IABSE-JSCE Joint Conference on Advances in Bridge Engineering-IV, August 26-27, 2020, Dhaka, Bangladesh
Amin, Okui, Bhuiyan, Rahman (eds.) ISBN: 978-984-34-8313-3
www.iabse-bd.org

Construction of the actual non-metal bridge

Y. Wada & Y. Fujii
West Nippon Expressway, Osaka, Japan

K. Ashizuka
West Nippon Expressway, Kagawa, Japan

T. Fujioka & N. Nagamoto
Sumitomo Mitsui Construction, Tokyo, Japan

ABSTRACT: Concrete bridges, as a result of salt damage and other factors, are at risk of reduced performance due to corrosion of steel reinforcements, prestressing steel and other steel components. Maintenance becomes increasingly important and there is consequently a need to enhance the durability of concrete bridges in order to reduce future maintenance work. Considering these circumstances, the Non-metal bridge was developed and that completely eliminates the use of steel members such as steel reinforcements and prestressing steel. Aramid FRP rods were used as prestressing tendons to provide bending moment and tensile force reinforcement. To eliminate the need for shear reinforcement, high strength fiber reinforced concrete was developed and used to the proposed structure. Wheel load running tests was carried out to verify the fatigue durability against the heavy traffic load of the structure. And, a half scale girder structure was built and tested to confirm that the structure had enough resistance against shear force. After that, the actual pilot bridge was built to confirm its whole structural performance. The bridge had been used as the part of a construction road for 2 years with full-time monitoring system. This result showed that the structure had enough performance for the actual bridge and the design method was appropriate for the structure. Based on these results, the world's first Non-Metal Bridge has decided to be applied to the actual expressway. The bridge name is Besso-dani Bridge, a simple PC box girder bridge with a bridge length of 27.5 m. The bridge has a butterfly web structure to reduce its own weight and rationalize shear reinforcement. The bridge is planned to be constructed by the precast segmental method, and the bridge axis direction is only reinforcement by prestressing of aramid FRP rods. Its behavior up to failure was investigated by nonlinear analysis.

1 INTRODUCTION

Prestressed concrete (PC) bridges and other concrete structures are highly durable in common environmental conditions. However, in coastal areas with pervasive airborne salt or in mountainous areas where large amounts of antifreeze agents containing high salt concentrations are sprayed, salt damage causes corrosion of steel reinforcements and prestressing tendons, resulting in structural performance deterioration and concrete spalling due to rust jacking following rebar corrosion. Concrete structures in severe environments prone to salt damage are not maintenance-free and require proper maintenance over their service period.

Today, West Nippon Expressway Co., Ltd. (NEXCO West) manages around 3500 km of highways, which includes a large number of concrete structures that require maintenance. Moreover, maintenance costs and large-scale renovation and repair costs have been mounting as the structures age, with over 40% of bridges in operation for more than 30 years, including the Meishin Expressway. Furthermore, new construction, four-lane highway widening, and other projects are in the works.

For these reasons, along with implementing an efficient maintenance plan, we have made it a priority to use structures with greater durability and to minimize the burden of future maintenance for bridges which are located in harsh environments prone to salt damage and are scheduled for construction or reconstruction.

Under these circumstances, NEXCO West and Sumitomo Mitsui Construction have been carrying out collaborative research since 2010 with the goal of developing a highly durable bridge that does not use any steel members such as reinforcing bars and steel PC tendons, which causes deterioration. The joint research began with the development of concrete materials and involved various experiments conducted to verify the shear strength characteristics of girders, fatigue durability of deck slabs, among others, as indicated by Ogata et al. 2016a, b. Following the research, we built a pilot bridge as part of a temporary construction access road. The bridge was used for heavy vehicle traffic under full-time monitoring for two years, in order to check the overall safety of the structure as well as the adequacy of the design and construction. Based on the results, we concluded that the bridge can adequately withstand loads for actual use as a highway bridge.

This paper discusses the construction of the pilot bridge, the results of the full-time monitoring, and the design of the world's first highway bridge adopting the structure which resulted from the findings of these studies.

2 NON-METAL BRIDGE CONCEPT

The concept of a Non-metal bridge is given below.

- The main body of the bridge superstructure (including bridge railing) is constructed so that it does not use any rebars or steel tendons that may corrode.
- For the web, a butterfly web structure is adopted in order to reduce the weight of the main girder and to rationalize the reinforcing against the shear force. The butterfly web structure is a structure using butterfly-shaped panels for the web. The shear force is decomposed into compression and tension forces in the panel and behaves like a double Warren truss.
- In principle, the Non-metal bridge is made of plant-fabricated segment girders to save on labor on site.
- Since high shear strength is required for the concrete in the superstructure main body, fiber-reinforced concrete with a design strength of 80 N/mm2 is used. Aramid FRP rods are used for tendons. Also, non-tensioned glass fiber FRP rods are used in some areas to reinforce against localized stresses.

3 PILOT BRIDGE CONSTRUCTION AND MONITORING

3.1 *Construction of the Pilot Bridge*

The pilot bridge was built and used as a construction access road to verify the safety of the overall structural system and the adequacy of the design and construction comprehensively, with the ultimate goal of employing the findings of these studies to actual bridges. The pilot bridge is a portion of a temporary bridge in Phase II road construction of the Nagasaki Expressway. Figure 1 shows a schematic diagram of the pilot bridge. A brief description of the bridge is shown below.

- Effective span: 14.0 m (Bridge length: 15.9 m)
- Overall width: 6.0 m
- Structural type: Simply supported girder bridge.
- Construction method: Erection with fixed staging.

The pilot bridge is composed of eight precast segments fabricated at a precasting plant and transported on public roads. At the erection site, the segments were lifted by a 220-ton crane truck and set on the fixed staging with 30 mm distance in between segments. After all the segments were set in place, the spaces between segments were filled and joined using high-strength non-shrink mortar with a design strength of 80 N/mm2. To reduce segment weight during transport, the end segments were fabricated with hollow crossbeams at end supports, which were later filled with concrete after erection. After strength development of the non-shrink mortar and filled concrete at end-support crossbeams was confirmed, the bundled aramid FRP rods in external cables were tensioned and integrated over the entire length, and the staging was lowered to make the bridge self-supporting.

Figure 1. Schematic diagram of the pilot bridge.

3.2 *Load Test*

Static and dynamic loading tests were conducted to verify bridge safety and the adequacy of the design immediately after completion and after two years of use as the access road as indicated by Ashizuka et al. 2017. A rafter crane truck with a known vehicle weight of 50 tons was used as test load and moved over the longitudinal direction of the bridge while various strains and displacements were measured. In addition, the vehicle was dropped from a height of about 10 cm to calculate the natural frequency of the pilot bridge. The results confirmed that the strains at upper and lower deck slabs and vertical deflections at each location are generally in agreement with analytical values, and that there were no joint openings observed between segments, all of which confirm the adequacy of the design. In addition, there were no changes in behavior observed from tests immediately after completion compared to after two years of use, as shown in Figure 2.

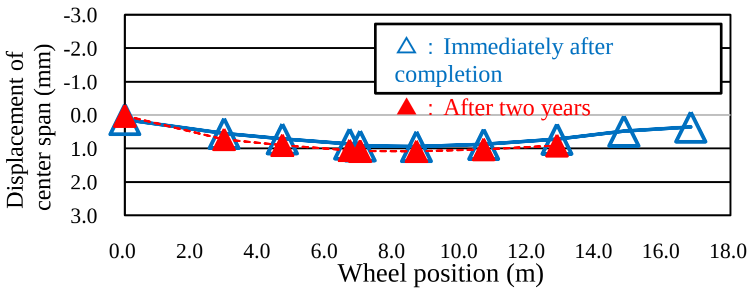

Figure 2. Loading test results.

3.3 *Full-Time Monitoring*

The pilot bridge is the first of its kind to have an external cable structure with deviators, although a previous study had used a structure with linearly arranged aramid FRP rods as indicated by Noritake et al. 1990. Thus, it was necessary to determine the tension fluctuation in the aramid FRP rods in detail. In addition, as a temporary bridge, large vehicles such as concrete mixers, trailers, and crane trucks go across the pilot bridge. Full-time monitoring was performed for two years to check the various strains developing in the segments and the opening of joints between segments and verify bridge safety.

The strains at upper and lower deck slabs, segment joint openings, and tension in the external cables were monitored using the various measuring devices shown in Figure 3. Figure 4 shows the tension fluctuation in the aramid FRP rods for the two-year period. Here, tension in the aramid FRP rods includes the tension decline due to relaxation of the material and the tension fluctuation associated with temperature change. Hence, the measured tension was corrected for tension fluctuation associated with temperature change in the main girders and aramid FRP rods to remove the effect of temperature change, and compared with the tension calculated using the relaxation formula as indicated by Asai 2012.The results confirmed that the temperature-corrected measured tension generally coincided with the calculated tension, and that the tension in the aramid FRP rods can be accurately estimated.

After the function of the bridge as a construction access road ended, a part of the precast segment was put on display at the NEXCO West Technical Training Center as a training material, which also serves as an exposure test (Photo 1).

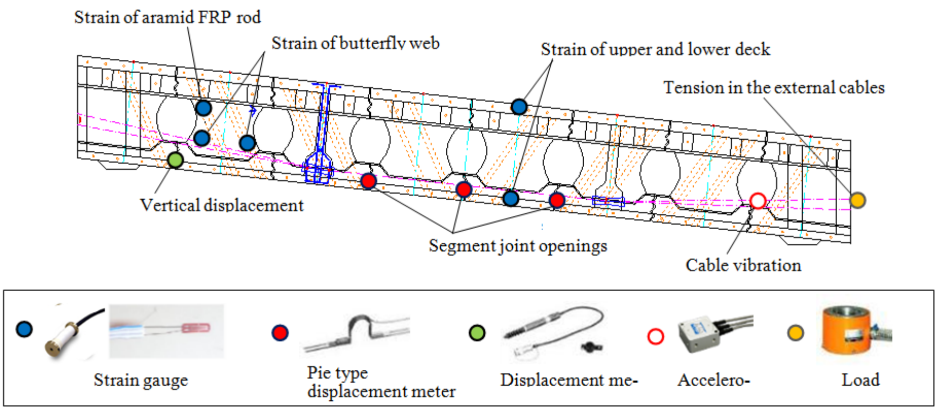

Figure 3. Full-time monitoring of the pilot bridge.

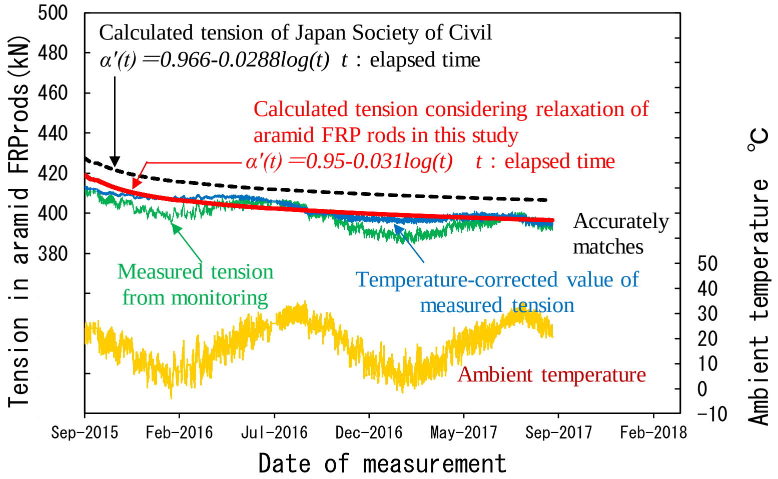

Figure 4. Tension fluctuation in the aramid FRP rods.

Photo 1. Pilot bridge segment on display.

4 ACTUAL USE AS A HIGHWAY BRIDGE

4.1 *Description of the Bridge*

Following the construction and monitoring of the pilot bridge discussed above, which provided good prospects for the application of the Non-metal bridge, we decided to put it into actual use as a highway bridge. First, we selected a bridge with a relatively short length, identified its technical issues, and studied its prospective construction cost, with the aim of gaining the knowledge and expertise for developing longer bridges in the future.

We selected the Bessodani Bridge (Figure 5), which is part of the additional lane construction project of the Tokushima Expressway. The bridge description is shown below.

- Effective span: 26.5 m (Bridge length: 27.5 m)
- Overall width: 11.55 m
- Structural type: Simply supported girder bridge
- Construction method: Erection with fixed staging

The bridge is composed of 16 precast segments fabricated at a precasting plant, which will be transported and erected on site.

4.2 *Design Approach*

The following approach was taken in designing the bridge.

- No steel members are used, including steel prestressing tendons and rebars, and stainless steel rebars.
- Axial reinforcement in the longitudinal direction of the bridge is provided by an entirely external cable structure using aramid FRP rods.
- The use of non-tensioned glass fiber FRP rods is allowed to reinforce against localized stresses on areas that cannot be reinforced using prestressing.

– Fiber-reinforced concrete with a design strength σck = 80 N/mm2 is used for the concrete in plant-fabricated segment girders.
– Butterfly web structure is adopted for the web section.

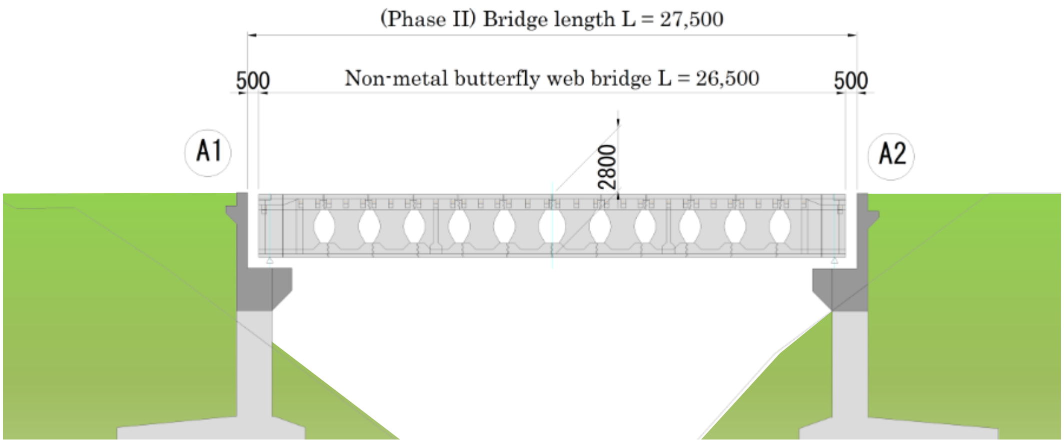

Figure 5. Elevation of the Bessodani Bridge, Tokushima Expressway.

4.3 *Design*

4.3.1 *Main structure*

For the structure, precast segments with butterfly webs are fabricated at the plant, transported on public roads, erected and joined together at the site. For tensile forces acting on the structure, aramid FRP rods are used as tensioning material instead of rebars or prestressing tendons. Since the load bearing mechanism is similar to that of conventional butterfly web box girder structures, such as Takubogawa bridge as indicated by Ashizuka et al. 2012 and Mukogawa bridge as indicated by Ashizuka et al. 2015. We used the basic design concept given in a previous paper as indicated by Nagamoto et al. 2010.

Specifically, butterfly web sections are discontinuous along the longitudinal direction of the bridge and do not contribute to the axial stiffness of the bridge. Hence, in the plane frame analysis, only the upper and lower deck slabs are considered for bending moment in the design cross section. Moreover, shear deformation in the butterfly web does not have a significant effect on the upper and lower extreme fiber stresses, which was calculated assuming that plane sections remain plane. Hence, we applied the Bernoulli-Euler beam theory to check bending stresses.

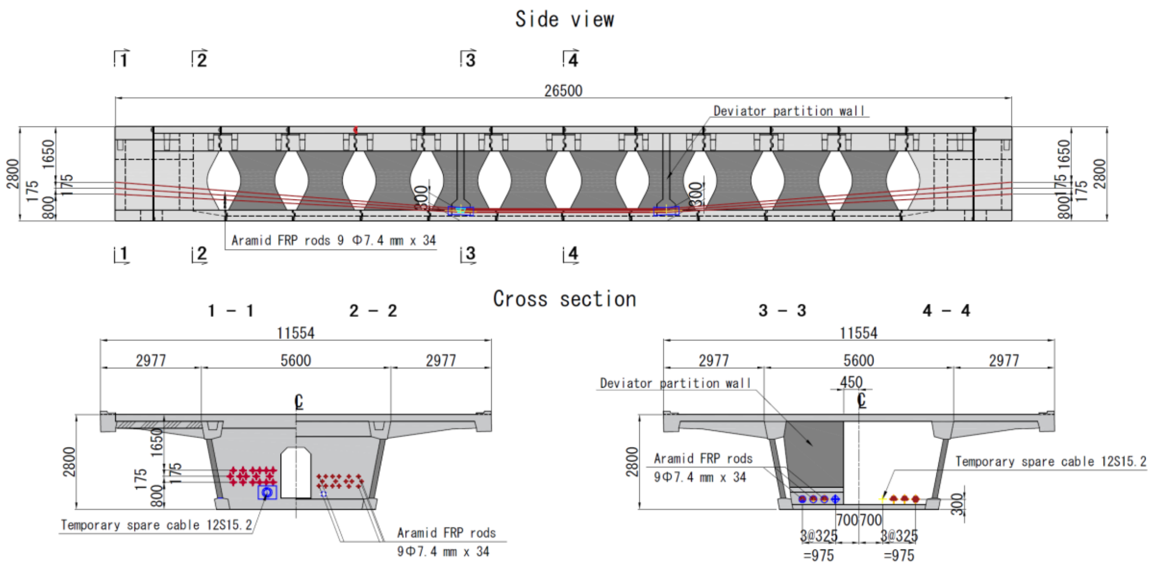

Figure 6. Layout of aramid FRP rods.

For shear forces, the upper and lower deck slabs and the butterfly web typically share the load in resisting the total shear force. However, since the shear bearing ratio is expected to change due to cracking at the upper and lower deck slabs during ultimate loading, the butterfly web section was designed to be able to resist the total shear force.

The design in the longitudinal direction used as a PC structure. Since the bridge is made of precast segments, we designed it to be fully prestressed under the design load.
Figure 6 shows a layout of the aramid FRP rods.

4.3.2 *Butterfly web panel*
The butterfly web is a panel member that joins the upper and lower deck slabs as well as a member that behaves like a double Warren truss. Therefore, the following was taken into account in the design of the panel in the in-plane direction shown in Figure 7.

- Strength verification against the total tensile force acting in the direction of tensile diagonal bracing of the truss.
- Strength verification against the total compressive force acting in the direction of compressive diagonal bracing of the truss.
- Pure shear strength verification of the narrow area against horizontal shear forces acting on the panel.

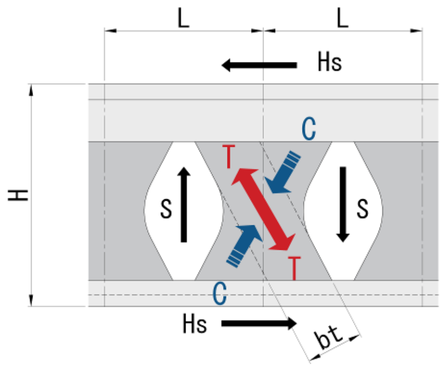

Figure 7. Acting forces in the plane of the butterfly web panel.

Next, the design in the out-of-plane direction takes into account the effect of uneven loading in the transverse direction to the bridge axis, such as live loads. The loading condition in which the swing moment is maximum is estimated using three-dimensional FEM analysis as shown in Figure 8, and the tensile stress generated in the butterfly web is calculated. The amount of aramid FRP rod reinforcement and member dimensions are then determined to resist this tensile stress.

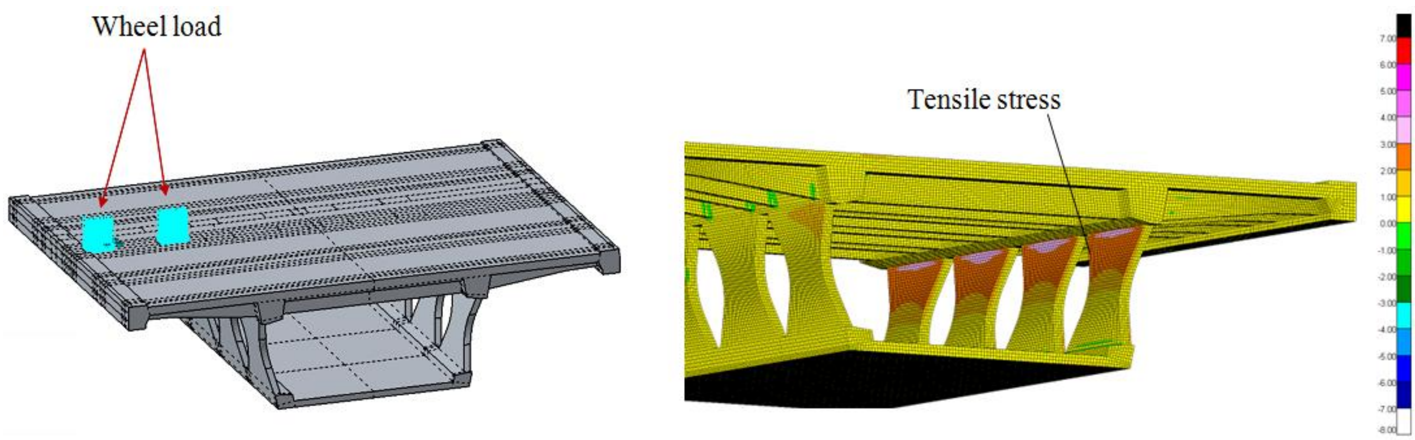

Figure 8. Forces acting out of plane forces due to swing moment.

4.3.3 *Deck slab*
The bridge has a ribbed deck slab structure to reduce the amount of reinforcement on the upper slab and reduce out-of-plane bending moment in the butterfly panel. Since complex stresses are generated in the ribbed deck slab by wheel loads, we performed the design using three-dimensional FEM analysis for a more detailed study, as shown in Figure 9.

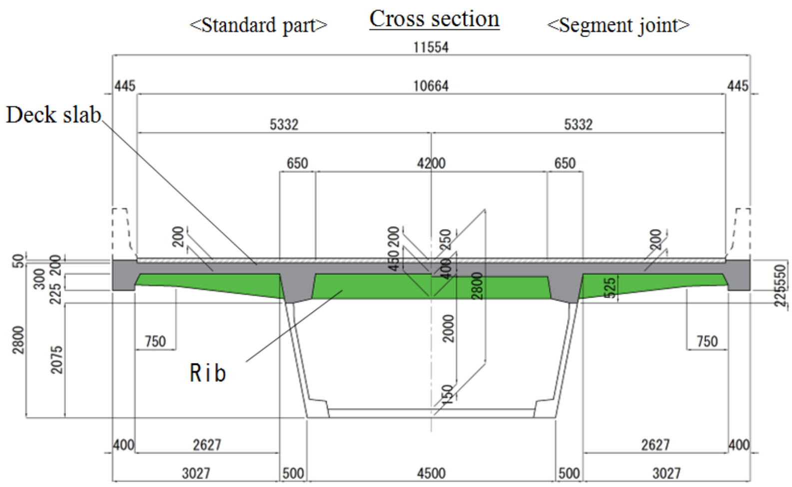

Figure 9. Modeling of the deck slab with ribs using three-dimensional FEM.

4.3.4 *End-support crossbeams*

The end-support crossbeams are subject to complex loadings, with shear forces from the main girders, support reactions, stresses due to external cable anchorage, among others. Hence, we evaluated the stress state, including localized stresses, using three-dimensional FEM analysis to determine the amount of reinforcement. The member is basically reinforced by the tensioning force in aramid FRP rods, although for localized stresses where tensioning cannot be introduced, glass fiber FRP rods are used to reinforce locally.

Figure 10 shows the analysis results at the girder end when the external cables are tensioned. Tensile forces act in the vertical direction of the crossbeam surface due to tension in the external cables. By distributing aramid FRP rods in the vertical direction of the partition wall reinforcement, a state of full prestressing is maintained immediately after introducing prestress and under dead loads.

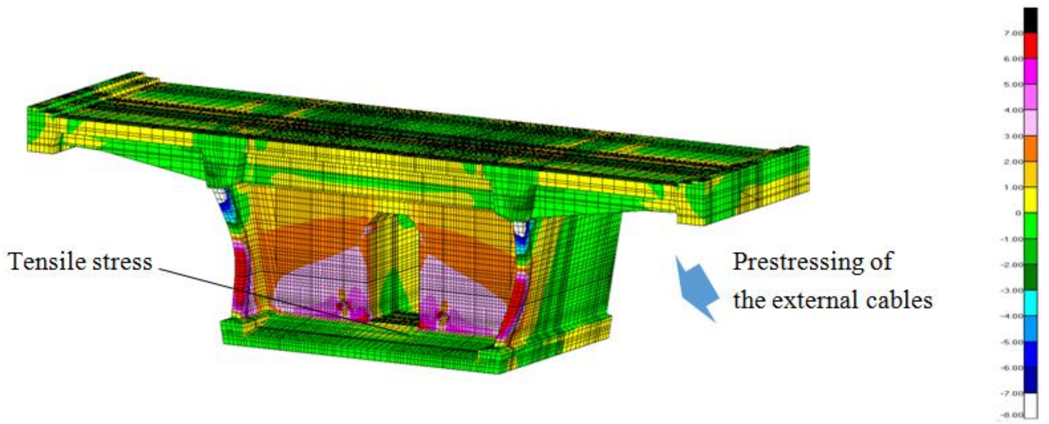

Figure 10. Analysis results for maximum principal stresses at end-support crossbeams.

4.3.5 *Bridge railing*

To make the parapet non-metallic, we developed a precast bridge railing based on the form of concrete bridge railing generally used on highways using GFRP rods instead of rebars (Figure 11). During development, a collision test was conducted using a bogie of approximately 70 kN as shown in Figure 12 and Photo 2. The test confirmed a safety level equivalent to or higher than that of a typical reinforced concrete bridge railing.

4.4 *Plant Fabrication*

Currently, the detailed design is almost complete and the fabrication of precast segments is about to commence. Photo 3 shows the fabrication work at the plant.

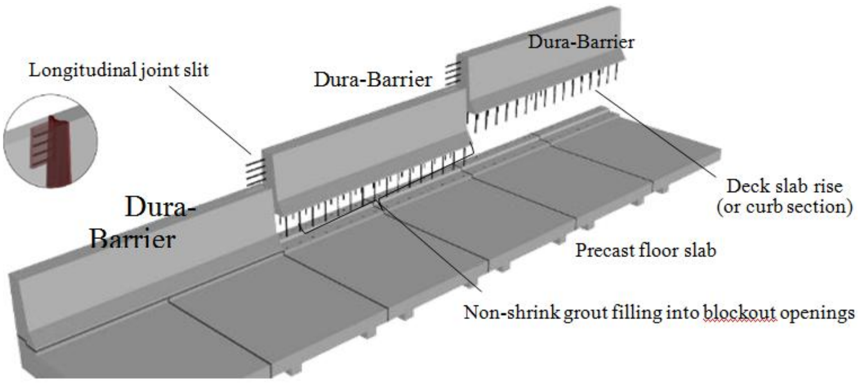

Figure 11. Developed non-metallic precast bridge parapet.

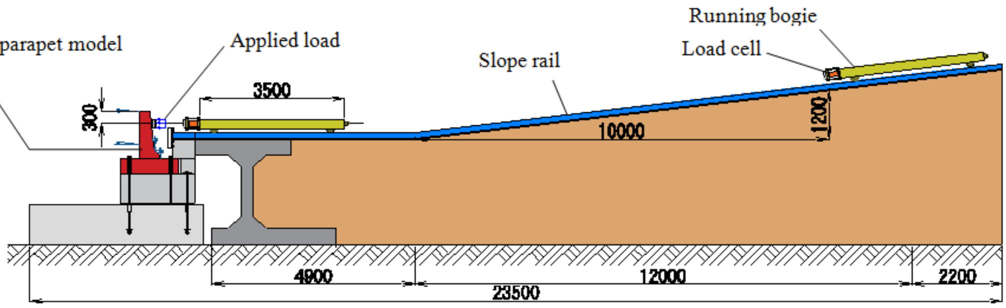

Figure 12. Diagram of the collision test.

Photo 2. Collision test.

Photo 3. Fabrication at the plant.

5 CONCLUSIONS

With the goal of greatly improving durability, the Non-metal bridge in this study is the world's first bridge developed without the use of materials that rust and with technologies that contribute significantly to reducing the burden of future maintenance.

With the rapidly worsening problems of falling birthrate and aging population in Japan, it is important to consider and reduce the burden on future generations starting from the construction stage, in order to retain or improve our current maintenance standards while coping with the diminishing labor force. This approach is required for Japan to continue developing sustainably.

As of November 2019, the detailed design of the Non-metal bridge has been completed and production of the precast segments has started in preparation for actual bridge construction. The Non-metal bridge will soon be a reality, with onsite construction scheduled to begin from early 2020.

In the future, we plan to prepare an operation and maintenance manual for Non-metal bridges, hand over the bridge conservation, and conduct post-service monitoring, with the goal of establishing and developing this technology.

We are also developing a Non-metal precast PC deck slab that uses the Non-metal bridge technology presented in this paper as indicated by Fukuda et al 2018, and plan to apply the results to future RC deck slab replacements of steel girders that have deteriorated due to fatigue and other causes.

We hope that the approach presented in this paper will prove helpful to similar technological developments in the future.

REFERENCES

Asai, H. (2012) A study on the practical application of aramid fiber tendons and reinforcement using development lengths. *Doctoral Dissertation*, Institute of Technology and Science, Tokushima University Graduate School.

Ashizuka, K., Hanada, K., Nishimura, I., & Kata, K. (2012). Design and construction of Takubogawa bridge on the higashikyushu expressway. *Bridge and Foundation Engineering*, 46(11), 5-10.

Ashizuka, K., Kurokawa, H., Morohashi, A., Matshubara, I., Mizuno, K., & Toyama, S. (2015). Design and construction of the Mukogawa bridge on the shin-meishin expressway. *Bridge and Foundation Engineering*, 49(3), 5-11.

Ashizuka, K., Fukuda, M., Nagamoto, N., & Sanga, T. (2017). Development and implementation of high-durable bridge. *Bridge and Foundation Engineering*, 51(8), 33-36.

Fukuda, M., Ashizuka, K., Karino, T., & Kasuga, A. (2018). Experimental study on fatigue durability of ultra high durable slab. *Proceedings of the fib symposium*.

Nagamoto, N., Kata, K., Asai, H., & Kasuga, A. (2010). Technical research on the new web structure using ultra high strength fiber reinforced concrete. *Journal of JSCE*, Vol. 66, No. 2, 132-146.

Noritake, K., Itai, E., Arai, H., & Mashiko, H. (1990.10). Design and construction of aramid FRP pretensioned bridge. *Proceedings of the Symposium on Prestressed Concrete Development*, 261-264.

Ogata, T., Oshiro, T., Fukuda, M., Kasuga, A., Asai, H., & Nagamoto, N. (2016a). Development and construction of non-metal bridge. *Proceedings of the fib symposium*.

Ogata, T., Oshiro, T., Nagamoto, N., & Kata, K. (2016b). Development of an ultra-high durability bridge and construction of bridge prototype. *Prestressed Concrete*, 58(2), 73-80.