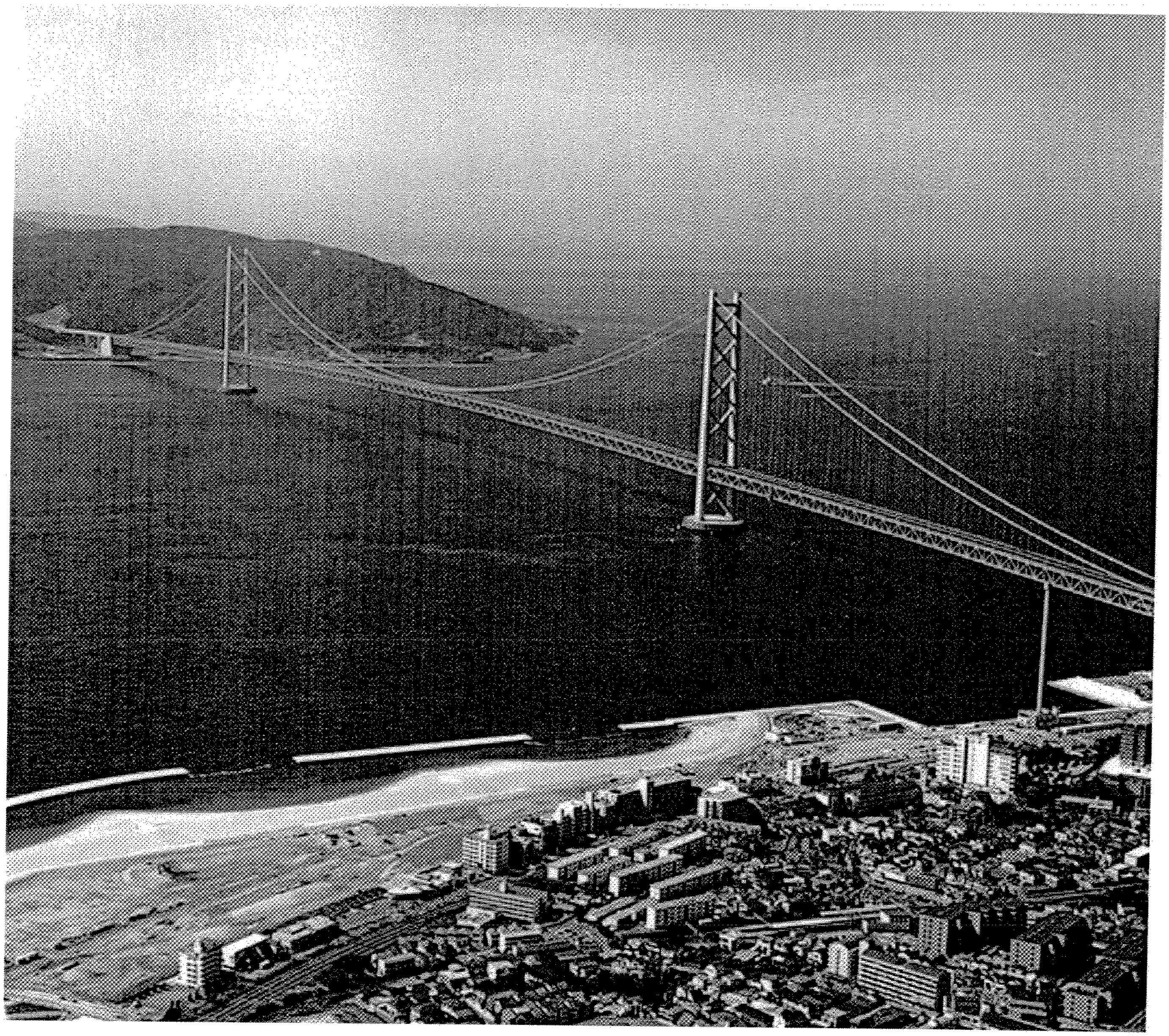
The Structural Art of the Akashi Kaikyo Bridge



Since World War II ended in 1945 Japanese civil engineering has made great progress to bring Japan to the level of other leading countries. They currently boast the longest spanning suspension bridge and the longest cable-stayed bridge in the world, the Akashi Kaikyo and Tatara Bridge respectively.

The Akashi Kaikyo Bridge is the perfect symbol of Japan's postwar achievement in civil engineering. It is the longest spanning bridge in the world currently and is part of a larger project, which has built several of the world's longest bridges including the Tatara. Known also as the "Pearl Bridge" in Japan it has been appropriately referred to as their "crown jewel."

The Akashi Kaikyo Bridge is a three span, two hinged stiffening girder system suspension bridge that spans from Maiko, Kobe to Matsuho, Awaji Island. The main span is 1991 meters long with a total length of 3911 meters. It took ten years to complete the bridge constructed in an area known for harsh weather conditions and earthquakes. An earthquake that killed over 5,500 people hit Kobe before construction was finished; yet no one was killed, only six people were injured and the Akashi Kaikyo sustained no structural damage. Completed on April 5, 1998, the Akashi Kaikyo became the longest suspension bridge in the world, longer than the Humber Bridge in England by 581 meters.

Honshu-Shikoku Bridge Authority and the Contractors Responsible for its bridges

The Honshu-Shikoku Bridge Authority was established in 1970 for the sole purpose of smoothing out traffic flow between Honshu and Shikoku. The authority intends to help Japan soundly develop its lands, by constructing and managing toll roads and railroads across the Honshu-Shikoku Bridges. The Authority oversees the design, construction and maintenance of all bridges in the circuit. It employs the use of many contractors in the completion of each individual bridge project as directed by public works policy in Japan. The project included ten suspension bridges, six cable-stayed bridges, one arch, and one truss bridge.

The authority must abide by the Laws Concerning Special Measures for Ferry Boat Companies in relation to the construction of the bridges and must conduct research surveys, designs, tests, and studies of long span bridges as requested by the national and local government

The Honshu-Shikoku Bridge Authority also has an international exchange program in which it shares the latest bridge building technologies with other countries. They also sign sister bridge affiliations with foreign long span bridges. The Akashi Kaikyo Bridge's sister bridge is the Great Belt Bridge in Denmark. This exchange program allows both countries to develop a mutually widening scope of commercial, social, and cultural exchanges.

The Akashi Kaikyo is part of one of the three major highway and bridge routes the bridge authority developed. The first route, the Nishi-Seto Expressway Route, features a four-lane highway with a design speed of 80 km/hr. It is 60 km long and is composed of 10 bridges. The second route is called the Seto-Chuo Expressway Route. It is a four-lane highway and a double track ordinary railway. In the future, two additional tracks for a shinkansen line are to be incorporated. Six double-decked bridges, the upper deck for car traffic and the lower deck for rail traffic, make up this route.

Finally, the third route, which contains the crowning achievement of the entire Honshu-Shikoku Bridge Project, the Akashi Kaikyo Bridge, is called the Kobe-Awaji-Naruto Expressway Route. This route contains two bridges and was designed for a speed of 100 km/hr. The master plan set by the national government included a double track shinkansen line, however, its construction has been delayed. Two bridges comprise this route; the Ohnaruto Bridge and the Akashi Kaikyo Bridge.

The end result of the Honshu-Shikoku Bridge Project is a network of bridges and roadways that have reduced travel time and enriched the Japanese economy. Simultaneously the project has been a source of pride for Japan, creating new monuments like the Akashi Straits Bridge, which can be seen from its own viewing platform.

The total time it took to travel between Kobe and Tokushima by ferry was 270 minutes. Using the Akashi Kaikyo and other bridges of the Honshu-Shikoku Bridge Project, travel time was drastically reduced to 100 minutes.

> More options of transportation and the expansion of the 3-hour traveling zone [equals] increased convenience in commuting to work and school, improved transportation of wide area emergency medical treatment.[1]

The Akashi Kaikyo also changed the economies of the areas it connected. The number of plants on Shikoku is increasing at a higher rate since its opening. The number of large retail stores also increased by 190%. The estimated value of the benefits of reduced travel cost and time saved totaled 250 billion yen a year. After four years, this value is expected to reach 8.7 trillion yen. Benefits based on gross production are estimated to be 1.21 trillion yen nationwide and 889 billion yen in bridge affected areas. Finally, because of this bridge project, there are 120,000 more jobs. So despite the

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[1] Honshu-Shikoku Bridge Authority. http://www.mof.go.jp/english/zaito/zaito2001e-exv/22.pdf

bridge's record setting cost, an estimated 4.3 billion U.S. dollars, it is more than paying for itself.

wow!

Need for the Akashi Kaikyo and the Honshu-Shikoku Bridge Project

> It was a natural course of selection for Japan to have accomplished a remarkable economic growth by promoting the modernization of her industries through dependence on exports, because it is the only alternative for the nation to catch up with other advanced industrial nations after the war and to survive by establishing a state on the basis of the foreign trade. Today, however, Japan has become a country in expediting economic structural change, namely emerging out of her export dependent economy into one led by domestic demand and expansion. [2]

Now that Japan has shifted its focus to promoting economic growth within, the need for faster routes between its islands is far greater.

To upgrade their national living standard Japan needs to convert her economic and social structures. The Akashi Kaikyo is quite a big upgrade in structure and it has added to the standard of living in Japan. The bridge has contributed to the greater activity between Honshu and Shikoku which has seen an 80% increase in people going back and forth between 1984 and 1999. The Akashi Kaikyo is the heaviest traveled of all the bridges in the project. 22,659 cars travel the bridge per day. The Tatara Bridge is passed by 3,888 cars per day, a figure that pales in comparison to the suspension bridge's, but is a significant figure in the overall picture of what the project has accomplished.

In 1973 the authority developed their initial plan for the Akashi Kaikyo Bridge. It would be a three span, two-hinged suspension bridge w/ center span of 1,780 meters,

[2] Fujii, Toshio. "Civil Engineers in the Coming of Age." ***Civil Engineering in Japan.*** Tokyo Japan: Japan Society of Civil Engineers, 1993.

sides of 890 meters, and total bridge length 3,500 meters. At the time it was intended to be a combined highway and railway bridge.

Connecting the Kobe-Naruto Route with the Keihanshin District and Shikoku promised great economic benefits and made the construction of Akashi Kaikyo an immediate priority. The authority was directed by government to study the feasibility of the bridge as an independent highway bridge in 1981. The report was submitted in 1985. The final plan was a 3-span, 2-hinge stiffening truss suspension bridge with a center span of 1,990 meters, 960 meter side spans, making the bridge 3,910 meters in total length. Groundbreaking took place in April of 1986 and two years later real site work began (May 1988).

The Akashi Kaikyo Bridge spans the Akashi Straits. Typhoon and earth quake considerations as well as the width of the straight and construction of main towers in deep sea during tidal currents made the construction of this bridge the most difficult in the project.

The size of the bridge made wind resistance even more critical than in other suspension bridges. Separate wind resistant design criteria have been created for the Akashi Kaikyo Bridge, making considerations for horizontal deflection components as well as vertical and torsion components of gust response.

The bridge was a success. The finished product is an elegant and enormous bridge connecting two islands for highway traffic. A parade of more than 1,500 invited guests helped Japan celebrate their masterpiece built by more than 100 contractors each with specialized task.

Construction

Main Tower Foundations

The first thing the Akashi Kaikyo would need to be successful was a stable foundation for the main towers. These foundations would transmit the 120,000 tons of force from the main towers to the support ground. The support ground, the Akashi stratum, located 60 meters below sea level, was dug using a grab bucket dredger. Using technologically advanced devices, challenging conditions such as digging in strong currents, deep water and strong waves were overcome. Miraculously, the vertical variation of +/-10 cm needed for proper installation of the caisson was achieved.

The caissons were made on land and then towed out to the site and submerged. This method had many advantages over the methods used for the installation of the Eads Bridge caisson or the Brooklyn caissons for many reasons. Some advantages are the elimination of Caisson Sickness and not having to transport workers from land all the way out to the caissons in the middle of the straight. After the caisson was sunk into the hole that was dredged from the riverbed, they were then filled with standard concrete and underwater nondisintegration concrete, which was specially designed to be used in the foundations. The caisson was purposely designed to be a cylinder so that it would be aerodynamic in the water, making it easier to handle the strong currents of the straight. It was also designed to resist severe earthquakes with a newly investigated seismic design method. The earthquake to which the bridge was designed was one which occurs off the Pacific coast about 150 km away with a magnitude of 8.5 on the Richter scale. Each

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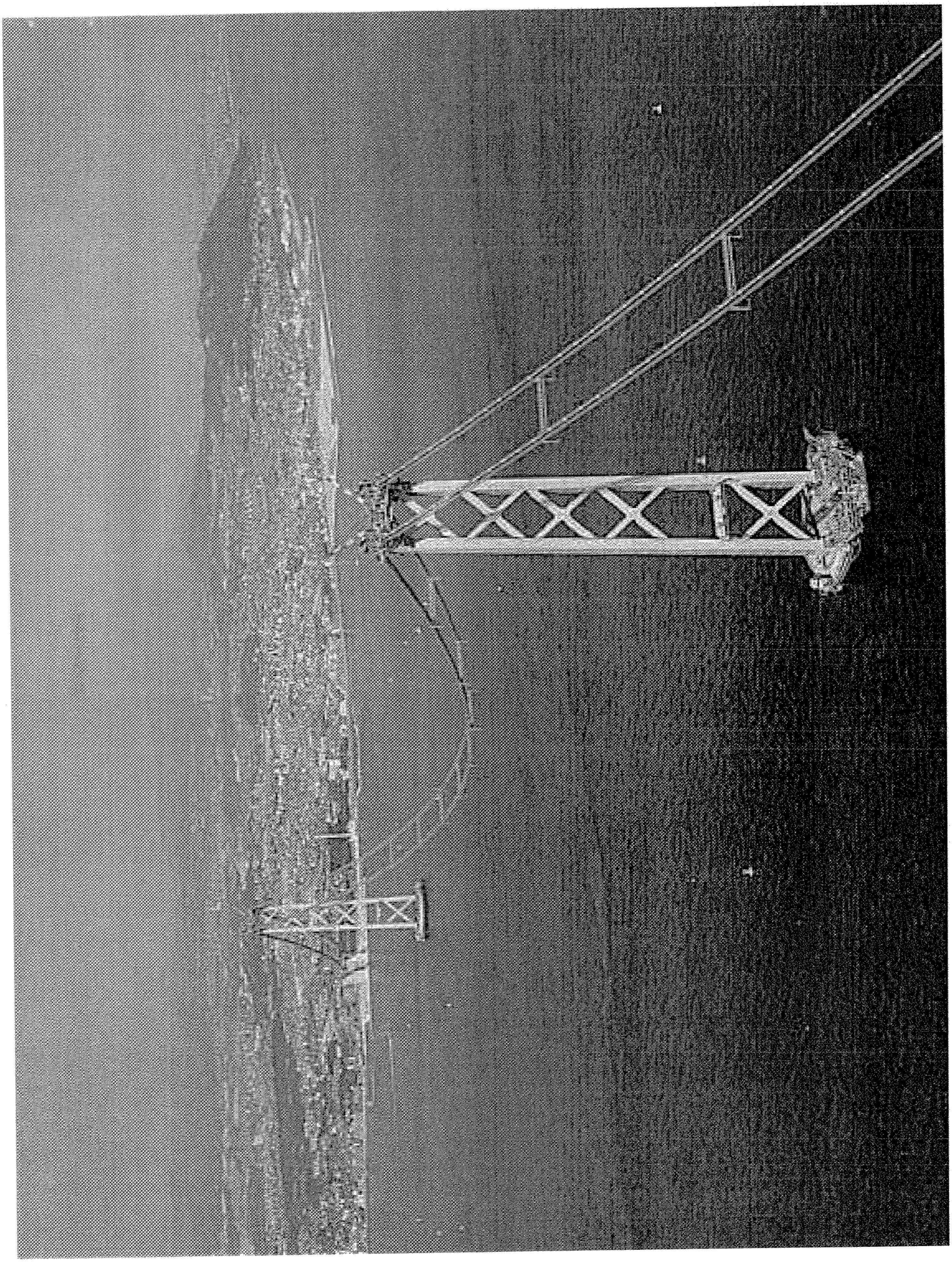


caisson was 80 m in diameter, 70 m high and used 15,800 tons of steel and 355,000 m^3 of concrete.

Main towers

When the caissons were securely in place, the building of the main towers began. The towers were built similarly to Roman columns, which were divided horizontally into separate sections. The Akashi Kaikyo main towers were divided into 30 horizontal sections, with each horizontal section divided into 3 blocks, so that the blocks would not exceed 160 tons each. The tower height is 282.8 meters and the max width is 46.5 meters. Each tower weighs approximately 23,000 tons. Their immense size subjects them to massive wind loads, which is counterbalanced by X braces in the cross sections that are insensitive to wind induced oscillations. Massive stabilizers called tuned mass dampers also counter wind load. Twenty of these dampers, weighing ten tons each, are built into the towers at the seventeenth, eighteenth, and twenty-first tiers. These tuned mass dampers are massive blocks that slide antiparallel to the direction the towers sway. This motion absorbs much of the energy exerted on the tower by the strong winds. At the top of the tower, the saddles transmit the weight of the bridge from the cables to the foundations. These saddles are located 297.3 m above sea level.

wow! TWO towers?

Anchorages

Installing the anchorages at the shores of the bridge involved having to reclaim land. The 1A anchorage on the Kobe side was constructed using the underground slurry wall method. The support below the anchorage was a huge manmade circular foundation measuring 85 meters in diameter and 63.5 meters deep, making it the largest anchorage foundation in the world. The anchorage on the other shore, the 4A anchorage, was constructed by a retaining wall using the spread foundation method of construction. The part of the anchorages that support the tension of the cables were made from highly workable concrete which was highly fluid and needed no compacting. Developed specifically for the bridge, this concrete increased efficiency in casting and reduced overall construction time. Anchorage 1A contains 140,000 cubic meters of concrete, which is about 350,000 tons. Anchorage 4A contains 150,000 cubic meters of concrete, which is about 370,000 tons.

Cables

The original design of the Akashi Kaikyo involved using a total of 4 cables to support the bridge. However, with the development of stronger galvanized steel wire specifically for the Akashi Kaikyo, only two cables were necessary. This wire had a tensile strength of 180 kgf/mm^2 whereas the old one only had a tensile strength of 160 kgf/mm^2. Each cable contains 290 hexagonal strands, which each contain within themselves 127 hexagonal galvanized steel wires. The method used to install these cables was called the Prefabricated Parallel Wires Strand method. A total of 300,000 km of wire was produced in a factory using this method. The length of wire created was enough to circle the earth 7.5 times. A corrosion resistance system was developed for the cables in which dehumidified air is run through the voids in the cable, thus drawing out humidity which would otherwise be trapped inside.

Stiffening Girders

Due to the immense size of the Akashi Kaikyo, the wind loads sustained by the stiffening girders are greater than any bridge in existence. However, with the use of high tensile strength steel as the material of choice, a strong yet lightweight and therefore economical solution was found. Of course, lightweight is used relatively; 90,000 tons of steel were used. The method used to construct the stiffening girders was called the plane block method. This technique begins at the main towers and anchorages, where 6 and 8 panel blocks were installed, respectively. The truss members that were preassembled in the factory were brought to the construction site and erected inwards from the anchorages and towers. The truss stiffened girder was chosen over a streamlined box girder because it had more aerodynamic stability and could be installed without interrupting the sea traffic below.

Aesthetic Considerations

The Akashi Kaikyo would be the longest spanning bridge in the world and thus, Japan designed it with much care, knowing it would be heavily examined and scrutinized by the rest of the world. The appearance of the tower had to meet three themes. The bridge had to give off the appearance of reliability and the ability to withstand loads caused by typhoons, earthquakes, and heavy traffic. The bridge also had to give off a sense of future by suggesting boundless possibility. Finally, the bridge had to strike the perfect balance between light and shade and enhance the beauty of the Seto-Inland Sea.

The structural features were also carefully designed to blend into the surroundings. The anchorages were specially designed so that they would appear less massive and balanced. This was achieved by using special shapes and an outer wall surface treatment. The color chosen for the Akashi Kaikyo was a greenish-gray because it is modern and harmonizes well with the urban landscape while looking vivid, yet soft, and adds to the colors of the sea and sky in the straight. Every detail was scrutinized, even the bridge illumination, which is changed monthly or seasonally following a predetermined plan. The Akashi Kaikyo has 1,173 illumination lights, 1,084 on the main cables, 116 on the main towers, 405 on the girders, and 132 on the anchorages. To reduce the maintenance costs of the bridge, the paint was coated with a newly developed fluorine-resin paint which had high durability. In this coating system, the zinc-rich paint plays a huge part in preventing corrosion of the steel.

Wind Tunnel Tests

Because of the huge scale of this bridge, it was deemed necessary to perform tests on a model instead of basing the decisions on calculations alone. To do this, the bridge authority built the world's largest boundary layer wind tunnel at the Public Works Research Institute. The standard 2 dimensional test with a rigid partial model was performed as well as an optional but decidedly necessary 3 dimensional test with a rigid partial model. Even thought the bridge was only 1:100 scale, it was still 40 m long. One of the outcomes of this test was to establish a flutter analysis method, which would allow the engineers to calculate the critical wind speed of flutter on the actual bridge.

Engineers also discovered that by adding a vertical stabilizing steel fin under the roadway of the main span, galloping and oscillations caused by vortex shedding would be reduced.

Area of the Cable

Each round cable is composed of 290 hexagonal strands.

Each hexagonal strand is composed of 127 round wires.

Each round wire is 5.23 mm^2.

The total diameter of the round cable is 1.122 m^2.

$$A_{Cable} = \frac{\pi}{4}d^2 = \frac{\pi}{4}(1.122m)^2 = .989m^2$$

Two cables = **1.98 m^2**

Dead Load

Main cable, hanger ropes, saddle, etc.: 57,700 tons

Main structure, maintenance road, etc.: 89,300 tons

Total Dead Load: 147,000 tons

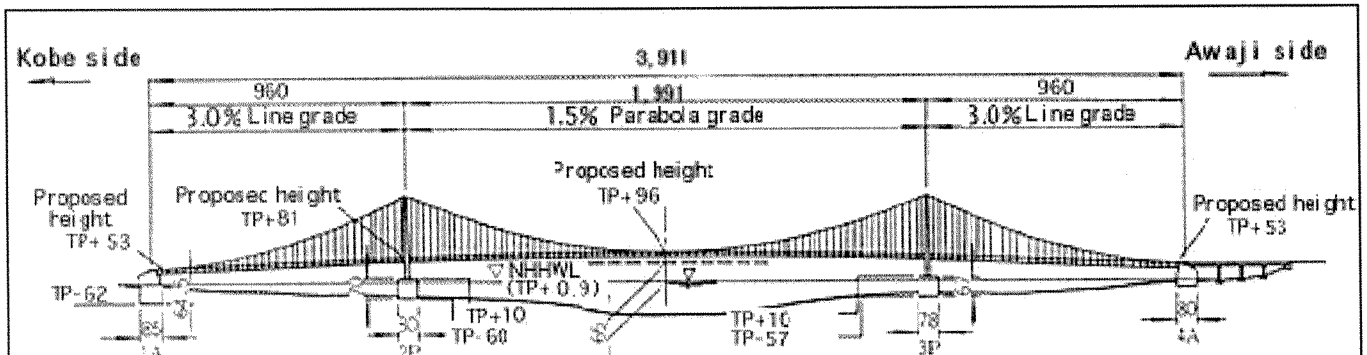
$$147{,}000tons * \frac{2000lbs}{1ton} * \frac{4.45N}{1lb} = 1.31X10^6\,kN$$

Q_{dead} = (1.31X10^6 kN)/(3911 m) = **335 kN/m**

Live Load

Taking the live load from the GWB, we found what that load would be on the Akashi Kaikyo Bridge by doing a ratio using the load vs. the # of lanes.

$$\text{GWB} \rightarrow \frac{46kip/ft}{8lanes} = \frac{x}{6lanes} \leftarrow \text{Akashi Kaikyo}$$


Kobe side
3,911
Awaji side
960
960
3.0% Line grade
1.5% Parabola grade
3.0% Line grade
Proposed height
TP+96
Proposed height
TP+53
Proposec height
TP+81
Proposed height
TP+53
TP-62
NHHWL
(TP+0.9)
TP+10
TP-60
TP+10
TP-57
2P
3P
78
80
4A

PROFILE

$$x = 34.5 \text{ kip/ft}$$

Converting to kN/m:

$$\frac{34.5X10^3 lb}{1ft} * \frac{4.45N}{1lb} * \frac{1ft}{12in} * \frac{1in}{2.54cm} * \frac{100cm}{1m} = 5X10^5 N/m = 504kN/m$$

This stress is caused by the worse case scenario of tractor trailers backed up bumper to bumper in all 6 lanes. To simulate a more realistic situation, ¼ of this load will be used in the following calculations. This fraction includes a factor of safety.

$$Q_{live} = (504 \text{ kN/m})/4 = \mathbf{126 \text{ kN/m}}$$

Force Calculations

$Q_{main} = (Q_{live} + Q_{dead}) = 126$ kN/m + 335 kN/m = 461 kN/m

$V_{center} = (461 \text{ kN/m})(1991 \text{ m}) = 9.2X10^6$ kN

$V_{center} = V_A = V_B =$ **$4.6X10^5$ kN**

X = ?

$Y = 4.6X10^5$ kN

$Z = (461 \text{ kN/m}) (995.5 \text{ m}) = 4.6X10^5$ kN

$M_C = (4.6X10^5 \text{ kN})(995.5 \text{ m}) - (4.6X10^5 \text{ kN}) (498 \text{ m}) - (X) (200) = 0$

$X = 1.14X10^6$ kN

$X = 1.14X10^6$ kN

Y = ?

$Z = (461 \text{ kN/m}) (960 \text{ m}) = 4.4X10^5$ kN

$M_D = (1.14X10^6 \text{ kN}) (200 \text{ m}) + (4.4X10^5 \text{ kN}) (480 \text{ m}) - (Y)(960 \text{ m}) = 0$

Y = **$4.6x10^5$ kN**

Total Force in Support: $2(4.6X10^5\ kN) = \mathbf{9.2X10^5\ kN}$

Stress Calculations

$\Theta = \tan^{-1}(995.5\ m / 200\ m) \approx \mathbf{78°}$

$\Theta = \tan^{-1}(960\ m / 200\ m) \approx \mathbf{78°}$

$9.2X10^5\ kN = 2T\sin(12°)$ $T = 2.2X10^6\ kN$

$Q_{Towers} = T / A_{Cable} = (2.2X10^6\ kN) / (1.98\ m^2) = \mathbf{1113\ MPa}$

$Q_{Midpoint} = T / A_{Cable} = (1.14X10^6\ kN) / (1.98\ m^2) = \mathbf{576\ MPa}$

High strength (1800 N/mm^2) galvanized wire was developed and used for the main cables, which allowed for the usage of one wire per side rather than two, even though the span of the bridge was very long and the sag/span ratio was 1/10.

$$\frac{1800N}{1mm^2} * \frac{(1000mm)^2}{1m^2} * \frac{1MN}{10^6 N} = \mathbf{1800\ MPa}$$

The stresses in the cable, 1113 MPa at the top of the tower and 576 MPa at the midpoint of the bridge are much lower than the 1800 MPa strength of the galvanized wire.

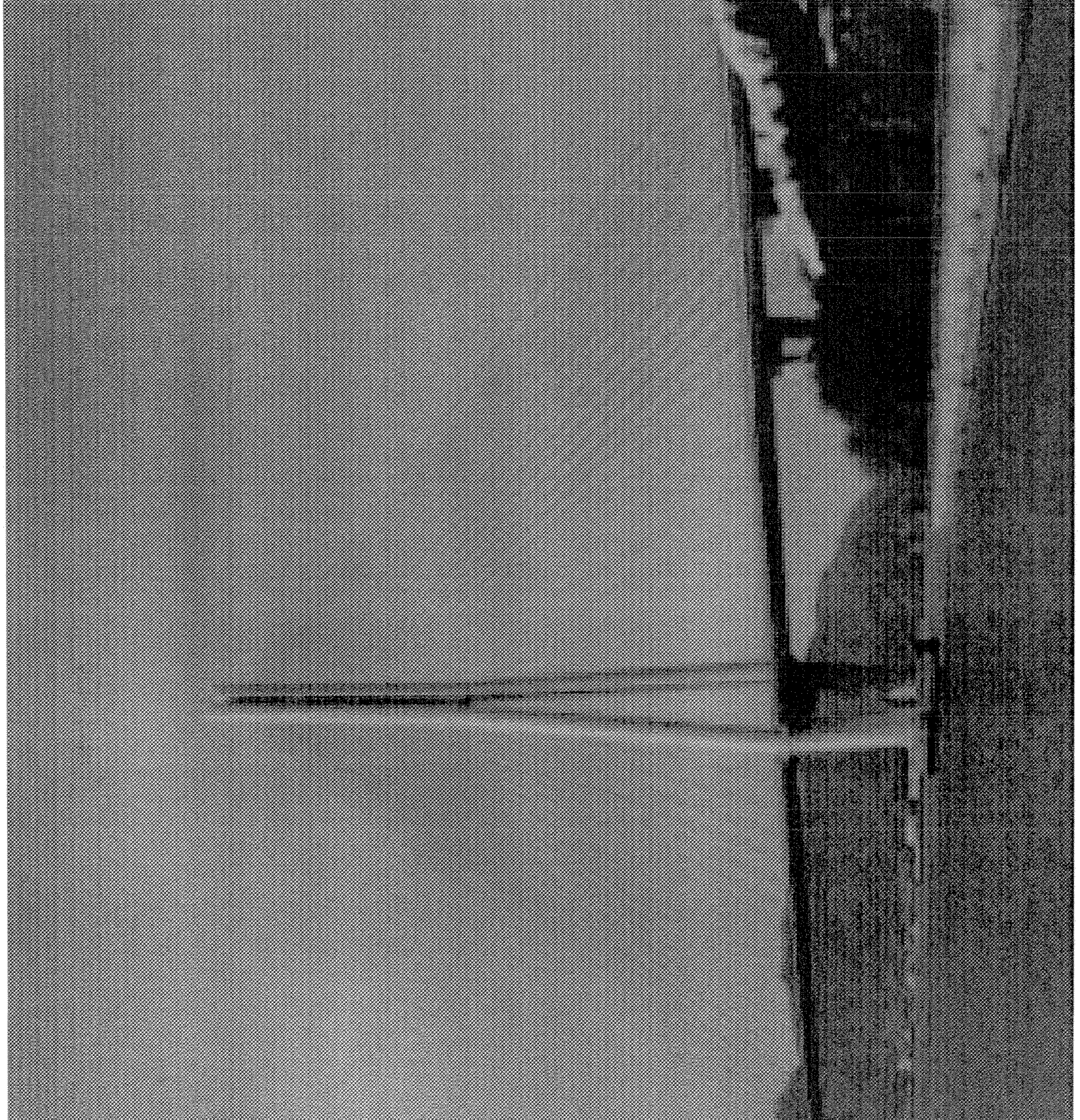
The Tartara Bridge is the longest spanning cable-stayed bridge in the world. It has a center span of 890m, less than half that of the Akashi Kaikyo Bridge. It opened only one year after the Akashi Straits Bridge, in May 1999. The cable-stayed bridge connects Honshu and Shikoku across the Seto Island Sea. The original plan for the bridge was developed in 1973. It was to be a suspension bridge but new developments in cable-stayed bridges persuaded the Honshu-Shikoku Bridge Authority to build another record setting bridge in the newer form.

The Tatara spans a total of 1480 meters, about 2.5 times less than the Akashi Kaikyo and rises 226 m high, about 70 meters less than the Akashi Kaikyo. The height of the towers varies directly to the length of the span, meaning the towers of the Akashi Kaikyo, had it been made a cable stay bridge, would have been 581 meters high. While this may show a suspension bridge to be more efficient, the cable stay bridge is very hard to beat in terms of airiness. While the cable stay towers are about equivalent to suspension towers, the cables used to support the Tatara are amazingly thin. They appear as if they are not even there, giving the ultimate sense of lightness and airiness.

What the Tatara lacks in elegance is attributable to its form. As a suspension bridge the Akashi Kaikyo is particularly elegant and light though its gigantic size is always obvious.

It is amazing that a bridge so massive can appear so light. The largest load acting on the bridge is the dead load; a reasonable live load is almost two thirds smaller than the dead load. Also, many truss-stiffened bridges have a deck that appears thick but the length of the bridge prevents this from happening.

Both bridges show that their designers are talented and make important aesthetic considerations; it is not surprising the same people are responsible for both bridges. The Akashi Kaikyo in particular is beautiful and intriguing and not merely due to size and form, though both are largely responsible for this outcome.



The title of longest bridge in the world has changed hands continuously. It is not necessarily one that promises its bearer is a work of structural art. However the current holder of the longest bridge title is a work of structural art. Its Honshu-Shikoku Bridge Authority employed new techniques and technologies in its design and construction. As a part of the Honshu-Shikoku plan it plays a role in improving Japan's economy while bringing pride to Japan's people and putting its engineering capabilities on display.

The Akashi Kaikyo surpasses the second longest bridge in the world by quite a significant amount. In the building of previous bridges in the Honshu-Shikoku plan the engineers and contractors gained a great deal of experience which they then applied to the Akashi Kaikyo Bridge. Its construction employed new techniques and new materials to make its span possible including much stronger cable so that two were not necessary and a helicopter to hang the cable without disrupting marine traffic in the strait. It is an incredibly light structure visually which is unexpected in a bridge that is able to span almost 2,000 meters.

The Akashi Kaikyo Bridge connects Kobe on Honshu to Awajishima Island as part of the Kobe-Naruto route in the Honshu-Shikoku Bridge plan. The Akashi Kaikyo Bridge is a crucial part of a plan enabling Japan's economy to grow while cutting travel time in half for people crossing these islands.

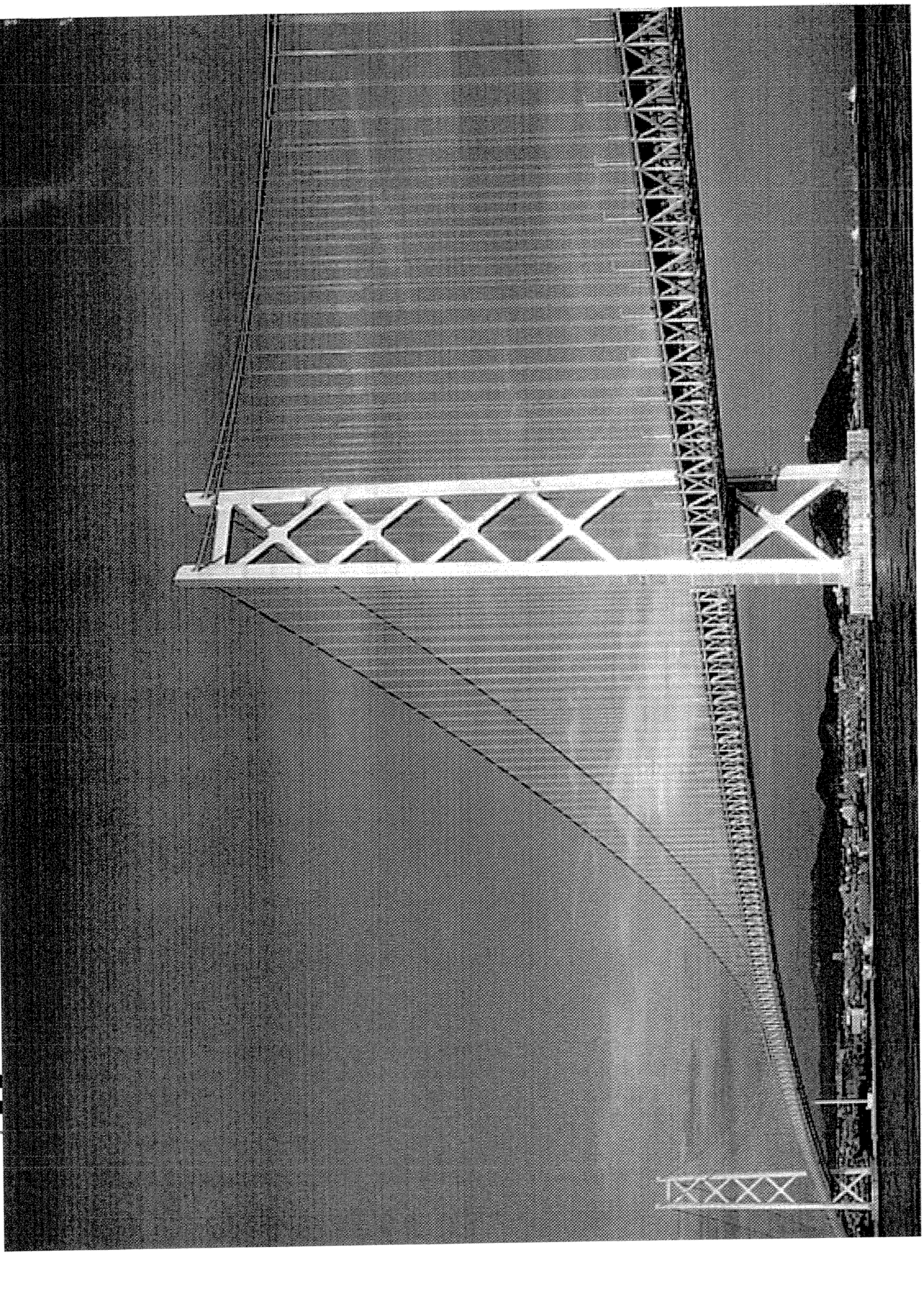
Not only does it serve its purpose and provide Japan with the title of longest bridge in the world, it puts on display Japan's relatively fast rise to the top in civil engineering. Almost 100 years after Darby built Iron Bridge in England, Japan was still constructing bridges which needed rebuilding every five years. In 1870 Japanese bridges

good

constructed with tree towers and spanned by two other trees were only fit for crossing on foot. With a lot of catching up to do the end of World War II gave Japan a push and an opportunity to do so. Following World War II, Japanese civil engineering made great strides, the Akashi Kaikyo Bridge is an end result of their development.

Other structures, such as Maillart's Salginatobel Bridge, which have been argued to be structural art, were the vision of one civil engineer. The Akashi Kaikyo Bridge was not the vision of one person; its design and construction was a collaboration of many contractors. This does not mean the Akashi Kaikyo Bridge is ineligible for consideration as structural art. The Salginotobel is Maillart's most famous work and it was a culmination of previous works that led him to this design. The Honshu-Shikoku Bridge Authority and its contractors gathered experience and knowledge as each new bridge in their project was completed. In this way their progression toward the Akashi Kaikyo was similar to Maillart's toward the Salginotobel. ?

The Akashi Kaikyo set records and will never be surpassed as the longest bridge built in the twentieth century. It is a beautiful, awing achievement and great source of pride for a country whose civil engineers and economy have done a lot of catching up in the last fifty years. The bridge has inspired artists who began drawing the bridge before it was completed and it has also inspired structural artists who, in Japan, are looking to break their own record.



Sources

Honshu-Shikoku Bridge Authority. 1996. http://www.hsba.go.jp/e-index.htm

Inamura, Hajime. ***Civil Engineering in Japan.*** Tokyo Japan: Japan Society of Civil Engineers, 1993.

Kanaori, Yuji. ***Earthquake Proof Design and Active Faults.*** New York : Elsevier, 1997.

Kippo News. "Akashi Kaikyo Bridge to Boost Economy." 1998. http://www.kippo.or.jp/KansaiWindowHtml/News/1998-e/19980113_NEWS.HTML

Normile, Dennis "Spanning Japan's Inland Sea" Engineering News-Record. November 4, 1996

Ochesndorf, John, David P. Billington. "Record Spans in Japan" Civil Engineering. February, 1998.

PBS Online. "Building Big." WGBH Educational Foundation, 2000-2001. http://www.pbs.org/wgbh/buildingbig/wonder/structure/akashi_kaikyo.html

Shimazaki, Toshikazu. ***Civil Engineering in Japan.*** Tokyo Japan: Japan Society of Civil Engineers, 1988.