Development of ductile cast-iron bridge slabs for onsite replacement

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Abstract

Most of the road bridges in Japan were constructed in the 1960s and 1970s, and many of them have been in service for more than 50 years. The reinforced concrete slabs of such bridges have been damaged and deteriorated by heavy traffic. Although these slabs have already been reinforced with steel plates, they have deteriorated further and need to be replaced.

The renewal of reinforced concrete slabs leads to increase of dead load, the fatigue damage at welds has not been completely solved in the case of steel slabs, and the social loss due to long-term road closures at the renewal construction of the slabs on urban highways. Therefore, there is an urgent need to develop an alternative slab that is lighter in dead weight, has good fatigue resistance, and can be installed rapidly.

The proposed slabs in this paper are made of ductile cast-iron instead of mild steel. Ductile cast-iron bridge deck can be light-weighted like mild steel, can show high fatigue resistance with improved residual stress and detail by integrally forming into complex shapes, and can be rapidly installed to the existing bridges by bolts.

The Hanshin Expressway has been conducting research and development for the practical application of ductile cast-iron slabs. This paper will introduce a ductile cast-iron deck, and will shows the study results of the details of the slab panels, the slab-to-slab connection method, and the slab-to-girder connection method.

Keywords: ductile cast-iron bridge deck; slab renewal; connection method; construction method

1 Introduction

The reinforced concrete slabs of Japanese road bridges have been damaged and deteriorated by heavy traffic. Although these slabs have already been reinforced with steel plates, they have deteriorated further and need to be replaced.

However, there are some problems with the renewal of reinforced concrete slabs: 1) it leads to an increase in dead load, 2) the fatigue damage of welds has not been completely solved with steel slabs, and 3) the social loss due to long-term road closures is a problem with the renewal of slabs on urban highways. Therefore, there is an urgent need to develop an alternative slab that is lighter in dead weight, has good fatigue resistance, and can be installed rapidly.

The proposed slabs in this paper are made of ductile cast-iron instead of mild steel. As shown in Figure 1, ductile cast-iron has excellent ductile performance, which is equivalent to that of mild steel. It can also be integrally molded into complex shapes and has high fatigue resistance due to improved residual stress and detail. However, the method of connecting the slab to the existing girder and the construction method to realize rapid construction have not been developed.

In this study, the connection method and construction procedure between the slab and the existing girder were investigated for the practical use of the ductile cast-iron slab.

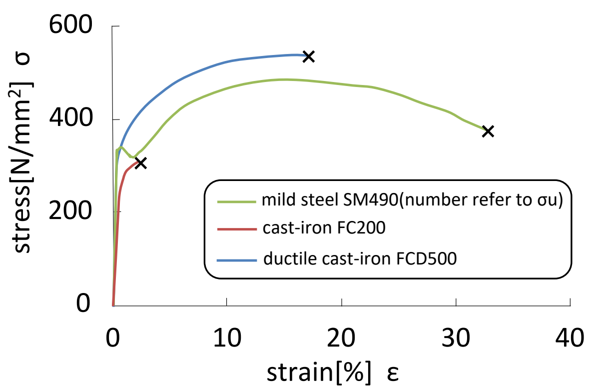


Figure 1. Stress-strain curves of mild steel(σ u=490MPa) cast-iron(σ u=200MPa) ductile cast-iron(σ u=500MPa)

2 Cast iron slab

2.1 Structural properties

The cast iron slab is a weldless structure that takes advantage of the high degree of freedom in forming. As shown in Figure 2, the root of the longitudinal ribs and the intersection of the main and sub ribs are arc-shaped in order to reduce stress concentration. The radius of curvature of the R shape was set to 10 mm based on FEM analysis to determine the optimum shape [1]. The unit area weight of the slab is 250 kg/m2, which is about the same as that of a steel slab.

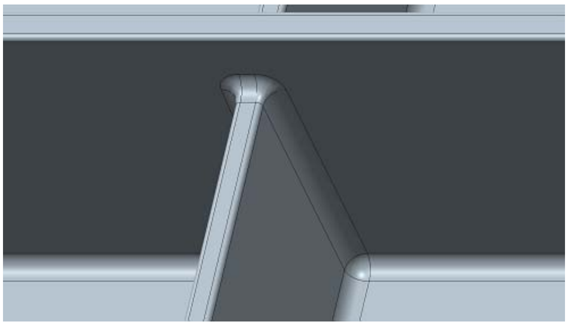


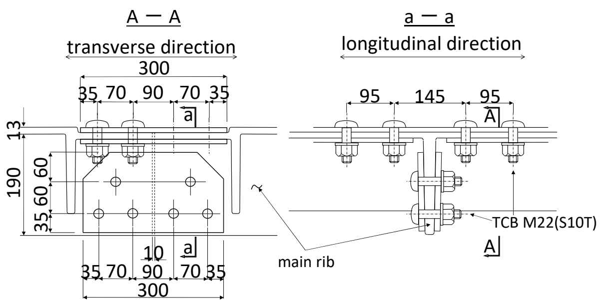
Figure 2. arc shape of the corner

2.2 Slab-to-slab connection method

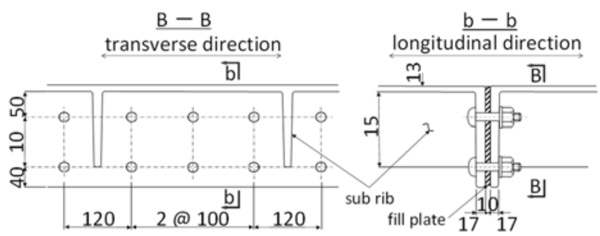
The size of the slab panels to be cast is approximately 1200 mm in the longitudinal direction and 1700 mm in the transverse direction due to manufacturing constraints, and multiple panels are joined to form a slab member. The structure of the joint between the slab panels is not a welded joint, which may cause cracking, but a high-strength bolt friction joint. The friction coefficient of the cast-iron member is 0.45, which is specified in the Japanese Specifications and Commentary for Highway Bridges II, Steel Bridge Edition [2], when the contact surface is coated with inorganic zinc-rich paint [3].

The joint in the longitudinal direction of the bridge is double-sided frictional joint using double connection plates, as shown in Figure 3(a), because the joint resists the bending moment caused by traffic loads. The upper surface of the deck plate was made to be less than the thickness of the connection plate (13 mm), taking advantage of the high degree of freedom in forming of cast iron, so that the pavement over the joint area would not be thin.

Since the bending moment due to traffic load is small and the main girder action stress is compressive in the case of simple girders, the joint at the joint line perpendicular to the bridge axis is an L-shaped structure that can resist the shear force between the slab panels, as shown in Figure 3(b). For this joint structure, FEM analysis with axial force introduced to the high strength bolts confirmed that there was no separation between the panels under truck load [1].



(a) Joint line of longitudinal direction



(b) Joint line transverse direction

Figure 3. Structure of the joint between slab panels.

2.3 Fatigue resistance

2.3.1 Fatigue test

The fatigue resistance of the slab panels was confirmed by fatigue tests, as shown in Figure 4. The load was applied with an amplitude of 154 kN, which is the allowable stress at the tip of the main rib. No cracks were observed at the base of the longitudinal ribs or at the intersection of the main and sub ribs under 10 million cycles of loading[1].

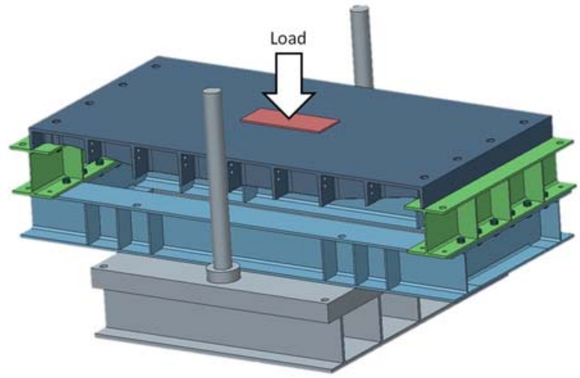


Figure 4. Fatigue test of slab panel

2.3.2 Wheel loading fatigue test

The fatigue resistance of the slab members, including the joints, was verified by wheel loading tests of the slab members on the main girder at 3 m intervals, as shown in Figure 5. After 2 million cycles of loading, there was no fatigue damage and no change in the stress and displacement at the measured position, confirming the high fatigue resistance.

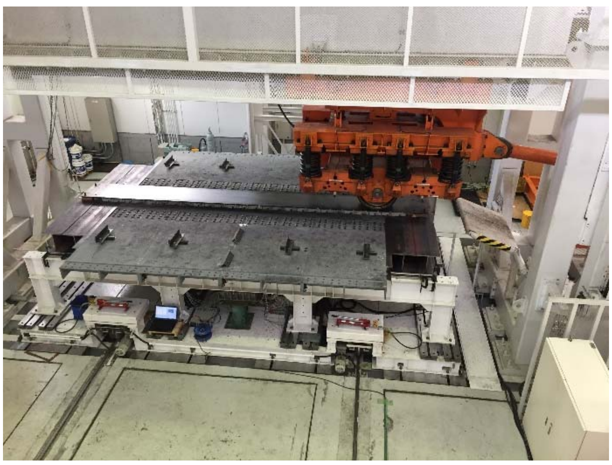


Figure 5. Wheel loading test of slab member

3 Construction Method for Renewal of Existing Reinforced Concrete Slabs

3.1 Conditions for construction method study

In the renewal of slabs, it is required to ensure the serviceability as much as possible where it is difficult to close the entire road. Even when partial serviceability is ensured, it is necessary to minimize the construction period while ensuring high construction safety in order to further reduce the social impact.

In this paper, the construction steps is studied for upgrading the reinforced concrete slabs of simple live load composite I-girder bridges, which were mostly constructed in the 1960s and 1970s, to cast iron slabs while ensuring serviceability. In addition, the construction ability was verified by a large-scale construction test using a full-scale specimen under the conditions of the removal method of the existing reinforced concrete slab as well as the connection structure between the existing main girder and the cast iron slab which can minimize the construction period and ensure reliable construction safety.

3.2 Construction steps

The construction steps for replacing the reinforced concrete slab with a cast iron slab on a four-lane road are shown in Figure 6. In Step 1, one lane is closed on each side and the existing reinforced concrete slab is cut out and removed. Then, in Step 2, the top surface of the existing girder was treated by removing stud bolts and surfacing to install the cast-iron slab. In Step 3, the new cast-iron slab members were installed.

3.3 Removal of existing reinforced concrete slab

After the slabs between the main girders are removed, the concrete blocks left on the main girders are cut horizontally with a wall saw, as shown in Figure 7(a). Water is used as a splash prevention measure when cutting the concrete blocks, so consideration must be given to the splashing of muddy water. The noise level is 85 to 90 dB at a distance of 6 m. Therefore, it is necessary to take soundproofing measures according to the surrounding environment. The horizontal cutting speed was about 3 m2/h, which is about 60% of the vertical cutting speed, as a result of cutting a specimen with welded studs of 22 mm diameter using a large wall saw with a blade diameter of 1200 mm.

The horizontal cutting height of the concrete blocks of the main girder should have a margin of height

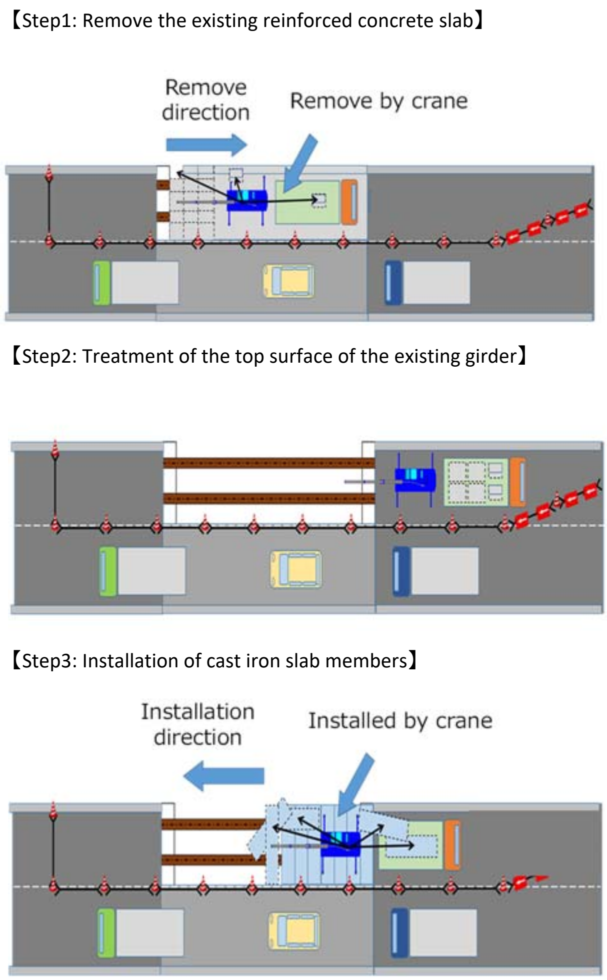


Figure 6. Construction steps for reinforced concrete slab renewal

between the cutting height and the top surface of the upper flange to avoid interference with the upper flange and main girder joints. In the horizontal cutting test using the specimen, concrete removal tests were conducted on the top surface of the upper flange with a margin height of 25 mm and 60 mm. When using a small chipper, the chipping speed was 6.5 m2/h with a clearance of 25 mm, while it was 0.75 m2/h with a clearance of 60 mm. The influence of the margin height on the chipping time is significant, and it is desirable to reduce the margin height as much as possible, taking into account the condition of the remained reinforcement of the concrete blocks and the connection plate on the upper flange of the target bridge.

After concrete block removal, the studs on the main girder were cut at the base of the stud using a special saw as shown in Figure 7(b), and the remaining welds were removed using a disc sander and then finished with a spark disc as shown in Figure 7(c).

In the trial construction using the specimen, the cutting speed by the special saw was 87 seconds per piece, and the finishing of the stud weld was 124 seconds per piece. However, the cutting speed by the special saw varied greatly depending on the wear and tension of the saw blade.

(a) Horizontal cutting of concrete blocks on main girder

(b) Cutting of studs on main girder

(c) Surfacing with spark disk

Figure 7. Removal of existing reinforced concrete slab

3.4 Connection between Slab and Girder

As shown in Figure. 8, the main girder and slab members are connected by high strength bolts through an inverted T-shaped support, after the upper surface of the girder is drilled and a filler plate is installed. The height adjustment during construction is done by the web height of the inverted T support, and the filler plate is tapered to accommodate the cross-slope. The inverted T support is made of cast iron with corner radius to ensure durability against deflection of the slab under live load and change in deflection angle on the main girder due to temperature effect.

The connection structure at the end of the girder for the composite girder slab was designed to strengthen the horizontal shear resistance so that the required number of bolts could be secured against shear forces due to temperature effects. Scratches and unevenness on the top surface of the upper flange are corrected by using epoxy resin adhesive. In this case, the effect of the adhesive is not considered because the design method has not been established yet.

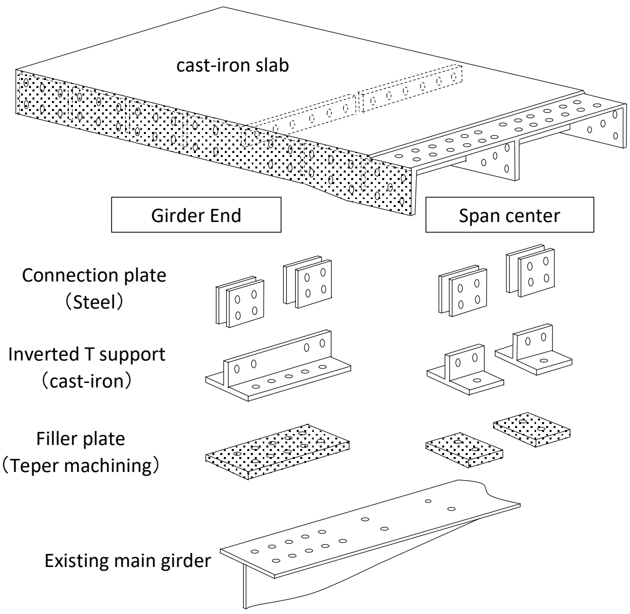


Figure 8. Connection structure of slab and girder

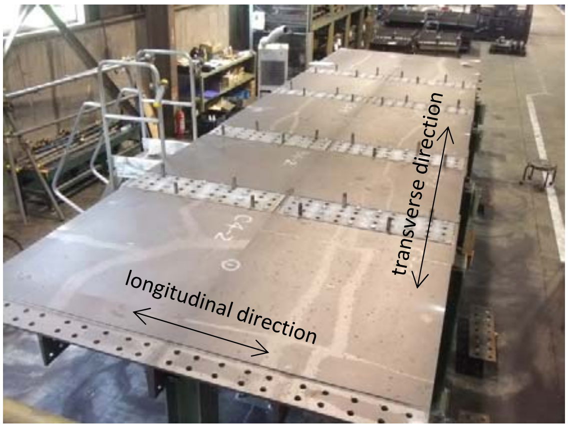
4 Large-scale assembling test

In order to verify the assembly of the slab panels and the erection of the assembled slab members on the girder, construction tests were conducted using full-scale members. The dimensions of the slab panels were determined based on the performance of the current manufacturing equipment. The main girders to which the slab members are attached are steel I-girders (three main girders) with 3 m spacing between the main girders, which have field joints and vertical stiffeners.

Figure 9(a) shows the assembly of 10 panels, two in the longitudinal direction and five in the transverse direction. The dimensions of the assembled slab members were 2.3 m in the longitudinal direction and 8.0 m in the transverse direction for transportation purposes. The bolt holes on the sides of the slab panels were drilled during assembly instead of during the casting stage in order to ensure assembly accuracy.

Figure 9 (b) shows the erection of two blocks of assembled slab members on the girder. A 10-mm filler plate was installed at the field joint of the slab members in the longitudinal direction of the bridge to accommodate construction tolerance. The following is a summary of the results of the large-scale assembly test.

1) Construction ability: It was confirmed that the field joints of the main girders and the areas where the vertical stiffeners and inverted T-shaped supports were close to each other could be installed by adjusting the placement of the supports. In the narrow area where the joints between the slab members and the main girder are close to each other, the bolts can be installed without interfering with each other, but it is necessary to pay attention to the tightening order.
2) Time required for slab erection: After the slab members of the first block were installed, the time required for erection of the adjacent slab members of the second block was approximately 80 minutes. In this test, the height of the slab was adjusted while the slab was suspended by a crane. The structure of the support for height adjustment needs to be studied from the viewpoint of improving safety during construction and shortening the construction period by reducing the crane operation time.
3) Tolerance in the bridge transverse direction: The error during assembly in the direction perpendicular to the bridge axis was less than 1.5mm for 8.0m. This error could be absorbed by the bolt holes, so it was confirmed that it would not be a problem during construction.
4) Tolerance in the bridge longitudinal direction: It was confirmed that the filler plates installed between the slab members in the bridge axial direction could be installed and that the error could be absorbed by varying the plate thickness. However, it is necessary to consider the procedure to prevent the plates from falling because the plates are installed from the top and supported at the bottom of the slab after the slab members are placed in position.



(a) Assembly of slab members

(b) Erection of slab members

Figure 9. Large-scale assembly test

In addition, it was verified whether this slab can be partially replaced when the slab member is damaged by some unexpected influence after service. In this verification, the slab panels were partially removed from the specimen after the large-scale assembly test and reinstalled. Figure 10 shows the removal of the slab panel using a jack. The partial removal of the slab panel was possible using a jack, but the filler plate for absorbing the construction error could not be installed during the reinstallation due to the release of internal stress. This indicates that partial replacement of cast iron panels is possible by preparing new filler plates.

Figure 10. Removing a slab using a jack

5 Conclusion

Ductile cast iron slabs, which are light and highly durable due to their weld-less structure that takes advantage of their high degree of freedom in forming characteristics, have been verified in terms of load-bearing performance and durability as slab members.

In this study, a method of removing the existing RC slab, a method of connecting the ductile cast-iron slab to the main girder, and a full-scale large-scale assembly test were conducted in order to apply the cast-iron slab in the field. The results of these studies are described below.

1) Horizontal cutting at the time of removal of the existing RC slab can be done as close as possible to the top of the top flange to reduce the construction time.
2) The connection between the slab and the girder can be made by using cast iron inverted T-shape supports and avoiding the vertical stiffeners and contact plates.
3) Field errors can be dealt with by installing filler plates between the slab members.
4) In case of damage after in-service, partial replacement is possible by preparing filler plates in advance.

There are still some technical issues to be resolved before applied in the field, such as the detailing of the attachment points for accessories such as wall railings, telescopic devices, and drainage basins, but the ductile cast iron slabs is being developed quickly and carefully with the goal of applying it to future slab renewal projects.

6 Acknowledgements

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7 References

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