Application of Waffle-shaped UHPFRC Slabs for a Highway Bridge — Shinanobashi Rampway Bridge on the Hanshin Expressway —

ワッフル型 UFC 床版の実適用 — 阪神高速 信濃橋入路橋 —

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Synopsis

Hanshin Expressway Co., Ltd. and Kajima Corporation have been conducting R&D on road bridge slabs using ultra-high-performance fiber-reinforced concrete (UHPFRC)[1] since 2011. These UHPFRC slabs are made of thin, lightweight, and extremely durable precast concrete (PCa) panels. There are two types of UHPFRC slab: flat slabs that are lighter than the thin reinforced concrete (RC) slabs designed to comply with the previous design standards, and waffle-shaped slabs that are as light as thin steel slabs.
The waffle-shape UHPFRC slabs have been adopted for the first time in Japan on the Shinanobashi Rampway Bridge, a new steel simple-span composite girder bridge crossing the national highway at the Shinanobashi rampway on Route 1. Compared to conventional concrete slabs, adaption of waffle-shaped UHPFRC slabs enabled the bridge to attain lighter weight, increased durability and shorter slab installation time.
This paper reports on the detailed design, manufacturing, and installation of the waffle-shaped UHPFRC slabs in their actual application.

Structural Data

Structure: Simple composite girder bridge
Bridge Length: 36.950 m
Span: 36.100 m
Width: 5.750–5.825 m
Owner: Hanshin Expressway Co., Ltd.
Designer: Kajima Corporation
Contractor: Kajima Corporation
Construction Period: Feb. 2020 – Apr. 2021
Location: Osaka Prefecture, Japan

1. Design of Waffle-shaped UHPFRC Slabs

(1) Structural Outline

The Shinanobashi Rampway is a simple-span composite steel girder bridge spanning over National Route 172. The bridge is 36.950 m long and 5.750 m wide. The girder height is 1,940 mm at the center of the span and reduced to 660mm at the NP5 side to match with the girder height of the adjacent prestressed concrete (PC) bridge on the same end pier (**Figs. 1** & **2**).
A waffle-shaped UHPFRC slab is a slab with ribs running in longitudinal and transverse directions. In other words, it is a lightweight structure with many box-out recesses on the underside of a flat slab[2] (**Fig. 3**). These slabs are supported by a structural frame composed of main girders, side beams, crossbeams, and horizontal ribs similar to a steel slab.

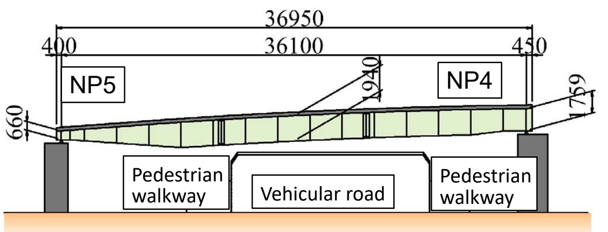

Fig. 1 Side view of the Shinanobashi Rampway Bridge

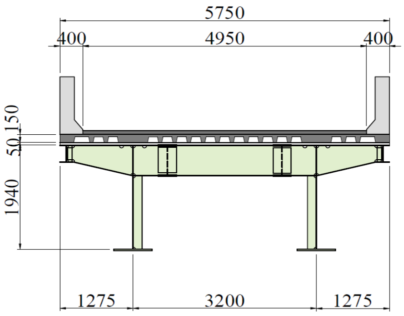

Fig. 2 Sectional view of the Shinanobashi Rampway Bridge

The waffle-shaped UHPFRC slabs have prestressing strands set within the ribs in both longitudinal and transverse directions, with prestress being induced using the pretension method. High compressive stresses of 10-20 N/mm^2 are induced by prestressing forces in both directions by utilizing the superior material properties of UHPFRC while restraining the superimposed stress below the crack initiation strength, even in thin materials with large stress fluctuations caused by active loading.

Fig. 3 Bottom view of a waffle-shaped UHPFRC slab

(2) Design of Precast Slab

Ettringite-generating UHPFRC was used for the waffle-shaped UHPFRC slabs on the Shinanobashi Rampway Bridge [3] with SWPR7BL 15.2 mm prestressing strand used as the prestressing material. The mechanical properties of ettringite-generating UHPFRC and the design limit values for this bridge are shown in **Table 1**.

Table 1 UHPFRC characteristic values and limit values for design

UHPFRC characteristics	Compression strength	f'_{ck} = 180 N/mm^2
	Crack initiation strength	f_{cr} = 8.0 N/mm^2
	Tensile strength	f_t = 8.8 N/mm^2
	Young's modulus	E_c = 46,000 N/mm^2
Limit values	Compression stress	f_{ca} = 0.6 f'_{ck} = 108 N/mm^2
	Tensile stress	f_{ta} = f_{cr} = 8.0 N/mm^2
	Tensile stress (slab joint)	f_{taj} = 0.0 N/mm^2
	Deflection of slab between horizontal ribs due to T-load	σ_a = 1.5 mm

This bridge has 15 PCa slab panels: 12 standard panels, 1 widened panel, and 2 edge panels where the expansion joints are installed. The width of each slab panel includes the width of concrete barriers on both edges, because those barriers are constructed directly on top of the panel (**Fig. 2**). The width of slab panel is 5,750 mm (**Fig. 4**) for the standard panel and increased upto 5,827 mm at the NP5 side accounting the road widening. The length of standard and widened panels was set to be 2,450 mm considering the land transportation. The length of edge panels, thicker than standard panels, was set to be 2,220 mm with the aim of keeping the weight of those panels to be the same as standard ones.

The total slab thickness of standard panels was set to be 150 mm, composed of 45 mm thick top layer supported by 105 mm height ribs, to restrain any relative deflection of the slab between horizontal ribs of the structural frame under T-loading (Japanese road traffic loads model) to be less than 1.5 mm. The top layer was set to be 5 mm thicker than the actual design requirement on assumption that the upper surface of the slab would be damaged when the pavement was removed and replaced.

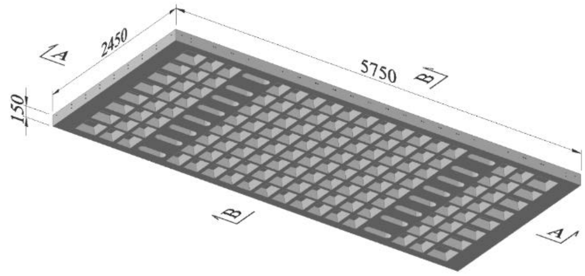

Fig. 4 Conceptual diagram of a standard panel

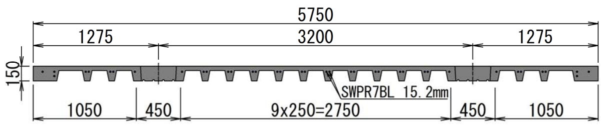

Fig. 5 Standard panel: transverse sectional view (Fig. 4 A-A)

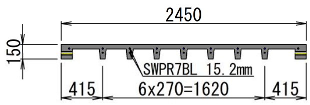

Fig. 6 Standard panel: longitudinal section view (Fig. 4 B-B)

The center spacing of the ribs in the longitudinal direction was set to be 250 mm such that there are always multiple ribs directly under any T-load (loading width: 500 mm) to conform with the specifications for road bridges, no matter where the load is applied (**Fig. 5**). On the other hand, geometric restrictions do not apply to the center spacing of the ribs in the transverse direction, and the design was drafted in a range where the stress generated is within the specified limits. Accordingly, for this bridge, the center spacing of the

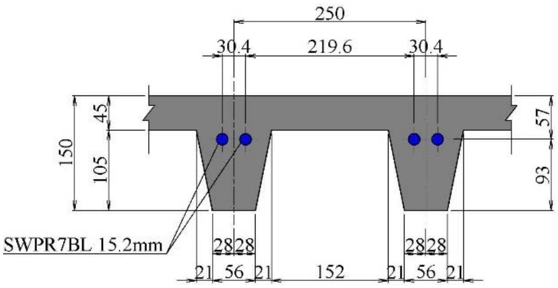

Fig. 7 Enlarged sectional view of ribs in the longitudinal direction

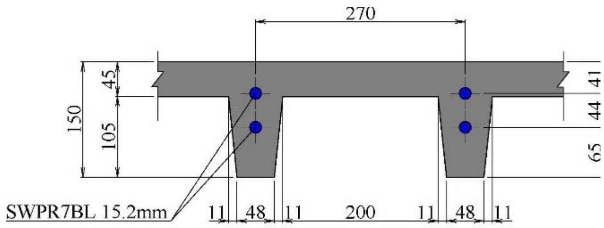

Fig. 8 Enlarged sectional view of ribs in the transverse direction

ribs in the transverse direction was set at 270 mm, which is 20 mm wider than those in the longitudinal direction (**Fig. 6**).

The cross-sectional width of the ribs in the longitudinal direction was set at 98 mm for the top and 56 mm for the bottom to ensure that it satisfies the specified cover from the prestressing strand to the left and right where the prestressing strand is arranged and narrows toward the bottom (**Fig. 7**). The cross-sectional width of the ribs in the transverse direction was set at 70 mm for the top and 48 mm for the bottom to ensure that it satisfies the specified cover from the prestressing strand to the left and right where the lower prestressing strand is arranged, and the width narrows toward the bottom (**Fig. 8**).

The eccentricity of prestressing strands are carefully studied and minimized to suppress warping of the slab panel due to prestressing. Two prestressing strands were arranged vertically in a row in the transverse direction (**Fig. 8**) while another set of prestressing strands were arranged side by side in the longitudinal direction (**Fig. 7**) between those prestressing strands in the transverse direction to minimize the eccentricity in both directions. Here as well, the authors assumed that the upper surface of the slab would be damaged when the pavement was removed and replaced, and thus a margin of 10 mm was retained as the specified cover (1.5 times the diameter of the prestressing strands) [4] for the upper prestressing strand in the transverse direction, 41 mm was set as the distance from the upper surface of the slab to the center of the prestressing strands, and 85 mm for the lower strand. The center of prestressing strands in the longitudinal direction is 57 mm from the top of the slab and arranged directly below the upper prestressing strand in the transverse direction. As a result, the eccentricity of the prestressing strands was set as 4.9 mm in the longitudinal direction and 15.5 mm in the transverse direction.

(3) Joint Design

For the Shinanobashi Rampway Bridge, in order to fabricate the overall slab structure including its joints with homogeneous materials as much as possible and bolster the anchorage strength between slab and steel girder, UHPFRC was used as the filler for both the joints between slab panels and those of the structural frame and panels, including the stud holes [5]. It was decided to reduce the amount of steel fibers in the ettringite-generating UHPFRC to ensure its packing performance as a filler, and only 15 mm steel fibers were mixed in at 0.75% by volume.

2. Manufacture of Waffle-shaped UHPFRC Slabs

General PCa slab panels with prestress in transvers direction can be manufactured on the production line of the typical PCa-component manufacturing plant, but waffle-shaped UHPFRC slabs with prestress in two directions cannot be manufactured using this conventional production line alone. Therefore, it was necessary to consider whether to either remodel an existing production line to enable prestress induction in two directions for manufacturing or install a new dedicated manufacturing system for production. For this construction, a dedicated manufacturing trestle made of concrete was constructed by referring to a past example in which prestress was induced in two directions using the pretension method.

(1) Dedicated Manufacturing Trestle

The dedicated manufacturing trestle has reaction-force vertical walls to tension the prestressing strands on all four sides (**Fig. 9**). The vertical walls on the long side of the manufacturing trestle have holes which to thread the prestressing strands to transmit their tensile force to the vertical walls as the prestressing strands in the longitudinal direction are tensioned without changing the spacing between panels.

When determining the dimensions of the dedicated manufacturing trestle, consideration was given to space to lift and lower the bottom formwork, space to install deflection plates for more-accurate positioning of the prestressing strands, and space to connect the strands to the prestressing steel bar to be described later. The vertical concrete walls and bottom slab are enough rigid to minimize any deformation caused by tension. External dimensions were 7.5 m × 9.5 m, with 1.2 m thick vertical walls and a 1.0 m thick bottom slab.

Fig. 9 Dedicated manufacturing trestle

(2) Manufacturing

A flexible urethane box-out recess formwork was used to create the waffle-shaped underside of a slab to prevent it from cracking because of UHPFRC shrinkage from casting to demolding and to facilitate the lowering of the bottom formwork.

If the prestressing strands (SWPR7BL 15.2 mm) set in the slab are to be directly tensioned and fixed with wedges, then the tension would vary after they were fixed, so instead two prestressing strands were paired and connected to a ∅32 mm prestressing steel bar, and tension fluctuation is restrained by tensioning and fixing this prestressing steel bar with nuts. Prestress was applied the morning after the UHPFRC was poured. The box-out recess formwork was lowered with the bottom formwork before prestressing because elastic shortening of the slab caused by prestressing restrained the box-out recess formwork (**Fig. 10**).

Fig. 10 Status after tensioning of PC steel bars

3. Installation of Waffle-shaped UHPFRC Slabs

The installation of the waffle-shaped UHPFRC slabs for this bridge was split into three steps, namely, transportation/installation, interstitial filling, and joining the precast panels. Because prestress was induced using the pretension method for each precast panel in the longitudinal direction, the installation procedure was simpler than that of flat UHPFRC slabs, which require the following procedures: filling the gaps between slabs after slab installation; insertion, tensioning, and grouting of prestressing strands in the longitudinal direction; and filling the gaps between slabs and steel girders.

The waffle-shaped UHPFRC slabs for this bridge weigh 35.3 kN for a standard panel and 38.3 kN for the heaviest edge panel. Thus, three precast panels could be loaded onto a 15-ton truck and transported to the installation site from the production plant. As a result, transportation of all waffle-shaped UHPFRC slabs was completed in five trips.

A 60-ton rough terrain crane was used to install the waffle-shaped UHPFRC slabs for this bridge, which enabled installation while only restricting two out of four lanes of traffic on National Route 172 in the evening.

Conclusions

A waffle-shaped UHPFRC slab having superb durability and weighing no more than steel slabs was developed and applied for the first time in Japan to the Hanshin Expressway Shinanobashi Rampway in anticipation of future applications to new routes.

For the design of the waffle-shaped UHPFRC slab, the slab deformation due to prestress, slab deflection under vehicle loads, and possible damages to the top of the slab when replacing pavement and many other technical concerns were carefully and deeply considered. For the manufacture of these waffle-shaped UHPFRC slabs, a new dedicated manufacturing trestle was built to streamline their production and induce very precise prestress, among other advantages.

Owing to their well-designed size and light weight, the installation of the waffle-shaped UHPFRC slabs required less labor input achieving labor-saving in all other related works at the site. At the same time, the effectiveness of the UHPFRC filler applied to the gaps was confirmed.

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概　要

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