Nondestructive Inspection of the Suspender Ropes in a Suspension Bridge

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Abstract

Two suspender ropes at Innoshima Bridge which elapsed 16 years after completion were removed and inspected to verify the state of interior corrosion. As the result, corrosion was found to be progressing inside the suspenders comparing with its surface, and the circumstances associated with the corrosion could be elucidated.

Thus, Honshu-Shikoku Bridge Authority undertook to develop the technology of non-destructive inspection of suspenders in order to perform future maintenance management rationally. From the results of examinations, it has been ascertained that the non-destructive inspection using the main flux method can verify the state of corrosion of the interior part of suspenders with sufficient precision.

1. INTRODUCTION

Innoshima Bridge is the first opened suspension bridge in the Honshu-Shikoku Bridges (1983). The suspender ropes of this bridge are center-fit-rope-core (CFRC) type, which is widely adopted in suspension bridges worldwide. The rope of this type hangs the saddle to a main cable, and is used.

Conventionally, external visual inspection has been relied upon to evaluate the soundness of the suspender ropes since no other effective method is available. Visual inspection of the Innoshima Bridge’s suspender ropes, conducted in 1997, revealed rust on the external surfaces of the suspender ropes, and rusty water oozing from the rope surfaces near the sockets. In 1999, two suspender ropes were removed from the bridge, and disassembled and inspected for internal corrosion. Local corrosion was identified inside the ropes though not serious enough to have an adverse influence on the rope strength. The inspection results showed that the locations of internal corrosion did not correlate with the external appearance of the ropes, and that internal corrosion cannot be detected by external visual inspection alone.

Under these circumstances, we developed a nondestructive inspection technique that uses an electromagnetic method (main flux method) to identify internal corrosion of suspender ropes from the exterior.

This report describes the results of inspection after disassembly of 16-year-old suspender ropes of the Innoshima Bridge, and the development of the nondestructive inspection technique for suspender ropes, and the results of an investigation of the bridge by the developed nondestructive inspection technique.

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2. INSPECTION AFTER DISASSEMBLY

2.1 DETAIL OF INSPECTED ROPES AFTER DISASSEMBLY

Suspender ropes from the Innoshima Bridge are CFRC cables with 54 mm in diameter. **Fig 1** shows a cross-section of the rope. The rope is composed of galvanized steel wires and painted on its outer surface as specified in **Table 1**.

From the 400 locations (100 panel points) subjected to close visual inspection in 1998, the approximate center of the center span was selected as the rope sampling point, for the reason that external corrosion was severe there and that suspender ropes in the center are shorter (approximately 14 m in length) and easy to replace. Two suspender ropes were removed from this point (**see Fig 2**).

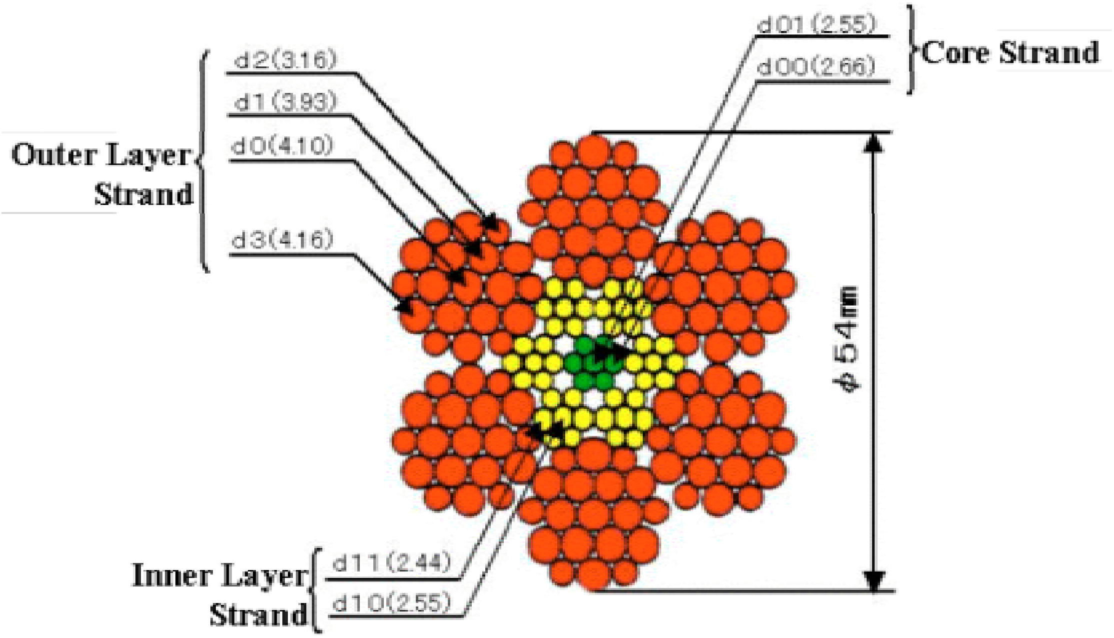


Fig 1　Cross Section of Suspender Rope

Table 1　Painting Specifications for Suspender Rope

Position of painted rope	Surface treatment	1st coat	2nd coat	3rd coat	4th coat	5th coat	Total dry coat thickness
1A - 3P (Brush-painted)	Cleaning	Chloroplane rubber calcium plumbate primer 35 μ (180g/㎡)	Chloroplane rubber calcium plumbate primer 35 μ (180g/㎡)	Chloroplane rubber calcium plumbate primer 35 μ (180g/㎡)	Chloroplane rubbe paint (Base coat) 35 μ (160g/㎡)	Chloroplane rubber paint (Surface coat) 25 μ (130g/㎡)	165 μ
3P - 4A (Dipping-painted)		Thick-coating epoxy resin (Base coat) 130 μ (280g/㎡)	Chloroplane rubber paint (Surface coat) 35 μ (150g/㎡)	–	–	–	

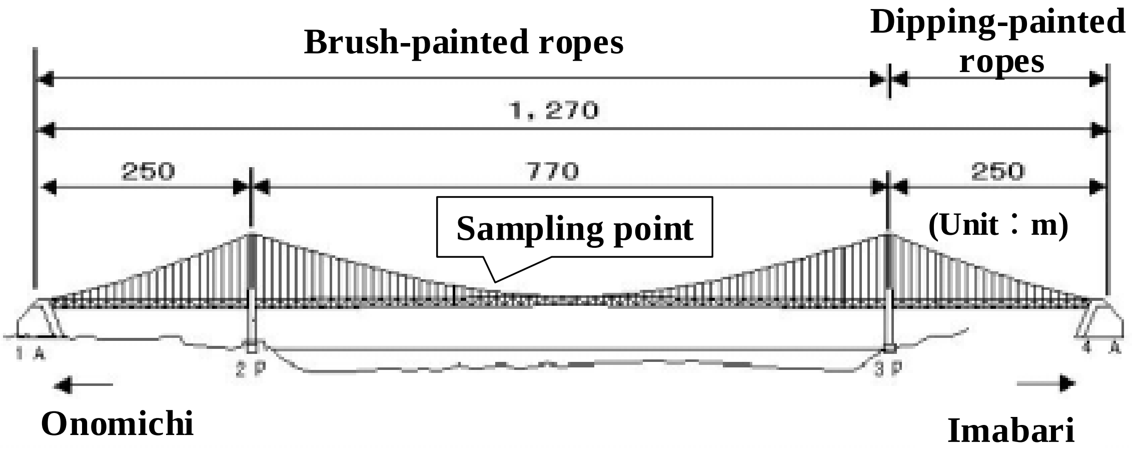


Fig 2 Sampling Point of Suspender (Innoshima Bridge)

2.2 TEST ITEMS

Table 2 shows the test items conducted after disassembly. The primary objectives of these tests are as follows:

① Determination of the internal corrosion status of the suspender ropes
② Determination of the suspender rope strengths
③ Identification of corrosion products in the case of the presence of corrosion

Table 2 Laboratory Test Items after Disassembly

Test item			Qty.	Application
1)	Visual inspection of rope before and after paint removal		2 ropes	Entire length (Paint removed : one rope)
2)	Visual inspection of strands (Inspection after disassembly)		1 rope	One of two removed ropes
3)	Rope test	Tensile test	3 times	One of two removed ropes was divided into three parts.
4)	Wire test	･Measurement of wire diameter and difference in wire diameter ･Tensile test ･Torsion test ･Winding test ･Zinc-deposit measuring test	27 wires for each	After visual inspection of strands, three sample wires were taken from each of corroded, intact and cable band portion of outer layer, inner layer, and core strands.
5)	Microscopic inspection of cross section		36 test pieces	Nine test pieces were prepared from each of corroded, intact, cable band portion of rope, and new rope.
6)	Qualitative and quantitative analyses of corrosion products		5 times	Corroded portion of outer layer, inner layer, and core strands Intact and cable band portion of inner layer strands

2.3 RESULTS OF INSPECTION AFTER DISASSEMBLY

(1) External visual inspection of ropes before and after removal of paint

The appearance of each suspender rope removed from the bridge was visually inspected before and after removal of the paint. The results of the inspection showed the following:

① Corrosion was found at many surface areas of the rope near the sockets.
② The rope surface under paint film remained intact (free of corrosion).

(2) Visual inspection of strands

Each removed suspender rope (14 m in length) was divided into 16 sections, and each section was disassembled into strands to inspect the interior of the rope visually. Rust was observed in the range shown in **Fig 3**. Close inspection revealed the following:

① The rope sections near the sockets remained intact though corrosion in these sections had been anticipated from overseas reports on corrosion.

② The core and inner strands corroded along the entire circumferential surfaces as shown in **Photo 1**.

③ Although the exterior side of each outer layer strand that has been protected by paint remained intact, corrosion was present on the interior side that had been in contact with the inner layer strands.

④ The strands of the cable band portion remained intact since the rope was entirely caulked.

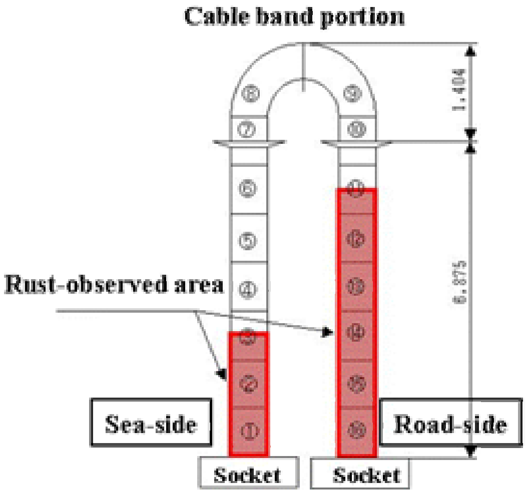


Fig 3 Development Picture of Suspender Rope

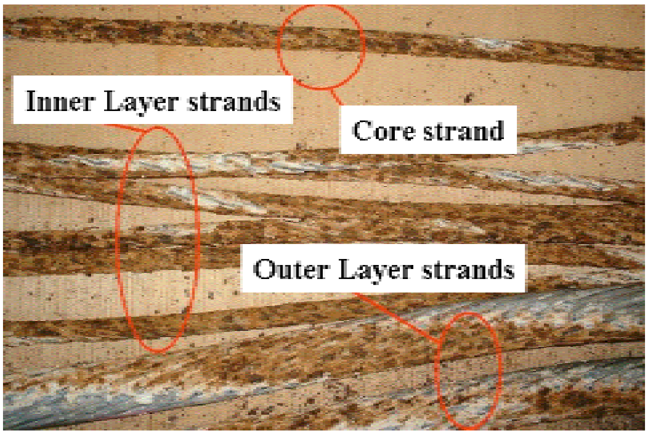


Photo 1 Corrosion of Each Strand

(3) Rope test

Table 3 shows the tensile test results of suspender ropes. The breaking load was far higher than the minimum breaking load (1,942 kN), and not lower than the average breaking load (2,246 kN) measured at the time of the rope's manufacture. That was, no drop in tensile strength was confirmed. However, initial wire-breaking noise was heard immediately before rope breakage, in the non-corroded strand, which was the cable band portion, and corroded strand was heard earlier.

Investigation of rope wires broken in the tensile test showed that the wires in the non-corroded cable band portion were broken uniformly at their approximate centers, while those in the rope sections with corrosion were broken at various locations.

Table 3 Tensile Test Result of Rope

	Length (mm)	Breaking load (kN)	Elongation (mm)	Elongation percentage (%)	Load for initial breaking noise(kN)
Sea-side	3,330	2,220	215.3	6.5	1,608
Cable band portion	3,330	2,273	258.3	7.8	2,256
Road-side	3,330	2,249	222.7	6.7	2,010

Note) "Load for initial breaking noise" refers to the load at which wire breaking noise is heard for the first time during tensile test.

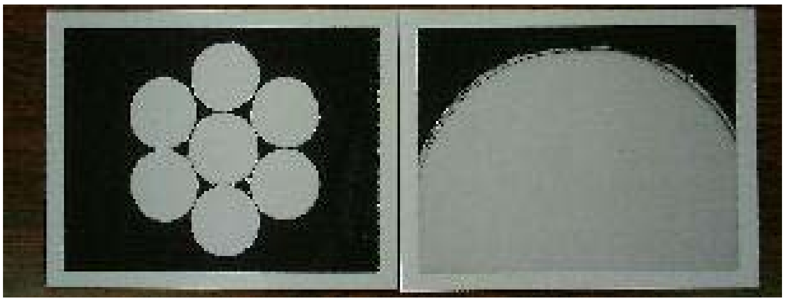
(4) Wire tests

To be subjected to the wire tests, d3 wires were sampled from an outer layer strand, d11 wires from an inner layer strand, and d01 wires from the core strand, in each of intact, cable band, and corroded sections of suspender ropes. All wires sampled from the strands in intact and cable band sections remained virtually unchanged in tensile strength. However, the tensile strength of wires from the inner layer and core strands in the corroded section had decreased below the standard value. And also, corroded wires had dropped in ductility.

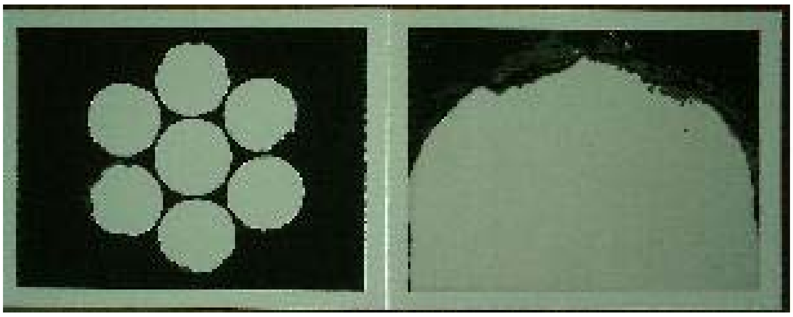
(5) Microscopic inspection of cross-section

The cross-section of each suspender rope was microscopically observed to determine the corrosion status. **Photo 2** shows the cross-sections of intact and corroded core strand sections.

The plating on the intact core strand section is partly reduced in thickness, presumably due to friction between strands when they were twisted to form the rope. The corroded core strand cross-section shows the occurrence of corrosion on the exterior side (in contact with the surrounding inner layer strands).



(a) Intact Core Strand Portion



(b) Corroded Core Strand Portion

Photo 2 Microscopic Photograph of Cross Section

(6) Qualitative and quantitative analyses of corrosion products

Corrosion products were qualitatively and quantitatively analyzed using electron probe microanalysis (EPMA) and X-ray diffract meter (XDM) techniques. Specimens were prepared by scraping the surfaces of the outer layer, inner layer and core strands of corroded sections, and the inner layer strands of intact and cable band sections. **Table 4** and **Table 5** show the analytical results.

The EPMA and XDM analyses revealed the following:

① The residual zinc amount in terms of zinc-to-iron weight ratio determined in the EPMA, was greater in the following order: intact section > cable band section > outer layer strand in corroded section > inner layer strand in corroded section > core strand in corroded section.

② The specimens taken from the inner layer strands in intact and cable band sections contained large quantities of $Zn_5(CO_3)_2(OH)_6$ (basic zinc carbonate). Due to a protective fixed film of zinc compound formed on the surface, corrosion had progressed extremely slowly on these strands.

③ A large quantity of Fe_3O_4 (magnetite) was contained in the corrosion products of iron. This phenomenon, corrosion had progressed in an oxygen-lean environment, implies that cell of light and shade of oxygen is one of the major causes of the corrosion.

④ Sodium was detected on the outer layer strand in corroded sections; this implied that salts flying in the air had entered the rope.

Table 4 Result of EPMA (Electron Probe Micro-Analysis)

		Corroded portion (Outer)	Corroded portion (Inner)	Corroded portion (Core)	Intact portion (Inner)	Cable band portion (Inner)
○	Carbon (C)	8.433	1.440	1.195	2.764	3.895
△	Oxygen (O)	21.559	25.394	24.550	25.262	25.601
	Sodium (Na)	1.736	—	—	—	—
△	Magnesium (Mg)	0.157	0.120	0.184	—	0.390
△	Aluminum (Al)	0.191	—	—	0.366	0.627
○	Silicon (Si)	0.476	0.180	0.194	0.930	3.876
○	Sulfur (S)	0.379	0.209	0.190	1.034	
△	Chlorine (Cl)	0.925	0.320	0.105	0.479	0.367
	Potassium (K)	0.148	0.054	—	0.127	0.125
△	Calcium (Ca)	0.725	0.340	0.212	0.179	0.818
△	Titanium (Ti)	0.878	0.494	0.149	0.531	0.231
○	Manganese (Mn)	0.291	0.380	0.385	—	—
	Iron (Fe)	30.069	39.248	43.008	0.242	0.786
	Zinc (Zn)	33.086	31.820	29.828	68.086	62.009
△	Lead (Pb)	0.947	—	—	—	1.068

Note) Weight percentage values (%) are given.
○ denotes elements contained in both paint and wire; △ denotes elements contained in paint only.

Table 5 Result of XDM (X-ray Diffract Meter) Analysis

Sampling portion	Detected crystal structure	Remark
Corroded portion (Outer Layer strand)	ZnO Fe_3O_4 α-FeOOH $Zn(OH)_2$ γ-FeOOH	① through ⑦ show the status of corrosion progressing in galvanized steel wire. ①Zn ②$Zn_5(CO_3)_2(OH)_6$ ③$Zn(OH)_2$ ④ZnO ⑤γ-FeOOH ⑥α-FeOOH ⑦Fe_3O_4 · “?” indicates that detection quantity is too small to definitely identify the crystal structure. · Zn in the intact and cable band portions presumably came from the zinc scraped off from galvanized steel wire when sample was taken. · Crystal structures are listed in the order of detection quantity.
Corroded portion (Inner Layer strand)	ZnO Fe_3O_4 α-FeOOH $Zn(OH)_2$ γ-FeOOH	
Corroded portion (Core strand)	ZnO Fe_3O_4 α-FeOOH $Zn(OH)_2$ γ-FeOOH	
Intact portion (Inner Layer strand)	Zn $Zn_5(CO_3)_2(OH)_6$ SiO_2? TiO_2? α-$K_2S_2O_7$?	
Cable band portion (Inner Layer strand)	Zn $Zn_5(CO_3)_2(OH)_6$ α-$K_2S_2O_7$? SiO_2? TiO_2?	

3. NONDESTRUCTIVE INSPECTION METHOD

Table 6 shows typical nondestructive inspection methods applicable to steel ropes, etc. The main flux method was adopted for nondestructive inspection of the Innoshima Bridge's suspender ropes since it can quantitatively evaluate the extent of corrosion in the ropes.

Table 6 Typical Non-destructive Inspection Methods

Inspection method		Characteristics	Wire breakage measurement	Corrosion measurement
Visual inspection		Assesses surface conditions only	△〜○	△
Electromagnetic method	Magnetic flux leakage method	Measures local defects, such as fatigue-caused wire breakage	◎	△
	Main flux method	Measures change in cross sectional area caused by abrasion or corrosion	△〜○	◎
Electromagnetic ultrasonic method		Produces elastic waves in the axial direction of rope by non-contact method, to check for reflection surface and elastic-wave attenuation	△〜○	△〜○
Acoustic emission method		Detects energy emission resulting from wire breakage	◎	×

Note) ◎: Certainly Possible, ○: Possible, △: Difficult, ×: Impossible

3.1 Inspection Using the Main Flux Method

The applicability of the main flux method was investigated in 1999. Consequently, the main flux method is applicable to nondestructive inspection of suspender ropes, though it provides a large measurement error at positions near ferromagnetic bodies, such as a rope anchorage zone. With the aim of reducing measurement error, solenoid type magnetizing coils were incorporated in the main flux method to improve the magnetizing capability and compensate factors that give influence to magnetic flux. This modified main flux method was used for the inspection conducted in 2000. The modified method provides four times higher magnetizing capability than the conventional method, and has substantially reduced measurement error so that it is practically usable to examine the corrosion of a suspender ropes. However, the measuring apparatus used for the inspection in 2000 is designed for measurement at the fixed points of suspender ropes, and not applicable for examining the entire length of rope. Therefore, it was not possible to locate the most severely corroded point. This measuring apparatus was improved to enable continuous examination of the entire length of rope, and the Innoshima Bridge's suspender ropes were inspected to evaluate the extent of corrosion in 2001.

3.2 Fixed-point Measurement and Continuous Measurement by the Main Flux Method

When a wire rope is strongly magnetized in the longitudinal direction, magnetic flux (the number of magnetic lines of force passing through a unit cross-sectional area) flows in the rope (**see Fig 4**). The main flux method is a nondestructive inspection technique based on the principle that the magnetic flux is proportional to a unit cross-sectional area. There are two types of main flux methods: fixed-point measurement method and continuous measurement method. The former method compares the magnetic flux in

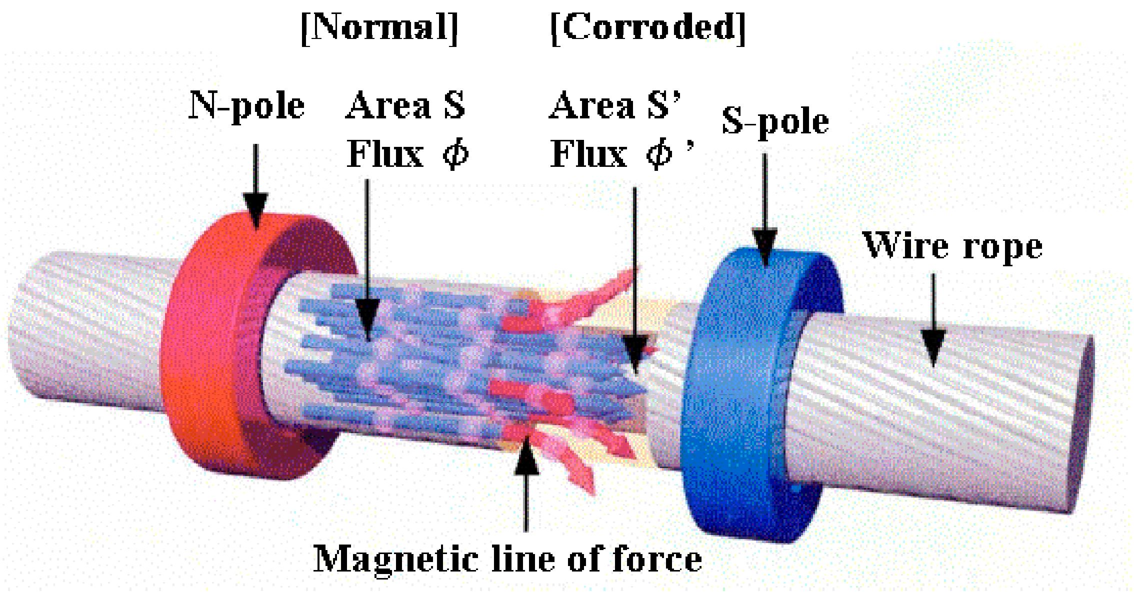


Fig 4 Principle of Main Flux Method

the approach-to-saturation region of an intact section with that of a corroded section to evaluate the extent of corrosion. The continuous-measurement method measures magnetic-flux variation at a certain magnetic field intensity. This method can locate defects along an entire length of rope and evaluate the degree of change in cross-sectional area.

3.3 Continuous Measurement Test by Main Flux Method in Laboratory

Prior to on-site inspection, laboratory testing was carried out using the continuous-measurement main flux method to evaluate changes in magnetic flux and magnetic field intensity. The measuring apparatus was moved along a 35.5-diameter rope with artificially created defects (four different patterns of changes in cross-sectional area at intervals of approximately 300 mm) to measure changes in magnetic flux and field intensity. **Fig 5** shows the results. The measured change of magnetic flux resembles the change in cross-sectional area caused by the artificial defects. The magnetic field intensity also changes at each artificial defect. These results indicate that the continuous-measurement of main flux method is effective in evaluating the extent of corrosion in suspender ropes.

The same test in laboratory was conducted on polyethylene-covered ropes, which are widely used as cables for cable-stayed bridges. The test yielded similar results without any influence on a cover and proved, proving that the continuous-measurement of main flux method was also applicable for evaluating the extent of corrosion in PE covered ropes.

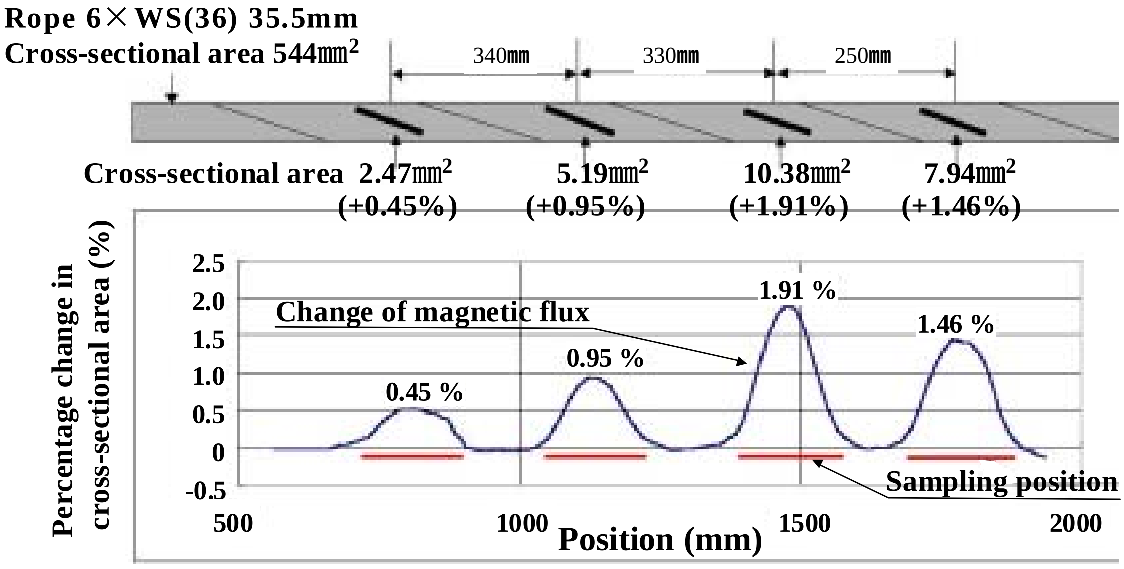


Fig 5 Result of Continuous Measurement Test by Main Flux Method in Laboratory

4. ON-SITE MEASUREMENT

Twelve suspender ropes (approximately 70 m in each length) near the main tower of the Innoshima Bridge were measured. The suspender ropes of this bridge are either brush-painted or dipping-painted. To compare the internal corrosion status between brush-painted and dipping-painted ropes, each six target ropes was selected, from the brush-painted and dipping-painted zones.

4.1 Paint Film on Suspender Ropes

Prior to the on-site measurement by the nondestructive inspection, the paint film status on the target suspender ropes was visually inspected. The inspection revealed the following:

(1) Brush-painted ropes (**Photo 3(a)**)

① There were areas in which the surface coat and base coat have almost completely been lost.

② In the grooves between strands, there were areas with multiple holes, with paint film completely lost.

(2) Dipping-painted ropes (**Photo 3(b)**)

① Paint film remained in larger areas, and there were fewer quantities of holes in the grooves than on brush-painted ropes.

(a) Brush-Painted **(b) Dipping-Painted**

Photo.3 Status of Paint

4.2 Measurement Results

To evaluate the extent of corrosion, the magnetic flux in each suspender rope measured by the continuous-measurement was compared with the average magnetic flux (standard value) measured suspender ropes which had been replaced in 1999. **Fig 6** shows the results.

(1) Brush-painted ropes

① Cross-sectional area reduction was detected at two to five positions in each rope.
② The maximum decrease percentage in cross-sectional area was approximately 1.5%.
③ No positional trend could be identified regarding reduction of cross-sectional area.
④ There was no correlation between external appearance and cross-sectional area reduction of rope.

(2) Dipping-painted ropes

① Reduction of cross-sectional area was detected in the entire upper section of each rope.
② The maximum decrease percentage in cross-sectional area was approximately 2%.
③ There was no correlation between external appearance and cross-sectional area reduction of rope.

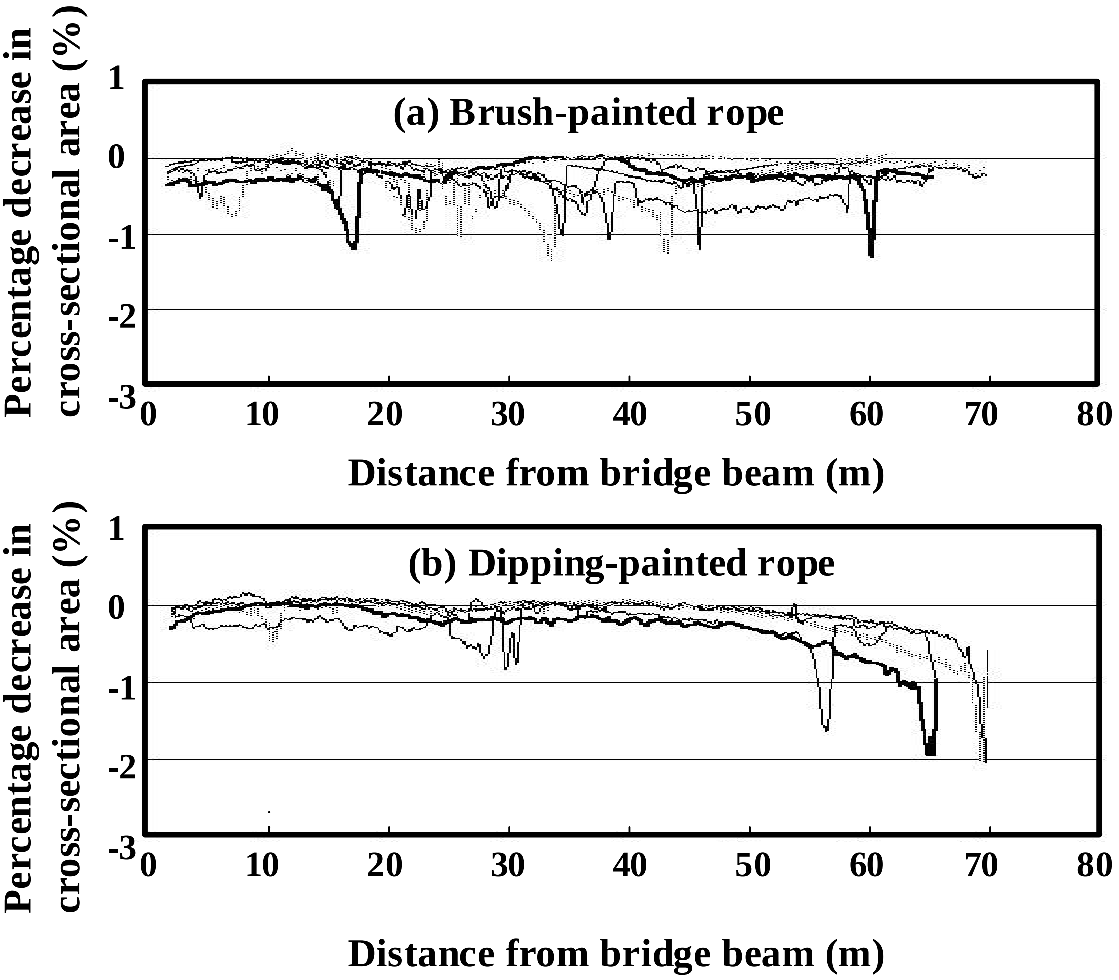


Fig 6 Result of Non-destructive Inspection

5. SUMMARY

Disassembly and inspection of suspender ropes of the Innoshima Bridge showed the occurrence of corrosion in unspecified areas inside the ropes. No correlation could be found between external appearance and internal corrosion and this indicated that the internal corrosion of ropes couldn’t be detected by external visual inspection alone.

At present, the corrosion has not progressed to reduction of the safety of the bridge by the impairment of rope strength yet. However, quantitative evaluation of the internal corrosion status of suspender ropes is essential to the rational maintenance of them, and we are sure that the developed nondestructive inspection technique will be effective on management of suspender rope.

Now, Honshu-Shikoku Bridge Authority is investigating the corrosion mechanism of suspender ropes and studies for a long-life of them. And Honshu-Shikoku Bridge Authority aims at the establishment of the maintenance method of suspender rope by using this nondestructive inspection technique together.