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65

Design Practice in Japan

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65.1 Design

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65.1.1 Design Philosophy

In the current Japanese bridge design practice [1], there are two design philosophies: ultimate strength design and working stress design.

1. Ultimate strength design considering structural nonlinearities compares the ultimate load-carrying capacity of a structure with the estimated load demands and maintains a suitable ratio between them. Generally, this kind of design philosophy is applied to the long-span bridge structures with spans of more than 200 m, i.e., arches, cable-stayed girder bridges, stiffened suspension bridges, etc.
2. Working stress design relies on an elastic linear analysis of the structures at normal working loads. The strength of the structural member is assessed by imposing a factor of safety between the maximum stress at working loads and the critical stress, such as the tension yield stress

TABLE 65.1 Loading Combinations and Their Multiplier Coefficients for Allowable Stresses

No.	Loading Combination	Multiplier Coefficient for Allowable Stresses
1	P + PP + T	1.15
2	P + PP + W	1.25
3	P + PP + T + W	1.35
4	P + PP + BK	1.25
5	P + PP + CO	1.70 for steel members 1.50 for reinforced concrete members
6	W	1.2
7	BK	1.2
8	P except L and I + EQ	1.5
9	ER	1.25

of material and the shear yield stress of or the compression buckling stress of material (see Section 65.1.4).

65.1.2 Load

The Japanese Association of Highways, the Standard Specification of Highway Bridges [1] (JAH-SSHB) defines all load systems in terms four load systems as follows:

1. Primary loads (*P*) — dead load (*D*), live load (*L*), impact load (*I*), prestressed forces (*PS*), creep (*CR*), shrinkage (*SH*), earth pressure (*E*), hydraulic pressure (*HP*), uplift force by buoyancy (*U*).
2. Secondary loads (*S*) — wind load (*W*), thermal force (*T*), effect of earthquakes (*EQ*).
3. Particular loads corresponding to the primary load (*PP*) — snow load (*SW*), effect of displacement of ground (*GD*), effect of displacement of support (*SD*), wave pressure (*WP*), centrifugal force (*CF*).
4. Particular loads (*PA*) — raking force (*BK*), tentative forces at the erection (*ER*), collision force(CO), etc.

The combinations of loads and forces to which a structure may be subjected and their multiplier coefficients for allowable stresses are specified as shown in Table 65.1. The most severe combination of loads and forces for a structure within combinations given in Table 65.1 is to be taken as the design load system. Details on the loads have not been given here and the reader should refer to the specification [1].

Limiting values of deflection are expressed as a ratio of spans for the individual superstructure types and span lengths.

65.1.3 Theory

In most cases, design calculations for both concrete and steel bridges are based on the assumptions of linear behavior (i.e., elastic stress–strain) and small deflection theory. It may be unreasonable, however, to apply linear analysis to a long-span structure causing the large displacements. The JAH-SSHB specifies that the ideal design procedure including nonlinear analyses at the ultimate loads should be used for the large deformed structure.

Bridges with flat stiffening decks raise some anxieties for the wind resistance. The designer needs to test to ensure the resistances for wind forces and/or the aerodynamic instabilities. In Japan, wind tunnel model testing including the full model and sectional model test is often applied for these verifications . The methods of model testing include full-model tests and sectional-model tests. The vibrations induced by vehicles, rain winds, and earthquakes are usually controlled by oil dampers, high damping rubbers, and/or vane dampers.

65.1.4 Stability Check

The JAH-SSHB specifies the strength criteria on stabilities for fundamental compression, shear plate, and arch/frame elements. The strength criteria for the stability of those elements are presented as follows:

1. Compressive strength for plate element — Fundamental plate material strength under uniform compression is mentioned here but details have not been given in all cases.

$$\left.\begin{aligned}\frac{\sigma_{cl}}{\sigma_Y} &= 1.0 \qquad \text{for } R \le 0.7 \\ &= \frac{0.5}{R^2} \qquad \text{for } 0.7 \le R\end{aligned}\right\} \tag{65.1}$$

where σ_{cl} = plate strength under uniform compression, R = equivalent slenderness parameter defined as

$$R = \frac{b}{t}\sqrt{\frac{\sigma_Y}{E}} \cdot \sqrt{\frac{12\left(1-\mu^2\right)}{\pi k^2}} \tag{65.2}$$

and b = width of plate, t = thickness of plate, μ = Poisson's ratio, k = coefficient applied in elastic plate buckling.

2. Compressive strength for axially loaded member — The column strength for overall instability is specified as

$$\left.\begin{aligned}\frac{\sigma_{cg}}{\sigma_Y} &= 1.0 && \text{for } \bar{\lambda} \le 0.2 \\ &= 1.109 - 0.545\bar{\lambda} && \text{for } 0.2 \le \bar{\lambda} \le 1.0 \\ &= 1.0/\left(0.773 + \bar{\lambda}^2\right) && \text{for } 1.0 \le \bar{\lambda}\end{aligned}\right\} \tag{65.3}$$

where σ_{cg} = column strength, σ_Y = yield-stress level of material, $\bar{\lambda}$ = slenderness ratio parameter defined as follows

$$\bar{\lambda} = \frac{1}{\pi}\sqrt{\frac{\sigma_Y}{E}} \cdot \frac{l}{r} \tag{65.4}$$

and r = radius of gyration of column member and l = effective column length. Thus, the ultimate stress of axially effective material, σ_c, is specified as

$$\sigma_c = \frac{\sigma_{cg} \cdot \sigma_{cl}}{\sigma_Y} \tag{65.5}$$

3. Bending compressive strength — The ultimate strength for bending compression is specified, based on the lateral-torsional stability strength of beam under uniform bending moment as follows:

$$\left.\begin{aligned}\frac{\sigma_{bg}}{\sigma_Y} &= 1.0 && \text{for } \alpha \le 0.2\\ &= 1.0 - 0.412(\alpha - 0.2) && \text{for } 0.2 \le \alpha\end{aligned}\right\} \tag{65.6}$$

where σ_{bg} = lateral-torsional stability strength of beam under uniform moment, α = equivalent slenderness parameter defined as

$$\left.\begin{aligned}\alpha &= \frac{2}{\pi} K \sqrt{\frac{\sigma_Y}{E}} \cdot \frac{l}{b}\\ K &= 2 && \text{for } A_w / A_c \le 2\\ &= \sqrt{3 + 0.5 A_w / A_c} && \text{for } 2 \le A_w / A_c\end{aligned}\right\} \tag{65.7}$$

and A_w = gross area of web plate, A_c = gross area of compression flange, l = laterally unbraced length, b = width of compression flange. The effect of nonuniform bending is estimated by the multiplier coefficient, *m,* as follows

$$m = \frac{M}{M_{eq}} \tag{65.8}$$

in which M = bending moment at a reference cross section, M_{eq} = equivalent conversion moment given as

$$M_{eq} = 0.6M_1 + 0.4M_2 \quad \text{or} \quad M_{eq} = 0.4M_1 \quad \text{where} \quad M_1 \ge M_2 \tag{65.9}$$

65.1.5 Fabrication and Erection

Fabrication and erection procedures depend on the structural system of the bridge, the site conditions, dimensions of the shop-fabricated bridge units, equipment, and other factors characteristic of a particular project. This includes methods of shop cutting and welding, the selection of lifting equipment and tackle, method of transporting materials and components, the control of field operation such as concrete placement, and alignment and completion of field joints in steel, and also the detailed design of special erection details such as those required at the junctions of an arch, a cantilever erection, and a cable-stayed erection. Therefore, for each structure, it is specified that the contractor should check

1. Whether each product has its specified quality or not.
2. Whether the appointed erection methods are used or not.

As a matter of course, the field connections of main members of the steel structure should be assembled in the shop.

Details on the inspections have not been given here and the reader should refer to the specifications [1].

FIGURE 65.1 Tennyo-bashi.

65.2 Stone Bridges

Tetsuya Yabuti

It is possible that stone bridges were built in very ancient times but that through lack of careful maintenance and/or lack of utility they were destroyed so that no trace remains. Since stone masonry is generally suited to compressive stresses, it is usually used for arch spans. Therefore, most stone bridges that have survived to the present are arch bridges. Generally, stone arch bridges are classified into two types: the European voussoirs are built of bricks and the Chinese type where each voussoir in arch is curved and behaves as a rib element.

Figure 65.1 shows Tennyo-bashi (span length, 9.5 m) located in Okinawa prefecture. This is the only area in Japan that has the Chinese type. This bridge is the oldest Chinese-type stone arch bridge in Japan that has survived to the present time; it was originally constructed in 1502. Figure 65.2 shows Tsujyun Bridge located in Kumamoto prefecture (length of span, 75.6 m; raise of arch, 20.2 m; width of bridge, 6.3 m). This bridge is typical of aqueduct stone arch bridges that have survived to the present in Japan and was originally constructed in 1852. Figure 65.3 shows Torii-bashi Bridge located in Oita prefecture which is one of the multispanned stone arch bridges constructed early in the 20th century. This bridge is a five-span arch bridge (length of bridge, 55.15 m; width of bridge; 4.35 m; height of bridge, 14.05 m) constructed in 1916.

Separate stones sometimes have enough tensile strength to permit their being used for beams and slabs as seen in Hojyo-bashi which is the clapper bridge shown in Figure 65.4. This bridge located in Okinawa prefecture has a span of 5.5 m and was originally constructed in 1498.

65.3 Timber Bridges [2,3]

Masatsugu Nagai

Since 1990, the number of timber bridges constructed has increased. Most of them use glue-laminated members and many are pedestrian bridges. To date, about 10 bridges have been constructed to carry 14 or 20 tf trucks. All were constructed on a forest road. We have no design code for timber bridges. However, there is a manual for designing and constructing timber bridges.

The following is an introduction to timber arch, cable-stayed, and suspension bridges in Japan.

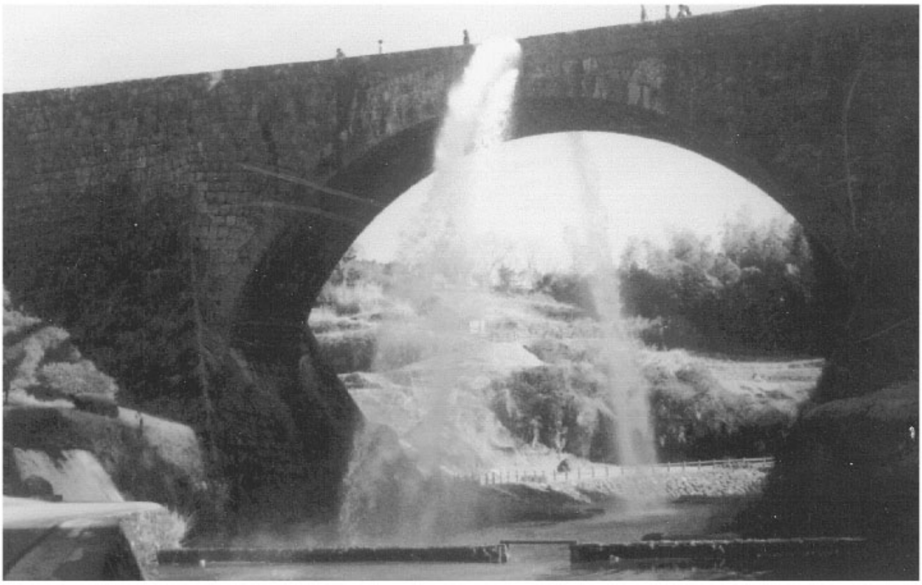

FIGURE 65.2 Tsujyun Bridge.

FIGURE 65.3 Torii-bashi.

1. Arch Bridges — Table 65.2 shows nine arch bridges. Figure 65.5 shows Hiraoka bridge, which, of timber arch bridges, has the longest span in Japan. Figure 65.6 shows Kaminomori bridge [4]. It is the first arch bridge, which carries a 20 tf truck load.
2. Cable-Stayed Bridges — Table 65.3 shows three cable-stayed bridges. Figure 65.7 shows Yokura bridge. It has a world record span length of 77.0 m, and has a concrete tower.
3. Suspension Bridges — Table 65.4 shows two suspension bridges. Figure 65.8 shows Momosuke bridge. Momosuke bridge is an oldest timber suspension bridge in Japan. It was constructed in 1922, and reconstructed in 1993.

FIGURE 65.4 Hojyo-bashi.

TABLE 65.2 Arch Bridges

Name	Span and Width (m)	Construction Year	Remarks
Yunomata	13.0 6.0	1990	Tied arch bridge for 14 tf truck loading
Kisoohashi	33.0 6.0	1991	Fixed arch pedestrian bridge
Deai	39.0 2.0	1992	Tied arch pedestrian bridge
Hiroaka	45.0 3.0	1993	Three hinged arch pedestrian bridge
Yasuraka	30.0 1.5	1993	Nielsen Lohse type pedestrian bridge
Chuo	21 5.0	1993	Lohse type pedestrian bridge
Kaminomori	23 5.0	1994	Two hinged arch bridge for 20 tf truck loading
Awaiido	24.0 8.0	1994	Lohse type bridge for 20 tf truck loading
Meoto	20 1.5	1994	Two hinged arch pedestrian bridge

65.4 Steel Bridges

Tetsuya Yabuti

In Japan, metal as a structural material began with cast and/or wrought iron used on bridges after the 1870s. Through lack of these utilities in urban areas, however, almost all of those bridges have broken down. Since 1895, steel has replaced wrought iron as the principal metallic bridge material.

After the great Kanto earthquake disaster in 1923, high tensile steels have been positively adopted for bridge structural uses and Kiyosu Bridge (length of bridge, 183 m; width of bridge, 22 m) shown in Figure 65.9 is a typical example. This eyebar-chain-bridge over the Sumida river in Tokyo is a self-anchored suspension bridge and a masterpiece among riveted bridges. It was completed in 1928.

FIGURE 65.5 Hiraoka Bridge.

FIGURE 65.6 Kaminomori Bridge.

Figure 65.10 shows one of the curved tubular girder bridges located in the metropolitan expressway. Curved girder bridges have become an essential feature of highway interchanges and urban expressways now common in Japan.

TABLE 65.3 Cable-Stayed Bridges

Name	Span and Width (m)	Construction Year	Remarks
Midori Kakehashi	27.5 2.0	1991	Two-span continuous pedestrian bridge
Yokura	77.0 5.0	1992	Three-span continuous pedestrian bridge
Himehana	21.5 1.5	1995	Three-span continuous pedestrian bridge

FIGURE 65.7 Yokura Bridge.

TABLE 65.4 Suspension Bridges

Name	Span and Width (m)	Construction Year	Remarks
Momosuke	104.5 2.3	1993	Four-span continuous pedestrian bridge
Fujikura	32.0 1.8	1994	Single-span pedestrian bridge

Figure 65.11 shows Katashinagawa Bridge (length of span; 1033.8 m = 116.9 + 168.9 + 116.9; width of bridge, 18 m) located in Gunma prefecture. This bridge is the longest curved-continuous truss bridge in Japan and was completed in 1985. Figure 65.12 shows Tatsumi Bridge (length of bridge, 544 m; width of bridge, 8 m) located in Tokyo. This viaduct bridge in the metropolitan expressway is a typical example of rigid frame bridges in an urban area and was completed in 1977. Figure 65.13 shows a typical π-shaped rigid frame bridge. This structural type is used as a viaduct over a highway or a highway bridge in mountain areas and is common in Japan.

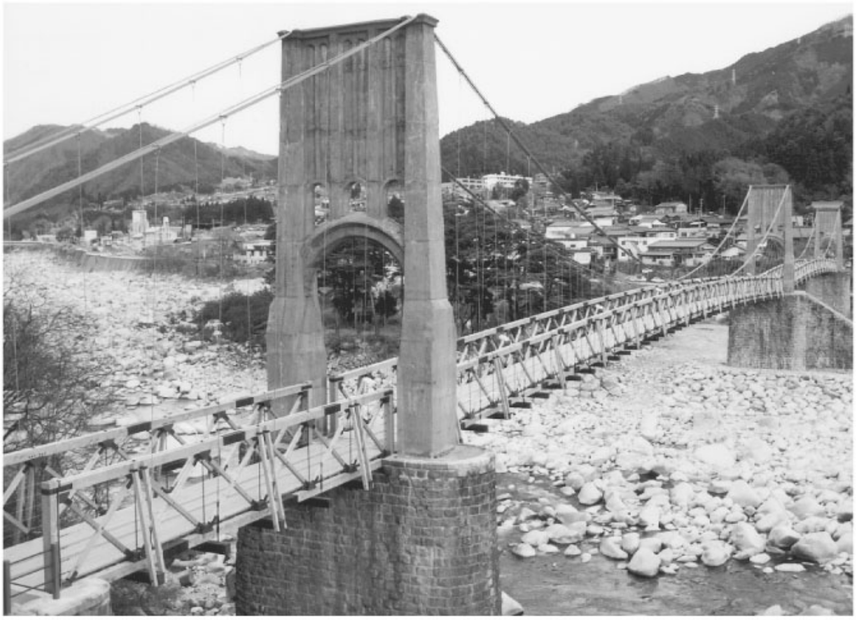

FIGURE 65.8 Momosuke Bridge.

FIGURE 65.9 Kiyosu Bridge.

FIGURE 65.10 A curved tubular girder bridge in a metropolitan express highway.

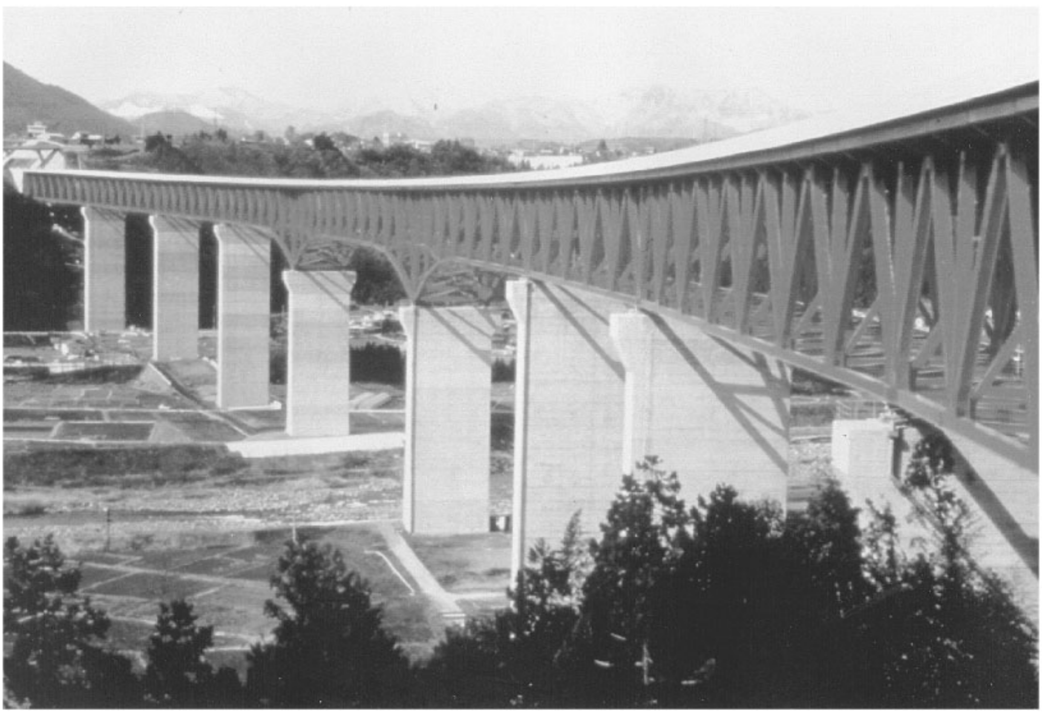

FIGURE 65.11 Katashinagawa Bridge.

FIGURE 65.12 Tatsumi Bridge.

FIGURE 65.13 A typical π-shaped rigid frame bridge.

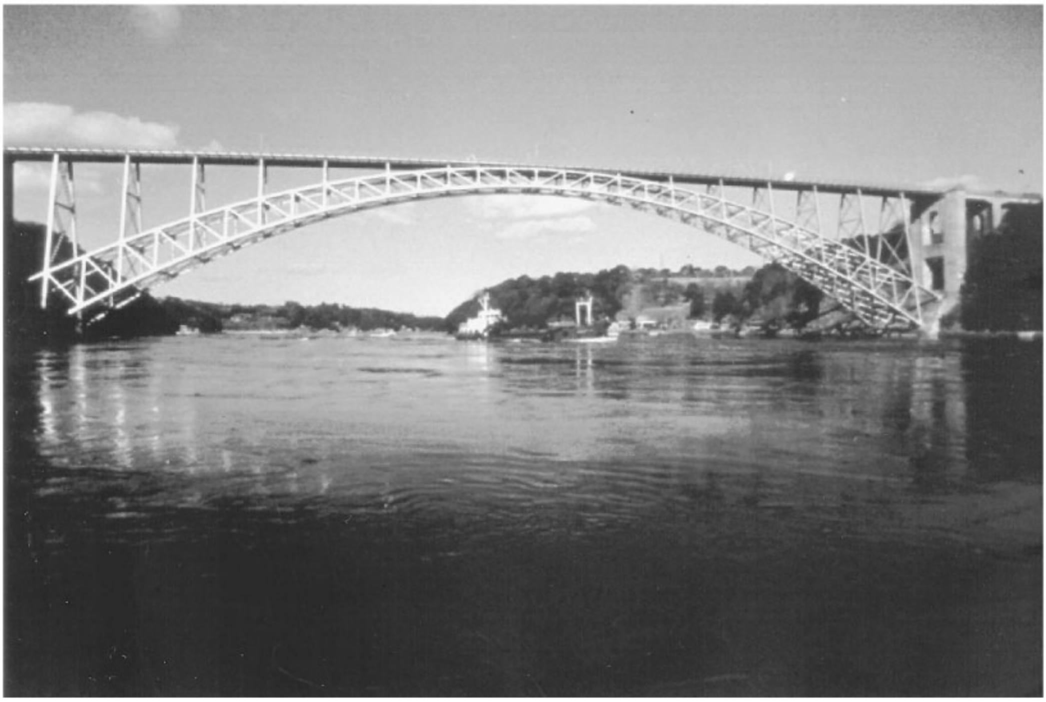

FIGURE 65.14 Saikai Bridge.

Saikai Bridge located in Nagasaki prefecture (length of span, 216 m; width of bridge, 7.5 m) shown in Figure 65.14 was completed in 1955. Construction of bridges in Japan after the World War II began in earnest with the Saikai Bridge. This bridge is a fixed arch bridge and the stress condition was improved by prestressing when the main arch was finally completed.

Figure 65.15 shows Ooyano Bridge located in Kumamoto prefecture. This bridge is a typical through-type arch bridge (length of bridge, 156 m; width of bridge, 6.5 m) and was constructed in 1966.

Figure 65.16 shows Ikuura Bridge located in Mie prefecture and completed in 1973. The main span of this bridge (length of span, 197 m; width of bridge, 8.3 m) is a tied arch with inclined hangers of the Nielsen system that is one of the most favored bridge types in Japan, along with the cable-stayed bridge.

Figure 65.17 shows Tsurumi-Tsubasa Bridge (length of bridge, 1021 m = center span of 510 m + two side spans of 255 m; height of towers, 136.7 m) located in Yokohama Bay, Kanagawa prefecture. This bridge is a single-plane, cable-stayed bridge with continuous three spans. It is the longest bridge of this type including those under design all over the world and was completed in 1994.

Figure 65.18 shows Iwagurojima Bridge (length of bridge, 790 m = center span of 420 m + two side spans of 185 m; height of towers, 148.1 m; width of bridge, 22.5 m) located Kagawa prefecture. This bridge completed in 1988 is a double-plane cable-stayed bridge with continuous three spans and is a combined bridge with highway and railway traffic. It has four express railways. The cable-stayed bridge with four express railways is unprecedented, including those under design worldwide. Figure 65.19 shows Kanmon Bridge (length of bridge, 1068 m = center span of 420 m + two side spans of 185 m) completed in 1973. This bridge spans over the Kanmon channel and links Moji in Fukuoka prefecture, Kyushu Island, and Shimonoseki in Yamaguchi prefecture, main island. It is the first bridge in Japan spanning a channel.

The Japan Association of Steel Bridge Construction has contributed to the preparation of some photographs in this section.

FIGURE 65.15 Ooyano Tsubasa Bridge.

FIGURE 65.16 Ikuura Bridge.

FIGURE 65.17 Tsurumu-Tsubasa Bridge.

FIGURE 65.18 Iwakuro Bridge.

FIGURE 65.19 Kanmon Bridge.

65.5 Concrete Bridges

Tetsuya Yabuki

Construction of reinforced concrete bridges began in the 1900s in Japan but has gradually become useless because of change of the utility conditions in urban areas. Since the 1950s, the use of prestressing spread to nearly every type of simple structural element and spans of concrete bridges became much longer. Probably the most significant observable feature of prestressed concrete is its crack-free surface under service loads. Especially, when the structure is exposed to weather conditions, elimination of cracks prevents corrosion. Many reinforced concrete bridges constructed previously are being replaced by prestressed concrete ones in Japan.

Figure 65.20 shows a typical reinforced concrete bridge damaged by corrosion. Most of these kinds of bridges have been replaced by prestressed concrete structures. Figure 65.21 shows Chousei Bridge (length of bridge, 10.8 m = three continuous spans of 3.6 m) located in Ishikawa prefecture. This bridge is a pretensioned simple composite slab bridge. It was completed in 1952 and is the first prestressed concrete bridge in Japan. Figure 65.22 shows Ranzan Bridge (length of bridge, 75 m = main span of 51.2 + two side spans of 11.9 m) located in Kanagawa prefecture. This bridge is a rigid frame bridge composed by three spans with a hinge. It was completed in 1959 and is the first bridge in Japan that was constructed by the cantilever erection.

Figure 65.23 shows International Expo No. 9 Bridge (length of bridge, 27 m; width of bridge, 5.5 m; thickness of slab, 0.1 m) located in Osaka. This bridge is a pedestrian bridge. It was completed in 1969 and is the first suspended slab bridge in Japan. Figure 65.24 shows Takashimadaira Bridge (length of bridge, 230 m = 75 + 75 + 80; width of bridge, 18 m) located in Tokyo. This viaduct in the metropolitan expressway is composed by linking three bridges and completed in 1973. Each one is a continuous three span-bridge (length of spans, 25 m + 25 + 25 m).

FIGURE 65.20 A typical reinforced concrete bridge damaged by corrosion.

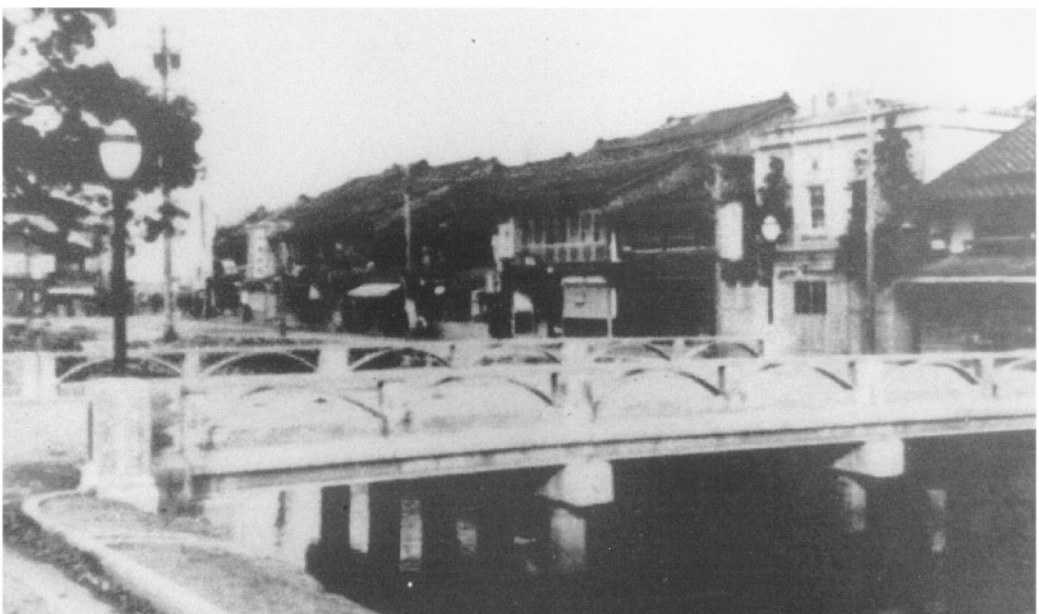

FIGURE 65.21 Chosei-bashi.

FIGURE 65.22 Ranzan Bridge.

FIGURE 65.23 International Expo No. 9 Bridge.

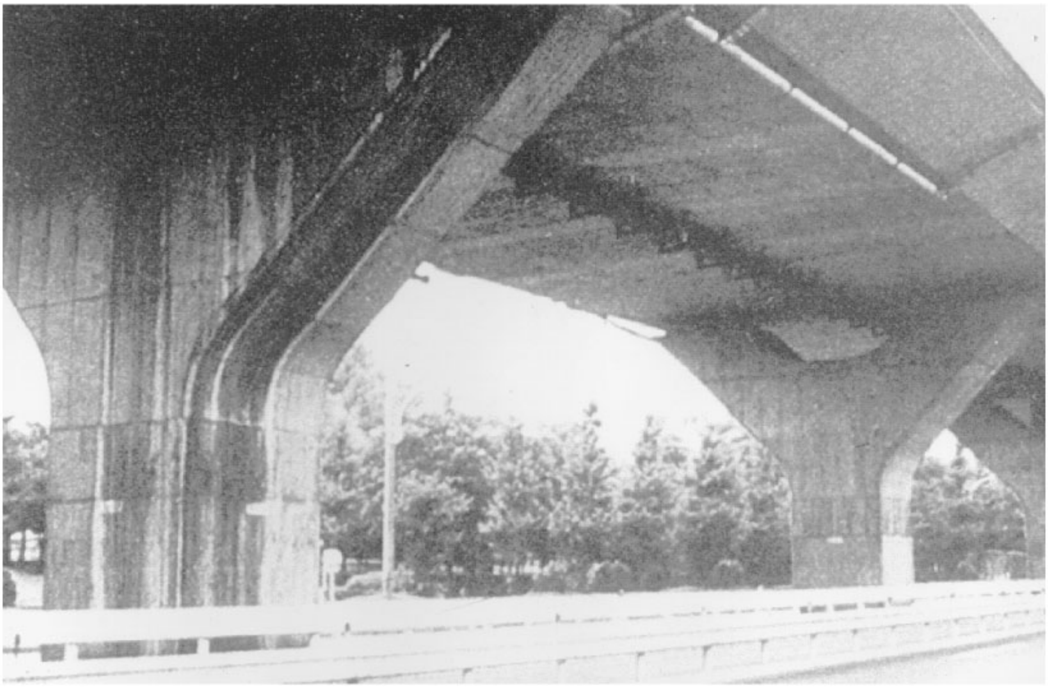

FIGURE 65.24 Takashimadaira Bridge.

Figure 65.25 shows Akayagawa Bridge (length of bridge, 298 m; arch span, 116 m) located in Gunma prefecture. This rib arch bridge is the longest concrete arch railway bridge in Japan and was completed in 1979. Its arch rib is composed of a plate with thickness of 0.8 m and mainly receives compressive stress. Figure 65.26 shows Omotogawa Bridge located in Iwate prefecture. This bridge was completed in 1979 and is the first prestressed concrete stayed railway bridge in the world.

The Japan Prestressed Concrete Association has contributed to preparation of some of the photographs in this section.

65.6 Hybrid Bridges

Masatsugu Nagai

Hybrid bridges consist of composite and compound bridges. Composite bridges have a cross section of steel and concrete connected by shear connectors. Compound bridges consist of different materials, such as steel and concrete. In Japan, many composite girder bridges have been constructed. However, since 1980, the number of composite girder bridges has decreased. One of main reasons is the damage of concrete decks due to overloading by heavy trucks. In recent years, for economic reasons, the choice of composite girder construction has been reconsidered. In bridge systems, prestressed precast concrete slabs are used to attain higher durability. The following is an introduction of the practices and plans of the hybrid bridges of Japan Highway Public Corporation.

Figure 65.27 shows Hontani Bridge (total span length, 197 m = 44 + 97 + 56 m; width, 11.4 m) constructed in Gifu prefecture in 1998. It has a box section with corrugated steel plate used as a web between upper and lower concrete slabs. To reduce the total weight of the concrete box girder, instead of concrete webs, a steel web was used. This kind of structural system was first employed in the Cognac Bridge in France. However, for the connection between concrete and steel plate, a simple system with reinforcing bars attached to the corrugated plate and without steel flange was used.

FIGURE 65.25 Akayagawa Bridge.

FIGURE 65.26 Omotogawa Bridge.

FIGURE 65.27 Hontani Bridge. (Courtesy of Japan Highway Public Corporation.)

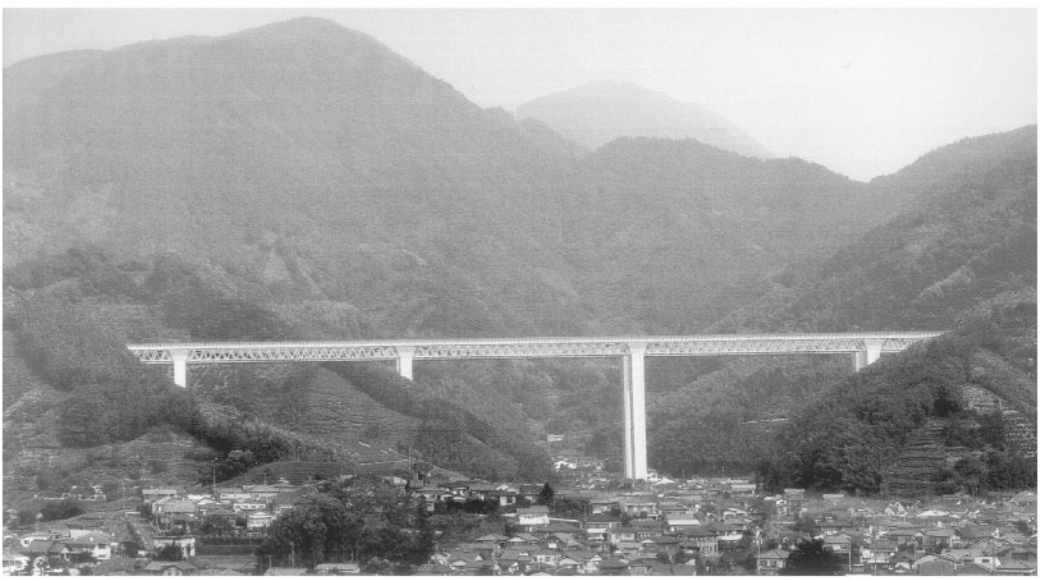

FIGURE 65.28 Tomoegawa Bridge. (Courtesy of Japan Highway Public Corporation.)

Figure 65.28 shows Tomoegawa Bridge (total span length, 475 m = 59 + 3 × 119 + 59 m; width, 16.5 m) which will be constructed on the route of the New Tomei Expressway discussed in Section 65.8.2. It has a box section, and a steel truss is used as a web between the upper and lower concrete slabs, whose main purpose is to reduce the total weight of the superstructures. When the span length becomes long, if a steel plate is used as the web, a horizontal connection in the bridge

FIGURE 65.29 Ibigawa Bridge. (Courtesy of Japan Highway Public Corporation.)

longitudinal direction is necessary for transportation from the shop to the site. To avoid the problem, a truss member is planned to be used. This kind of bridge system was first used in Arbois Bridge in France. However, in this bridge, a new connecting system between truss member and concrete slab will be used.

Figure 65.29 shows Ibigawa Bridge (total span length, 1397 m = 154 + 4 × 271.5 + 157 m; width 33 m) which will be constructed on the route of the New Meishin Expressway. It crosses the Ibi River near Nagoya City. Kisogawa Bridge, which crosses the Kiso River running parallel to the Ibi River, has a structural form similar to that of Ibigawa Bridge. The bridge consists of concrete and steel girders. The steel box girders are used for the middle part with a length of 100 m in the central four spans, and are connected to the concrete girder. The concrete girder is suspended by diagonal stays from concrete towers. The height of the tower from the deck level is lower than that used in conventional cable-stayed bridges. Since the span length is 271.5 m, if the concrete bridges are used, considerably greater depth is inevitable. By suspending the concrete girder and using a steel girder with lighter weight in the central portion of the bridge, reduction of depth is attained.

Figure 65.30 shows Shinkawa Bridge (total span length, 278 m = 2 × 40 + 113 + 2 × 40 m; width 21.4 m) which will be constructed on the highway in Shikoku Island. It consists of the concrete and steel box girders. Since the side span length is planned to be short, a concrete box girder is used and connected to the steel girder in the side span adjacent to the main span. The purpose of this countermeasure is to balance the weight.

Figure 65.31 shows Kitachikumagawa Bridge (total span length, 346.7 m = 84.35 + 2 × 89 + 84.35 m; width, 10.4 m) which is located near Nagano City and was constructed in 1997. In this bridge, reinforced concrete piers were connected to the steel box girders. By employing a rigid frame structure, the bearings are avoided and good performance against earthquake is attained.

Shigehara Bridge (total span length; 166.8 m = 47.4 + 72 + 47.4 m; width, 10.4 m) was constructed on the highway in Kyushu Island in 1995. It has composite piers, in which steel pipes are encased instead of reinforcing bars as shown in Figure 65.32. This system is developed to reduce the volume of the reinforcing bars, and resulted in the reduced construction work.

FIGURE 65.30 Shinkawa Bridge. (Courtesy of Japan Highway Public Corporation.)

FIGURE 65.31 Kitachikuma Bridge. (Courtesy of Japan Highway Public Corporation.)

FIGURE 65.32 Piers of Shigehara Bridge. (Courtesy of Japan Highway Public Corporation.)

65.7 Long-Span Bridges (Honshu–Shikoku Bridge Project)

Masatsugu Nagai and Shuichi Suzuki

The Honshu–Shikoku Bridge Project is a national project to link the Honshu and Shikoku Islands. Construction of the long-span bridge started in 1975 and was completed in 1999. Figure 65.33 shows three routes, in which many long-span cable-supported bridges are constructed. The following is an introduction of the super- and substructures of these cable-supported bridges.

65.7.1 Kobe–Naruto Route

This route is 89 km long, and two suspension bridges are arranged. Figure 65.34 shows the Akashi Kaikyo Bridge [5] (total span length, 3911 m = 960 + 1991 + 960 m) which is a three-span, two-hinged suspension bridge, and has a world-record span length of 1991 m. The distance between two cables is 35.5 m. This bridge was opened to traffic in 1998. The original plan was to carry both rail and road traffic. In 1985, this plan was changed so that the bridge carries highway traffic only. It is known, in the design of long-span suspension bridges, that ensuring safety against static and dynamic instabilities under wind load is an important issue. Aerodynamic stability was investigated through boundary layer

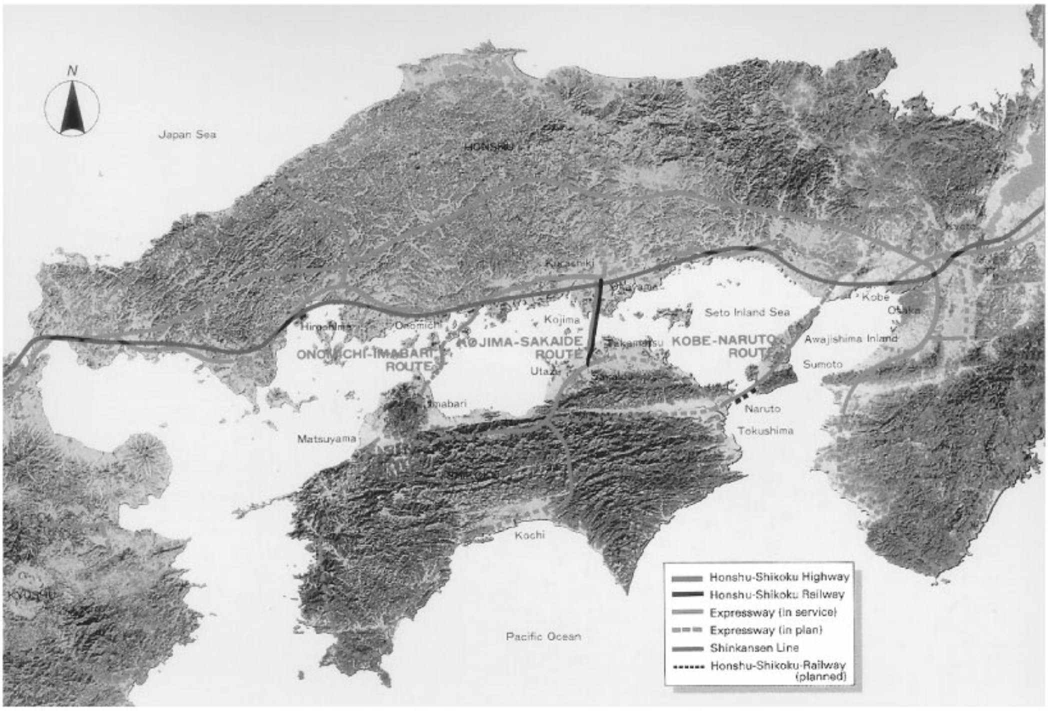

FIGURE 65.33 Honshu–Shikoku Bridge connecting route.

wind tunnel test with a 1⁄100 full model, and the test was conducted as a cooperative study between the Honshu–Shikoku Bridge Authority and the Ministry of Construction. Through the test, it was confirmed that flutter occurred at a wind velocity exceeding 78 m/s, a value was well above the required wind velocity. To avoid two main cables on each side, wires with a tensile strength of 1760 MPa (higher than that used in other suspension bridges) was used. Further, since the ratio of live load to dead load is small, the factor of safety of 2.2 against tensile strength was utilized.

The laying-down caisson method was adopted for the main tower foundations. The method is to install a prefabricated steel caisson shown in Figure 65.35 on a dredged seabed and subsequently complete a rigid foundation structure by filling concrete inside the caisson compartments. Desegregation concrete was developed for this purpose. The anchorage foundation was constructed with an underground slurry wall method on the Kobe side and the spread foundation method on the Awajishima side. Highly workable concrete was developed for the body of anchorages shown in Figure 65.36.

Figure 65.37 shows the Ohnaruto Bridge completed in 1985. The center and side spans are 876 and 330 m, respectively. The distance between two cables are 34 m. To achieve aerodynamic stability, vertical stabilizing plates were installed under the median strip of the deck to change the wind flow patterns. This kind of stabilizing countermeasure was also adopted in the stiffening truss of the Akashi Kaikyo Bridge.

The multicolumn method, aiming to avoid disrupting the famous Naruto Whirlpools in the Naruto Straits, was used for the main and side tower foundations.

65.7.2 Kojima–Sakaide Route

This route is 37 km long, and three suspension bridges and two cable-stayed bridges were constructed. Since the bridges carry both roadway and railway traffic, a truss girder was selected; its upper deck is used for the roadway and the lower deck for the railway.

FIGURE 65.34 Akashi Kaikyo Bridge.

The laying-down caisson method was utilized for 11 underwater foundations in this route. Prepacked concrete, in which coarse aggregate was at first packed inside the steel caisson and then mortar was injected into voids of the aggregate, was developed for the underwater concrete of the foundations.

Figure 65.38 shows the Shimotsui-Seto Bridge completed in 1988, which is a single-span bridge with 940 m in span length. The distance between two cables is 35 m, a value that is common to all suspension bridges on this route. The main cables of most long-span suspension bridges in Japan have been erected by the prefabricated strand (PS) method. However, this bridge employed the air spinning (AS) method. Since the cable is anchored to the rock directly (a tunnel anchor), the AS method enabled making the anchoring system small.

Figure 65.39 shows the Kita Bisan-Seto Bridge and the Minamai Bisan-Seto Bridge. These bridges have a three-span continuous truss girder. The center spans of theses two bridges are 990 and 1100 m, respectively, and their side spans are each 274 m. These bridges were constructed in 1988. The side view is similar to that of the San Francisco–Oakland Bay Bridge in the United States. The cables of two bridges are anchored to opposite sides of one common anchorage. Hence, the anchorage is subjected only to the difference between the horizontal components of tension in the cables of the two bridges. At the end the bridge, an expansion joint allowing 1.5 m movement was installed, and, also, a transition girder system was used to absorb large amounts of changes in inclination in the track for ensuring running stability of the train. The laying-down caisson method was used for the six underwater foundations. The Sikoku side anchorage foundation is the largest one in this route, reaching 50 m below sea level.

Figure 65.40 shows the Iwakurojima Bridge and the Hitsuishijima Bridge. Both bridges have center spans of 420 m and side spans of 185 m. These bridges were constructed in 1988. First, these bridges were designed as a Gerber-type truss girder. After carrying out a study on the

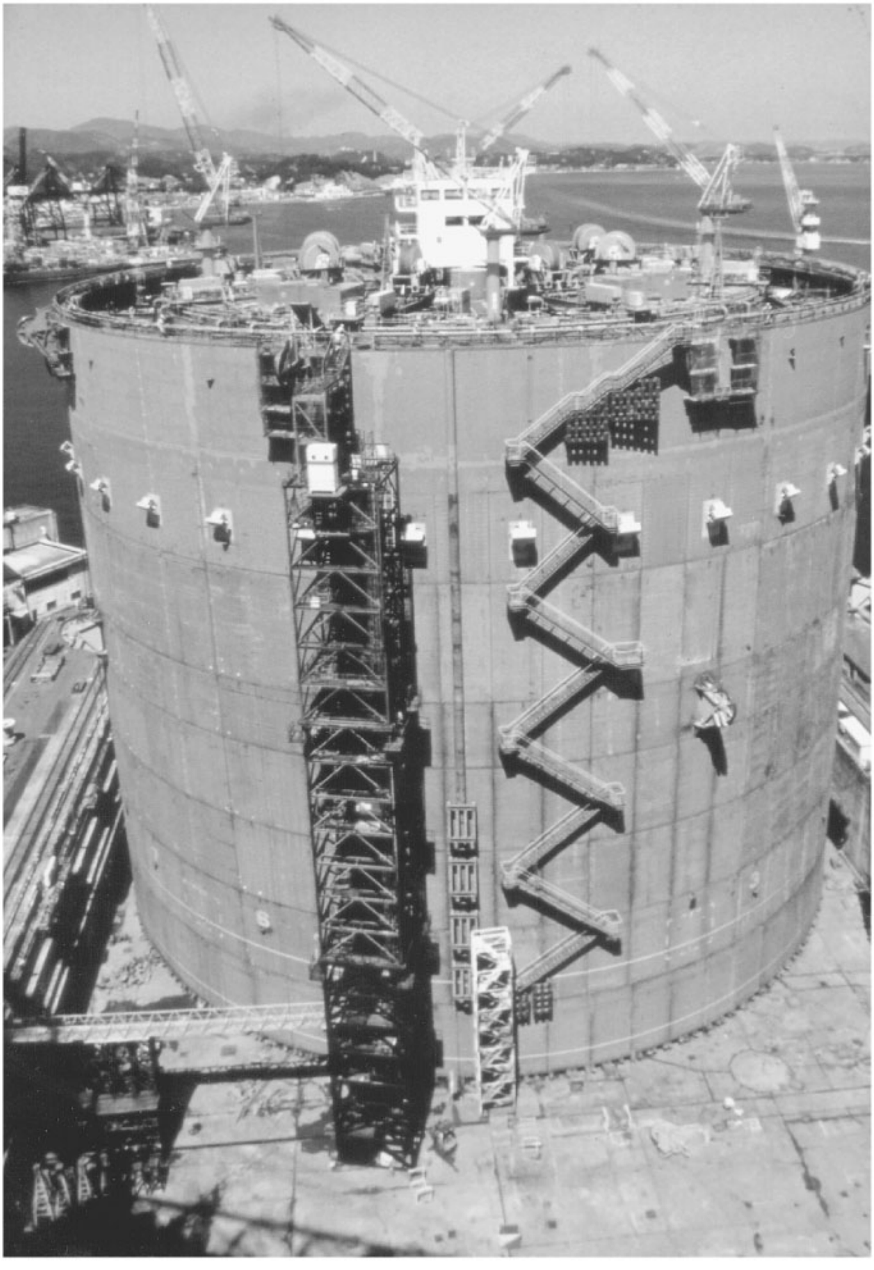

FIGURE 65.35 Steel caisson.

possibility of cable-stayed bridges, the bridges were changed to that type. Because the weight of the girder required to carry road and rail traffic is substantial, two parallel cables were anchored to an upper chord on one side of the truss girder. Due to the narrow distance between the two cables, wake galloping in the leeward cables was observed. To suppress oscillations, a damping device connecting two cables was used. At each end of the girders, elastic springs in the bridge longitudinal direction were installed. This elastic support adjusts the natural period of the bridge, resulting in a reduction of inertia force due to earthquake. The laying-down caisson method was used for five underwater foundations.

FIGURE 65.36 Body of anchorage.

65.7.3 Onomichi–Imabara Route

This route is 60 km long. In this route, five suspension bridges and four cable-stayed bridges were opened to traffic.

Figure 65.41 shows the Ohsima Bridge completed in 1988, which is a single-span bridge with a 560-m span length. The distance between two cables is 22.5 m. For the stiffening girder, a trapezoidal box section with a depth of 2.2 m was used because of its economical efficiency and maintenance. This is the first application of the box girder to the stiffening girder of a suspension bridge in Japan. A spread foundation was adopted for all the anchorages and the main towers which were constructed on land.

Figure 65.42 shows the Innoshima Bridge whose center and side spans are 770 and 250 m, respectively. The distance between two cables is 26 m. This bridge was constructed at an early stage of the grander project. One strand consisting of 127 wires, which are larger than the more commonly used size of 61 or 91, were developed. A reduced construction period was attained by using this strand. The same type of foundations as the Ohsima Bridge was adopted for this bridge.

Figure 65.43 shows the Kurishima Kaikyo Bridges, which are three consecutive suspension bridges. These bridges were opened to traffic in 1999. The center spans of the three bridges are 600, 1020, and 1030 m. The distance between two cables is 27 m. The girder has a streamlined box section with a depth of 4.3 m. The block of the girder is transported by a self-sailing barge, lifted up with the lifting machine, and finally fixed to hanger ropes. For connection of the block of some parts of the tower, tension bolts instead of friction bolts were employed. Two common anchorages that have a similar cable strand anchoring system as the Kita and Minami Bisan-Seto

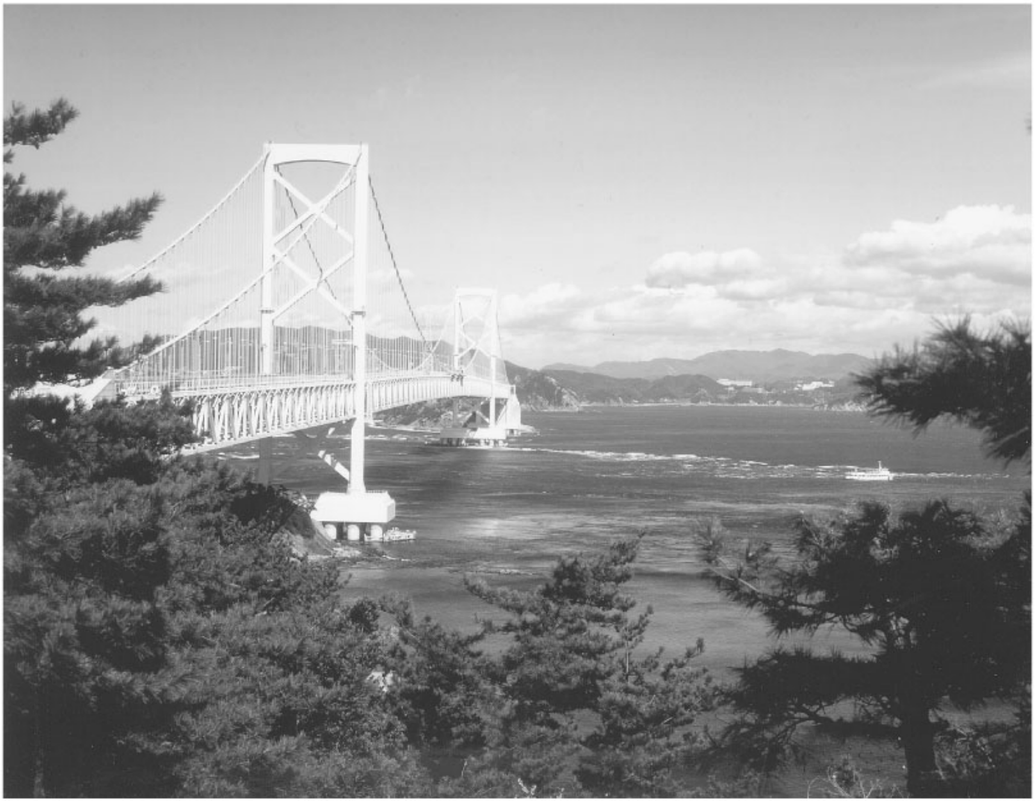

FIGURE 65.37 Ohnaruto Bridge.

Bridges were constructed in these three bridges. The laying-down caisson method was adopted for six underwater foundations. A concrete caisson was used for the two relatively small caissons, while the other caissons were made of steel.

Figure 65.44 shows the Tarata Bridge [6,7], which has a world-record span of 890 m and side spans of 320 and 270 m. This bridge was opened to traffic in 1999. Since the side span is short, prestressed concrete girders with a span of 110 and 62.5 m from both abutments are used, and connected to steel girder. These prestressed concrete girders work to counter the large uplifting forces and contribute to an increased in-plane flexural rigidity of the bridge. The depth of the girder is 2.7 m and the ratio of the center span length to girder depth is around 330. Buckling instability of the girder was investigated through analytical and experimental studies. In the experimental study, a $\frac{1}{50}$ full model was used. Aerodynamic stability was investigated by wind tunnel tests with a $\frac{1}{70}$ full model and a $\frac{1}{200}$ full model. In the latter model, the influence of the surrounding topography on aerodynamic behavior was also investigated. The laying-down caisson method was used for two of the tower foundations.

Figure 65.45 shows the Ikuchi Bridge completed in 1989. The center span is 490 m and the side span is 150 m. Again, since the side span length is short, prestressed concrete girders were used in both side spans and were connected to the steel girder. Various connecting methods were investigated, through which a combination of bearing plate and shear studs was used. Each cable consists of galvanized steel wires with a diameter of 7 mm, and is coated with polyethylene (PE) tube. A pile foundation was adopted for all piers since the ground was composed of weathered rock.

FIGURE 65.38 Shimotsui-Seto Bridge.

65.8 New Bridge Technology Relating to Special Bridge Projects

Masatsugu Nagai

65.8.1 New Material in the Tokyo Wan Aqua-Line Bridge [8]

The Tokyo Wan Aqua-Line with a 15.1 km length crosses the Tokyo Bay, and links Kanagawa and Chiba prefectures. It was opened to traffic in December 1997. It has a marine section of 14.3 km, and consists of an approximately 9.5-km-long tunnel and 4.4-km-long bridge structures. Here, an outline of the bridge and new material for corrosion protection of steel piers are introduced.

Figure 65.46 shows a general view of the bridges, which consists of 3-, 10-, 11-, 10-, and 9-span continuous steel box girder bridges. Since the maximum span length of 240 m is needed for a navigation channel and the strength of soil foundation is weak, steel box girders were designed and constructed. For erection of most of the bridges, floating cranes and deck barges were used. After completion of the superstructure, vortex-induced oscillation with an amplitude over 0.5 m was observed. To suppress it, 16 tuned mass dampers, as shown in Figure 65.47, were installed. Part of the steel deck was cut out and stiffened. After installing the tuned mass dampers, the removed plates were welded to the original position.

To attain higher durability of steel piers, titanium-clad steel is attached to the steel piers. Figure 65.48 shows the pier with the titanium-clad steel. It was used in the region of the steel piers affected by tidal movement and saltwater spray. By employing this system, a maintenance-free system more than 100 years is expected.

FIGURE 65.39 Kita-Bisan Seto and Minami-Bisan Seto Bridges.

65.8.2 New Bridge System in the New Tomei Meishin Expressway

Japan Highway Public Corporation started constructing the New Tomei (between Tokyo and Nagoya City) Meishin (between Nagoya and Kobe Cities) Expressway which is around 600 km long and links the big cities of Tokyo, Nagoya, Osaka, and Kobe.

Figure 65.49 shows a plate I-girder bridge with a small number of main girders, which is a new bridge system employed for Ohbu Viaduct near Nagoya City. This viaduct was constructed in 1998. Conventionally, the distance of the I-girder, which corresponds to the span of concrete slabs, has been designed to be less than 3 m. However, in this project, using prestressed, precast concrete slabs,

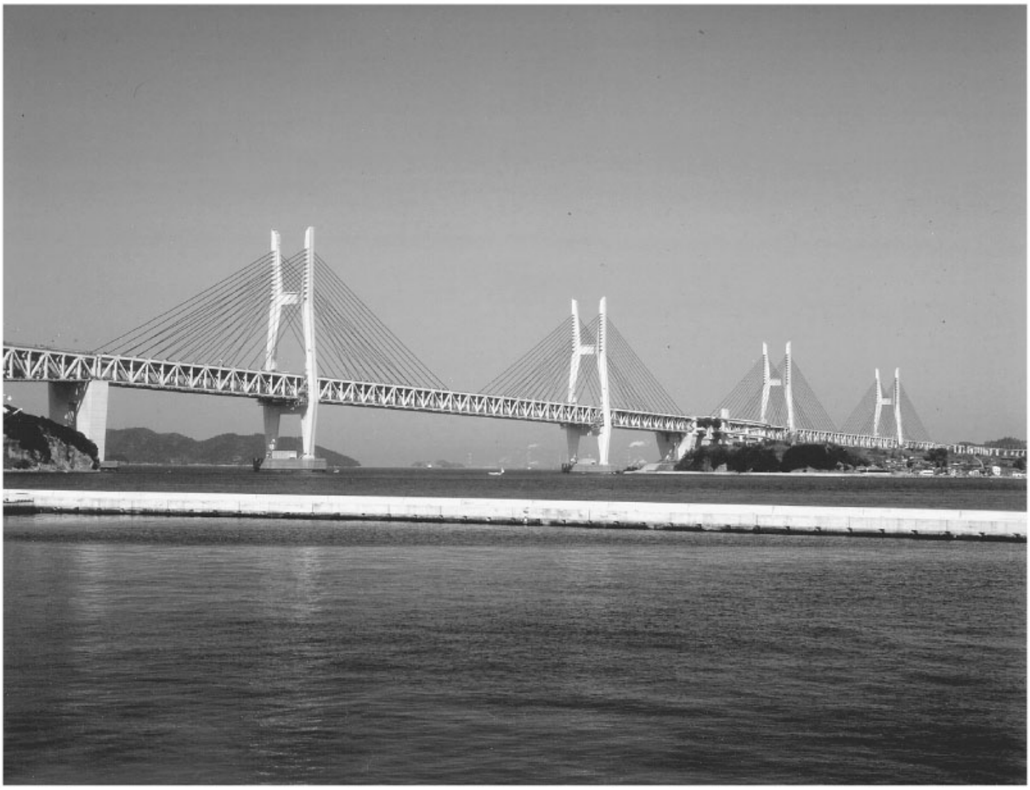

FIGURE 65.40 Iwakurojima and Hitsuishijima Bridges.

the span of the slab extended to 6 m. Hence, for a three-lane bridge with a width of around 15 m, the number of the I-girders is reduced from 6 to 3. Further, the I-girders are connected by simple beams arranged at a distance of around 10 m only. Conventionally, I-girders have been stiffened by cross-beams or bracing, which are installed at a distance less than 6 m, and a lateral bracing member, which is installed at a lower level of the girder. This simple bridge system can reduce the construction cost and also the painting area. Further, this system leads to easy inspection.

65.8.3 Superconducting Magnetic Leviation Vehicle System [9]

Japan Railway Corporation has a plan of constructing a new line, the Chou–Shinkansen line. Using a high-speed train, it will run through the central part of Japan from Tokyo to Osaka. Now, in a test line with a 18.4 km length constructed in Yamanashi prefecture, the running stability, etc. of the high-speed train is being tested.

Figure 65.50 shows the Maglev car running through Ogatayama Bridge which will be explained later. It levitates 100 mm from the ground and runs at a speed of 500 km/h. A repulsive force and an attractive force induced between the superconducting magnets on the vehicle and the coils on the side walls (propulsion coils and levitation coils) are used for propelling and levitating the car. The following are the major technical issues involved in designing the structures.

1. The deflection of the structures should be small to ensure running stability and riding comfort of the train.
2. High accuracy should be attained when positioning the coil on the side walls.
3. Magnetic drag force due to magnetic phenomenon produced between the magnet and steel should be small.

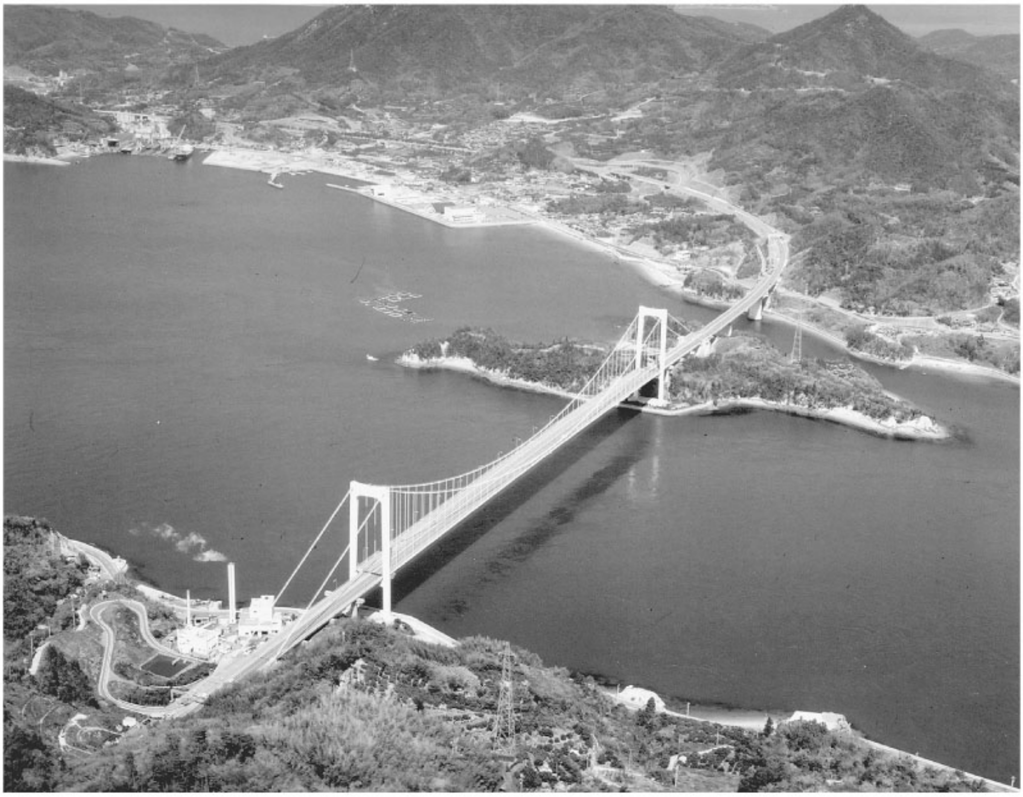

FIGURE 65.41 Ohshima Bridge.

The countermeasure of the third issue is to use a low-magnetic metal such as austenitic high-manganese steel when the metal is positioned within 1.5 m of the superconducting magnet.

Ogatayama Bridge completed in 1995, a Nielsen Lohse bridge, is shown in Figure 65.50. The span and arch rise are 136.5 and 23 m, respectively. The width between the center of the arch chords is 15 m at springing and 9.6 m at arch crown. In this bridge, the steel structures such as the arch chord and floor system are designed to be positioned 1.5 m apart from the magnet. However, for the reinforcing bars encased in the guide way, high-manganese low-magnetic steel is used.

65.8.4 Menshin Bridge on the Hanshin Expressway

Early in the morning on 17 January 1995, a huge earthquake shook the densely populated southern part of Hyogo prefecture. Many steel and concrete bridges fell due to the collapse of reinforced concrete piers. Many steel piers suffered buckling damage and two collapsed. Immediately after the earthquake, investigation began to identify the causes of damage and repair work, such as encasing the concrete piers and increasing longitudinal ribs in the steel piers. The concrete deck changed to the steel deck, and the collapsed prestressed concrete girders changed to steel bridges. This is to reduce the weight of the superstructures. In addition, metal bearings were also replaced by rubber supports for greater damping.

Figure 65.51 shows the typical rubber support. Almost all metal bearings were changed to this type. Figure 65.52 shows the rigid-frame-type piers. At the foot of a column, rubber bearings were installed to isolate earthquake acceleration. Bridges with these isolating system are called Menshin bridges.

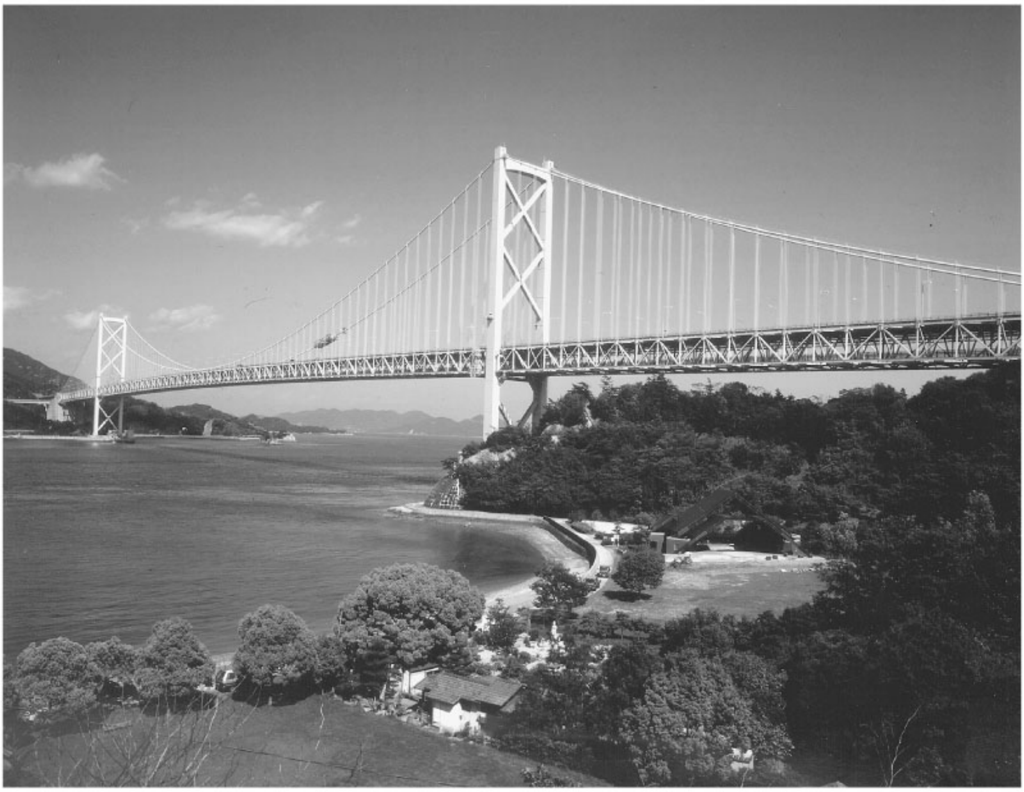

FIGURE 65.42 Imnoshima Bridge.

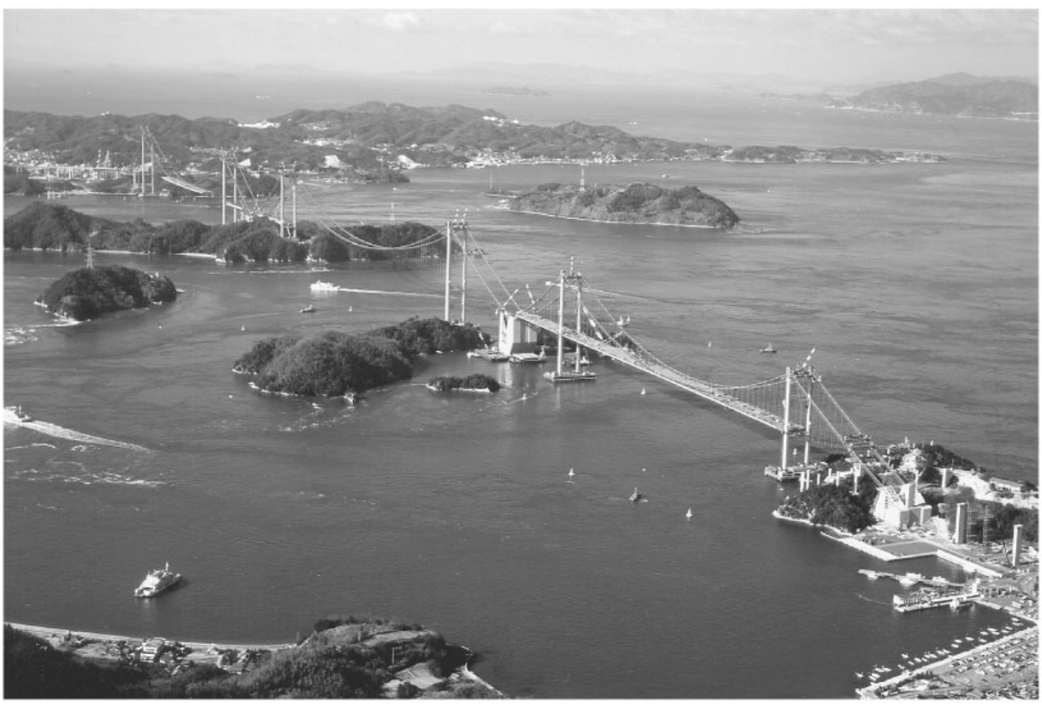

FIGURE 65.43 Kurushima Kaikyo Bridges.

FIGURE 65.44 Tatara Bridge.

FIGURE 65.45 Ikuchi Bridge.

FIGURE 65.46 Steel bridges on Tokyo Wan Aqua-Line. (Courtesy of Trans-Tokyo Bay Highway Corporation.)

65.8.5 Movable Floating Bridge in Osaka City [10]

The world's first swing and floating bridge is under construction in the Port of Osaka. It will be completed in 2000. The main role of the bridge is to connect two reclaimed islands (the names are Maishima and Yumenoshima). The width of the waterway between the two islands is around 400 m. In case of the occurrence of unforeseen accidents in the main waterway of the Port of Osaka nearby, this warterway (subwaterway) will provide an alternative entrance. On such occasions, large-sized vessels will pass the subwaterway. In addition, the soil foundation is not strong enough to resist the loads of a conventional bridge. Hence, a movable floating bridge with two pontoon foundations and a swing type has been conceived. The bridge has a total length of 940 m and a width of 38.4 m. The floating part has a length of 410 m and a main span length of 280 m with a double-arch rib rigidly connected to two steel pontoons as shown in Figure 65.53. Safety against dynamic responses subjected to waves, winds, earthquake, and heavy track loading have been investigated through numerical and experimental studies.

65.9 Summary

Tetsuya Yabuki

A chronological table of the major revisions of the standard specification of highway bridges and the concrete standard specification in Japan during the latter half of the 20th century is shown in

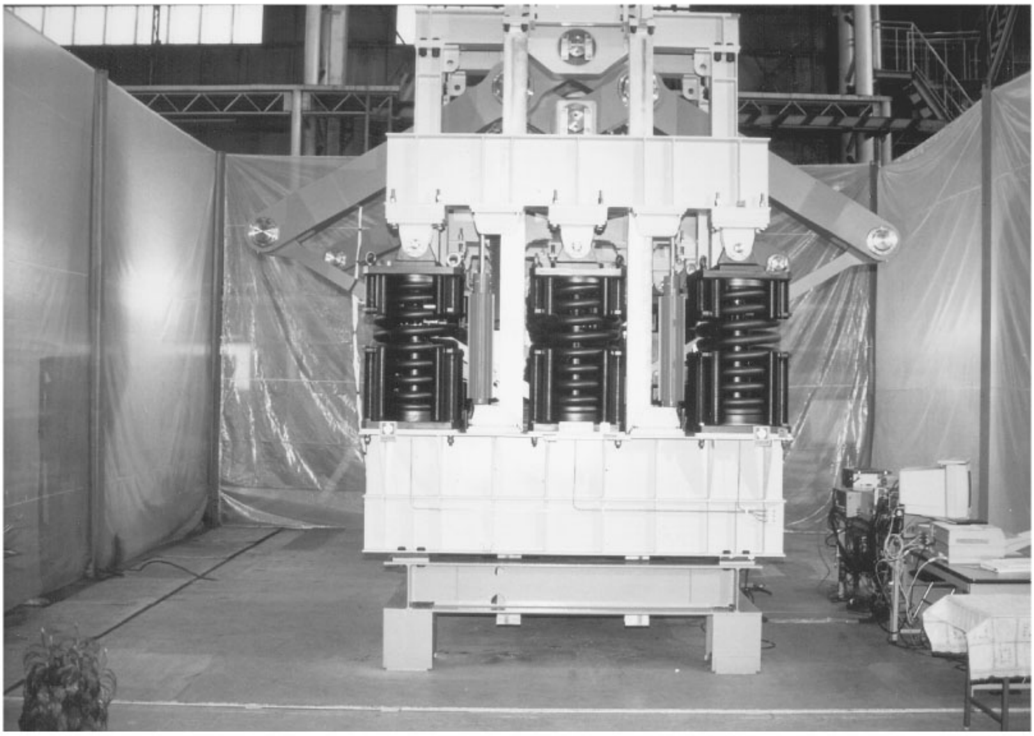

FIGURE 65.47 Tuned mass damper. (Courtesy of Trans-Tokyo Bay Highway Corporation.)

TABLE 65.5 Chronological Table on the Revisions of the Standard Specifications and the Major Earthquake Disasters in Japan

Epoch	Occurrences
1948	Fukui earthquake disaster
1956	Revision of the Standard Specification of Highway Bridges
1964	Niigata earthquake disaster
1968	Tokachi offshore-earthquake disaster
1971	Establishment of self-editing on the seismic design specification in Standard Specification of Highway Bridges
1973	Revision of the Standard Specification of Highway Bridges
1978	Miyagi Prefecture offshore-earthquake disaster
1980	Revision of the Standard Specification of Highway Bridges
1986	Revision of the Concrete Standard Specification
1995	Great Hanshin-Awaji earthquake disaster
1996	Revision of the Standard Specification of Highway Bridges
	Revision of the Concrete Standard Specification

Table 65.5. The major earthquake disasters in Japan are also shown in Table 65.5 for reference purposes. The design specifications of bridges have been revised mainly whenever strong earthquakes have occurred as shown in Table 65.5. We may be able to make the statement that the most important influence on the evolution of bridges in Japan has been earthquakes. This shows that disasters have controlled bridge engineering. The evaluation of conditions to produce an efficient bridge for seismic motion is distinctly an engineering problem. Therefore, bridge engineers have to escalate their efforts from now on so that bridge engineering can control bridge disasters. The evolution of bridges will be achieved by bridge engineers' efforts to develop optimum structural performance with materials that will be in shorter supply, be longer in durability, give higher strength, and bring less dynamic inertia force.

FIGURE 65.48 Steel pier with titanium-clad steel. (Courtesy of Nippon Steel.)

FIGURE 65.49 Plate I-girder with simple cross-beams.

FIGURE 65.50 Maglev car and Ogatayama Bridge. (Courtesy of Japan Railway Corporation.)

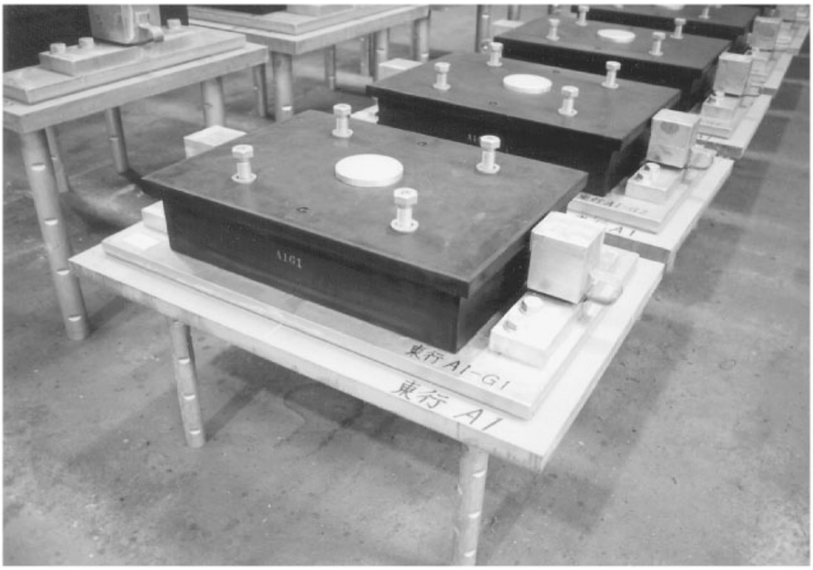

FIGURE 65.51 Rubber bearings.

FIGURE 65.52 Rigid frame pier of Benten section. (Courtesy of Hanshin Expressway Public Corporation.)

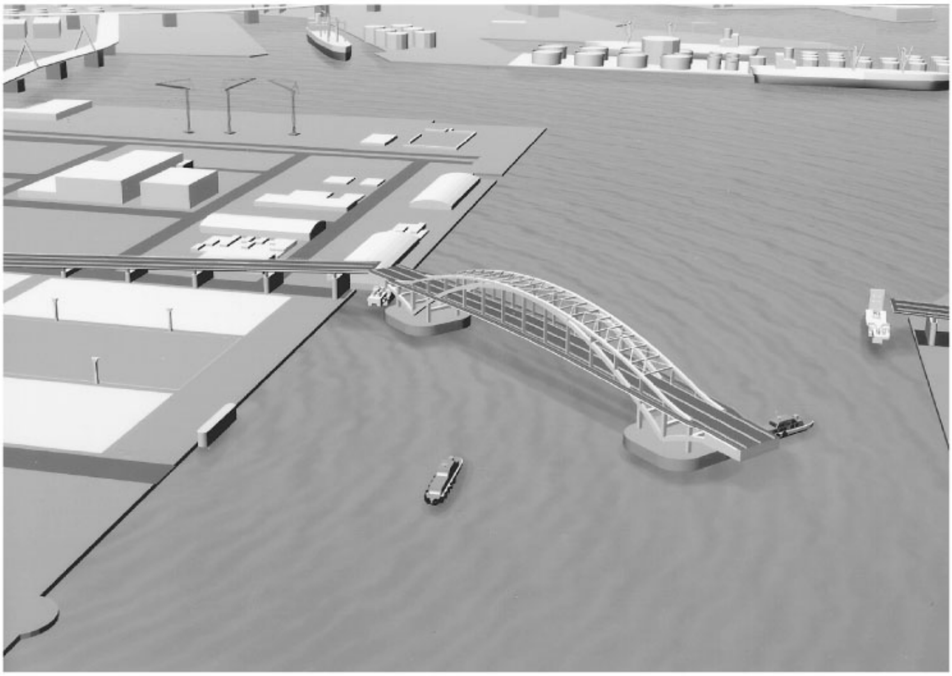

FIGURE 65.53 Yumeshima-Maishima Bridge. (Courtesy of Osaka Municipal Government.)

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