Non-metallic Bridge for Ultra-high Durability — Bessodani Bridge —

超高耐久性を実現した非鉄製橋梁 — 別埜谷橋 —

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Synopsis

Concrete is naturally long-lasting and highly stable construction material, with concrete structures built during the Roman Empire still in use today. However, ever since the invention of reinforced concrete structures around 150 years ago, corrosion of steel members embedded in the concrete has become a common problem that has undermined the innate durability of concrete structures.

Bessodani Bridge is the world's first non-metallic bridge built on a highway (**Fig. 1**). Its structure was developed to regain the inherent high durability of concrete structures while retaining the superior properties of modern prestressed structures.

Aramid FRP (fiber reinforced polymer) rods were used as prestressing tendons to reinforce against tensile stresses generated by bending moments and axial forces, and to eliminate the need for steel prestressing strands and reinforcing bars. For the web, a butterfly web structure was adopted as an efficient means of reducing the main girder weight while reinforcing against shear forces. The butterfly web structure is characterized by its ability to decompose the acting shear forces into compressive and tensile forces. After erecting the segments, aramid FRP rods were installed as external cables and post-tensioned to integrate the structure[1].

Structural Data

Structure: single-span non-metallic butterfly web box girder bridge
Bridge Length: 26.55 m
Span: 25.5 m
Width: 11.55 m
Owner: West Nippon Expressway Co., Ltd.
Designer: Sumitomo Mitsui Construction Co., Ltd.
Contractor: Sumitomo Mitsui Construction Co., Ltd.
Construction Period: Jul. 2019 – Mar. 2021
Location: Tokushima Prefecture, Japan

1. Introduction

Bessodani Bridge is a precast segment box girder bridge made of high-strength fiber reinforced concrete.

Fig. 1 Bessodani Bridge

2. Development

(1) Production of Butterfly Panels

The non-metallic butterfly web structure was developed to eliminate the need for shear reinforcing bars. The maximum amount of coarse aggregates in the concrete mix was added to leverage the synergistic effects of fiber cross-linking and interlocking of coarse aggregates and achieve a high-strength fiber reinforced concrete with a shear strength of at least 17 MPa. The concrete design strength was 80 MPa.

Loading tests were used to verify that the non-metallic butterfly web structure made from the developed concrete had the required shear strength. The tests confirmed that the required shear strength could be attained without using rebars in the butterfly panel (**Fig. 2**).

Fig. 2 Testing for shear capacity

(2) Fatigue Characteristics of Deck Slab under Wheel Loads

The characteristics of highway bridge decks continually subjected to cyclic traffic loads are generally known. However, the deck slabs of non-metallic bridges potentially differ significantly from typical deck slabs because the former have no steel prestressing strands or rebars. Therefore, a wheel load running test was conducted on a full-scale specimen to verify the structure's fatigue characteristics (**Fig. 3**). The results showed no observable damage even under cyclic loading equivalent to 100 years on the highway with the heaviest traffic load in Japan, confirming that the deck slab is highly resistant to fatigue due to wheel loads.

Fig. 3 Wheel load running test

(3) Prototype Bridge for Safety Verification of the Entire Bridge

The design method and structural details of the non-metallic bridge were developed through a series of development processes, including those discussed in the previous sections. A 15.9-m-long prototype bridge was built on a construction access road used by large cranes and trailers and was used for two years to verify the overall safety and workability of the structure (**Fig. 4**). During its service period, the prototype bridge was monitored constantly by a monitoring system to observe the strain and displacement, tension in external cables and collect other data. Static and dynamic loading tests were also performed before and after its service life to verify the adequacy of the design and the safety of the entire structure.

The construction and monitoring of this prototype bridge enabled verification of the safety and workability of non-metallic bridges. Consequently, plans were made to put the technology into actual use as a highway bridge.

Fig. 4 Prototype non-metallic bridge

3. Construction of Bessodani Bridge

(1) Bridge Description

Fig. 5 shows a structural overview of the Bessodani Bridge, which is a 25.5-m single span non-metallic butterfly web box girder bridge[2]. The girder depth was designed to be 2.8 m to enable segments to be transported on public roads. In Japan, the transportation weight on public roads is generally restricted to within 30 tons; therefore, the standard segment was set as a 1.97-m-long full cross-section segment on a 12-segment layout. End-support segments were fabricated in three parts and transported to the site. Their two half-section segment parts were structurally integrated by tensioning aramid FRP rods in the transverse direction of the bridge. The third segments were connected in the longitudinal direction in a similar manner by tensioning aramid FRP rods. Thereafter, concrete was cast in place to fill the interiors of the end-support segments and construct the crossbeams. Clearances of 30 mm filled with ultra-low shrinkage and ultra-high-strength mortar were provided between standard segments, and the external cables were post-tensioned to integrate the structure.

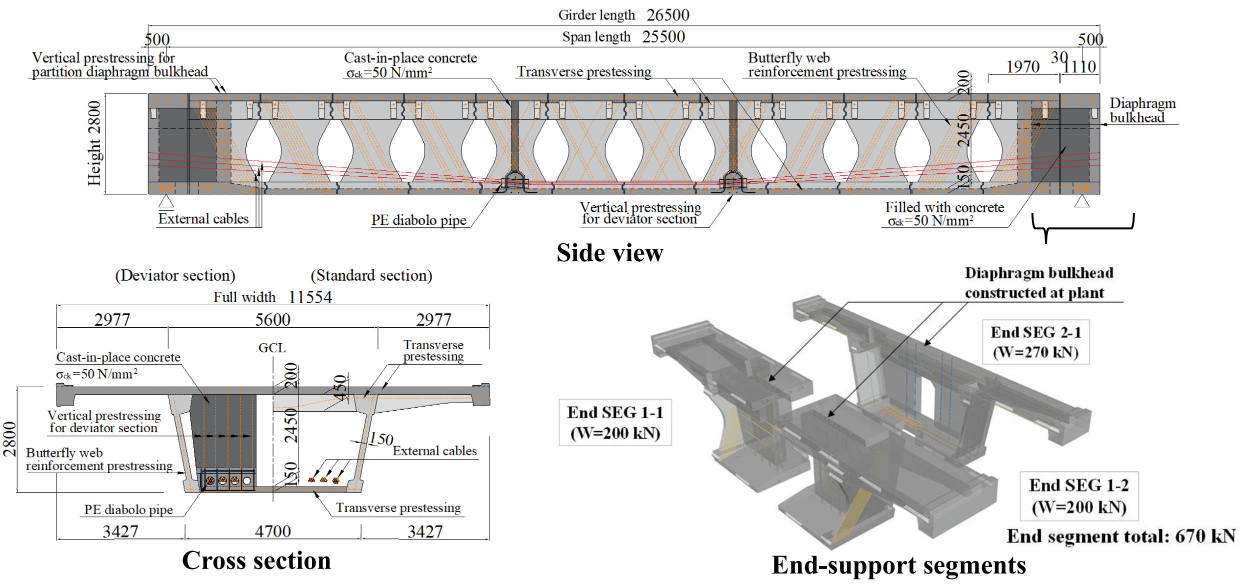

Fig. 5 Structural overview of the Bessodani Bridge

(2) Segment Fabrication Work

For this bridge, butterfly webs were first fabricated separately before the segments. This was done by arranging aramid FRP rods in a butterfly-shaped formwork mounted on a pretensioning device, prestressing them, and then pouring high-strength fiber reinforced concrete (**Fig. 6**). After concrete placement, steam curing was carried out, controlling the curing temperature and time to meet the required strength.

Segments were fabricated by installing the butterfly web panels in the formwork and pouring the concrete for the upper and lower deck slabs. The butterfly web and upper deck slab were connected using special joint keys provided at the upper part of the butterfly web panel, while the lower deck slab was connected using transverse tendons made of aramid FRP rods. Concrete for both upper and lower deck slabs was placed on the same day, and wet curing was performed for three days. After the concrete compressive strength reached the design strength, prestressing was introduced to the upper and lower deck slabs. Transverse tendons in the deck slab ribs were tensioned in the stockyard via a post-tensioning system using aramid FRP rods.

Fig. 6 Butterfly web fabrication

(3) Segment Erection Work

Segments were transported on trailers using approach routes from the highway in service and were erected using a truss falsework. Using a 220-ton crane, segments were mounted onto traveling mechanisms deployed on top of the truss falsework and moved into position by sliding from the abutment A2 side toward abutment A1 (**Fig. 7**). A device for lifting a segment without the need for through holes on the deck slab was developed and used during segment erection to eliminate a cause of deck slab deterioration. The gaps between segments were filled with ultra-low shrinkage, ultra-high-strength mortar with significantly improved shrinkage properties. This made it possible to reduce the number of cracks caused by shrinkage of the mortar filling.

Fig. 7 Segment erection

(4) External Cable Work

In total, 34 external cables were installed, with nine 7.4-mm-diameter aramid FRP rods bundled into a single cable. After tensioning the external cables, ultra-high-strength, non-shrink mortar was injected into the external cable anchorage holes at the end-support crossbeams and in the gaps between the aramid FRP rods to directly bond and anchor the rods to the

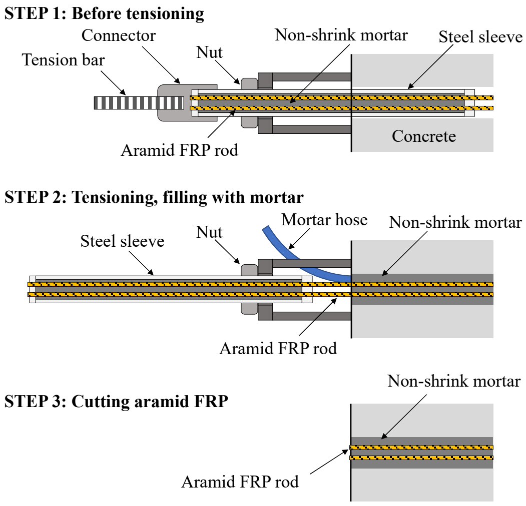

Fig. 8 Tensioning procedure for external cables

crossbeam concrete. The temporary anchorage devices used for tensioning were then removed, resulting in an aramid FRP external cable structure with no steel members (**Fig. 8**).

(5) Precast Barrier Erection Work

For this bridge, a non-metallic precast concrete barrier wall was developed that uses glass FRP rods for reinforcement as well as high-strength fiber reinforced concrete using vinylon fibers with a design strength of 80 MPa. These precast barriers were structurally connected to the deck slabs by inserting glass FRP rods sticking out from the bottom of the members into blockouts in the deck slab, and then filling the gaps with ultra-high-strength, non-shrink mortar. Collision tests simulating vehicles were conducted to verify that the structure has adequate impact resistance for use in highway bridge concrete barriers.

4. Environmental Impact

Although Bessodani Bridge involved no carbon emissions due to steel use, it involved increased carbon emissions due to the larger amount of cement used and the use of polymer in the aramid FRP rods. Taking these into account, the amount of CO_2 emissions during construction was roughly the same as that during construction of a conventional PC bridge. However,

Table-1 Lifecycle CO_2 emissions (structure only)

	Non-metallic bridge	Conventional bridge
During construction (EN15978: A1-A5)	225 t-CO_2	230 t-CO_2
During service life (including renovation) (EN15978: B1-B5)	0 t-CO_2	344 t-CO_2
Total	225 t-CO_2	574 t-CO_2

because a non-metallic bridge has no deteriorating elements, carbon emissions due to periodic repair and retrofit work are reduced, as are emissions due to maintenance work throughout its service live. Comparing CO_2 emissions over a 100-year service life, the use of a non-metallic bridge may cut emissions by roughly half (**Table-1**). This suggests that highly durable structures containing no deleterious elements can greatly help in achieving decarbonization.

5. Conclusion

Japan continues to experience both a declining birthrate and an aging population, giving rise to serious concerns about the lack of engineers for infrastructure maintenance in the future. Therefore, creating new construction systems that minimize the burden of maintenance in terms of both human resources and costs is essential. To realize a sustainable economy, it is also important to consistently provide reliable road network services with minimal traffic restrictions due to repair and retrofitting work caused by aging infrastructure. Furthermore, making bridge structures non-metallic lessens the need for maintenance, repair, and retrofitting during their service lives, thereby lowering their environmental impact throughout their lifecycle. Bessodani Bridge was recognized for its creativity and was granted Exceptional Recognition in the 2022 fib Awards for Outstanding Concrete Structures.

References

[1] Wada, Y., Fujii, Y., Ashizuka, K., Sanga, T., Fujioka, T.: *Construction of actual non-metal bridge*, Proceedings of the fib 2020 Symposium, China, Shanghai, pp.1262-1274, Nov. 2020.

[2] Matsuo, Y., Wada, Y., Fujioka, T., Nagamoto, N.: *Construction of Non-metal bridge*, Proceedings of the fib 2021 Symposium, Portugal, Lisbon, pp.163-172, Jun. 20.

概　要

別埜谷橋は，鉄筋や PC 鋼材を一切用いない「超高耐久橋梁」を世界で初めて高速道路橋へ適用した事例である。超高耐久橋梁は，従来のコンクリート道路橋が抱える経年劣化や塩害等に起因した鋼材腐食に伴う維持管理の負担増加や著しい耐久性の低下に対し，抜本的な解決策を講じることを目的として開発された。本構造ではプレキャスト部材に高強度繊維補強コンクリートを適用し，アラミド FRP ロッドを緊張材としたプレストレスにより補強している。ウェブには，主桁の作用せん断力に対して合理的に設計ができるバタフライウェブ構造を採用し，せん断補強鉄筋の配置回避と自重の軽量化を図っている。主ケーブルには，鋼製の緊張定着具を必要としないアラミド FRP ロッドを外ケーブル構造として配置し，将来における維持管理性の向上を実現している。別埜谷橋は，独自性が極めて高いプレストレストコンクリート構造であることが認められ，*2022 fib Awards* 特別賞を受賞している。