Extradosed Bridge with High-Performance Concrete and Y-Shaped Pylon
— Yumekake Bridge —

高強度コンクリートを用いた Y 字形主塔を有するエクストラドーズド橋
— 夢翔大橋 —


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Synopsis
The Yumekake Bridge is an extradosed bridge over the Kumano River in a steep ravine located near the UNESCO World Heritage Site of Sacred Sites and Pilgrimage Routes in the Kii Mountain Range (**Fig.1**)[1]. This bridge is the nation's first extradosed bridge with high-strength and self-compacting cast-in-place concrete having a specified compressive strength of 60 MPa (cylinder strength) for the pylon and the box girder. The high-strength materials are also employed for the piers. Super high damping bearings are adopted to absorb seismic energy to obtain seismic performance against large scale strong earthquake.
The Y-shaped pylon secures clearance between stay cables and structural gauge of curved road alignment with elegance.
This solution ensured seismic safety with structural slenderness that led to mitigate environmental impact.

Fig.1 Yumekake Bridge

Structural Data
*Structure:*3-span continuous extradosed bridge
Bridge Length: 290.0 m
Span: 42.250 m + 127.000 m + 118.900 m
Width: 11.400-14.442 m
Pylon Height: 25.0 00 m (*pier height*: 50.500 m)
Owner: Government of Nara Prefecture
Designer: Chodai Co., Lid.
Contractor: Joint Venture of The Zenitaka Corporation & Showa Concrete Industry Co., Ltd.
Construction Period: Mar. 2007 – Mar. 2010
Location: Gojo City, Nara Prefecture, Japan

1. Introduction
The Yumekake Bridge was constructed as a part of Tsujidoh Bypass in Nara Prefecture; Tsujidoh Bypass of the National Highway No. 168 is a north-south running artery to serve as the core of regional revitalisation of Kii Peninsula. Constructed as a part of Tsujidoh Bypass, the bridge comprises two-span continuous prestressed concrete rigid frame box girder bridge and three-span continuous extradosed prestressed concrete rigid frame box girder bridge which spans the Kumano River (**Fig.2**).
For the latter structure, (between sections P2 to A2), advanced technology was applied; high strength and self-compacting concrete with a specified compressive strength of 60 MPa (cylinder strength) using normal cement for the pylon and the girder, whereas high strength rebar grade SD490 was employed for the longitudinal rebar of the piers and the pylon.

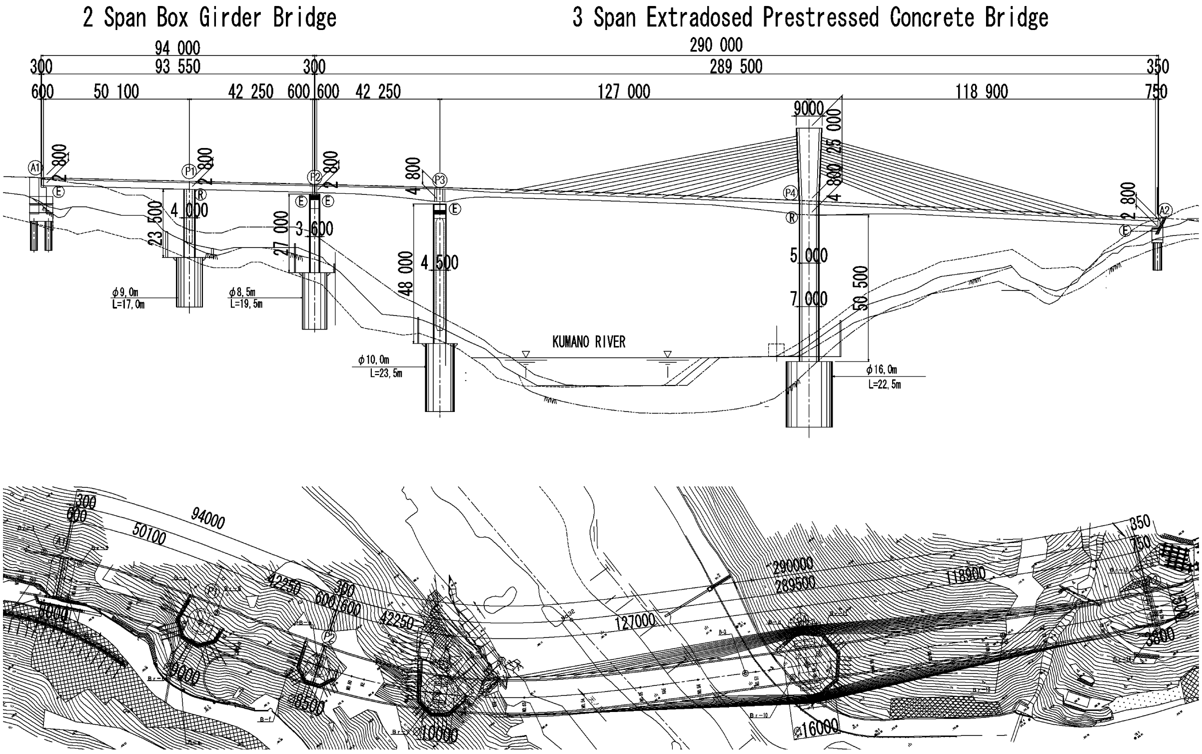

Fig.2 Elevation and plan of Yumekake Bridge (Units: mm)

2. Design

(1) General Description of the Bridge

The bridge location required to minimise the foundations to mitigate environmental impact around the Kumano River and to avoid any interference with the existing highway near the P4 pier. The extradosed bridge with high-strength material solution enabled compact piers, foundations and lightweight superstructure. The solution is particularly effective in regions where seismic load is dominant for dimensioning of piers and foundations as in Japan.

In addition, the flexibility of the structure gives low seismic response because of the effect of long natural period (longitudinal first bending mode: T = 1.97 s, transverse first bending mode: T = 1.95 s).

Seismic design was conducted taking into account the dynamic behaviour with the curved alignment, isolation bearings and influence of ductility.

(2) Structural Characteristics

As described, the bridge employed high-strength materials. This gives prominent slenderness in comparison to conventional extradosed bridges. The structural data of major extradosed bridges in Japan are shown in **Table-1**. The ratio of depth/converted span length of the bridge (H_s/L) is *ca.* 1/80, whereas the values of general extradosed prestressed concrete bridges are *ca.* 1/60.

(3) Structural Design

1) Foundations

Pier shaft foundations (caisson-type pile foundations)

Table 1 Comparison of structural properties of major extradosed bridges

	Pylon Height	Converted Span	Depth at Pier Head	Standard Depth	Pylon/ Span	Depth/ Span	Stress Amplitude	Load Share Ratio	Safety Factor	Concrete Strength
	H_t	L*1	H_P	H_S	H_t/L	Hs/L	σ_a	γ_s	F_s	f'_{ck}
	m	m	m	m	–	–	MPa	–	–	MPa
Yumekake Bridge	25.0	221.3	4.8	2.8	1 : 8.9	1 : 79.0	41	19.7%	1.67	60
Tokunoyama-Hattoku Bridge	22.5	220.0	6.5	3.5	1 : 9.8	1 : 62.9	55	25.7%	1.67	50
Sannohe-Bokyo Bridge	25.0	200.0	6.5	3.5	1 : 8.0	1 : 57.1	47	25.3%	1.67	40
Tsukuhara Bridge	16.0	180.0	5.5	3.0	1 : 11.3	1 : 60.0	36	22.0%	1.67	40
Shoyoh Bridge*2	22.1	180.0	5.6	3.3	1 : 8.1	1 : 54.5	105	61.0%	2.50	40

*1 Converted span length "L" is 1.8 multiplied span length for single pylon bridge to convert correspondent multi-pylon bridges.

*2 Shoyoh Bridge is bearing supported bridge, whereas the others are continuous rigid frame bridges.

*3 Load share ratio is defined as the ratio of the sum of vertical component of stay cable force for uniformly distributed vertical loads.

*4 Stay cable safety factor is defined as the ratio of stay cable tension to tensile strength in serviceability limit state.

were adopted for all the piers because of the steep geometric and geological reasons around the Kumano River. The dimension of the pier shaft foundation of P4 is ϕ16.0 m (diameter) × 22.5 m (depth) determined by the seismic design for large scale strong earthquake (hereinafter referred to as "Level 2 earthquake").

2) Piers

Generally, concrete with a specified compressive strength of 30 MPa and grade SD345 rebar (yield strength $f_y = 345$ MPa) are used for piers in Japan; however, the geometric condition across the Kumano River and existing highway required employing of high-strength materials to downsize the dimension of the substructures including foundations.

The piers were designed with concrete having a specified compressive strength of 40 MPa, grade SD490 ($f_y = 490$ MPa) longitudinal rebar and grade SD345 confinement rebar. The cross-section areas of the pier and foundation of P4 are decreased by 28.0% and 16.4% respectively (**Fig.3**). That resulted in 7% of cost reduction including excavation.

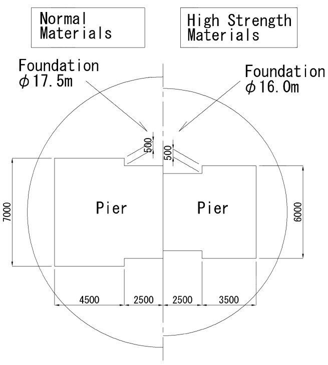

Fig.3 Comparison of P4 cross section (Units: mm)

3) Pylon

The pylon was designed with concrete having a specified compressive strength of 60 MPa, grade SD490 longitudinal rebar and grade SD345 confinement rebar for high level compressive stress by the vertical component of stay cable force and the bending moment under seismic load. A Y-shaped inclined pylon was adopted to secure clearance between the stay cables and the structural gauge of the curved road alignment (**Fig.4**). The inclination of the pylon counterbalances the bending moment originating from the transverse component of stay cable force with the bending moments originating from the vertical component of stay cable force and self-weight of the pylon.

Saddle solutions are often applied to stay cable layout in the pylons of the extradosed bridges; however, the asymmetric and intricate forms of the saddles with individually different stay cable directions result in an increase in the fabrication cost for this bridge. Besides, a steel anchor box solution allows easier maintenance than saddle solution.

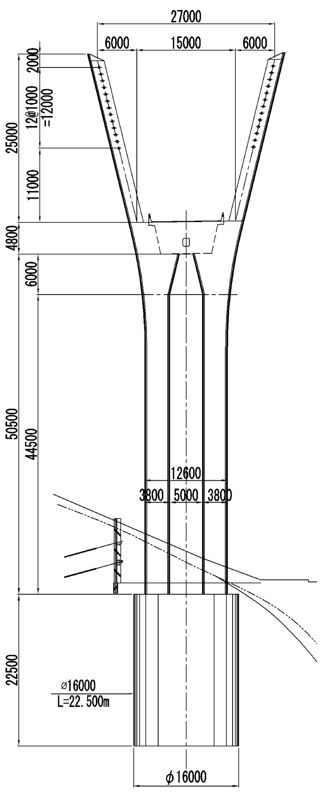

Fig.4 P4 front elevation (Units: mm)

Hence, the steel anchor box solution was adopted for its cost and maintenance friendly aspects. The stay cables were anchored in the anchor boxes embedded in the pylon. The anchor boxes were divided into 1.0 m high segments, the height of which is the same as the spacing of the stay cables for their constructionability.

(4) Seismic Design

The seismic design was conducted with three-dimensional non-linear dynamic analysis for Level 2 earthquake motions that include ocean inter-plate earthquake motions and inland epicentral earthquake motions. The peak ground acceleration of the ocean inter-plate earthquake is 322.7 gal, and that of inland epicentral earthquake is 812.0 gal. The ocean inter-plate earthquake is dominant event for this bridge because of its long natural period.

Super-high damping rubber bearings, the damping properties of which are higher than those of conventional rubber isolation bearings by *ca.* 20%, were employed to decrease the seismic response. They were adopted, except at P4 pier that was rigidly articulated with the box girder.

Although high-strength materials are effective to obtain higher load resistance than normal materials, they decrease the ductility of the structure compared with normal materials. Hence, the ductility factors should be limited than those of structures made of normal materials. The safety factors for the plasticity ratio limits were taken as twice that of normal structures in this bridge; the values were taken as 6.0 for ocean inter-plate earthquake motions and as 3.0 for inland epicentral earthquake motions considering the repetition of the strong earthquake motions and frequency of event occurrence.

3. Construction

(1) High Strength and Self-Compacting Concrete

Since high strength concrete with a specified compressive strength of 60 MPa has high viscosity and congested rebar prevents from easy compaction of concrete, self-compacting concrete was employed to ease sufficient compaction for the box girder and the pylon, whereas normal concrete was applied to the concrete of the piers and the box girder between A1 and P2 that has a specified compressive strength of 40 MPa. The slump flow and other fresh concrete properties including time-dependent stability are important for secure construction. The slump flow of the concrete was specified as 600mm with tolerance of ± 50mm, and besides, flow time to achieve the specified slump flow with the range of 5-20 seconds to check the segregation.

Time dependent variance of slump flow was also tested in trial mixing. Little variance of slump flow was observed after sixty minutes from the mixing. After ninety minutes from the mixing, the fresh concrete properties were also in good condition. With regard to the results of the trial mixing and fresh concrete tests, concreting was planned and carried out within 60 minutes from the mixing in actual construction.

(2) Erection of box girder

The bridge was constructed by balanced cantilever erection with overhead form traveller (**Fig.5**). The erection procedure of the superstructure is shown in **Fig.6**. The traveller on P4 cantilever was dismantled and removed at the forefront of the cantilever without returning to the pylon. The girder erected from P4 by travellers was symmetrically divided in 35 segments, whereas the girder erected from P3 by travellers was asymmetrically divided in 9 (P2 side) and 4 (P4 side) segments.

(3) Pylon

As the horizontal force of the stay cables are designed exclusively to load the anchor boxes to avoid cracking in the concrete of the pylon, the anchor boxes were wrapped with concrete after the stressing of each stay cable. Thus, the concrete of the pylon was stepwisely cast along with the stay cable erection and stressing by 1.0 m segments in height that correspond to the height of a individual anchor box segments.

(4) Stay cables

Multiple strand cable system ($27 \times \phi 15.2$) with factory applied multiple layer protection has been adopted to the stay cables for its constructionability including non-grouting merit and reliable durability.
The stress limit of the stay cables in the serviceability limit state is specified as 60% of the ultimate tensile strength considering the variable stress amplitude for fatigue, whereas it is limited to yield strength under Level 2 earthquake motions.

4. Conclusions

Slenderness was achieved for the piers, the pylon and the girder also in spite of the high-risk seismic zone as Japan. High-strength materials give not only slenderness and lighter weight but also load resistance and seismic performance, because the slender and elegant form of the structure greatly improves seismic response compared with normal materials. Self-compacting concrete was employed for the pylon and the box girder, the specified compressive strength of which was 60 MPa. It eased sufficient compaction in thin and crowded rebar members. In addition, high-strength materials also give highly durable performance besides the above described benefits.
However, appropriate design and construction considering the differences in properties from normal materials as described on the ductility and fresh concrete properties are essential to obtain effectively the benefits of high-strength materials.

Fig.5 Cantilever erection

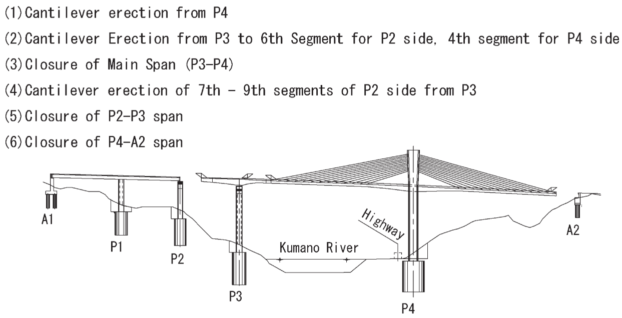

Fig.6 Erection procedure

References

[1] Akiyama, H., Nakayama, M., Kayanoki, H.: *Extradosed Prestressed Concrete Bridge with High- Strength Concrete, Japan - Yumekake Bridge*, Structural Engineering International, Vol.21, No.3, IABSE, Zurich, pp.366-371, Aug. 2011.
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概 要

夢翔大橋は，国道168号線辻堂バイパス整備事業の一環として建設された一級河川熊野川を渡河する PC2径間連続箱桁橋および PC3径間連続エクストラドーズドラーメン箱桁橋からなる橋梁群である。このうち，PC3径間連続エクストラドーズドラーメン箱桁橋区間（P2～ A2）では，主桁および主塔に設計基準強度60MPa の高強度コンクリート，橋脚躯体に設計基準強度40MPa の高強度コンクリート，橋脚・主塔の主鉄筋に高強度鉄筋 SD490，曲線橋における斜材と建築限界との離隔確保のために採用した Y 字形主塔および鋼殻を用いた主塔部斜材定着構造など特色ある技術を採用した。

また，主桁に設計基準強度60MPa の高強度場所打ちコンクリートを用いた PC 箱桁断面を有するエクストラドーズド橋としてはわが国初の試みである。