Railways and Bridges 2

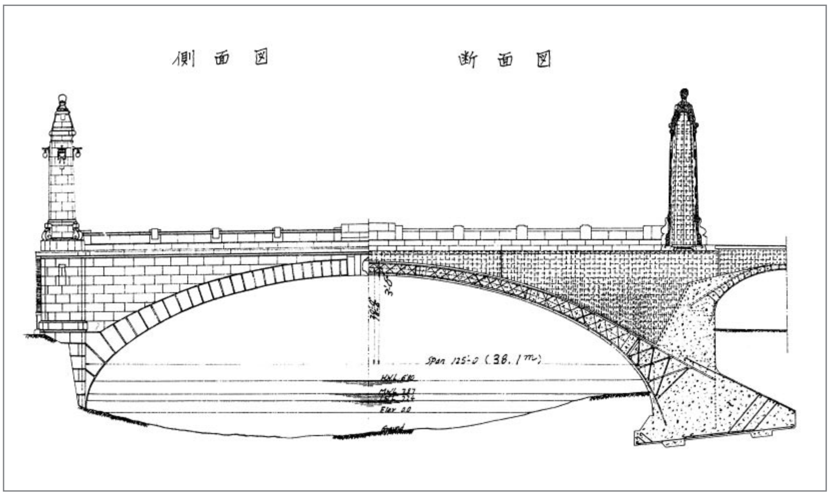
Junichi Konishi

Concrete Construction

Started with small arch culverts

Reinforced concrete construction was introduced to Japan during the first part of the 20th century. The first reinforced concrete railway bridges started with arch culverts underneath embankments. The Shimadagawa Bridge completed in 1907 (San'in main line, Shimane Prefecture) was the first and it was small with a span of 1.83 m and an axial length of 10.67 m. Several small concrete arches were constructed with a span of less than 6.7 m through 1912 but since there were no design and construction standards, Muneharu Okodo (1877-1960), who had returned from studying in Europe, prepared the first draft of *Specifications for Design and Construction of Reinforced Concrete Structures*. Based on this, *Instructions for Design of Reinforced Concrete Bridges* was published thereafter in 1914. Furthermore, *Standard Drawings of Reinforced Concrete Half-egg-shaped Arches*, *Standard Drawings of Reinforced Concrete Semi-circular Arches*, and *Standard Drawings of Reinforced Concrete Box Culverts* were published one-by-one from 1916 to 1917. Finally, standard designs and drawings for bridge abutments, bridge piers, well foundations etc., were established from 1917 to 1920; standards for construction and other civil engineering-related specifications were established in 1917, so systems for designing and constructing based on concrete and reinforced concrete (replacing brick and stone) and the application scope centred around small bridges grew gradually.

Shimadagawa Bridge (San'in Line, Shimane Pref.) (Author)



Sotobori Arch Bridge (Tohoku Line, Tokyo) (History of Railway Engineering Development Vol. 2)

Large arch bridge designed by two engineers

In 1919, the Sotobori Arch Bridge with a span of 38.1 m, which was revolutionary at the time, appeared on the Tokyo Metropolitan Elevated Line. It was designed by Dr Mikishi Abe (1883-1905) of the Railway Agency and is a Melan-type reinforced concrete arch. The seven-centred circular arch approximates the shape of pressure lines generated by weight. It is just north of the magnificent red-brick Tokyo Station so the surface was covered by stone to make it look like a stone arch bridge and it has four very large main pillars. The keystone has a relief of a driving wheel and the bridge has extraordinary focus on railway bridge design. It is still in use but is not treated as a famous bridge, due to the metropolitan expressway crossing over the top and the loss of main pillars caused by track expansion etc.

After completing the Sotobori Arch Bridge, Dr Abe retired from the Railway Agency, opened the Mikishi Abe Office and designed many superb reinforced concrete structures. For railways, he designed two reinforced concrete arch bridges for the Hankyu Kobe Line with a span of 40.0 m in 1936 and contributed to the widespread use of urban railway reinforced concrete rigid-frame viaducts.

In 1925, a reinforced concrete filled spandrel arch bridge with a span of 32.9 m was built where an elevated railway track crosses the Kanda River between Tokyo and Ueno. The design was by Muneharu Okodo of the Government Railways. It was a normal reinforced concrete structure that used steel rods and a transformed catenary was used as the arch axis line. This shape matches the arch axial lines with the arch pressure lines generated by loads on the top surface of the arch and is considered ideal for flat low arches compared to span. Many large reinforced concrete arches built during the 1930s and thereafter use a transformed catenary as the arch axial line.

Mr Okodo made a great contribution to advancing reinforced concrete technology, playing a central role in writing *Reinforced Concrete Standards and Specifications* published by the Japan Society of Civil Engineers. He retired from the Government Railways in 1931, becoming a professor at the Imperial University of Tokyo and 25th President of the Japan Society of Civil Engineers in 1937.

Large span arch bridges during steel shortages

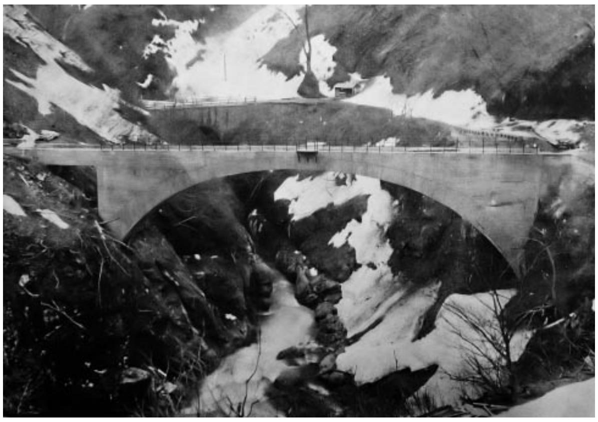
Due to difficulties in obtaining steel because of the war in China from 1935, many bridges for local lines were built using reinforced concrete in place of steel girders Those with a span of 30 m or more used an open-spandrel arch, ultimately achieving spans of 45 m. In addition to single-span bridges, multi-span bridges were also constructed. While never actually built, there are completed drawings for a reinforced concrete arch with a span of 102 m for the No. 3 Tadamigawa Bridge on the Tadami Line. The reinforced concrete arch bridges with a span of 30 m or more constructed prior to 1941 are listed in Table 1.

Kandagawa Arch Bridge (Tohoku Line, Tokyo) (Author)

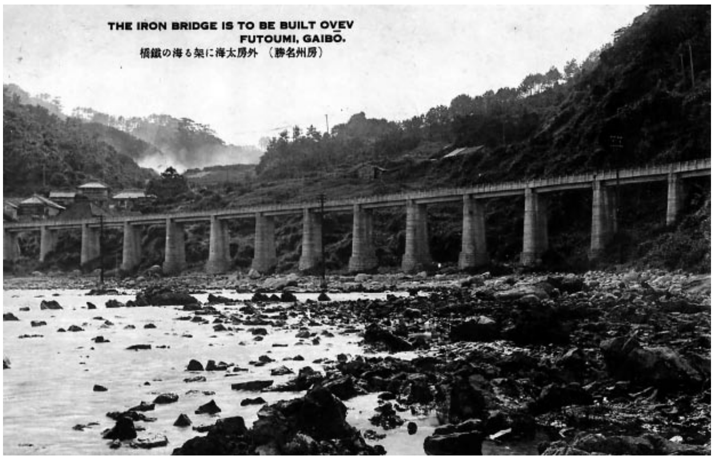
Table 1 Reinforced Concrete Arches before 1941 (span larger than 30 m)

Name	Railway Line	Place	Span (m)	Spandrel	Const. Year
Sotobori	Tohoku	Tokyo	38.1	filled	1918
Kanda-gawa	Tohoku	Tokyo	32.9	filled	1925
Megane	Yonesaka	Yamagata	34.0	filled	1934
No. 3 Otobuke	Shihoro †	Hokkaido	32.0	filled	1936
Nada	Hankyu-Kobe	Hyogo	40.0	filled	1936
Harada	Hankyu-Kobe	Hyogo	40.0	filled	1936
No. 4 Hiraishi-gawa	Tadami	Niigata	40.0	filled	1937
Tsunanose	Hinokage †	Miyazaki	45.0	open	1937
Motodani-gawa	Dosan	Kochi	35.0	open	1937
Shinkai	Dosan	Kochi	40.0	open	1938
Funahira	Dosan	Kochi	40.0	open	1938
Otani-gawa	Tadami	Fukushima	45.0	open	1939
Otanba-gawa	Hikawa †	Tokyo	45.0	open	1941

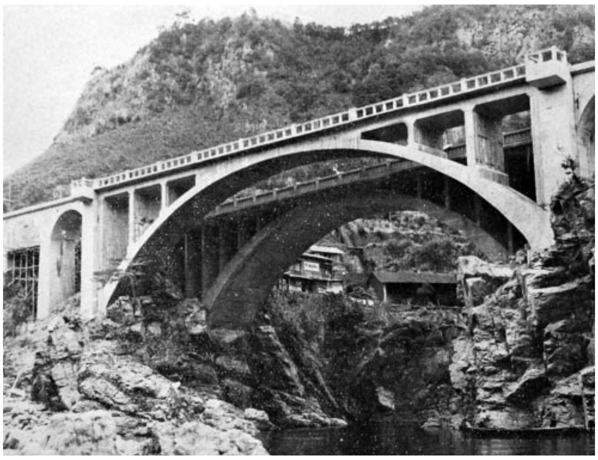
†: line closed



Megane Arch Bridge (Yonesaka Line, Yamagata Pref.)
(Civil Engineering, 1935)



Yamobe Bridge (on coastal Uchibo Line, Chiba Pref.) (Shigeru Onoda)



Tsunanose Arch Bridge (Takachiho Railway, Miyazaki Pref.)
(Civil Engineering, December 1936)

Sogogawa Bridge (on coastal San'in Line, Yamaguchi Pref.) (Author)

The Megane Arch Bridge on the Yonesaka Line is a filled-spandrel arch with a span of 34.0 m. It is a Melan type and the arch shape is a transformed catenary. The open-spandrel arch Tsunanose Bridge on the Hinokage Line (Takachiho Railway) had the longest span prior to 1941 at 45.0 m.

Girder bridges

The beam takes straightforward advantage of the characteristics of reinforced concrete in girder, rigid-frame, and slab-girder bridges.

The first fully fledged reinforced concrete railway girder bridge is the Yamome Bridge (Uchibo Line, Chiba Prefecture) completed in 1920. Since the line follows the coast, it was decided to use reinforced concrete and a row of 16 T-shaped girders made up of two 9.14-m long T-shaped beams. This bridge is still in use and reinforced concrete girders were used for many bridges on local lines thereafter.

Viaducts

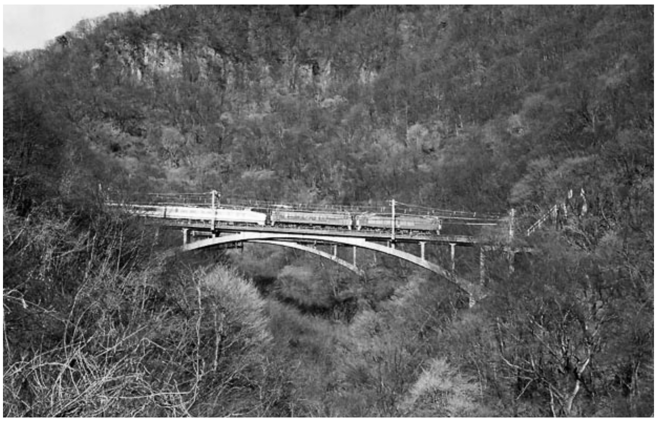
Elevated railways are now common in many rural cities as well as large metropolises, but the first elevated railway was planned in 1889 for the Shimbashi–Ueno section of the Tokyo Metropolitan Elevated Line. However, construction was delayed and the viaduct built mainly of brick arches in the south section of Tokyo Station was completed in 1909.

The Tokyo–Manseibashi section completed in 1919 used a girder structure and rigid frame structure as well as reinforced concrete arch with brick exterior.

A reinforced concrete rigid frame structure was used throughout for the elevated section between Tokyo and Ueno completed in 1925. In Tokyo and Kanagawa, many elevated lines of both government and private railways, such as the Ochanomizu–Ryogoku section of the Sobu main line were constructed in reinforced concrete. Around Osaka and Kobe, following the completion of the Tenjinbashi-suji Viaduct on Hankyu Railway's Senri Line in 1925, elevated railways were constructed one after another by government and private railways. Excluding over-road bridges, most structures used reinforced concrete rigid frame construction.

A well-known reinforced concrete rigid frame bridge not in an urban area is the Sogogawa Bridge on the San'in main line along the Japan Sea coast, It is a two-tier rigid frame bridge for a single-track railway and has a height of 11.6 m

Intermediate support of the three-span continuous truss of Saigawa Bridge (Author)



Abandoned Usuigawa Bridge with max. span of 70 m as RC railway arch bridge on 66.7‰ grade (Author)

Three-span continuous half through plate girder of up line of Fujigawa Bridge (Author)

above the pier foundation, a span of 10.0 m, and an overall length of 180 m.

Postwar Bridges

Construction for railways restarted after WWII following the old prewar specifications until new specifications were established in 1956.

Continuous girders

In 1953, a three-span continuous deck truss was designed for the No. 3 Tadamigawa Bridge. This was followed in 1955 by a welded three-span continuous Warren truss constructed without any vertical members to replace the Tenryugawa Bridge on the Iida Line. Similarly, in 1957, a three-span continuous Warren truss without vertical members was designed and three welded trusses were constructed on the Kisogawa Bridge on the down track of the Tokaido main line, and two riveted trusses was constructed on the Saigawa Bridge on both the up and down tracks of the Shin'etsu main line. These experiences were carried over to continuous trusses for the shinkansen. In 1956, three of three-span continuous half through plate girders were constructed as the Fujigawa Bridge on the up track of the Tokaido main line. It was a revolutionary long span for a plate girder railway bridge.

All-welded construction trusses

As described above, the first all-welded construction truss was for the Tenryugawa Bridge designed in 1955 and thereafter continued with the Kisogawa Bridge (1957) and the Shin-Jintsugawa Bridge (double track, 1959). Thereafter, all the trusses for the Tokaido Shinkansen were of all-welded construction.

Stiffened arches

Stiffened arches named Langer girder and Lohse girder were used for large-span bridges in cities.

In 1959, the first Lohse girder was constructed on the Harumi Bridge of the port line of the Tokyo Bureau of Ports and Harbours. It was designed by Japanese National Railways.

Reinforced concrete arches

There are few reinforced concrete arches, but rigid frame arches were constructed for the Mattogawa Bridge on the Kitakami Line (span 52.0 m, 1960), the Shin-Usuigawa Bridge on the Shin'etsu main line (span 70.0 m, flat open-spandrel arch, 1963), the Oyobitosawa Bridge on the Chuo Line (span 58.0 m, rise 20.0 m, open-spandrel arch, 1966), etc., and a maximum span of 70 m was reached. Larger spans were achieved using pre-stressed concrete construction.

Reinforced concrete girder bridges

The maximum span for a reinforced concrete girder bridge is the 32-m Hanamigawa Bridge on the Sobu main line completed in 1957. It is a three-span continuous box girder bridge for a double track with span lengths of 16.0, 32.0, and 16.0 m.

Daidogawa Bridge—start of PC bridge advancement (Shigaraki Kougen Railway)

No. 8 Tonegawa Bridge down line (Author)

Pre-stressed concrete bridges

Research on pre-stressed concrete started in the 1930s but full construction only started with the Daiichi-Daidogawa Bridge (1954); it is a post-tensioned pre-stressed concrete girder bridge on today's Shigaraki Kougen Railway (Shiga Prefecture). The No. 8 Tonegawa Bridge on the down track of the Joetsu Line (Gunma Prefecture) completed in 1963 is a pre-stressed concrete π-shaped rigid frame bridge with a span of 62.0 m. It has a shapely appearance with a span as long as the trusses.

Modern Bridges

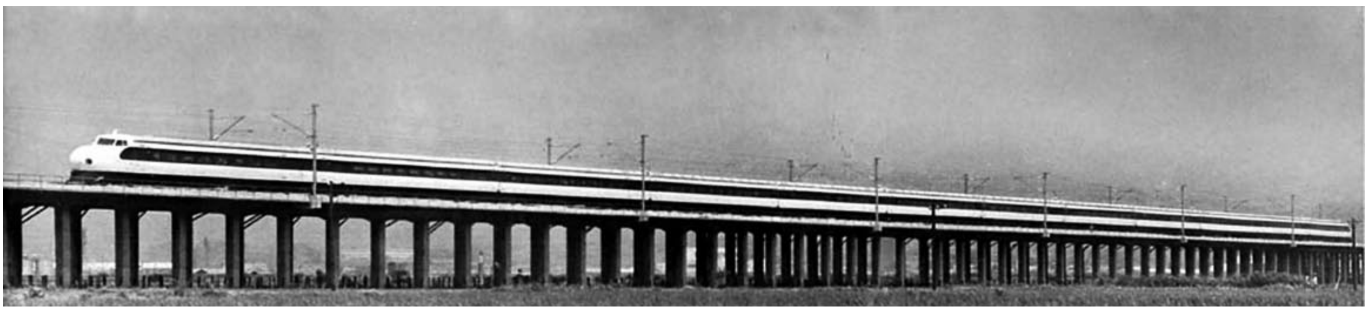
Tokaido Shinkansen Bridges

The shinkansen is fully grade-separated from all other railways and roads. Trains are all EMUs and controlled from a central location.

The first Tokaido Shinkansen is characterized by the extensively used reinforced concrete rigid-frame viaducts in place of embankments and the welded steel continuous Warren trusses. Both were thoroughly standardized and deployed on all sections. The track of the shinkansen is basically straight course in plan, and structures were designed in rectilinear shape, completely changing the rural Japanese landscape.

Tokaido Shinkansen truss bridge, 1965 (The Railway Museum)

Saigawa Bridge on Hokuriku Shinkansen during bridge decking construction (Author)



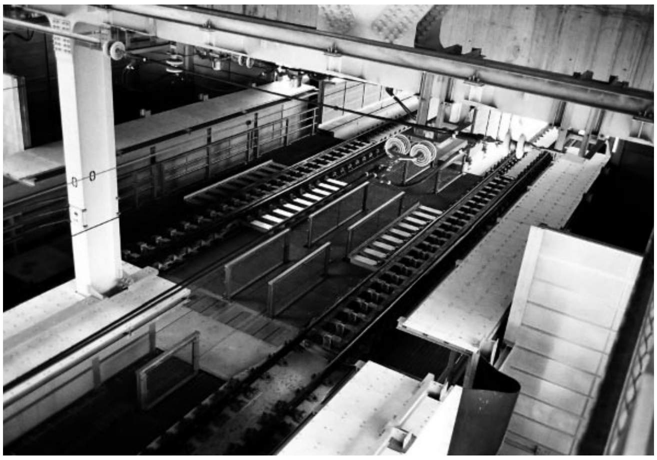
Tokaido Shinkansen viaduct, 1965 (The Railway Museum)

Truss girders were refined based on the experience of the parallel-chord welded Warren continuous truss without vertical members as mentioned above. Welding was used also for all kinds of other girders. Thereafter, railways in Japan shifted completely to welded structures.

The later San'yo Shinkansen (west of Okayama), Tohoku Shinkansen, and Joetsu Shinkansen use slab track with rails attached directly to the reinforced concrete slab. With the development of the steel truss girder using a concrete slab to reduce noise, more concrete bridges were built than steel bridges. One photograph on the previous page shows the deck of the Saigawa Bridge (truss) on the Hokuriku Shinkansen.

Bridges between Honshu and Shikoku

Railways on Japan's main island of Honshu are connected to Kyushu and Hokkaido by undersea tunnels but Honshu is connected to Shikoku by three bridges. The middle route linking Okayama Prefecture and Kagawa Prefecture is a dual-use road and railway (narrow gauge) bridge. On a very long suspension bridge or cable-stayed bridge hung by cables, the passage of heavy trains causes large deflection, resulting in large angular rotation and expansion and contraction at both ends of the bridge and tower supports, so extraordinary structural work is required. Therefore, a continuous stiffening truss system was used and an auxiliary girder for controlling angle change and expansion (transition track girder with expansion joint) was developed.



Honshu Shikoku Bridge Authority's Shimotsuiseto Bridge with auxiliary girders for controlling angle change on Honshu side (Author)

Akatanigawa Bridge (Joetsu Shinkansen, Gunma Pref.) (Author)

Steel bridges without any coating made of weather-resistant steel

Unclad bridges with weather-resistant steel plates

One of the cost problems of steel girders is re-coating (re-painting). Construction using weather-resistant steel without coating is based on the method that uses rust to prevent rust. The first bridge without coating is the deck truss girder of the No.3 Okawa Bridge on Aizu Railway completed in 1980. After that, several steel girders were constructed in rural area based on bare specification using weather-resistant steel, reflecting various technical developements and improvements.

Steel arch bridges in scenic landscape

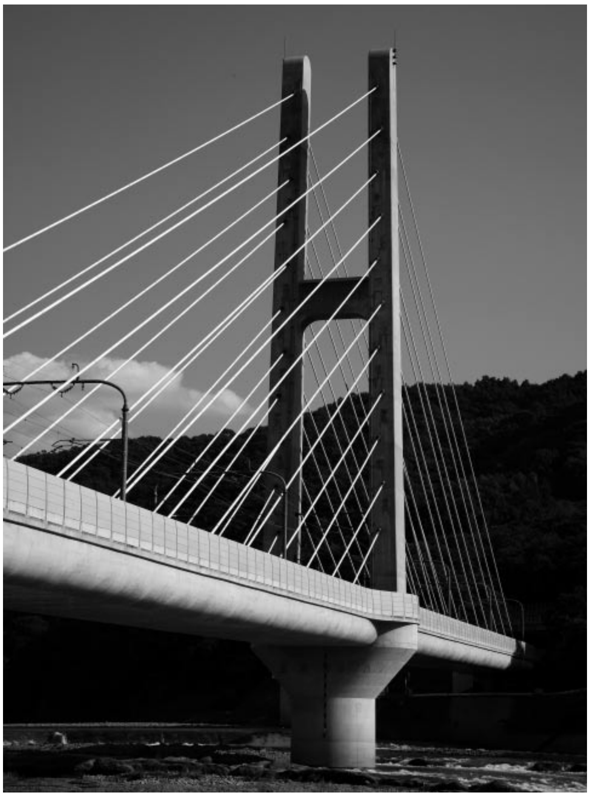
After aesthetic design considerations, steel arch bridges and steel π-shaped rigid frame bridges were adopted over the scenic Hozugawa River. Seen from the side, the individual bridges look elegant but when seen from tourist boats, they may seem incompatible with the scenery of the Hozugawa valley. This may not be a problem of design but may be a problem of route location. Concrete slab bridges are increasingly being used in favour of open-floor bridges to prevent noise and support slab track.

Pre-stressed concrete long bridges

The era of long steel truss railway bridges continued for a long time but, recently, long-span pre-stressed concrete bridges have been used extensively in various shapes and forms. In terms of design limits, these pre-stressed concrete bridges have superior appearance because they offer a higher degree of design freedom than steel bridges. In the 25 years since the JNR division and privatization, many recent railway bridges are especially impressive.

Deck-type pre-stressed concrete deck-stiffened arch (Langer type)

The Akatanigawa Bridge on the Joetsu Shinkansen (Gunma Prefecture) completed in 1979 during the JNR era has an arch span of 116 m, exceeding the 100-m mark for a concrete arch bridge for the first time. It is not a pure arch bridge, having girders of high rigidity. The arch ribs are thin and draw polylines, and the girders are reinforced by this thin plate arch rib.



No. 2 Chikumagawa Bridge (Author)

Yashiro Minami Overbridge (Author)

Sannaimaruyama Overbridge (JRTT)

No. 2 Agatsumagawa Bridge (S. Saito)

Cable-stayed bridges

These bridges hang oblique pre-stressed concrete girders by cables from high towers (pylons). An example with a span longer than 100 m is the No. 2 Chikumagawa Bridge on the Hokuriku Shinkansen opened in 1998. It has two spans of 139.9 m and a girder length of 270 m; the main tower height is 65 m above the bridge surface. Although symbolic from the aesthetic standpoint due to its high towers, the girder height had to be increased to 3 m to raise the rigidity of the main girders for use as a shinkansen bridge with stringent deflection restrictions. Problems such as departure from essential structural characteristics of a cable-stayed bridge, long period deflection of girders due to the effects of concrete creep and drying shrinkage, and inspection difficulties due to the height of the towers have been noted.

Extra-dosed cable stayed bridges

Compared to a standard cable-stayed bridge with high main towers, this bridge type has lower main towers and increased main girder rigidity, making it closer to a girder bridge than a suspension bridge. The angle of the diagonal cables is closer to horizontal than a cable-stayed bridge because the towers are low, reducing stress fluctuations in diagonal members due to live loads and preventing fatigue failure. Furthermore, inspection and maintenance of towers and diagonal members is easy, making the design ideal for railway bridges.

Himekawa Bridge (JRTT)

Haruda Overbridge (JRTT)

The Yashiro-minami Overbridge on the Hokuriku Shinkansen (max. span 105 m), the Onogawa Bridge on the Kyushu Shinkansen (max. span 113 m), and the Sannaimaruyama Overbridge on the Tohoku Shinkansen (max. span 150 m) are all shinkansen bridges with maximum spans exceeding 100 m.

Concrete sheathed cable-stayed bridges

This extra-dosed cable stayed bridge has PC cable diagonal members covered with concrete. The Ganter Bridge in Switzerland with PC cables radiating from a low tower and covered with triangular-shaped concrete slabs was completed in 1980 to worldwide acclaim.

The diagonal members covered with concrete reduce worries about cable corrosion. The overall bridge rigidity is high and the deflection is small, making it an ideal design for a railway bridge. JR East completed the 108-m Natorigawa Bridge on the Tohoku main line in 1996 and has had good results with several other bridges thereafter. The Sendaigawa Bridge (96 m) on the Kyushu Shinkansen was completed in 2002. The No. 2 Agatsumagawa Bridge on the JR East Agatsuma Line with a centre span of about 167 m was completed in 2010.

Pre-stressed concrete continuous girder with finback shaped side wall

Matching the bending moment of the continuous girder, part of the main girder of bridges of this type protrudes on the bridge pier like a dorsal fin on the top side of the girders and PC cables are embedded inside. This helps reduce the height from the rail surface to the bottom surface of the girders. The waves generated by the dorsal fin and curved side surface of the girders give the bridge a soft impression unlike previous railway bridges. The first example is the six-span continuous through-type girders of the Narusegawa Bridge on the JR East Senseki Line completed in June 2000. The Himekawa Bridge on the Hokuriku Shinkansen (total length of 462 m, seven span, completed in 2007) uses a similar design.

Through-type concrete deck-stiffened arch (Langer type)

Through-type steel Langer girders started with the Sumidagawa Bridge on the Sobu main line in 1932; a similar through-type concrete deck stiffened arch (Lohse type) girder was constructed for the first time in Nagano Prefecture in 1936 and then became commonplace. Use of the through type reinforced concrete deck stiffened arch started relatively recently. Thin arch ribs are added to the top of through type reinforced concrete or pre-stressed concrete girders, resulting in increased girder rigidity. It reduces the girder height and lessens deflection. In addition to reduced girder height, the bridge arch alleviates oppressiveness, making it ideal for viaducts; it could be further improved by design efforts, such as adding unevenness to the girders and arch side surfaces. There are several bridges of this type on the JR East Nanbu and Agatsuma lines. More recent examples are the Harada Overbridge on the Kyushu Shinkansen (span length of 61.0 m) completed in 2002. ■

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