

Design and Fabrication of Prestressed Concrete Box Girder Bridge with U-Shaped Segments

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Abstract. The bridge in this project is a two-span continuous prestressed concrete box girder bridge with U-shaped precast segments (PC composite U girder bridge) under construction across a valley in Tokushima, Japan. This bridge type was selected from among others for simplified on-site construction and optimum cost reduction. The bridge has a continuous structure prestressed with internal and external tendons. Large capacity tendons (19S15.2) were used to apply prestressing force externally at the support cross beams in two different stages: when the cross section was in a U shape and then in a composite shape. As compared to that in the composite section stage, the prestressing process in the U-shaped section stage could cause excessive tensile stress in the cross beams. The other concern was cracking risk associated with tensile stress occurring on the inside of the sloped webs of the U-shaped cross section of the main girder during the temporary storage of the precast segments. In order to investigate reinforcing methods, the authors carried out three-dimensional finite element analysis for the two cases: at prestressing of the tendons and at temporary storage of the segments. Measures were also taken to improve quality of the precast segments and construction efficiency during the fabrication process. This paper reports planning, design and construction of the PC composite U girder bridge.

Keywords: PC composite U girder bridge · External tendons · Precast segments · Finite element analysis · Fabrication

1 Outline of the Bridge

Table 1 and Fig. 1 respectively show the specifications and the side view of the bridge.

Table 1. Specifications of the bridge.

Structure	Two-span continuous prestressed concrete box girder bridge with U-shaped precast segments (PC composite U girder bridge)
Bridge length	75.000 m
Span lengths	47.050 m + 27.050 m
Total width	9.200 m
Alignment	A = 75 to R = ∞
Transverse profile	4.1% to 1.5%
Materials	Main girder and cross beam concrete: σ_{ck} (specified compressive strength) = 50 N/mm ²
	Main girder internal tendons: 12S12.7 mm
	Main girder external tendons: 19S15.2 mm

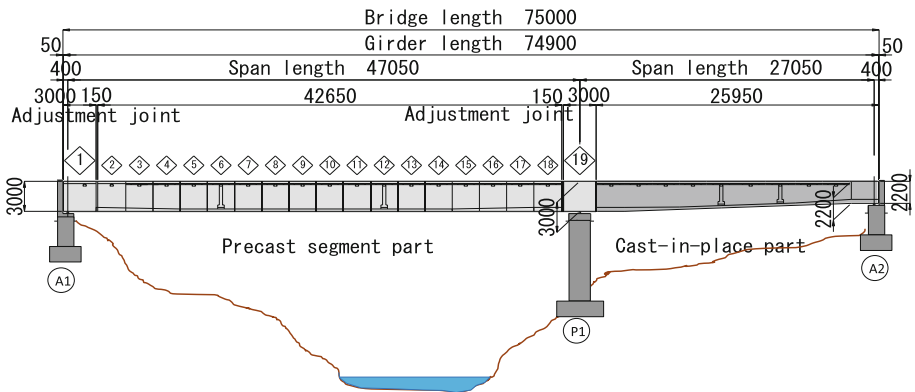


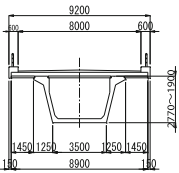
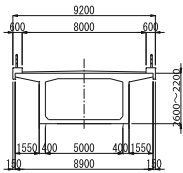
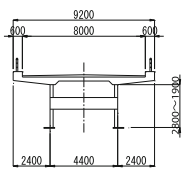
Fig. 1. Side view of the bridge.

2 Selection of the Bridge Type

There were two major requirements in selection of the bridge type: simplified on-site construction and optimum cost reduction for the erection of the A1-P1 span across the valley. The locational condition also limited the space available for the construction yard and thus the use of heavy construction equipment. Therefore, special consideration was given to construction efficiency (simplified on-site construction for the A1-P1 span) as well as to economic efficiency. Three plans were chosen for comparison as

shown in Table 2 for the span in consideration. For Plan 1, a PC composite U girder bridge was selected because the span length of this bridge was longer than the applicable length with I-shaped section. Plan 2 with a PC box girder bridge to be cast in place requires increased work at site, being inferior to Plan 1 in construction efficiency. Plan 3 with a twin I-girder bridge requires a field assembly yard for the main girder and additional space for the assembly cranes. Work efficiency will be significantly reduced due to the limited space available for the construction yard. On the other hand, the U-shaped precast segments for Plan 1 can be lifted and placed in position by the erection girder directly from the trailer for transport to site (Fig. 2, Photo 1). Thus, construction efficiency was judged as Excellent. These pointed to the two-span continuous PC composite U girder bridge as the most appropriate bridge type. The positive use of precast members leads to simplified on-site construction. The precast PC panels used in the slabs provide high durability, which is expected to reduce life cycle cost of the bridge.

Table 2. Comparison of the bridge types.

	Plan 1: two-span continuous PC composite U girder	Plan 2: two-span continuous cast-in-place PC box girder	Plan 3: two-span continuous composite twin I-girder
Cross sectional view			
Construction efficiency	Excellent	Moderate	Good
Economic efficiency	Excellent	Good	Moderate
Overall rating	Excellent	Good	Moderate

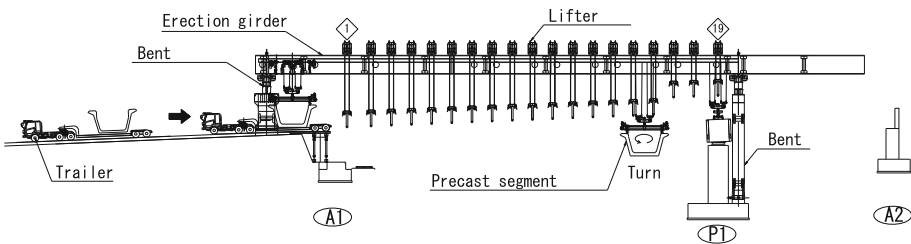


Fig. 2. Erection method.



Photo 1. Erection situation at site.

3 Features of the PC Composite U Girder Bridge

Figure 3 shows the cross sectional view of the PC composite U girder bridge in this project. The U-shaped section has a higher cross section performance compared to the I-shaped section of a conventional composite bridge (Fig. 4). The wider bottom flanges provide increased construction safety. External tendons can be installed inside the box girder like in a general PC box girder bridge, enabling to make the structure continuous for a longer span. The features of this bridge type are summarized as follows:

- (1) **Higher durability.** The U-shaped main girder segments fabricated at a factory under strict quality control are ensured to have high quality. Increased durability is provided to the deck slab by adopting a PC composite structure using precast PC panels designed with no tensile stress.
- (2) **Increased construction safety.** The U-shaped section has a higher cross section performance compared to the conventional I-shaped section, which provides higher stability during erection. The PC slab panels can serve as forms and scaffolding, increasing safety of the workers during construction of the slab.
- (3) **Simplified and rationalized construction.** The main girder consists of precast segments, and the precast PC panels of the slab also serve as the forms for in-situ casting. Such positive use of prefabricated members achieves significant reduction in work at site. Simplified construction leads to a shorter construction period.
- (4) **Cost reduction.** The shorter period of on-site construction achieved by the positive use of the precast members leads to reduction in the initial costs, and the increased durability leads to reduction in the life cycle cost of the bridge.

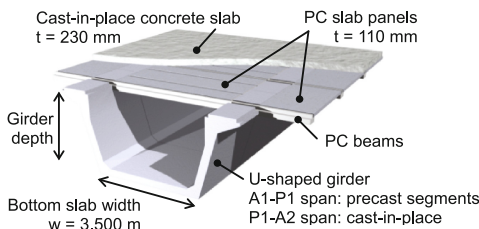


Fig. 3. Cross sectional view of the U-shaped section.

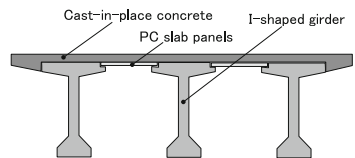


Fig. 4. Cross sectional view of the I-shaped section.

4 Examination on the Support Cross Beams

4.1 Considerations and Construction Steps

The prestressing force in the tendons causes deformation similar to plate bending in the A1 cross beam as shown in Fig. 5, which causes tensile stress in the P1 side (hereinafter referred to as the “back side”) of the cross beam. The cross beam in the U-shaped section stage is supported at three edges by the webs and the bottom slab, whereas the top slab also supports the cross beam in the composite section stage, forming a four-edge support. Since the absence of support or restraint at the top of the section could cause excessive deformation and tensile stress, the authors carried out the following examination. The construction steps of the main girder of the bridge is shown in Fig. 6. Three-dimensional finite element (3D FE) analysis was made for each prestressing stage (the U-shaped or composite section stage) in these construction steps, and the sum of the tensile stress values was obtained to determine total tensile stress occurring in the back side of the cross beam. Where transverse tensile stress exceeded the concrete tensile strength $f_{tk} = 3.12 \text{ N/mm}^2$ ($\sigma_{ck} = 50 \text{ N/mm}^2$), transverse prestressing tendons were

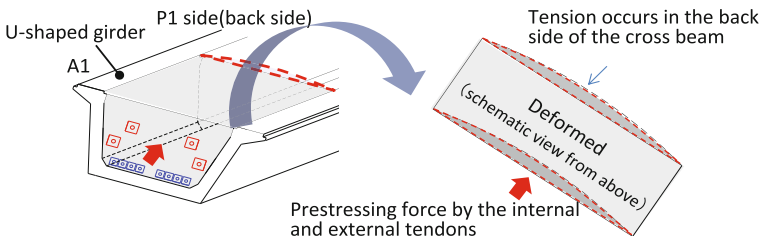


Fig. 5. Schematic view of the deformation of the cross beam.

STEP 1 (U-shaped section)	Place the precast segments, and cast concrete of the cross beams of A1 and P1. Place the prestressing steel of the A1-P1 span, and apply tension.
A1 cross section 2 external tendons (19S15.2,A1-P1) 8 internal tendons (12S12.7,A1-P1)	
STEP 2 (U-shaped section)	Cast concrete of the main girder and cross beam of A2. Place the prestressing steel of the P1-A2 and A1-A2 spans, and apply tension.
A1 cross section 2 continuous external tendons (19S15.2,A1-A2) 2 external tendons (19S15.2,P1-A2) 2 internal tendons (12.S12.7,P1-A2)	
STEP 3	Place the PC beams and PC slab panels over the A1-A2. Cast concrete of the cast-in-place slab over the A1-A2.
STEP 4 (composite section)	Apply tension to the secondary tendons for the A1-A2.
A1 cross section 2 continuous external tendons (19S15.2,A1-A2)	

Fig. 6. Main girder construction steps.

added to reduce the tensile stress, and further strengthening using additional reinforcing bars was adopted to deal with the reduced tensile stress level.

4.2 3D FE Analysis Results

Figure 7 shows maximum principle stress by the analysis for the A1 cross beam. The prestressing force in the external tendons was found to cause tensile stress in the transverse direction in the back side of the cross beam. The value in the U-shaped section stage (Steps 1 and 2; four external tendons) was 3.44 N/mm^2 , exceeding the tensile strength of the concrete ($f_{tk} = 3.12 \text{ N/mm}^2$). The tensile stress reached 4.02 N/mm^2 after prestressing of the continuous tendons (secondary tendons; two external tendons) in the composite section stage (Step 4). However, the increase in Step 4 was as small as 0.58 N/mm^2 , which was likely due to the aforementioned difference in support or restraint conditions of the cross beam. In order to reduce the transverse tensile stress, eight transverse prestressing tendons (1S28.6 mm) were placed in the back side of the cross beam. With the additional prestressing force introduced, tensile stress was reduced to 2.76 N/mm^2 . For strengthening against the vertical tensile stress and residual transverse tensile stress after application of prestressing force, additional D16 reinforcing bars were placed in a grid pattern. Figure 8 shows the strengthening measures.

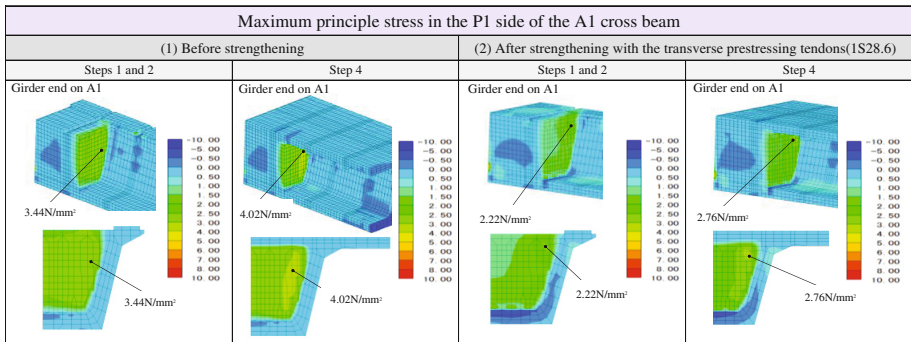


Fig. 7. Analysis results (maximum principle stress distribution).

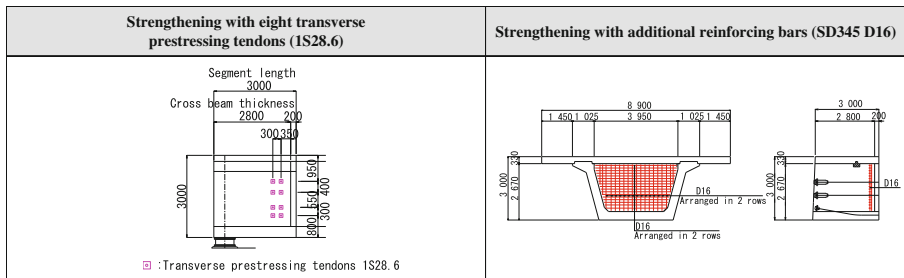


Fig. 8. Schematics of the strengthening measures.

5 Examination on the Segments During Temporary Storage

The main girder of the bridge has a U-shaped section with sloped webs. Cracks could occur in the precast segments during the temporary storage due to the tensile stress induced on the inside of the webs as they deformed outward. FE analysis was made to determine the tensile stress occurring in the webs. Figure 9 shows a schematic of the web deformation and the analysis results. Vertical tensile stress was found to reach 2.14 N/mm^2 in the haunches on the inside of the sloped webs. It was decided to add D13 reinforcing bars in the haunches to cope with the vertical tensile stress.

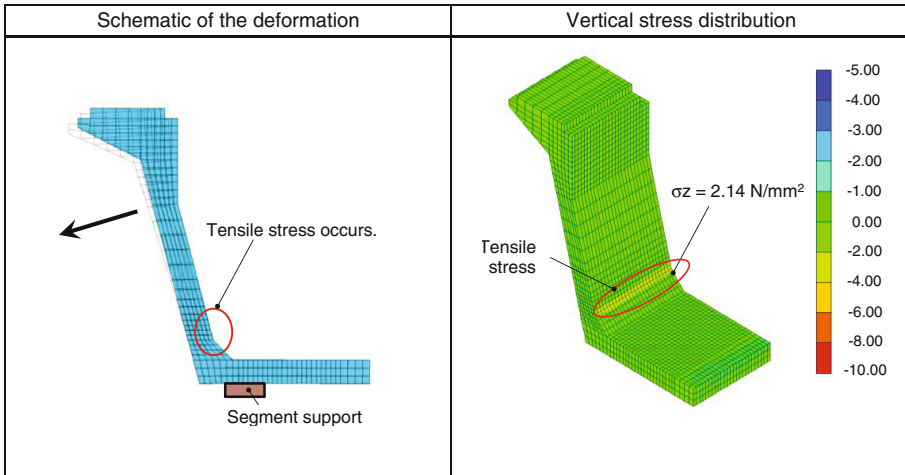


Fig. 9. Schematic of the deformation and vertical stress distribution.

6 Fabrication of the Precast Segments

A long line system was adopted for the fabrication of the segments to make the fabrication period shorter. The large depth of girder (2.770 m) and heavy weight of reinforcement could lead to difficulties in assembly work of reinforcement in a limited space inside the concrete form. To solve this problem, a steel frame was prepared in the same shape as the concrete form for prefabrication of the reinforcement cage (Photo 2). This enabled performing other operations in parallel, as well as improved the construction efficiency, consequently reducing the number of days required to complete the segment fabrication cycle by one day. Poor concrete filling of the bottom slab could occur due to the dense and complicated reinforcement layout in the slab segments, especially those in the end parts. As a countermeasure to this problem, high-flow concrete was used.



Photo 2. Prefabrication of reinforcement.

7 Summary

Several bridge types were examined for the bridge in this project, and a PC composite U girder bridge was selected as the most appropriate structure for simplified on-site construction and optimum cost reduction. This type of bridge changes its cross-sectional shape during construction, which requires careful consideration for every stage. The authors carried out 3D FE analysis for the cross beams of the bridge in this study, and found that the prestressing force in the internal and external tendons would cause a tensile stress more than 4.0 N/mm^2 in the back side of the cross beam. In order to reduce the stress, transverse prestressing tendons (1S28.6 mm) and additional reinforcing bars were included in the design. Since the U-shaped section had sloped webs, another FE analysis was carried out to determine the tensile stress occurring in the segments during temporary storage. Additional reinforcing bars were adopted to prevent cracks. Efforts to reduce the fabrication period were also made in the fabrication of the precast segments, with high quality of the products ensured.

The authors deeply appreciate all of the support and instruction provided in the planning, design and fabrication of the bridge, and hope this report will be a useful resource for planning, design and fabrication of PC composite U girder bridges.

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