Conceptual Design of Extradosed Bridge Using Butterfly Webs over the Fault Fracture Zone

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Summary
The Nakatsugawa Bridge is a triple-span extradosed PPC bridge in a steep ravine which is located between tunnels. There were several site constraints in designing the bridge. Piers and pylons shall be placed at a distance from a river and tunnels, electrical cables. In addition, fault fracture zones are widely spread under the bridge and these faults are possibility large displacement. Because of these constraints, the span distribution of the bridge became unbalanced, we have planned to extend a part of the side span into the tunnel to improve weight balance, and lightweight concrete precast panels "Butterfly Webs" were applied in the central span to improve the balance. We have selected an extradosed PPC bridge to prevent collapse and unrepairable damage in case of a large displacement at huge earthquake. The paper describes the conceptual design of extradosed bridge using butterfly webs over the fault fracture zone.

1 INTRODUCTION
The Shin-Tomei Expressway connects three major metropolitan areas - Tokyo, Nagoya, Osaka - to The Shin-Meishin Expressway. It provides logistical support for the Japanese economy as a commercial artery and as an alternate for the Tomei Expressway. The Nakatsugawa Bridge is under construction as a part of the Shin-Tomei Expressway in Kanagawa prefecture.

It's a triple-span extradosed PPC bridge over the Nakatsugawa River in a steep ravine with confirmed faults and is located between tunnels. General drawing of the outbound line bridge is shown in Figure 1 and Figure 2. According to a detailed geological survey, an extensive fault fracture zone is widely spread, and these faults are possibility large displacement. A conceptual diagram of fault displacement is shown in Figure 3. Considering these topographical and geological conditions, the bridge is designed as a triple-span extradosed PPC bridge to prevent collapse and irreparable damages. Towers and piers are located to avoid the river and fault zones which are in a slope area, this would make the side span of extremely short compared with the central span and a negative reaction force at the edge of supporting point is inevitable.

Especially, the side span of Pier 2 is extremely short in comparison with the central span, we plan to extend a part of the side span into the tunnel to reduce negative reaction force. In addition, lightweight Butterfly Webs are applied at the central span to improve the span balance. It is impossible to prevent uplift of the girder at the end of supporting point "Abutment 2" in the tunnel in case of a huge earthquake by simply improving the weight balance, so an innovative structure that prevents uplift have developed. Furthermore, a variety of concrete precast members are planned for construction, such as large Butterfly Webs and a stay cable anchorage using Precast Ribs, and Precast Form without removal for the tower, to enhance productivity.

This paper describes the conceptual design of extradosed bridge using butterfly webs over the fault fracture zone.

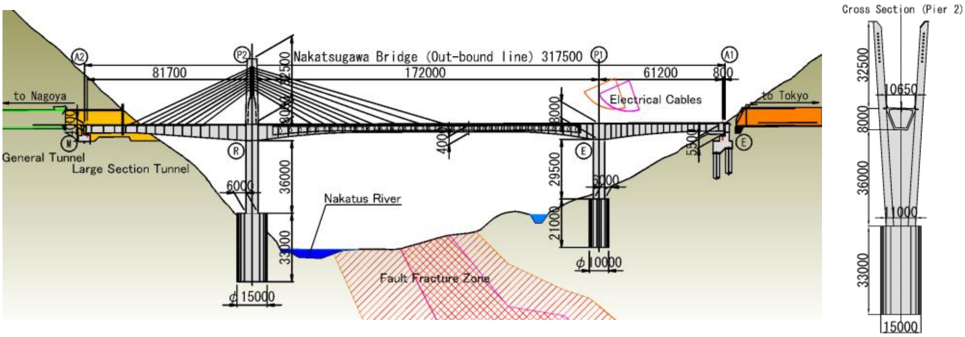


Fig. 1 General drawing of outbound line bridge (Side View)

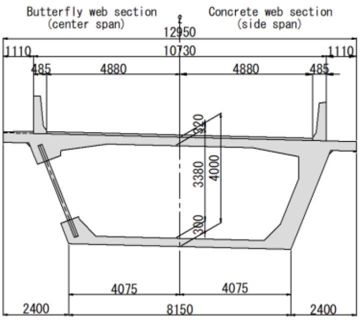


Fig.2 Cross section of the bridge

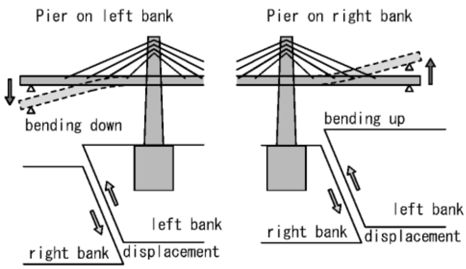


Fig.3 Conceptual diagram of fault displacement

2 CONCEPTUAL DESIGN OF BRIDGE

2.1 Bridge type

Initially, we have planned to construct a three or four span continuous prestressing box girder bridge with corrugated steel webs as shown in Figure 4, because this type of bridge was common one. The bridge is able to satisfy the specifications which is usually applied in Japan including a seismic design specification. However, it cannot prevent serious damage by a fault displacement.

A fault displacement is a particular design condition for Nakatusgawa Bridge, and by detail geological survey, the displacement is expected 3m vertically and 1.8m horizontally. So, the bridge shall be designed to prevent collapse and irreparable damages in such a condition.

Steel bridge structure was also considered as a bridge type with the flexibility to bear such a large displacement, but it would be difficult to transport and install girders on steep ravine as shown in Figure 5. Therefore, triple-span extradosed PPC bridge was selected, which this type of bridge can behave resiliently against forced vertical displacement.

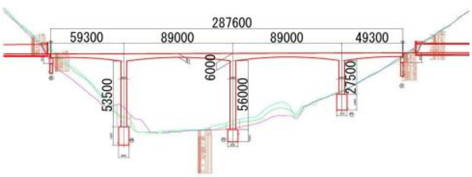


Fig.4 General drawing of box girder bridge

Fig.5 Bridge construction in steep ravine

2.2 Arrangement of piers and pylons

Pylons and piers need to be avoided a fault fracture zone, and the flow of the river could not be obstructed by piers. It was necessary to locate the piers in a position that could ensure the distance between the bottom of the deep foundation (casted in situ pile) and the fault zone.

The distance between the fault fracture zone and a bottom of the deep foundation shall be about three times diameter caisson pile width, as indicated in the SPECIFICATIONS FOR HIGHWAY BRIDGES Part IV [1]. We conducted a two-dimensional FEM analysis to confirm the distribution of ground reaction forces. As a result, we have decided that the bridge can prevent serious damage because the ground reaction force at the bottom of the foundation have reduced to about 3% in the fault fracture zone line.

2.3 Shortening of the side span length

Arrangement of piers and pylons are by these constraints, as a result, if we design the bridge as a common prestressed concrete box girder, it was necessary for the side span to be extended 45.5m into the tunnel shown in Figure 6. Also, stay cables must be placed partially in the tunnel. Consequently, as shown in Figure 7, the tunnel should be an extremely large cross-section of about 380m^2 (Normal 80m^2).

The large tunnel would be further construction period and high costs. Furthermore, because some stay cables were placed inside the tunnel, there was uncertainty about the safety and behavior of the bridge in case of a tunnel fire. So, side span shall be shorted to mitigate disaster for sustainability.

The extension of the girder length into the tunnel was designed in order to prevent negative reaction forces at the edge of supporting point, even when the bridges were exposed to “Level 2 Earthquake Ground Motion”—the largest scaled earthquake from past records in Japan [2]. Therefore, a new structure has been developed which can prevent uplift of the girder (detail are shown in chapter 5).

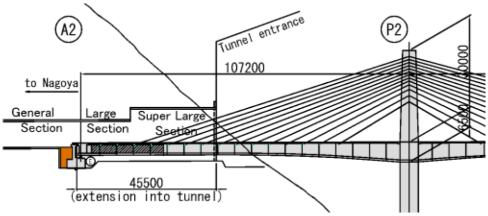


Fig.6 Extension into the tunnel (planed common bridge).

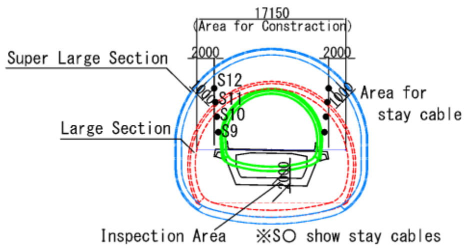


Fig.7 Comparison of tunnel section

In addition, by applying lightweight butterfly webs at the central span, the weight of the superstructure could be reduced by approximately 10% and the moment balance was improved, which enabled the extension of the girders into the tunnel to be reduced to 20m, while also avoiding the need to place stay cables inside the tunnel, thereby reducing the tunnel cross-section to approximately 250m^2.

3 DESIGN OF SUPERSTRUCTURE

3.1 Butterfly Web Bridge

“Butterfly Web Bridge” is a type of the prestressed concrete box girder bridge [3] [4]. In a Butterfly Web Bridge, the panels used as the web are cut so as to appear pinched in the center, giving a butterfly-wing shape. The 80MPa with steel fiber reinforced concrete is used for the butterfly shaped web which has a precast panel with a thickness of only 150mm. The characteristics of Butterfly Web bridge are as follows:

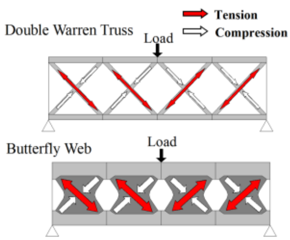


Fig.8 Behaviour of Butterfly Web Bridge

① In the Butterfly Web Bridge, the butterfly-shaped web behaves like a double warren truss (Figure 8).

② It has a structure the concrete of which resists force in the compression direction, but in the tensile direction, prestressing steels are installed for reinforcement (Figure 9).

③ The web is easily united with cast-in-situ upper and bottom slab concrete.

④ Since the Butterfly Web is not connected with each other, and has low rigidity in the bridge axis direction, prestress can be efficiently introduced into the upper and bottom slabs.

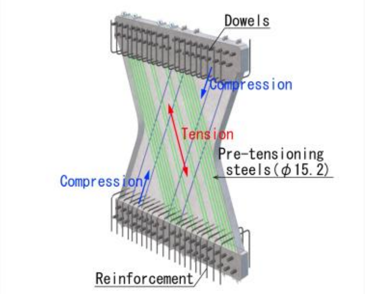


Fig.9 Structure of a Butterfly Web

⑤ High-strength fiber reinforced concrete make butterfly web so durable and make it possible to reduce web weight in comparison with a common prestressing box girder.

⑥ Inside girder is very bright, which makes inspection easy.

3.2 Development of Large Butterfly panel

Five bridges have constructed as a Butterfly Web bridge in Japan, maximum span length is 100m and girder height of these bridges are equal. On the other hand, Nakatsugawa bridge is an extradosed bridge with a maximum span length of 172m, and near the pier head, girder height is changing 8.0m to 4.0m.

The Butterfly Web near the pier head is subjected to shear force about twice as large as that of bridges before constructed (Terasako Chocho Bridge, etc. [5] [6]), so prestressing steels in the tension direction placed inside the panel must be about twice as large as that of past ones. This is the reason that we must make the Butterfly Web larger.

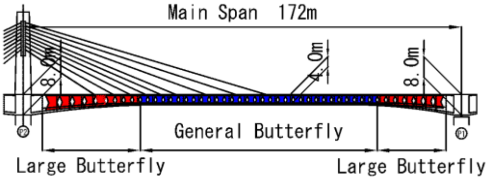


Fig.10 Arrangement of Butterfly Webs

Two types of Butterfly Web are used as shown in Figure 10. “General Butterfly Webs” are arranged where the girder height is around 4.0m, and “Large Butterfly Webs” are near the pier head.

The structure of the Large Butterfly Webs is shown in Figure 11. Due to their size, they cannot be transported from the manufacturing factory to the construction site, so they are manufactured by three parts at the factory and after transported, they are integrated in site using post-tensioned steels.

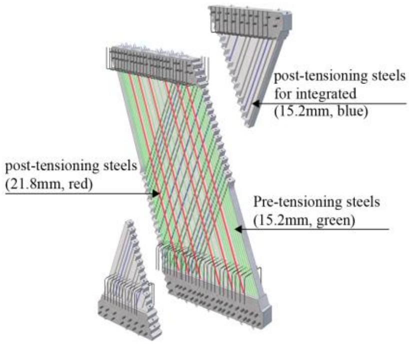


Fig.11 Structure of a Large Butterfly Web

The tensile stress caused by dead load and live load is reinforced by pre-tensioned steels installed at the factory. On the other hand, tension forces that occur in the opposite direction in case of an earthquake, are reinforced by combining post-tensioned steels and non-tensioned steels. Width of the joint between precast panels are 10mm to 20mm, and we fill non-shrink mortar into that. After filling the mortar, joints are integrated by post-tensioned steels.

3.3 Structure of stay cable anchorage of girder

Since stay cables are anchored outside the cross-section as shown in Figure 12, the span of upper slab is approximately twice as long as those of common bridges. In addition, compared to concrete web, Butterfly Web has a minimal rigidity at the cross-section. So, we concerned that slab and webs would be suffered excessive deformation caused by prestressing force of stay cable.

The Precast Rib is installed under the upper slab to solve this problem and three-dimensional linear FEM analysis was conducted to evaluate the impact of the stay cable tensioning. Figure 13 shows the deformation and tensile stress distribution when stay cables are prestressed. Upper slab is deformed by stay cables, and tensile stress area is mainly distributed in the Precast Rib. This stress can be reinforced by pre-tensioning steels inside it. Butterfly Webs are also bended, but the difference of stress tensile between inside and outside is only 3.2N/mm^2, and this difference can be reinforced by pre-tensioning steels inside the panel.

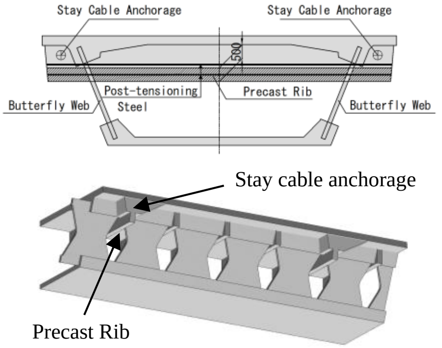


Fig.12 Stay cable anchorage of the girder

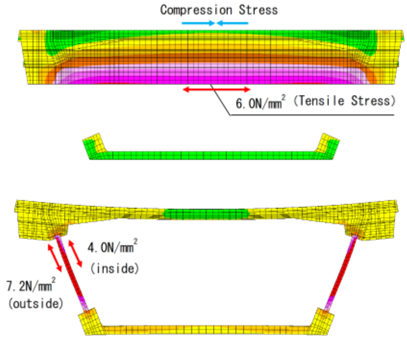


Fig.13 Results of FEM analysis

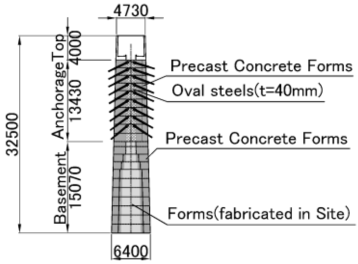
4 DESIGN OF PYLON

A half-Precast Form is applied for labor-saving and improving the quality, shown in Figure 14. This is no need to remove after casting concrete and hoop reinforcement is prefabricated, so we can reduce form fabrication in site. This has been conventionally applied for pier construction [7], we first apply it for pylon construction.

A new separate anchorage structure has been developed for stay cable anchorage, using a steel-concrete composite member. In recent years, separate anchorage structures are often applied for pylon, because easy inspection inside a pylon. However, if the structure is consisted of only concrete, a lot of reinforcement with rebars and prestressing steels are required as shown in Figure 15, which makes construction complicated and increases the weight. To solve these problems, a separate anchorage structure using oval steel as shown in Figure 16 and in Figure 17 have developed. The concept is as follows:

① Reinforcing bars and members of stay cable inside an oval steel are prefabricated off-site in a factory, in-site we can cast concrete right after installing it. This method enhances the quality of the anchorage fabrication. In addition, working at height can be reduced.

② Horizontal force caused by stay cables are resisted by being transmitted to the oval steel plate via the concrete bearing pressure and the stud dowels. We don't need lateral prestressing steels for reinforcement.



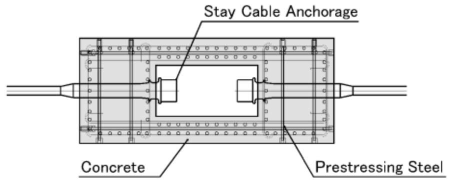


Fig.14 Layout of Precast Form for pylon

Fig.15 Anchorage consisted only by reinforced concrete.

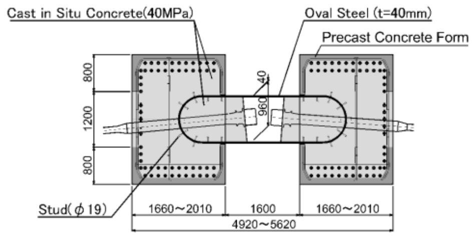


Fig.16 Concrete-steel composite anchorage

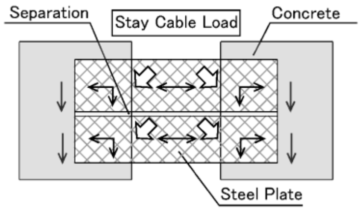


Fig.17 Transmission of stay cables tensioning

5 UPLIFT PREVENTION STRUCTURE IN TUNNEL

When the bridge is exposed to "Level 2 Earthquake Ground Motion [2]", a negative reaction force at the edge of supporting point "Abutment 2" is inevitable because of shortened side span length. So, the new structure has developed to prevent uplift of a girder as shown in Figure 18.

The negative reaction force is approximately 1,600t (15,700kN), and the structure was designed to resist this force and prevent uplift. Figure 18 shows the "Uplift Prevent Structure" to prevent uplift. This is consisted of three members: reinforced concrete blocks, ground anchors, uplift prevention cables. The reinforced concrete blocks are constructed at both sides of A2 Abutment, and those are fixed to by ground anchors. Superstructure and those are connected by cables which are non-tensioned 19 strands 12.7mm. Cables are not prestressed because they shall not prevent girder moving by temperature change.

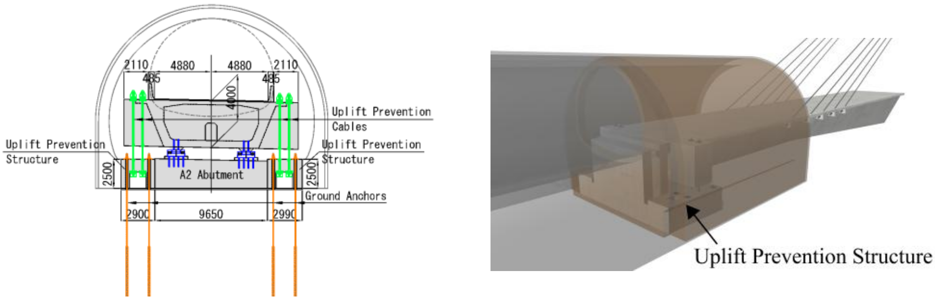


Fig.18 Uplift Prevention Structure in a tunnel

6 SEISMIC DESIGN IN CASE OF FAULT DISPLACEMENT

The response of the bridge in case of fault displacement has calculated by applying forced displacement using nonlinear static analysis. Figure 19 shows the deformation when forced displacement occurs.

Pier No.2 with the pylon would be relatively lower than Pier No.1, and tensile forces of stay cables decrease slightly as shown in Figure 20. The vertical reaction of Pier No.2 reduces and shifts it to Pier No.1. The response rotation angle of the bottom of piers is about the same as that of Level 2 earthquake, and the response curvature of the main tower is smaller.

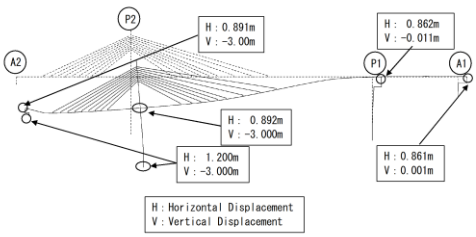


Fig.19 Deformation in case of fault displacement

The superstructure is most affected by the fault displacement. A response curvature near the central span greatly exceeds that of the Level 2 Earthquake [2]. The allowable curvature of the superstructure was set at a curvature equivalent to that a strain of reinforcing bar get to three times yield stress, as the limit state for ensuring repairability. Prestressing steels have been increased in the central span, because we had to reinforce the girder to satisfy this limit value. Figure 21 shows the results of the analysis after reinforcement. We have reduced the curvature almost equal to yield strain of reinforcing bar.

We confirm that the bridge is not collapse in case of fault displacement, and irreparable damage can be avoided by adding prestressing steels and upgrading reinforcing bars.

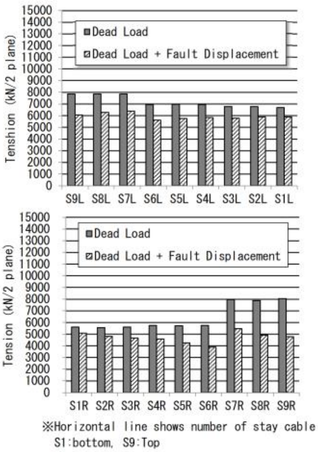


Fig.20 Tension of stay cables.

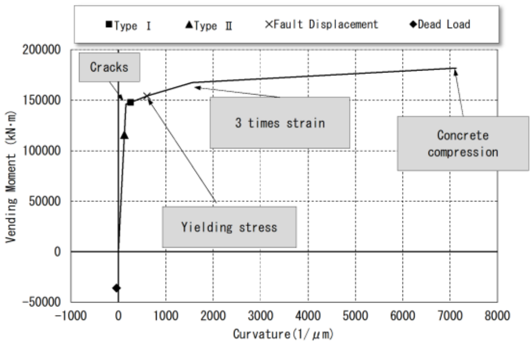


Fig.21 Relationship vending moment and response curvature.

7 CONCLUSIONS

We have described the conceptual design of extradosed bridge using butterfly webs over the fault fracture zone. Because of several site constraints, the span distribution of the bridge became unbalanced, and bridge type was limited by site situation and possibility of large fault displacement. To solve these problems, we have developed new concept and structures, such as Large Butterfly Webs and Uplift Prevention Structure. The results of this paper can be summarized as follows:

① Considering these topographical and geological conditions, the bridge is designed as a triple-span extradosed bridge to prevent collapse and irreparable damages in the event of a fault displacement.

② Piers and pylons are arranged to keep the safe distance to the fault fracture zone.

③ Applying lightweight Butterfly Webs and Uplift Prevention Structure enables the extension of the girder into the tunnel to be reduced to 20m.

④ Precast Ribs can be a rational anchorage for stay cables.

⑤ Bridge collapse and irreparable damages can be avoided by adding prestressing steels and upgrading the reinforcing bars even in case of fault displacement.

⑥ Precast Form and Oval Steel Anchorage improve quality and productivity of pylon construction.

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