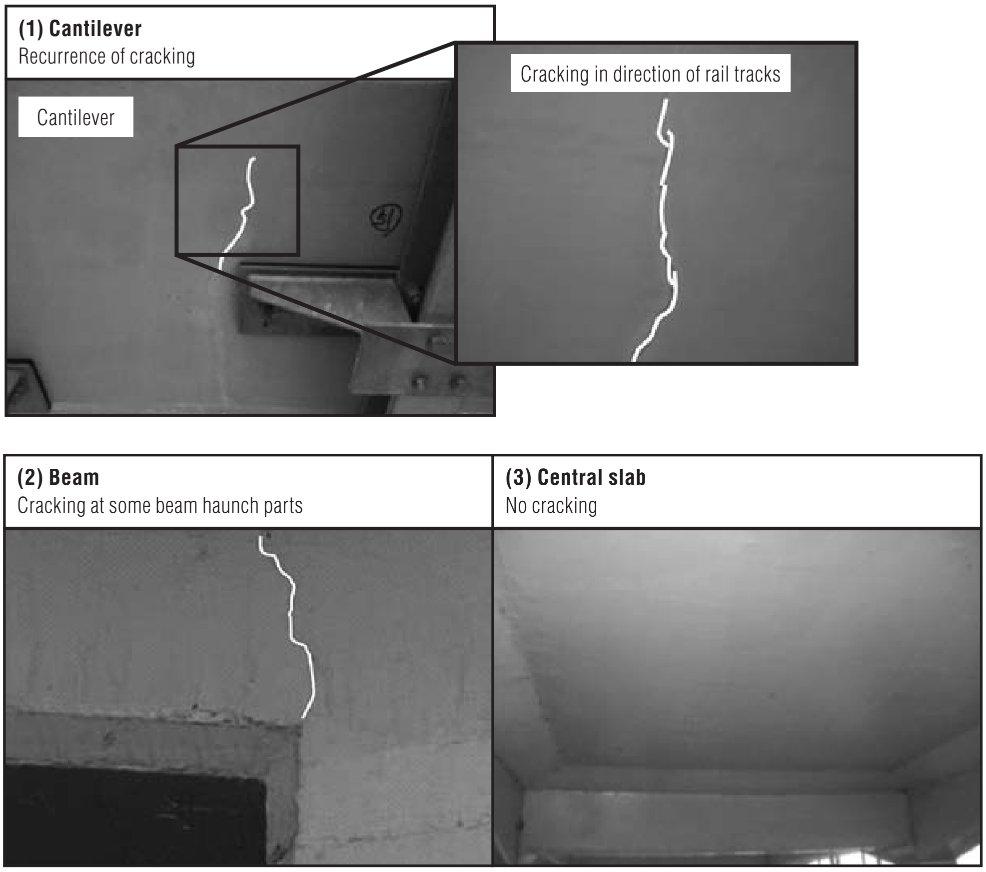
Rail bending and irregularities can be kept in check by inserting sleepers to make plate-bearing structure and spread the heavy axle loads (Figure 11). Making a very rigid floor system helps cut stress on longitudinal fillet welds. FEM analysis and measurement on actual track before and after construction confirmed reduced stress in fillet welds.

Maintaining and Reinforcing Concrete Bridges

Issues with concrete bridges

When the Tokaido Shinkansen was built there were no design criteria for carbonation of RC structures. The rebar cover thickness was 25 mm for slabs, 27 mm for beams, and 35 mm for columns, all less than required for new constructions today. RC structures carbonize with time due to the effects of atmospheric carbon dioxide; carbonation reduces the strength of RC structures if the rebar has been corroded by the carbonation. Surveys found that the carbonation depth in 1995 averaged 15.1 mm, and carbonation was predicted by the square-root-t law to reach the rebar in 15 to 20 years in the slabs. Consequently, the RC surfaces have been coated with protective resin since 2000 to inhibit carbonation. However, some protected surfaces are starting to crack on some cantilevers due to repeated loads from passing trains. Cores from protected uncracked sound surfaces confirm that the carbonation is being held in check, but at places with cracking, carbonation is still progressing along the cracks. This is leading to localized rebar corrosion and the risk that the performance required for continued

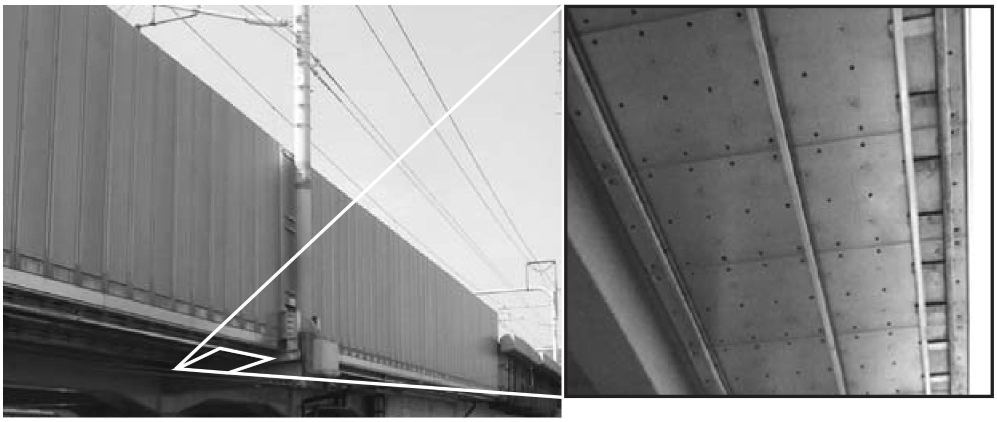
Figure 12 Recurrence of Cracking in Protective Surface Coatings of RC Structures



(1) Cantilever
Recurrence of cracking

(2) Beam
Cracking at some beam haunch parts

(3) Central slab
No cracking



Repair (steel-plate cladding) of full cross-section on actual viaduct (JR Central)

use cannot be met. Repair (steel-plate cladding) of the full cross-section of structures has been considered as a drastic countermeasure to carbonation for these types of cracked cantilevers.

Overview of construction methods

Cracking has been confirmed in protective surface coatings applied on cantilevers since 2000. Although visible cracking has not occurred on beams, some cracking has been confirmed in the haunch parts of some viaducts. Recurrence of cracking in the central slab has not been confirmed (Figure 12).

Onsite inspections led to the decision to first implement repair (steel-plate cladding) of the full cross-section of structures for cantilevers, then apply conventional protective surface coating to beams and central slabs, and observe the effects over time. Cracking on the haunch part of some viaducts is caused by the vertical movement of columns as trains pass. Measures to increase the support of substructures and restrict vertical movement of columns are

Table 2 Specific Countermeasures for Concrete Bridges

Measure		Measures to inhibit age-related deterioration	Overall renovation
Content of work	Cantilever	(1) Cladding with steel plates	
	Column	(1) Cladding with steel plates	
	Central slab	(1) Protective surface coating	(2) Cladding with steel plates
	Beam (Beam of concrete rigid frame viaduct)	(1) Protective surface coating (1) Addition of piles and underground beams	
	Beam (Beam of concrete bridge)	(1) Protective surface coating	(2) Cladding with steel plates

Figure 13 Overview of Large-Scale Renovation (Concrete Bridges)

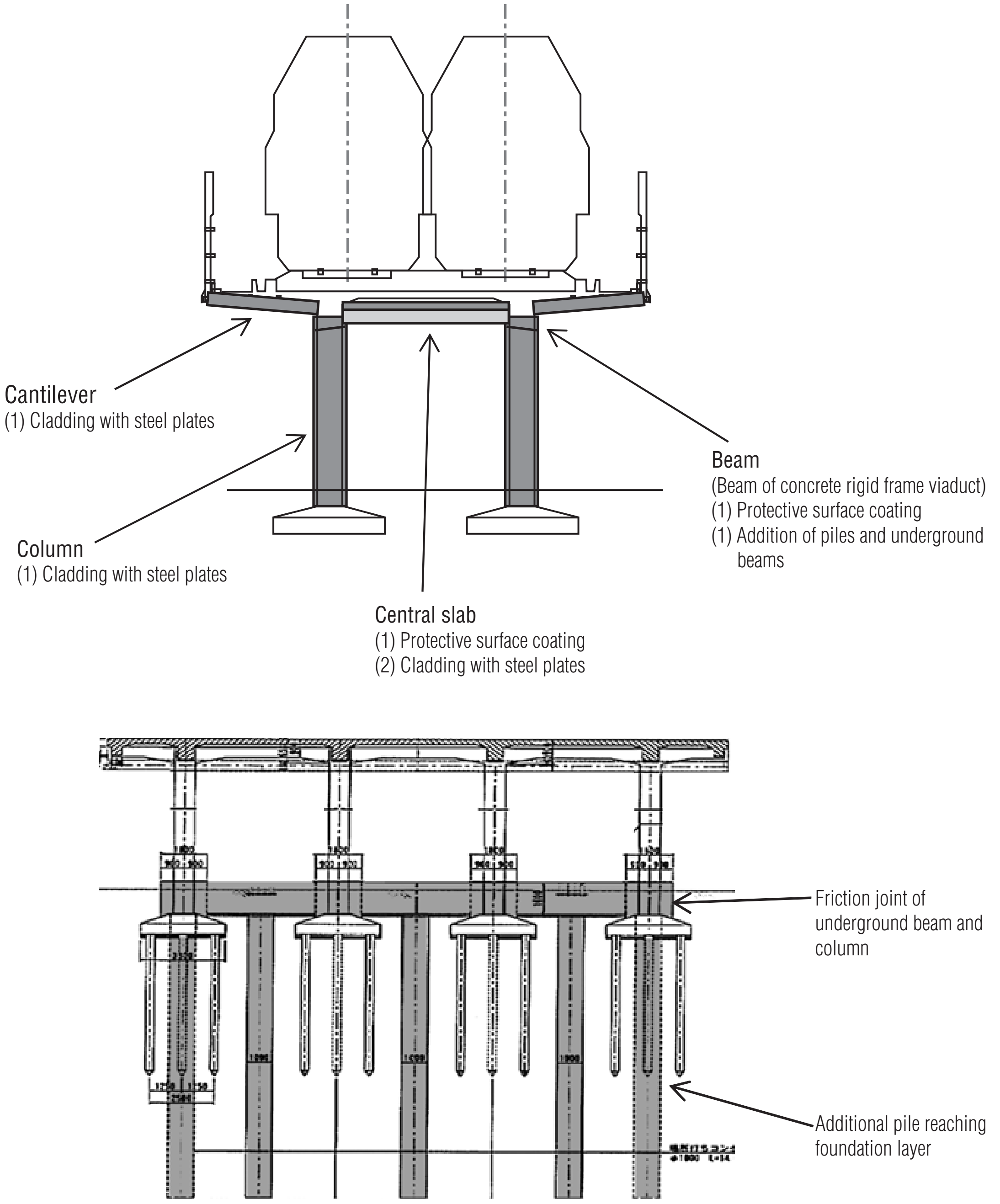
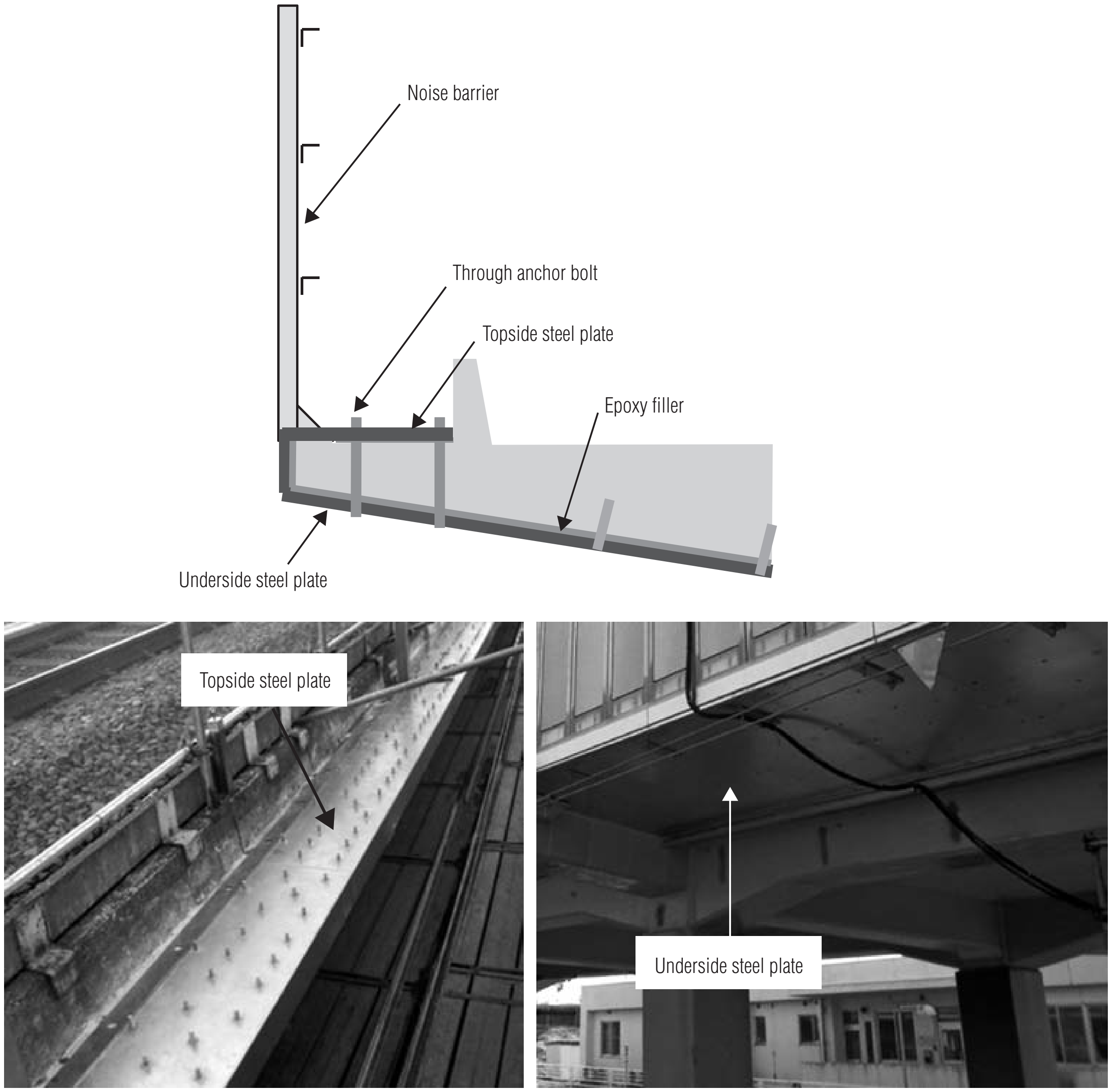


Figure 14 Overview of New Repair Method (Steel-Plate Cladding) for Full Cross-Section of Structures



being implemented by reinforcing the foundation by adding piles and underground beams. The decision on when to add steel-plate cladding to the underside as an overall renovation to maintain and reinforce beams and central slabs will be made based on the condition of structures (Table 2, Figure 13). Timing these measures appropriately is expected to maintain the soundness of RC structures.

Details of specific measures

Repair (steel-plate cladding) of the full cross-section of structures studied so far has been implemented by attaching multiple 6-mm thick steel plates to the concrete underside using multiple anchor bolts and welding them together. Next, epoxy resin is injected into the gap between the plates and concrete surface to create an integrated structure.

Test constructions were conducted to confirm any problems with the conventional method and two issues were found.

First, if drilling the holes for the anchor bolts damages the rebar, the holes must be re-drilled, further damaging the concrete casing. Consequently, the number of anchor bolts must be minimized.

Second, heavy steel plates have poor workability, so the weight must be reduced.

Using a new repair method improved these two points in comparison to the conventional method and the new structure is shown in Figure 14.

Figure 15 Steel Plate Mechanical Lap Jointing Method

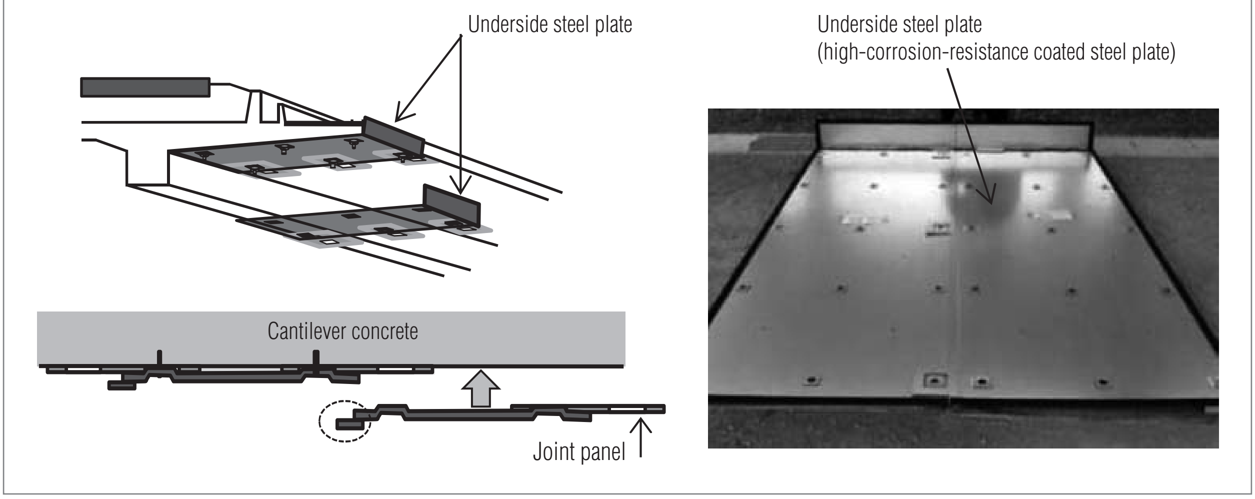
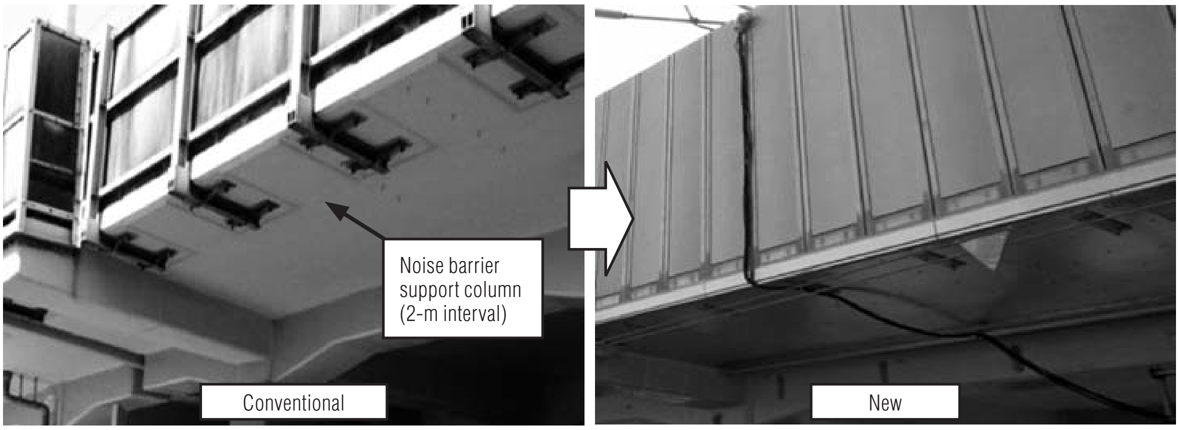


Figure 16 Change in Method for Attaching Noise Barrier Support Columns



The first improvement is the reduced weight of the steel plates and the smaller number of anchor bolts to fix these plates. In the conventional method, the steel plates must be 6-mm thick for butt welding. The new mechanical lap jointing method (Figure 15) without welding allows the steel plates to be 2.3-mm thick and lighter. At fixing, the number of anchor bolts is minimized by considering the added strength of the epoxy resin.

The second improvement is an optimum design with consideration for attaching noise barriers to cantilevers. In the conventional noise barrier design, considerable load acts on the cantilevers via the support columns at 2-m intervals (Figure 16). To unify the load on cantilevers via noise barriers, a new design was adopted where the noise barriers are set on the top of cantilevers. Securing steel plates to both sides of the slab using through anchors achieves the uniformity of a composite structure of steel plates and existing concrete framework, so the load is borne by the whole plane.

The effects of this design have been confirmed by 3D FEM analysis, load tests on full-scale models, and test construction on an actual line.

Tunnels

Issues with tunnels

The soundness of concrete tunnel lining is maintained by the dynamic balance with the lining and surrounding ground. However, concrete shrinkage at curing and loosening of the ground during and after excavation can cause cracking and other deformation. Slight cracking in the concrete lining has occurred in tunnels on the Tokaido Shinkansen, and these cracks have been filled where needed. In addition, cracking progresses as a result of the combined effects of vibration and air-pressure changes as large numbers of trains run through the tunnels. Consequently, use of the upper cross-section repair method (Figure 17) whereby reinforcing steel panels completely cover the upper inside cross-section of

Figure 17 Overview of Upper Cross-Section Repair Method

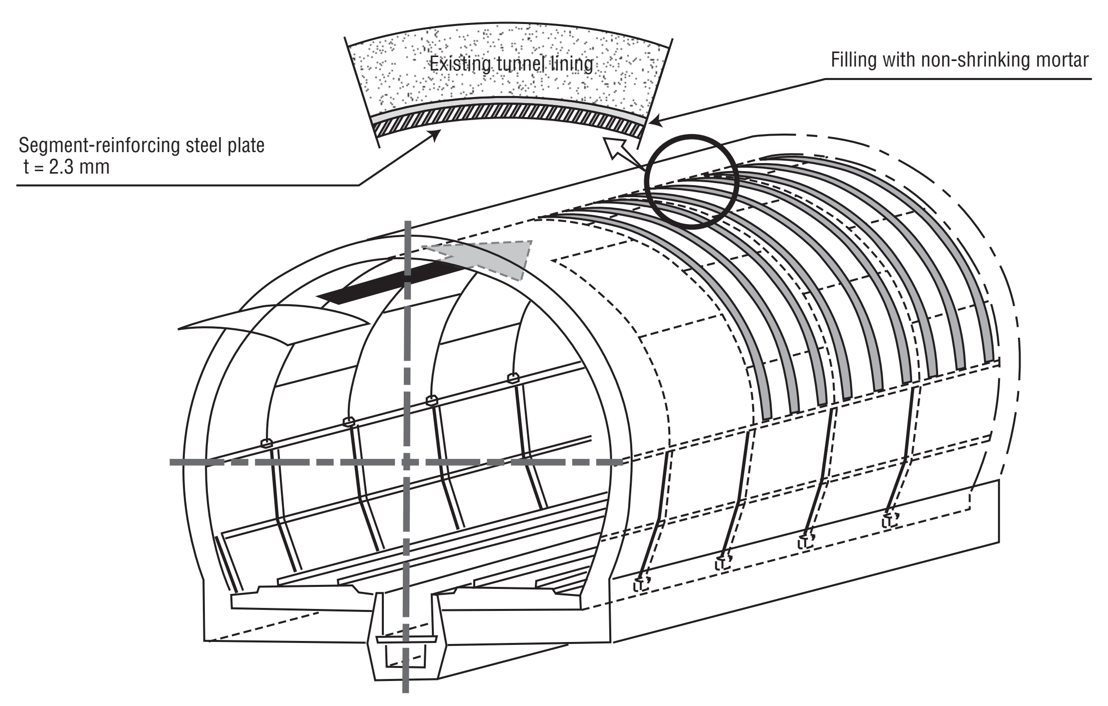
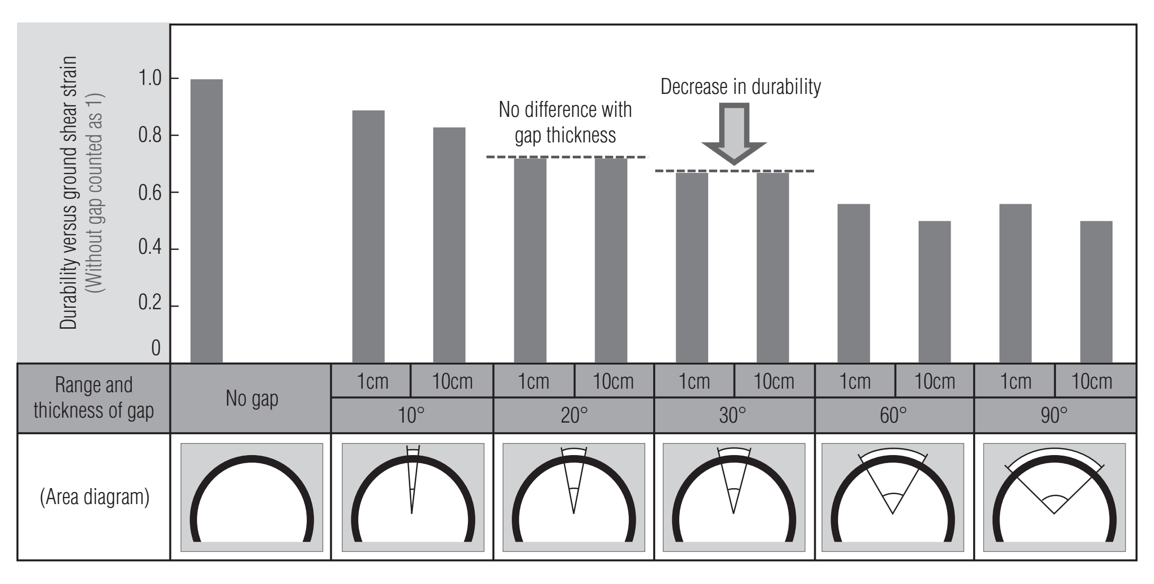


Figure 18 Results of Explicit Finite Difference Analysis



the tunnel was planned in 2002 to physically prevent lining spalling. However, fixing steel plates to concrete lining takes long construction times, requiring cancellation of some early morning trains and slower running through tunnels all day. As a result, the first plans were abandoned and other methods causing less timetable disruption were studied.

Overview of construction measures

To identify the causes of crack progression, on-site exploration, monitoring surveys at 130 locations, and drilling surveys of gaps behind linings were conducted. The results showed that gaps are present behind linings whenever crack progression is confirmed.

When gaps are present behind the lining, integrity with the ground is lost, reducing the concrete lining durability. This decrease has been assumed to increase directly with gap size, but explicit finite difference analysis (Figure 18) showed no significant difference in lining durability for 10 and 1-cm gaps, meaning even slight gaps behind the lining must be filled. Moreover, Tokaido Shinkansen tunnels used sheet lining at construction and sampling surveys by radar and coring have shown that gaps are probably present

Figure 19 Overview of Large-Scale Renovations (Tunnels)

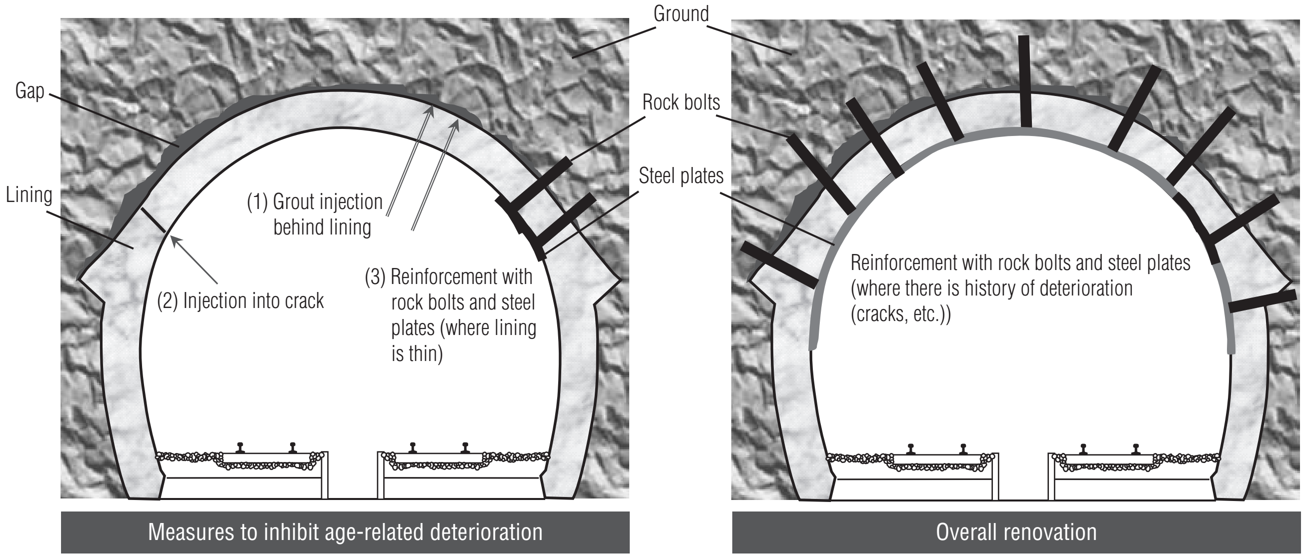


Table 3 Specific Measures for Tunnels

Measure	Measures to inhibit age-related deterioration	Overall renovation
Content of work	(1) Grout injection behind lining (2) Injection into crack (3) Partial reinforcement with rock bolts and steel plates	Reinforcement with rock bolts and steel plates

behind the linings of all tunnels. To inhibit crack progression and prevent lining spalling, gaps are filled with non-shrink mortar and cracks are filled with resin to integrate the lining with the ground and increase the lining durability. Where needed, rock bolts and steel plates are used to inhibit further deformation. Moreover, at locations with a history of lining deformation, by special overall inspections, rock bolts and steel plates will be used to prevent lining spalling as an overall renovation (Table 3, Figure 19). The remediation timing is decided on a case-by-case basis upon observation of the condition after filling gaps behind linings.

Details of specific measures

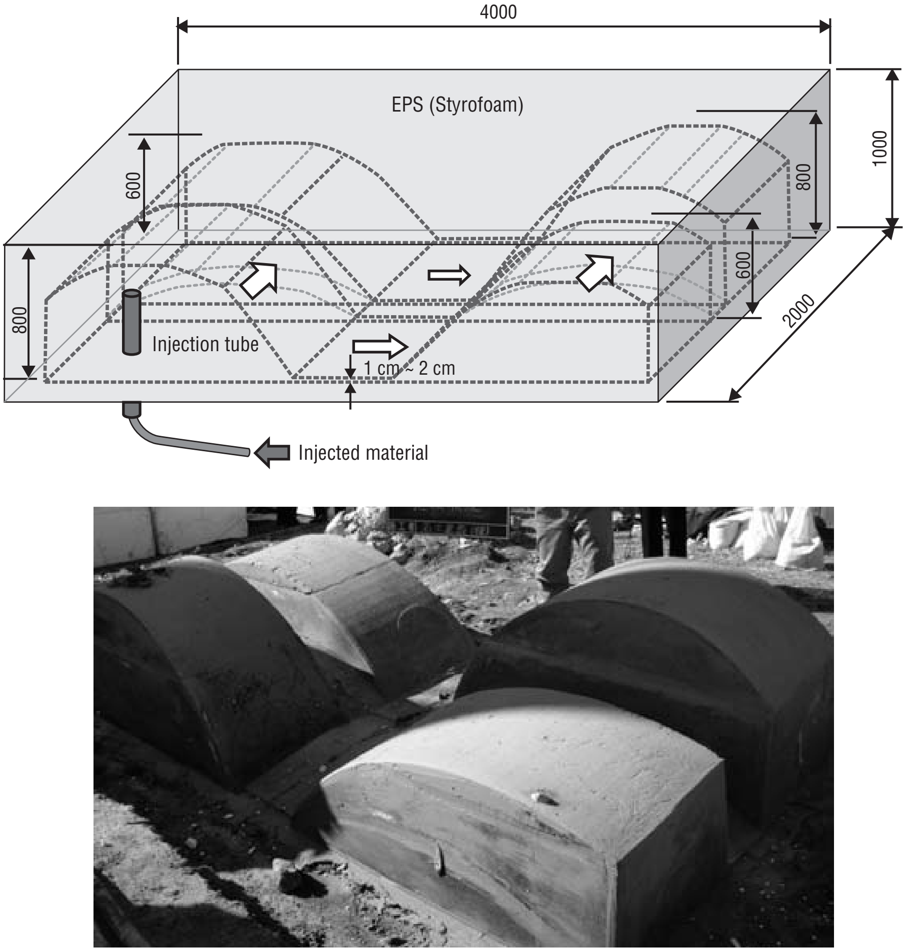
In the past, gaps behind linings of railway and road tunnels have been filled using various materials. However, there has been little proof that small gaps of about 1 cm can be filled completely. As a result, the Komaki Research Centre ran full-size injection tests (Figure 20) to confirm whether small 1-cm gaps can be filled completely. Tests in the laboratory and on operating lines were used to establish a construction and management method, leading to establishment of a standard method. Although a staggered arrangement had been used for injection tubes previously, it was changed to a lattice arrangement with a leak confirmation hole at the crown apex. The result is about twice the previous number of injection tubes and leak tubes, and tests on operating lines showed that even minute gaps could be filled completely with the injected material.

Conclusion

This article describes some of JR Central's large-scale renovations now in progress on the Tokaido Shinkansen. Maintaining the safety and soundness of this key transport artery into the future is essential for Japan's economy and society. By starting these renovations this fiscal year while simultaneously working to make the Chuo Shinkansen maglev line a reality, JR Central is creating a duplex system for assuring Japan's future.

It is worth remembering that much of Japan's infrastructure was constructed in the high-economic growth period between 1955 and 1973. Consequently, the

Figure 20 Experiment to Replicate Injection



problem of ageing infrastructure deterioration will become more evident and widespread, making maintenance and management a major social issue in terms of both safety and cost. I hope this article will prove useful in maintaining and enhancing infrastructure into the future. ■

Further Reading

1. Atsushi Tanabe, Masaki Seki, Akio Matsuura 'Evaluation of effects of heavy wheel load on steel truss bridges by using 3D dynamic FEA', *Journal of Structural Engineering*, Vol. 56A (March 2010)
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