Irabu Bridge—100-Year Durability

1. Introduction

The Irabu Bridge connects the remote islands of Miyakojima and Irabujima and has a total length of 6.5 km (including 4.3 km above the sea). The main section is 3.54 km long and consists of a three-span continuous steel floor-slab box-girder bridge spanning the Nagayama Channel (main line section bridge) and 32-span and 14-span multiple-span continuous PC box girder bridges.

Situated in a subtropical region, Miyakojima Island is hot and humid and surrounded by the sea. Not only is the salt content of the air from the sea higher* than in other regions of Japan, but the bridge crosses the sea. This creates a severely corrosive environment for both concrete and steel structures.

Moreover, the bridge would be the only means of transportation between the two remote islands. Hence, current design and construction technologies were thoroughly studied in order to ensure that the bridge would have high durability and a long service life.

This paper describes the efforts that were made to work out various measures concerning durability performance.

*) According to a comparison of atmospheric sea salt amounts at Japan’s standard exposure testing sites, the levels were 0.486 mdd at Miyakojima, Okinawa Prefecture, and 0.227 mdd at Choshi, Chiba Prefecture. Japan Weathering Test Center, Survey results of 2013.

Photo 1. Irabu Bridge (Irabujima Island in the background)

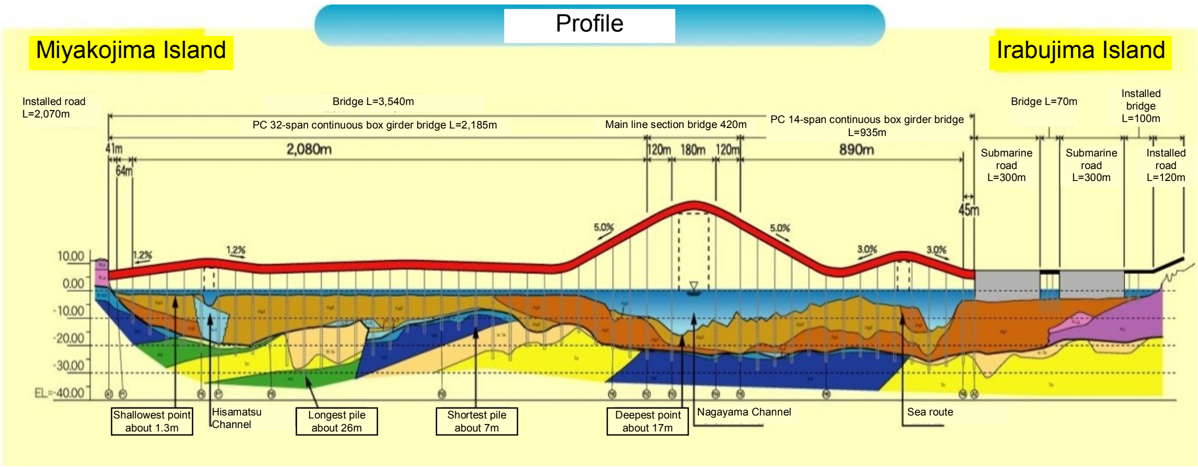

Figure 1. Side view of Irabu Bridge plan

2. Overview of Irabu Bridge and development of construction work

The people living on Irabujima Island are disadvantaged and inconvenienced in terms of medial service, education, welfare, and other aspects. The island has various problems characteristic of remote islands, such as depopulation and declining industry.

In an attempt to eliminate these inconveniences, basic investigations commenced in FY1992. The preliminary investigation started in FY2001, the ground-breaking ceremony was held in March 2006, and after nearly 10 years of construction, the bridge opened on January 31, 2015. This is the 15th bridge in Okinawa Prefecture to connect remote islands.

- Line name: Hirara-Shimojishimakuko Line, a general prefectural road
- Project year: FY2001-FY2014
- Road standard: Type 3 Class 3 (Velocity=60 km), A live load
- Total length: 6,500 m (main bridge: 3,540 m and submarine road: 600 m, installed bridge: 170 m, and installed road: 2,190 m)
- Width: Bridge section: 8.5m
- Superstructure: PC continuous box girder bridge (general section), steel floor-slab box-girder bridge (main line section), and hollow floor slab (installed bridge)
- Substructure: RC bridge leg (general section), T-shaped bridge leg (main line section), and inverted T-shaped abutment
- Foundation system: Two spread foundations, 30 steel-pipe pile foundations (ø1000 mm), 18 steel sheet-pile foundations (ø1000 mm and ø1200 mm), and two caisson foundations (installed bridge)

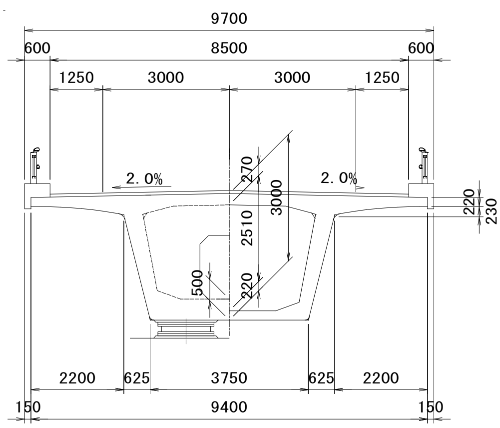

Figure 2. Section of the main line section

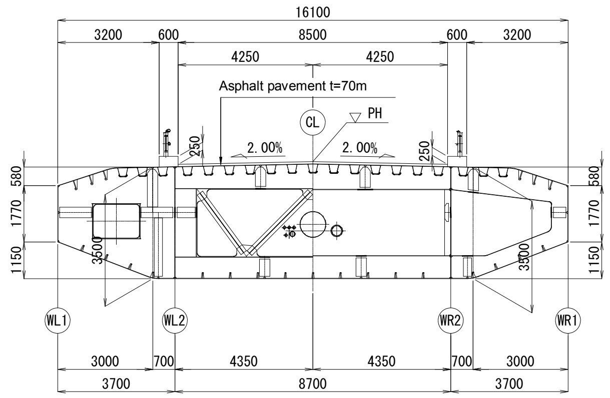

Figure 3. Section of the main line section

3. Salt-damage protection for substructure and PC bridge section

Salt damage is often seen on concrete bridges in sea and coastal areas, including prestressed concrete (PC) bridges. The deterioration of concrete bridges is difficult to identify and is very expensive to repair and reinforce. Some situations require the bridges to be replaced.

To develop damage-protection measures for concrete bridges, the substructures of bridges about 10 years old and connecting remote islands in an environment similar to that in Miyakojima Island were investigated. These investigations revealed a salt penetration concentration of 1.2 kg/m^3 around the steel reinforcements, which was the corrosion limit for steel materials. The chloride ion coefficient was nearly twice the value assumed in the Guidelines for Road Bridges.

Photo 2. Erection of coated reinforcement steel for substructure

Table 1. A comparison of ion concentrations, etc., with measured values

	Estimated value from bridge at site	Base equation in Guidelines for Road Bridge
Chloride ion concentration on concrete surface	About 8-10kg/m^3 > 6.4kg/ m^3	
Chloride ion diffusion coefficient	1.1m^2/year > 0.64 m^2/year	

Table 2. Salt damage protection measures for concrete

Material

Steel reinforcement	Epoxy resin coated steel, stainless steel (ground cover section), CFCC (Carbon Fiber Composite Cable) (lower floor slab and steel arrangement in shoe-sheet mortar
PC strand	Epoxy resin covered steel strand
Sheath	Polyethylene sheath

Structure

Concrete covering	Outside the box girder: 7.0 cm, inside the box girder: 3.5 cm, and substructure: 9.0 cm
Concrete composition	Superstructure: Use of only crushed sand to counter the alkali-silica reaction*1 Reduction in water/cement ratio Use of fly ash concrete (substructure)
Expansion joint	Design minimizes the number of joints provided on the bridge (32-span continuous bridge)

Construction

Steel reinforcement	Touch-up of defects in epoxy resin coated steel after assembly Use of urethane resin rollers as bending machine
Concrete covering	Supervision to confirm coverage of all segments
Concrete composition	Confirmation of the water/cement ratio

*1 The alkali-silica reaction causes cracking in concrete, which concurrently prompts corrosion of the steel reinforcement. This measure controls the cracking and also effectively protects against salt damage.

3 (1) Salt damage protection for substructure

Based on the results of the above investigation, the salt damage protection measures provided in the 2002 Guidelines for Road Bridges was applied to the Irabu Bridge. A 9 cm-thick concrete covering and epoxy resin coated steel were used. Because this was the first time for fly ash concrete to be used for a remote island-spanning bridge in Okinawa, the durability of the concrete was enhanced by controlling salt penetration, implementing alkali-silica reaction (ASR) prevention measures, etc. The ASR prevention measures served also to protect against salt damage at the site, where reinforcement steel was susceptible to corrosion due to sea water and atmospheric salt as a result of cracking after ASR had occurred. Moreover, because fly ash concrete had never been used for such a large-scale bridge, a study on its quality and use in construction was conducted and testing carried out.

The amount of air in the fly ash concrete was lower due to the effect of unburned carbon. However, the amount was not stipulated because the site was in a subtropical region (no frost damage), and so the required workability was obtained.

Table 3. Concrete composition for substructure

Type of composition	W/(C+F1) (%)	sF2/a (%)	Unit amount (kg/m^3)								AE water-reducing agent (high-performance)	AE aid
			Water	Cement	Fly ash		Fine aggregate		Coarse aggregate			
					Internal ratio	External ratio	Sea sand	Crushed sand	4020	2005	(C+F1)%	(C+F1)%
			W	C	F1	F2	S1	S2	G1	G2		
27-40-12	49.5	38.6	156	250	65	25	399	273	458	687	0.5	0.003

3 (2) Salt damage protection for superstructure

For the superstructure for the bridge, a box girder was used because it has a smaller area to which atmospheric salt could adhere than I and T girders (Figure 2).

By designing 32-span and 14-span continuous bridges, fewer expansion devices were needed, which both increased comfort during travel as well as reduced the number of joints through which salt could penetrate to the girders. However, because the 32-span continuous bridge section extended for 2 km, the post-slide system (Figure 4) was adopted to accommodate the expansion and contraction of the girders caused by creeping and dry-shrinkage, which could create about 40 cm of displacement.

As for materials, epoxy coated reinforcing steel, epoxy resin covered PC steel strands, and polyethylene sheaths were used early in the construction work to provide double and triple salt damage protection and reduce the life-cycle cost (Photo 3).

Because ASR could be caused by the sea sand commonly used as a fine aggregate for concrete in Okinawa, the concrete for the superstructure was prepared using only crushed sand that was confirmed to not cause ASR. A 100% crushed sand content, however, would reduce workability due to the poor grain shape. Therefore, fly ash appropriate for the superstructure was used as an admixture to improve workability.

Table 4. Concrete composition for superstructure

Composition type	W/(C+F1) (%)	sF2/a (%)	Unit amount (kg/m^3)						AE water-reducing agent (high-performance)	AE aid
			Water	Cement	Ordinary expansion agent	Fly ash	Fine aggregate	Coarse aggregate		
						External ratio	Crushed sand	2005	(C+F1)%	(C+F1)%
			W	C	H-EX	F2	S	G		
50-20-18	33.5	42.9	156	446	20	22	723	1004	0.85	-

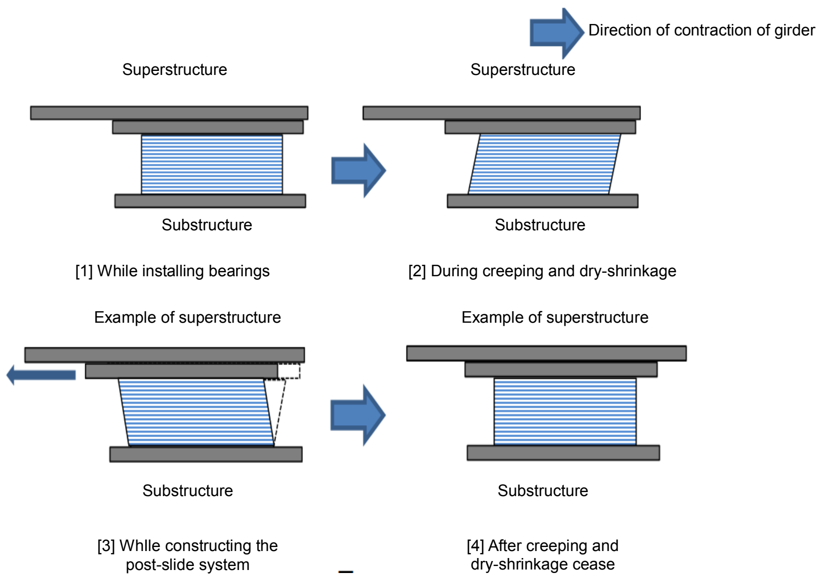

Figure 4. Construction procedures for post-slide system

Photo 3. Salt damage protection measures for superstructure (coated reinforcing steel and polyethylene sheath)

4. Salt damage protection in steel bridge section

The main line section of the Irabu Bridge crosses a sea route for 2,000-t class cargo ships and passenger liners. This 3,540 m section consists of a 420 m three-span continuous steel floor-slab box-girder (Figures 1 and 3).

The durability of the steel superstructure was improved mainly by the following methods:

[1] The external joint surfaces were welded, not bolted (Photo 6).

Photo 6. Completed main line section

Table 5. Specifications for coating used on Irabu Bridge

Coating process	Paint	Amount (g/m^2)	Film thickness (μm)
Surface treatment	Blast treatment ISO Sa3.0		
	Surface roughness: Ra8μm or greater and Rz50μm or greater		
Thermal metal spraying	A195-Mg5 alloy	-	150-500
Sealing treatment	Metal spray sealing treatment agent	200	-
Undercoating	Epoxy resin paint	540	120
Intermediate coating	Fluorine resin paint	170	30
Finishing coating	Fluorine resin paint	140	25

[2] Thermal metal spraying was employed to form an anticorrosive base coating on the external surfaces.

As Figure 3 shows, the main line section was constructed as a steel floor-slab box-girder bridge with an octagonal planar section for the same reasons that a box girder was selected for the concrete bridge. The inner webs were bolted together and the steel floor slab section, lower flanges, and outer webs were welded.

4 (1) Thermal metal spraying for anticorrosive base coating

To improve the anticorrosive properties of this bridge, which was constructed in a severely corrosive environment, the bridge's base coating was a highly durable aluminum magnesium alloy (Al 95%-Mg 5%) rather than an inorganic zinc-rich paint. This anticorrosive base coating was applied by means of thermal metal spraying and met the C-5-based coating specifications for the general external surface.

4 (2) No bolts used for joining external girder surfaces

Corrosion develops easily in the bolt joint section of a steel bridge because atmospheric salt is deposited on the concave and convex parts and the the nuts are difficult to coat to a proper thickness. For this bridge, the external surfaces were welded rather than bolted. The welded beads were finished flat to reduce irregularities on the external surface (Photo 6).

4 (3) Shape of member's corner

The corner of a member is a region where a coating is thin, and is difficult to construct and maintain. Because of this, as Fig.-5 shows, the corner folds of flanges were bent and the corners of all members on the external surface were provided with a round corner radius of 3mm.

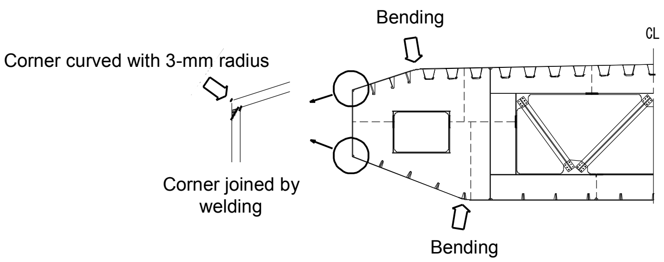

Figure 5. Shapes of corner folds and member corners

4 (4) Marine transportation and simultaneous erection of large blocks

Welding and metal spraying at the site were minimized to create a high quality steel bridge. Consequently, the 140-m long steel girders for the main line section were fabricated as large blocks at off-site factories and transported by large barges to Miyakojima Island. The large blocks were then simultaneously erected at the site (Photo 7).

Because one factory was about 2,000 km from the Miyakojima Island, there was concern about the possibility of waves damaging the girders during transportation. Therefore, the amount of deflection in the blocks during transportation, coating film cracking caused by fatigue cracking, residual deformation in regions of local buckling, and wave stress frequency were checked.

To erect the blocks, Japan's largest-class floating crane ship, 44 m x 120 m x 140 m (W x L x H) in size and with a 4000-t lifting capacity, was used to lift the blocks directly from the barges moored at the wharf and tow them while suspended for about

5 km to the erection points, where they were installed at predetermined bridge leg positions (Photo 8).

This sequence of large-block operations, from fabrication to transportation and erection, minimized on-site welding and metal spraying work, resulting in higher quality block joint sections.

Photo 7. Large blocks in transit

Photo 8. Simultaneous erection of large blocks

5. Wind-resistance (stability)

The initial plan in the basic design phase called for a half-through steel arch bridge with arch ribs rising in the air to serve as a local symbol. However, after Typhoon No. 14 hit Miyakojima Island in 2003 and caused great damage, the wind resistance (stability) of the bridge was reviewed in detail. The design reference wind velocity was also changed from 73.4m/s in the basic design stage to 82.2m/s in the working design stage. Wind tunnel experiments revealed problems of fatigue durability for the half-through steel arch bridge. As a result, the design was changed to a steel floor-slab box-girder bridge that excelled in wind resistance (Figure 6).

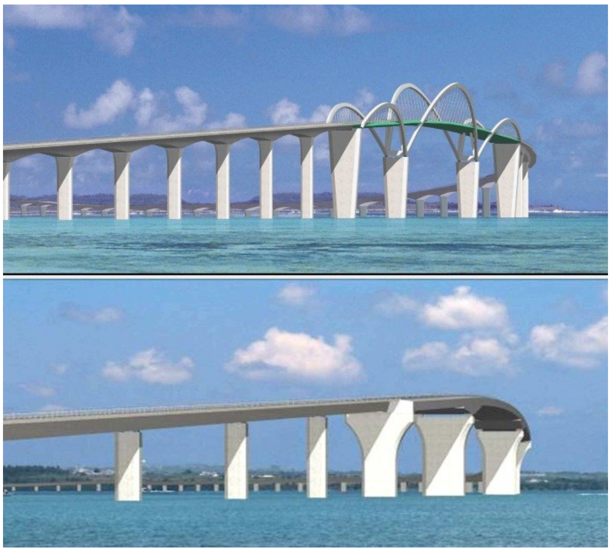

Figure 6. Top: The initial plan called for a three-span continuous half-through steel arch bridge. Bottom: The final plan called for a three-span continuous steel floor-slab box-girder bridge.

6. Okinawa Prefecture Remote Island Bridge 100-Year Durability Research Project

The Okinawa Prefectural Government, the Public Works Research Institute, and the Okinawa Prefectural Center for Construction Technology concluded a three-party agreement in 2009 to research the construction of bridges connecting the remote islands (Figure 13). The goal of the project is to establish maintenance and management techniques and technological standards that would allow bridges to operate for 100 years in an environment that is conducive to salt damage by accumulating research data in Okinawa Prefecture, which experiences Japan's severest salt damage.

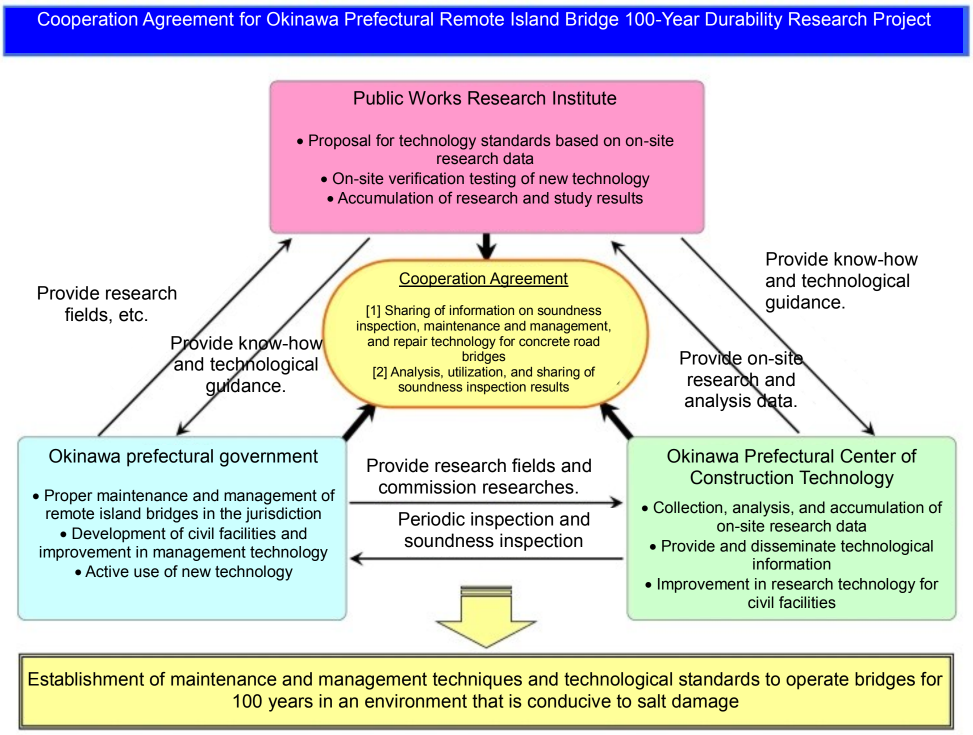

Figure 8. Framework of 100-year durability project

7. Afterword

The Irabu Bridge was equipped with the best available measures at the time of construction in terms of design and material selection and construction. This, however, does not necessarily ensure durability for 100 years.

In this project, the objective of 100-year durability was openly declared so that the morale among those working at the site, including the owner, would be enhanced and they would work toward delivering a bridge structure with high quality and long durability.

Considering the difficulty of maintaining sea bridges, we hope that this bridge receives the best possible maintenance and displays good maintainability, thus contributing to the region for an extended period of time.

Furthermore, we hope that the durability technology developed during the project is applied to civil structures inside and outside Okinawa so that high quality infrastructure can be utilized for many years.

Acknowledgement

For the design and construction of the Irabu Bridge, committees on specific subjects were created to seek advice. We believe these committees helped to bring the latest civil engineering technology to Japan.

We would like to extend our renewed gratitude to those who worked with the Irabu Bridge Construction Technology Study Committee, the Irabu Bridge Concrete Durability Performance Study Committee, the Irabu Bridge Wind Resistance Study Committee (tentative title), the Irabu Bridge Foundation Work Study Committee, the Irabu Bridge Main Line Section Bridge Type Study Committee, the Irabu Bridge Main Line Section Design and Construction Committee, and the Irabu Bridge Landscaping Study Committee.