PREVENTIVE MAINTENANCE OF LONG-SPAN BRIDGES OF HONSHU-SHIKOKU BRIDGE EXPRESSWAY

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Abstract

The Honshu-Shikoku Bridge Expressway (HSBE) has 17 long-span bridges located over straits where environment is very harsh. In order to keep these bridges in sound state for more than 200 years, the Honshu-Shikoku Bridge Expressway Company Limited (the company) is conducting maintenance based on the concept of the preventive maintenance. This paper describes the idea of preventive maintenance and each maintenance element of the HSBE.

Introduction

The HSBE consists of three routes (total length of 172.9km) between Honshu and Shikoku (Figure 1). It unifies the region of Seto Inland Sea and plays an important role as a part of the arterial high-standard highway network. The feature of the HSBE can be described as maintenance of 17 long-span bridges (Table 1) located over straits where environment is very harsh. Photo 1 shows signature bridges of the HSBE. The Akashi Kaikyo Bridge is the longest suspension bridge in the world. The Seto-Ohashi Bridges are one of the longest highway-railway combined bridge link. The Kurushima Kaikyo Bridges are the unprecedented three consecutive suspension bridges.

In 1979, the first portion including Ohmishima Bridge, a steel arch bridge, completed and opened to traffic. Then the Seto-Chuo Expressway that includes the Seto-Ohashi Bridges and the Kobe-Awaji-Naruto Expressway that has the Akashi Kaikyo Bridge opened to traffic in 1988, and 1998 respectively. And the completion of the Nishi-Seto Expressway brought the HSBE from the construction era to the maintenance era.

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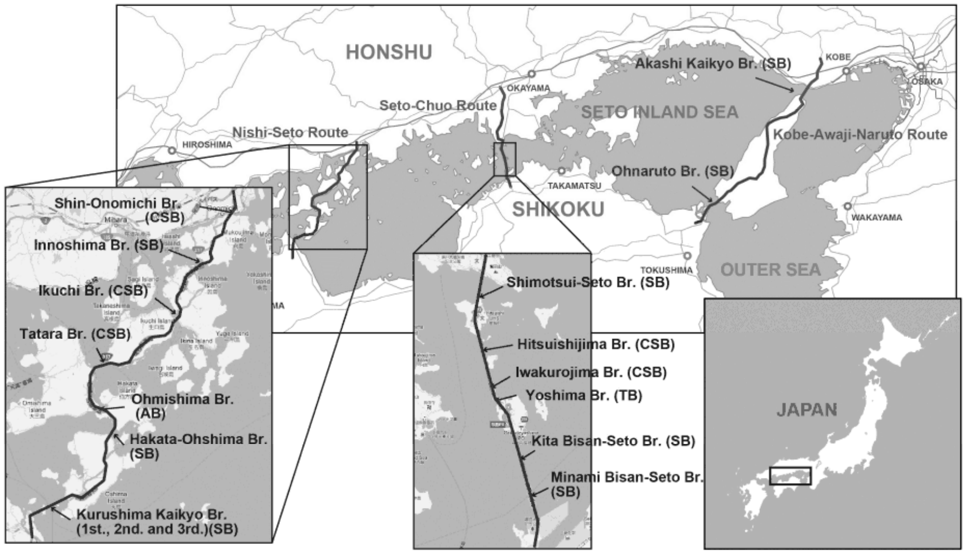


Figure 1 Honshu-Shikoku Bridges
(SB: suspension bridge, CSB: cable-stayed bridge, TB: truss bridge, AB: arch bridge)

Table 1 Long-Span Bridges of HSBE

Bridge	Completion (year)	Type	Length (m)	Height of Tower (m)
Kobe-Awaji-Naruto Expressway				
Akashi Kaikyo	1998	suspension	3,911	297
Ohnaruto	1985	suspension	1,629	144
Seto-Chuo Expressway				
Shimotsui-Seto	1988	suspension	1,400	149
Hitsuishijima	1988	cable-stayed	790	152
Iwakurojima	1988	cable-stayed	790	161
Yoshima	1988	truss	850	-
Kita Bisan-Seto	1988	suspension	1,538	184
Minami Bisan-Seto	1988	suspension	1,648	194
Nishi-Seto Expressway				
Shin-Onomichi	1999	cable-stayed	546	77
Innoshima	1984	suspension	1,270	146
Ikuchi	1991	cable-stayed	790	127
Tatara	1999	cable-stayed	1,480	226
Ohmishima	1979	arch	328	-
Ohshima	1988	suspension	840	97
Kurushima Kaikyo 1st.	1999	suspension	960	149
Kurushima Kaikyo 2nd.	1999	suspension	1,515	184
Kurushima Kaikyo 3rd.	1999	suspension	1,575	184

One article of the business policy of the company, says that it “will try to conduct through maintenance in order to let the bridges used for more than 200 years.” Although the ages of the HSBE’s long-span bridges range between 15 and 35 and they are considered as relatively young, progress of the deterioration is observed nowadays. Therefore, the company is trying to avoid large-scale repair or replacement and to minimize life cycle cost (LCC) of the long-span bridges by promoting the preventive maintenance. In order to secure implementation of the preventive maintenance for all the structures based on the long-term view, the company is promoting a concept of asset management. Based on the concept, PDCA cycle that comprises of periodical inspection and survey, evaluation of structures, prediction of deterioration, repair or rehabilitation, and the follow up was established. Also, in efforts to enhance durability and to reduce LCC, the company is working on the research and development such as new coating system that has much higher durability than the one used at the time of construction.

(A) Akashi Kaikyo Bridge (B) Seto-Ohashi Bridges (C) Kurushima Kaikyo Bridges

Photo 1 Signature Bridges of HSBE

Features of the HSBE's Long-Span Bridges in Maintenance

The company is conducting maintenance based on the following features of the HSBE's long-span bridges.

1) Since they are located over straits, they are considered in very harsh corrosive environment such that they are exposed to strong wind that brings chloride particles from the sea.
2) Since the superstructures are in high location over straits, they are not easily accessible and construction of scaffoldings required for inspection or repair works becomes extensive work.
3) Volume of the maintenance target is massive. Signature example is 4,000,000m^2 of the external surface of the steel structures that needs to be recoated multiple times during the life time of the structures.
4) For the new materials or special structures utilized in the bridges, maintenance experience is scarce and durability is not fully known.
5) Since there are no alternative routes, repair works under traffic closure are not favorable.

Preventive Maintenance of Long-Span Bridges

For the maintenance of the long-span bridges with above-mentioned features, massive workforce and cost are required. In order to avoid large-scale repair or replacement and to minimize LCC, the company is conducting maintenance based on the concept of the "preventive maintenance." By the accumulation of inspection data and repair history and the analysis and evaluation of them, the company is trying to realize rational maintenance.

In order to maintain the long-span bridges for more than 200 years, the company drew up long-term maintenance plan until 2100 based on the concept of asset management. Figure 2 is a long-term recoating plan until 2100. Figure 3 is a maintenance cost until 2100. This plan is based on the data obtained through the past maintenance. The plan will be updated as new data is accumulated.

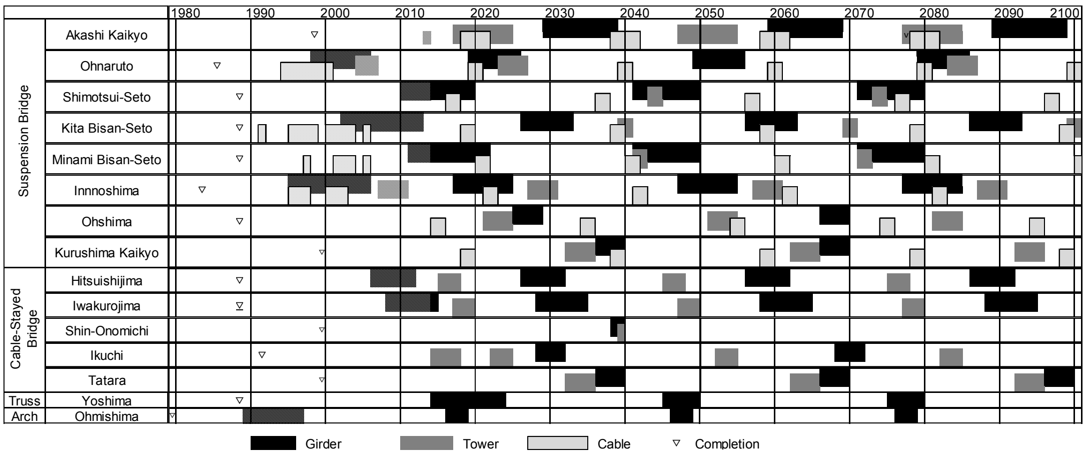


Figure 2 Long-Term Recoating Plan for Long-Span Bridges

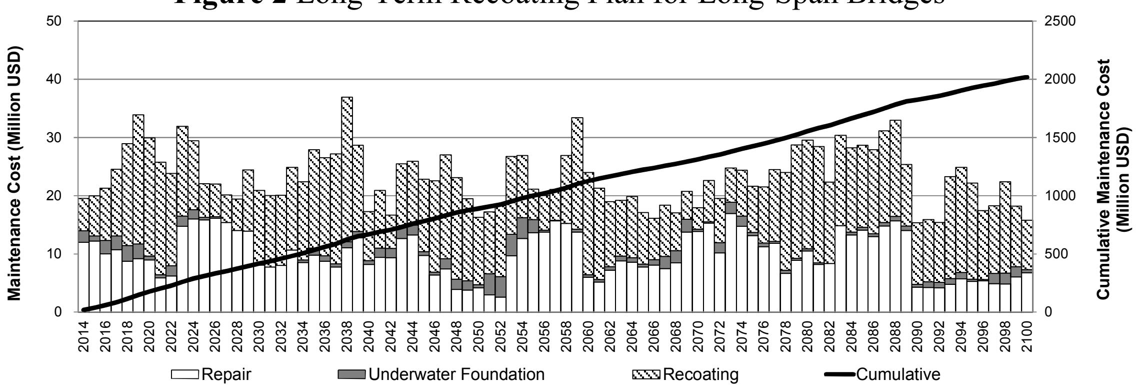


Figure 3 Maintenance Cost

(1) Inspection

Inspection of the long-span bridges is conducted based on the Inspection Manual established by the company. The manual has been revised several times in response to the advancement of the maintenance technology, the change of the social demands and so on. The types of inspection are categorized in the manual as in Table 2. Following the 2014 revision of the ministerial order that mandates that all the road bridges shall be inspected from close distance, the method of basic inspection in the company's manual was revised to conform to the order.

Anomalies found in the inspections are categorized according to the manual as in Table 3 and recorded in the inspection database system. The data base can be accessed from all the computers in the company's offices.

Although the manual was revised to inspect all the members from the close distance, many portions are not accessible from maintenance ways or maintenance gantries. Approach ratio (accessible surface area / all surface area) of truss girders is lower than that of box girders (Table 4). The company is studying to improve the low approach ratio. The Ohnaruto Bridge was selected as a study target because the bridge is in very harsh corrosive environment and the approach ratio is lower. Figure 4 shows current accessible areas by the inside gantry and the outside gantry. The company is studying modification of the gantries and additional scaffoldings expanded from the existing maintenance ways. Figure 5 shows improved accessible area. By this modification, approach ratio of the Ohnaruto Bridge will improve from 40% to 60%. In terms of the number of anomalies observed in the girder, approach ratio will improve from 70% to 99%.

Table 2 Types of Inspection

Type	Purpose	Method	Interval (Timing)
Scheduled Inspection			
Patrol	Detect anomalies that affect users or third person.	Visual from maintenance ways	1-6 months
Basic	Detect anomalies that affect performance of structures. By the gathered data, necessity of repair is judged.	Visual (close), touch by hands, slapping (by hammer) from inspection ways or maintenance gantries	1-2 years
Detailed	Detect significant anomalies that affect safety or serviceability of whole bridge.	Measuring devices	5 years
Non-Scheduled Inspection			
Emergency	Grasp condition of structures at the time of natural disasters. Gathered data is used for emergency measure.	Mainly visual	At the time of natural disasters
Special	Complement scheduled inspection results. Follow condition after repair.	As-needed methods	As needed

Table 3 Category of Anomalies

Rank	Description
E	Anomaly puts road users or third person in danger. Requires immediate repair.
A	Anomaly is significant in view of safety or serviceability. Requires immediate repair.
B	Anomaly that reduces safety or serviceability. Requires repair but not immediate.
C	Anomaly that has little effect on safety or serviceability. Follow up or conduct precise investigation
D	Anomaly is slight.
Q	Difficult to judge the anomaly. Requires supplemental inspection by other methods

Table 4 Approach Ratio

Bridge	Girder Type	Approach Ratio
Akashi Kaikyo	Truss	82%
Ohnaruto	Truss	40%
Tatara	Box	100%

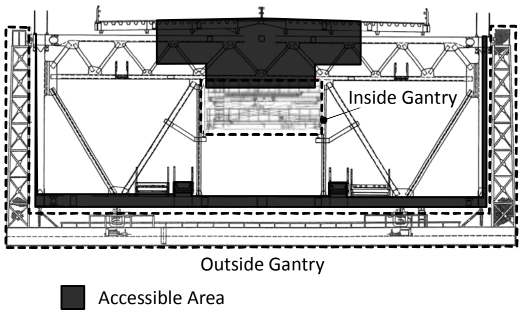


Figure 4 Accessible Area of Truss Girder of Ohnaruto Bridge

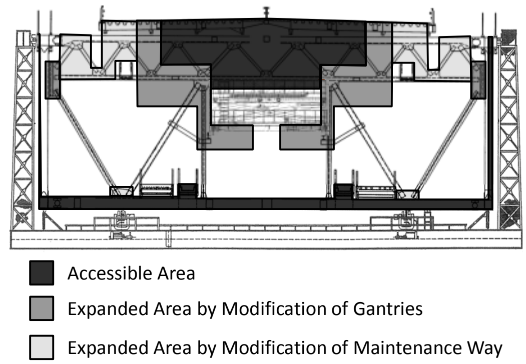


Figure 5 Improved Accessible Area of Truss Girder of Ohnaruto Bridge

(2) Coating for Steel Structures

Since the total external surface of the steel members of the HSBE's long-span bridges is about 4,000,000m^2, maintenance of coating is a major task. The long-span bridges were built across straits where corrosive environment is severe. Therefore, the heavy duty coating system is used to prevent corrosion. The coating system consists of rust-preventive thick inorganic zinc-rich paint as a primary layer and weather resistant fluorine resin paint as a top layer. Before the Akashi Kaikyo Bridge, polyurethane resin paint was used for top layer. Coating specification for external surface of steel structures is shown in Figure 6.

Recoating policy restricts recoating layers to deteriorated top and intermediate coats, keeping the inorganic zinc-rich paint in a sound state (Figure 7). This is because the recoating of the entire coat requires on-site blasting that is disadvantageous in terms of quality control, cost, and environment. In early recoating, fluorine resin paint was used as top coat. After 10 years of research, highly durable fluorine resin paint that has higher durability than existing top coat was developed and has been utilized for recoating since2010.

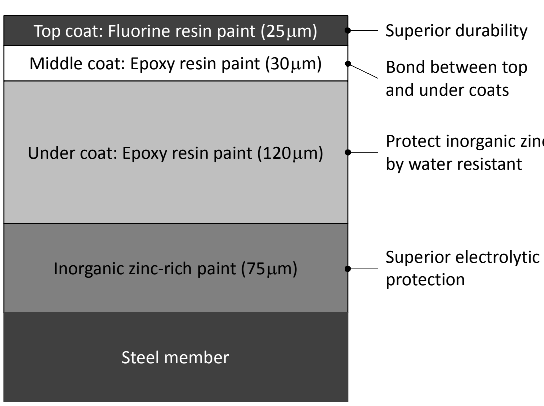


Figure 6 Heavy-Duty Coating

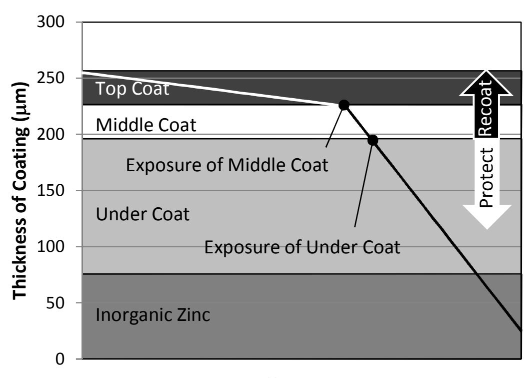


Figure 7 Consumption of Coating

In order to grasp the optimum recoating cycle, i.e., the timing when the top and middle coats disappears, consumption rate of coating must be understood with satisfactory accuracy. Since visual observation is not sufficient for this purpose, fixed observation points were set up on the existing bridges. At these points, thickness, glossiness, and adhesion of coating are tracked periodically. From the past results, measured consumption rates were found to be smaller than those initially estimated. Since the prolongation of recoating cycle significantly reduces LCC, the company is trying to improve the estimation accuracy by increasing the number of observation points.

In the current recoating process, different materials are used for top and middle coats and therefore it requires two painting processes and drying time between the applications of two coats. If the function of these two layers can be replaced by one layer coating, recoating cost can be reduced significantly by the reduction of the work period. The company is working on the development of the paint with simplified application process.

(3) Maintenance of Concrete Structures (Hanai, 2012)

For the maintenance of the concrete structures, the company has established the "Manual for Non-Destructive Testing of Concrete Structures in Periodical Inspection (draft)" (HSBE, 2001) and has conducted Non-Destructive Testing (NDT) since 1999. Maintenance flow of concrete structures described in the manual is shown in Figure 8. The items of surveys are cover thickness, chloride ion, carbonation depth and rebar corrosion (by self-potential).

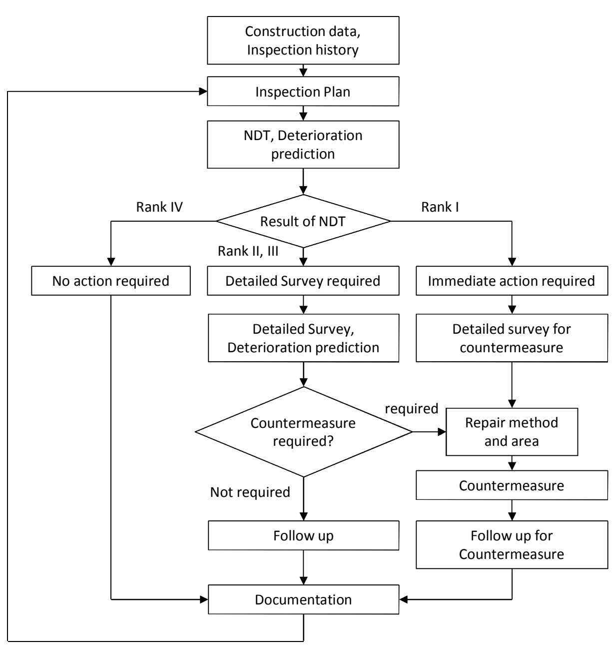


Figure 8 Maintenance Flow of Concrete Structures

Most of the substructures of the HSBE's long-span bridges are massive concrete structures and located in the straits. It is generally difficult for such massive concrete structures to suppress cracks by the shrinkage during curing and drying process. For the HSBE's substructures, cracks initiated during construction stage were repaired and the surface of concrete was coated to prevent intrusion of chloride ion in some structures. However, because there was not enough knowledge about concrete surface coating, the company started study about the coatings applied to the HSBE's concrete structures and the exposure test specimens. After more than 20 years of survey, the company established the "Guideline for Coating of Mass Concrete Structures of Long-Span Bridge." Distinct point of the guideline from the other manuals is that it requires high elongation characteristic of 2mm in zero-span test in order that the coating film can follow the movement of existing cracks by seasonal variation of temperature. In the guideline, acrylic rubber and polybutadiene are introduced as recommended coating materials, which satisfy the specification.

(4) Cable Dehumidification System for Suspension Bridge

The main cable is one of the most important members of the suspension bridge. Therefore, protecting the cable from corrosion is an important task in maintenance. The conventional anti-corrosion measure is shown in Figure 9, which aims to prevent water from penetrating into the cable from the surface.

Between 1989 and 1993, investigations of the cables of the existing suspension bridges in Japan, which had been in service for 4 to 6 years, were conducted. In the investigations, it was found that the deteriorated paste retained water and that induced corrosion of the cable wires within a few layers from surface (Photo 2). Following the investigation, the company initiated the development of a new anti-corrosion measure that will improve corrosive environment inside the cable in addition to preventing water penetration.

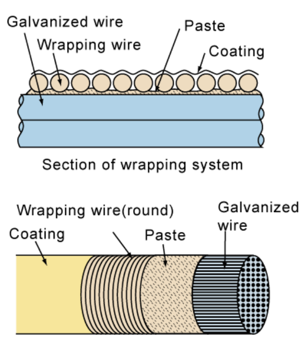


Figure 9 Conventional Anti-Corrosion Measure for Main Cable

Photo 2 Unwrapped Main Cable of Kita Bisan-Seto Bridge

Cable dehumidification system is to dehumidify inside of the cable by injecting dry air into the cable (Figure 10). By laboratory tests, it was confirmed that if the relative humidity inside the cable is lower than 60%, corrosion of the cable wire will not occur. The system was developed in parallel with the construction of the Akashi Kaikyo and

Kurushima Kaikyo Bridges. For these new bridges, new wrapping system was used for air and water tightness (Figure11). These wrapping system were installed in the all of the HSBE's suspension bridges (Table 5).

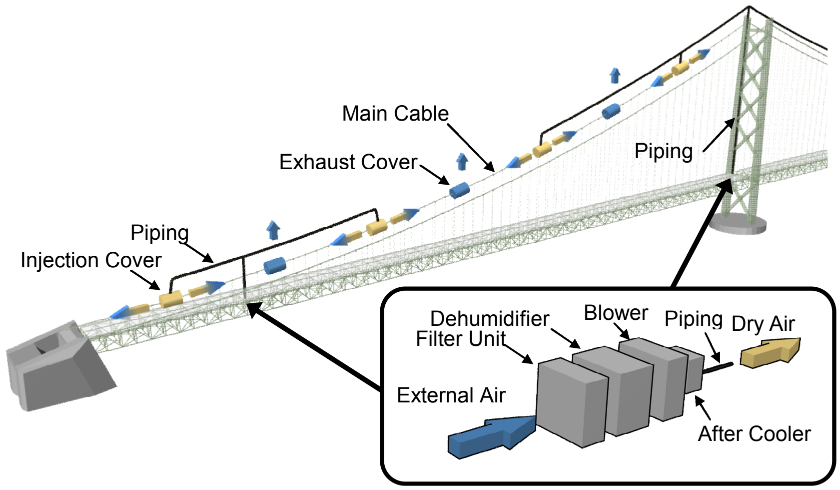
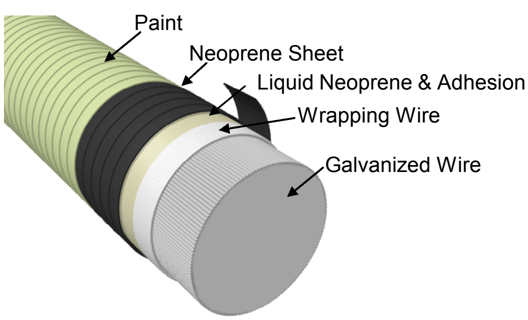
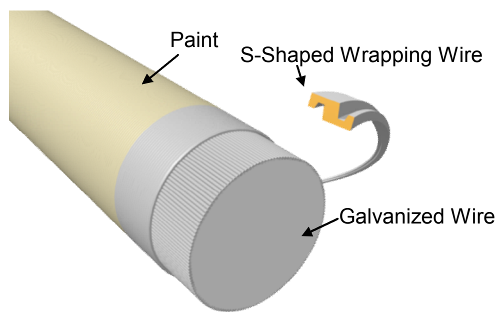


Figure 10 Cable Dehumidification System (Akashi Kaikyo Bridge)



(a) Akashi Kaikyo Bridge



(b) Kurushima Kaikyo Bridges

Figure 11 New Wrapping Systems for Newly Built Suspension Bridge Cable

Table 5 Cable Dehumidification System in HSBE's Suspension Bridges

Bridge	Completion	System Installed	Number of Injection Points		Number of Units	
			Original	Present	Original	Present
Akashi Kaikyo	1998	1997	32	32	8	6
Ohnaruto	1985	1997	13	27	2	2
Shimotsui-Seto	1988	1999	6	8 (12)*	3	3
Kita Bisan-Seto	1988	1998	6	12	3	3
Minami Bisan-Seto	1988	1999	6	12	3	3
Innoshima	1983	1999	8	8	2	2
Ohshima	1988	1998	8	8	2	2
Kurushima Kaikyo 1st.	1999	1999	8	8	2	2
Kurushima Kaikyo 2nd.	1999	1999	12	8	3	2
Kurushima Kaikyo 3rd.	1999	1999	12	8	3	2

* ( ) planned

For the monitoring and evaluation of the system, the company has established the "Humidity Measurement Manual for Cable Dehumidification System" and periodical measurement is conducted according to the manual. By evaluating the measured data, repair or modification plan is made. The majority of the repairs are enhancement of air tightness by repairing of sealing. If the system requires drastic modification, shortening of air flow length by additional injection points is effective. In the Ohnaruto, Shimotsui-Seto and two Bisan-Seto Bridges, this measure was taken. Also, it is known that the installation of "pre cooler" before filter unit improves efficiency of the production of the dry air. For the Kurushima Kaikyo Bridges, pre coolers were added and the humidity was improved.

(5) Anticorrosion System for Underwater Steel Structures (Kusuhara, 2013)

For the most of the underwater foundations of the HSBE's long-span bridges, steel caisson foundations were selected. Although the role of the steel caissons was initially considered as formworks for underwater concrete which was cast in the seawater at the construction stage, it is advantageous to protect them in order to keep the foundations in sound condition for more than 200 years.

28 years after the installation of the underwater foundation of the Minami Bisan-Seto Bridge, corrosion survey was conducted. Progress of corrosion was the most severe in the tidal zone and the reduction of the thickness of the steel plate of 10mm thick was up to 3mm. On the other hand, while the corrosion rate in underwater zone is smaller, local pitting corrosions at which whole thickness of the steel plate was lost were observed (Photo 3). If this kind of pitting corrosions is left unrepaired, seawater may corrode steel members inside the concrete, expansion pressure of corroded steel members may damage the concrete, and finally, integrity of foundations may be lost. In order to avoid this kind of risk, the company decided to protect the steel caissons.

For the steel caissons of the HSBE's long-span bridges, except for those of the Tatara Bridge and the Kurushima Kaikyo Bridges in which cathodic protection was applied at the construction stage, long-term anticorrosion measures were not taken. As a result of comparison of various existing methods, electrodeposition (ED) method (Figure 12), in which calcium and magnesium contents in the seawater are deposited on the surface of the steel caissons and form protective layer, was tested in the actual structures because the method does not require diver work and therefore is considered as safe and economical.

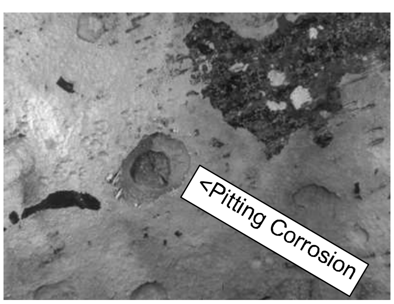


Photo 3 Pitting Corrosion of Steel Caisson

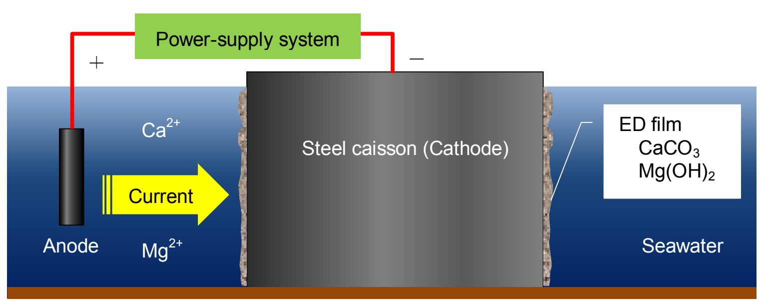


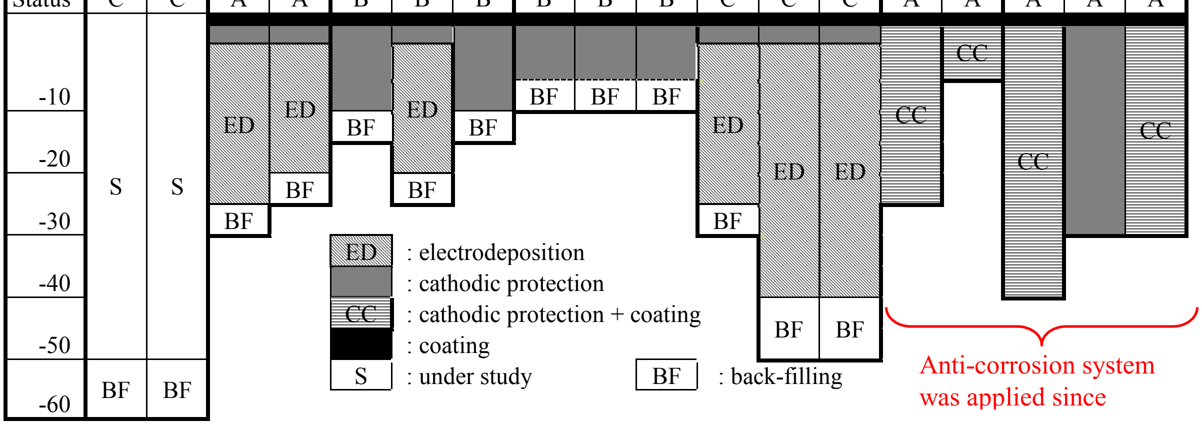
Figure 12 Concept of Electrodeposition Method

On the other hand, since the splash zone and tidal zone are not always in the seawater, the ED method is not applicable. For these zones, an anticorrosion measure with coating system which is applicable to wet surface is selected. In order to long-lasting stable coating, rust on the surface of the steel caissons must be removed completely by blasting. Furthermore, at the boundary of each method, neither ED film nor coating may be applied and it becomes weak point. Therefore, for this boundary, cathodic protection method was applied with aluminum alloy anodes.

For shallow foundations, since the ED facility may be excessive and uneconomical, cathodic protection method was selected for under water zone. And for deep foundations, safe and economical method has to be studied because the application is considered to be difficult by the current ED facility.

Anticorrosion measures for the steel caissons is summarized in Figure 13.

	Akashi		Hitsuishi		Iwakuro			Kita/Minami Bisan						Tatara		Kurushima		
	2P	3P	2P	3P	2P	3P	4P	2P	3P	4A	5P	6P	7A	2P	3P	3P	4A	5P
Depth (m)	-50	-47	-25	-20	-10	-20	-10	-4	-4	-4	-25	-40	-40					
(base) (m)	-60	-57	-28	-25	-15	-23	-14	-10	-10	-10	-32	-50	-50	-33	-13	-40	-30	-29
Status	C	C	A	A	B	B	B	B	B	B	C	C	C	A	A	A	A	A



Status A : Completed B : Under construction C : Under study

Figure 13 Anticorrosion Measures for Steel Caissons of HSBE's Long-Span Bridges

(6) Maintenance of Suspender Ropes (Takeuchi, 2013)

Out of HSBE's 10 suspension bridges, 7 use center fit wire rope core (CFRC) ropes for suspender ropes (Figure 14, 15). Although each wire is galvanized and external surface of the rope is coated with polyurethane paint, corrosion was occasionally observed in these ropes (Photo 4). As shown in Figure 14, CFRC has void inside. Intrusion of water induces corrosion in this member.

In order to evaluate remaining strength of the corroded suspender ropes, some ropes were removed and tested. Figure16 shows relation between the reduction of the cross section and the reduction of the tensile strength. From the test, if the reduction of the cross section reaches 20%, the remaining strength becomes half of that of the intact ropes.

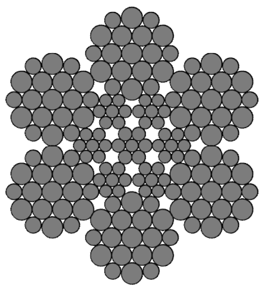


Figure 14 Cross Section of CFRC Rope

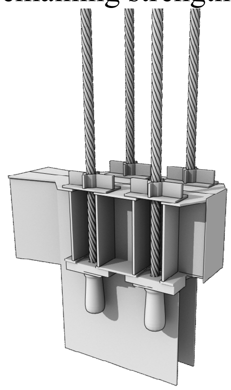


Figure 15 Anchorage of Suspender Ropes

Photo 4 Corrosion of Suspender Rope Near Anchorage (Ohnaruto Bridge)

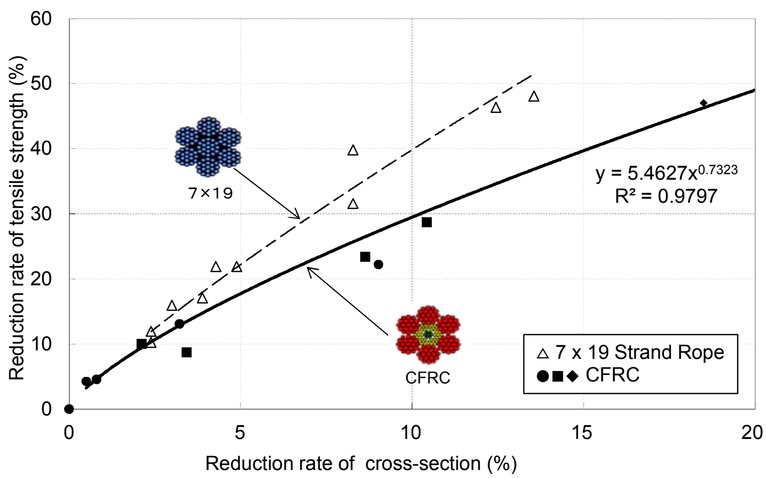


Figure 16 Relation Between Reduction of Cross Section and Reduction of Tensile Strength

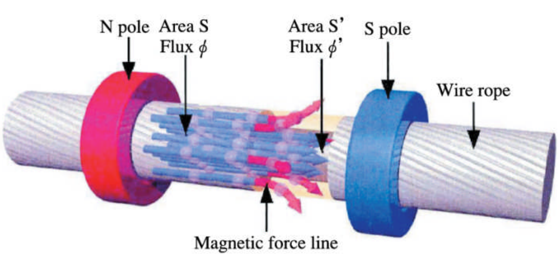


Figure 17 Principle of Main Flux Method

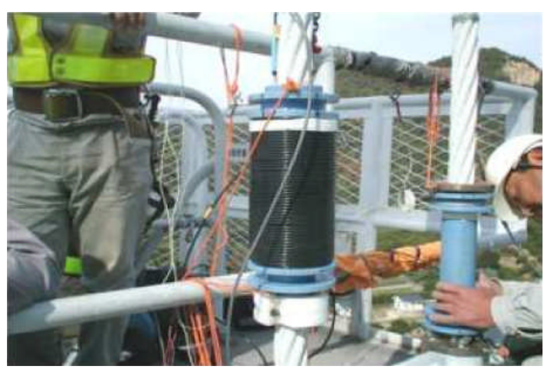


Photo 5 Application of Main Flux Method

It is difficult to evaluate internal corrosion state of CFRC ropes by visual inspection. The company developed a non-destructive inspection method using the electromagnetic method, main flux method. When a rope is strongly magnetized in longitudinal direction, magnetic flux is generated. Since the cross sectional area is proportional to the magnetic flux, remaining cross section can be calculated from the measured data. Principle and application of main flux method is shown in Figure 17 and Photo 5, respectively.

Figure 18 shows a maintenance flow of CFRC suspender ropes. If the corrosion state of the external surface by visual inspection is slight, recoating method is selected. If it requires detailed survey, reduction ratio of cross section is measured by the main flux method. If the ratio is less than B (5%), recoating method is selected. Threshold A is defined to keep safety factor (SF) of 3.0 considering measured tensile force of ropes. Since some bridges are designed with much larger loads, they have large safety margin. Therefore, A varies with each bridge. If the ratio is larger than A, the rope is replaced partially or wholly depending on the length of the rope. If the ratio is between A and B, infill method is selected. Infill method is to inject anticorrosive agent into the void of the rope. Through the investigation, petrolatum paste is found to be the best material.

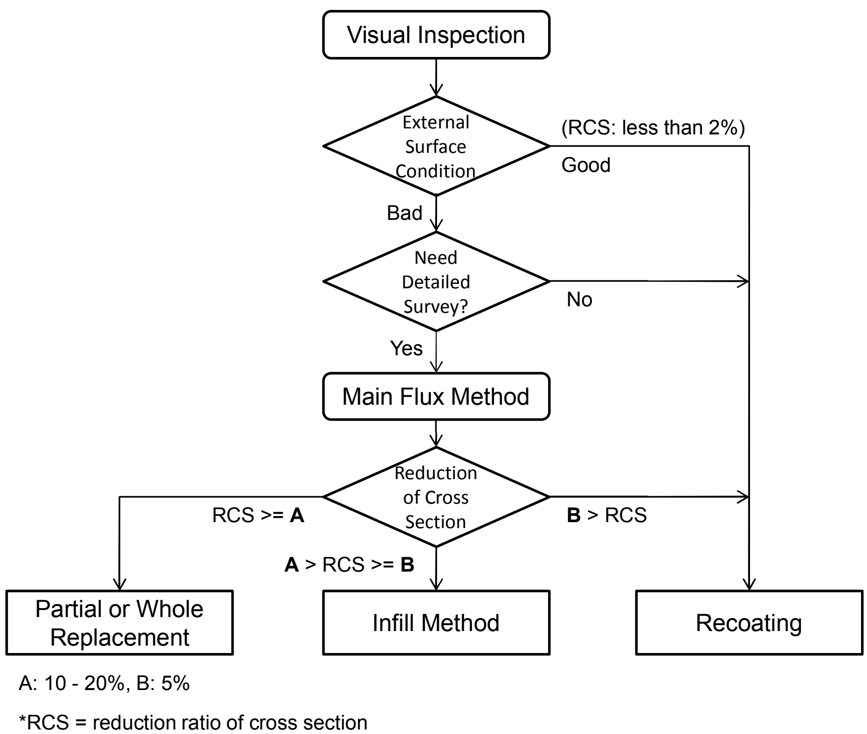


Figure 18 Maintenance Flow of CFRC Suspender Rope

Concluding Remarks

Deterioration of the certain components of the HSBE’s long-span bridges has already started. However, it requires long time to evaluate new maintenance technology or high-precision deterioration prediction method. In this situation, it is important to continue the development of the maintenance technology that will enhance durability and reduce LCC in order to execute secure maintenance.

The company is promoting the maintenance aiming to minimize LCC by the reliable inspection, accumulation of data, and analysis and evaluation of that database.

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