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Corrosion Protection for the Main Cables of Suspension Bridges

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Summary

Corrosion was found in investigative studies on the main cables of suspension bridges in service. These cables have mainly been protected from corrosion by a waterproof system composed of a surface paste on the wire surface, wrapping wires, and top coating. However, in the following studies, it has been clarified that the waterproofing would be gradually decreased due to the surface paste aging, and thermal cracks developing in the top coating. Therefore, various studies were carried out on the corrosion-proofing. As a result of these studies, it was concluded that some improvements should be made in the atmospheric environment inside the cable system. Eventually, further study was focused on development of a system which would dehumidfy the inside air by dried air injection. This paper introduces various findings on effectiveness and feasibility of this system.

1. Introduction

A study of more efficient method to protect suspension bridge cables against corrosion was started in 1988, being stimulated by an increase in cable wire strength (from 160 kgf/mm^2 to 180 kgf/mm^2) and a reduction in safety factor (from 2.5 to 2.2) in the design of the Akashi-Kaikyo Bridge.

Conventionally, bundled cables are protected from water ingress by overlaying them with a paste, wrapping the bundle in wire, and coating it with paint. However, this method was shown to offer inadequate protection in 1988, when a survey of the literature on suspension bridge cables in Japan and overseas, and visual checks of cables on Japanese bridges, was carried out. In 1989, an inspection of the interior of a cable bundle on the Innoshima Bridge, which entered service in 1983, demonstrated that water was present in the bundle and corrosion was found in the cable.

Following this finding, other suspension bridge cables were inspected. The cause of the corrosion was diagnosed, and tests aimed at improving the quality of sheathing materials and paints were implemented. The results of these efforts, however, demonstrated that a paste cannot adequately protect the cables if water is present within the cable bundle.

Given this proven difficulty in protecting a cable bundle from water ingress over the long term, it was decided that the corrosive environment within the bundle should be improved. Studies of various methods led to adoption of a dry-air injection system, whereby the cable bundle is made airtight with a sheath and dry air is blown into the bundle.

This was not the first time that such a method was tried; a similar drying technique has been used to protect cable sprays in anchorages in Japan and in box girders abroad. However, this was the first attempt to dry an entire cable bundle consisting of 5-mm wires by injecting dry air. Thus it was necessary to demonstrate that protection against corrosion could be achieved as designed. A variety of tests were implemented to verify the effectiveness and feasibility of this method. This paper describes the results of these various investigations and tests.

2. Inspection of Existing Suspension Bridge Cables

2.1 Conditions Within Cable Bundles

Inspections of conditions within cable bundles on various Honshu-Shikoku Bridges, including the Innoshima, Onaruto, Oshima, and Seto Bridges, led to the conclusions below.

(i) Water was present inside the cable bundles.
(ii) The sides and bottoms of cables in a bundle were wet, but the upper area was dry.
(iii) The paste had deteriorated and was retaining water.
(iv) Corrosion had proceeded over the entire cable surface.
(v) Typical cable sections showed evidence of advancing corrosion and red rust was present to a depth of a few layers.
(vi) Band sections of the cable remained sound, with white corrosion present only on the bottom.
(vii) Corrosion began at an early stage.
(viii) The high corrosion-prevention paste protected only wires in direct contact with the paste, while inner wires were unprotected

2.2 Humidity Within a Cable Bundle

Temperature and humidity measurements within a cable bundle on the Onaruto Bridge revealed the conditions outlined below.

(i) In ordinary cable sections, the relative humidity within the bundle was high and was affected little by the outside air.
(ii) In band sections, the relative humidity within the bundle correlated with ambient humidity.

2.3 Mechanism of Cable Corrosion Within a Bundle

The inspections of suspension bridge cables revealed that water, possibly left within cable bundles during construction or permeating through cracked paint after entry into service, was present within cable bundles. This clarified that bundle interiors are subjected to repeated wetting as the water vaporizes when the temperature rises and then condenses as it cools. By carrying out a corrosion test on galvanized wire strands wrapped with wet gauze, it was demonstrated that strands corroded quickly and weakened under wet conditions. This does not only affect the surface layer; the inner layers of cables close to the surface also corrode.

Corrosion was severe on the sides of cable bundles, indicating that the surface layers on the sides had remained wet for a long time. Further, paste deterioration in which water was retained was supposed to be the cause of hastened corrosion.

3. New specifications to protect cables from corrosion

3.1 Study of New Specifications

To isolate the cause of the corrosion and study measures to protect cables, a series of tests was performed: tests of paste characteristics; accelerated tests using 29 scale-model specimens (20 mm in diameter; 70 cm in length; 1,270 strands) formed with conventional pastes (calcium plumbate, red lead, and high-polymer organic lead), improved pastes (aluminum phosphate, thiokol, sodium vanadate, and alkyl benzene sulfenic acid), and new sheathing materials (rubber, plastic, thermal-insulating materials, and S-shaped wires); and an exposure test using 52 small and 18 large (60 cm in diameter; 2 m in length; 11,557 strands) model cable specimens.

These tests led to the following understanding:
(i) None of the conventional pastes is able to fully protect cables against corrosion.
(ii) All of the modified pastes are better in protecting cables from corrosion.
(iii) No corrosion occurred when water was kept out of the cable bundle, but corrosion occurred within the bundle regardless of the paste type when water was already present within the bundle.

In practice, however, it proves impossible to protect the whole length of a cable from the entry of water by a cable sheathing method. For this reason, a study of the simple and highly feasible dry air injection method was initiated in 1993. A verification test using specimens on actual bridges began in 1994.

3.2 Study of Dry-air Injection System

To demonstrate the feasibility of using a dry-air injection system, several issues were investigated. The tested items, conditions, and the results follows.

1) Protection of cables from corrosion by injecting dry air

The system is based on the experimental result that steel hardly corrodes at all under dry conditions.[1] A test was conducted to ascertain whether such conditions can be realized by injecting dry air into a cable bundle. Attention focused on whether it would be possible to prevent the formation of the white corrosion found within cable bundles in the scale-model tests carried out during 1993. The test conditions were as outlined below.
(i) Test specimen: overlaid with a paste, wrapped with wire, and finished with paint (two specimens)
(ii) Test period: approx. 3 months
(iii) Temperature and humidity: 60°C and 85% RH for 12 hours + 20°C and 95% RH for 12 hours (with 1 hour/day under rainy conditions)
(iv) Wet conditions: 250 cc of water injected into specimen
(v) Dry air injection: injection of air (at about 20% RH and an air flow rate of 15 cm/min.).

Since it took about a month to dry out the specimen, white corrosion formed on the bottom where the water pooled. However, the original galvanized color was visible elsewhere, demonstrating the effectiveness of dry-air injection. Although other tests with volatile corrosion inhibitors and hollow pipe covers to facilitate the flow of air were carried out, they demonstrated no significant advantages. Further, no advantage was noted in tests with and without a paste, thus demonstrating that the use of paste would become unnecessary if the dry-air injection method were adopted.

2) Drying of cables by injecting dry air through one part of the cable bundle section

It was questionable whether dry air would flow across the entire section of a cable bundle. To check whether drying takes place in the sections through which the air does not actually flow during injection of dry air, a test was carried out using a 60 cm diameter by 2 m long model cable (11,557 strands of 5 mm diameter wire at a void ratio of 18%) with 2,500 cc of water added.

Dry air was injected through part of the cable bundle section. Dry-air injection removed all water after 300 hours.

3) Injection of air into a cable through the cable surface

One means of injecting air into the cable bundle on an actual bridge would be to force it into the bundle through the surface (with no wrapping material). To verify whether this is possible and whether injected air spreads through the cross-section, air was injected locally from the top face into a specimen with the same dimensions as in 2) above. This verified that air could be injected through a 13.5 cm by 5 cm opening at an air-flow rate of 0.19 m^3/min. at a low pressure of 90 mm aq. (0.009 atmospheric pressure). (It was later verified in tests for the Akashi-Kaikyo Bridge that it is possible to inject air through an opening of about one meter.) It was also verified that air injected through the side spread in the cross-sectional direction, although the flow rate was very small.

4) Critical humidity for the corrosion of galvanized steel strands

It is a known fact that galvanized steel strands hardly corrode when the relative humidity is below 60%.[1)] However, the effects of rust, paste, and salt buildup on corrosion are unclear. Accordingly, an investigation was carried out to determine the effects of various parameters on this value of critical humidity: the clearance between steel strands, the presence of white corrosion or red rust deposits or deteriorated paste, and the presence of trace amounts of salt that might be entrained by the injection of dried ambient air. In particular, the effects of trace quantities of salt were investigated quantitatively. The test was implemented by placing specimens in a desiccator, and adjusting the humidity by controlling the concentration of a sulfuric acid solution.

This test verified that galvanized steel strands rarely corroded below a relative humidity of 60% even in the presence of these buildups. Small amounts of white corrosion were found on steel strands where deteriorated phosphate paste had built up, whatever the humidity level. Although the degree of corrosion increased with salt buildup, galvanized steel rarely corroded when the relative humidity was below 60%.

5) Extent of dried area when dry air is injected into a cable bundle

A test was carried out on the Bisan Seto Bridge, whose cable diameter was 998 mm. After temporarily wrapping the bundle with rubber, dry air was injected at the saddle atop one of the towers. It was possible to lower the humidity within the bundle at distances of 140 m and 215 m from the tower to the same level as at the dry-air injection nozzle, i.e. to less than 30%, in about six months and one year, respectively. At the Innoshima Bridge (cable bundle diameter: 610 mm) a dry air injection test was carried out by fitting a dry-air injection cover over the bundle near the middle of the central span and injecting air into the bundle through a nozzle on the cover. As shown in Fig. 14, the humidity within the bundle at a distance of 230 m was fully reduced, while at a distance of 250 m it was continuing to fall.

6) Removal of salt from air before injection

To remove the salt from injecting air, a special system was developed using six different filters which removed 99.97% of salt particles over 0.3 μm in diameter. (Salt particles range mostly from 0.5 μm to 30 μm in diameter.)

4. Corrosion Protection System for the Akashi-Kaikyo Bridge Cables

After studying the results of the tests, it was decided to adopt a dry-air injection system as described below for the protection of the Akashi-Kaikyo Bridge cables.

(1) Cable sheathing system

To enhance air tightness and protection against water permeation, the conventional wire wrap is enhanced by wrapping with rubber. For the reasons given earlier, the paste is eliminated. To seal the cable band sections, the cable bundle is covered with butyl rubber on the bottom and with modified silicone on the top surface to increase air tightness and durability (Fig. 1).

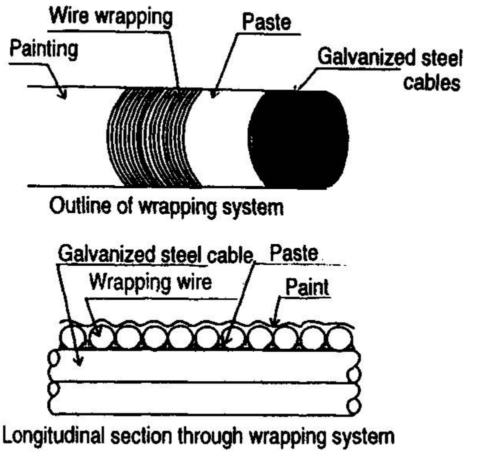

Fig. 1 Conventional cable protection system

(2) Dry air injection system

The basic design policy adopted for the dry-air injection system is as follows.

(i) Air is injected through cable covers placed at intervals of about 140 m.
(ii) The dry-air flow rate at each cover is 3 m^3/min. and the pressure within the cable bundle is kept below 300 mm aq. (0.03 atmospheres), taking into account the rupture pressure of seals and sheathing materials.
(iii) Dry-air injection covers are located as close to cable bands as possible.

Figures 2 and 3, and Photo 1, show the arrangement of pipes, a schematic drawing, and a dry-air injection (exhaust) cover, respectively.

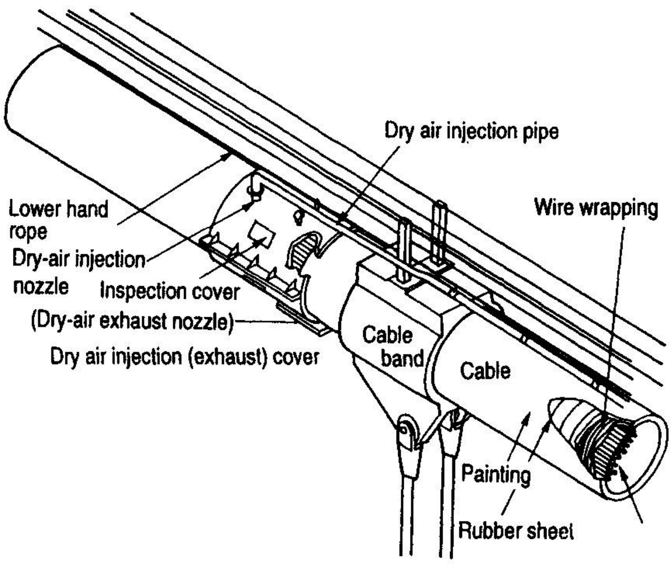

Fig. 2 Dry Air injection system (arrangement of pipes)

(3) Maintenance plan

(i) It is important to take particular care in inspecting dryers, blowers, and salt filters.
(ii) Dry-air injection pipes and cable sheathing materials must be well maintained.
(iii) Cable bundles are checked visually through inspection covers on the dry-air injection/exhaust covers.
(iv) Temperature and humidity within the dry-air injection/exhaust covers are measured periodically.

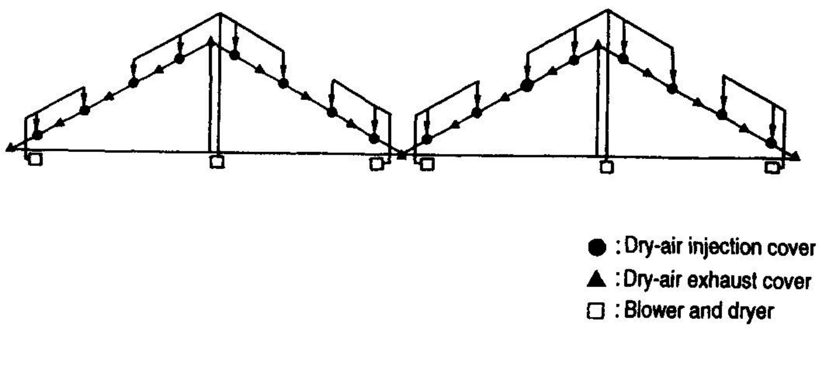

Fig. 3 Schematic drawing of dry-air injection system

(v) Cable bundles interiors are inspected after a few years of operation.

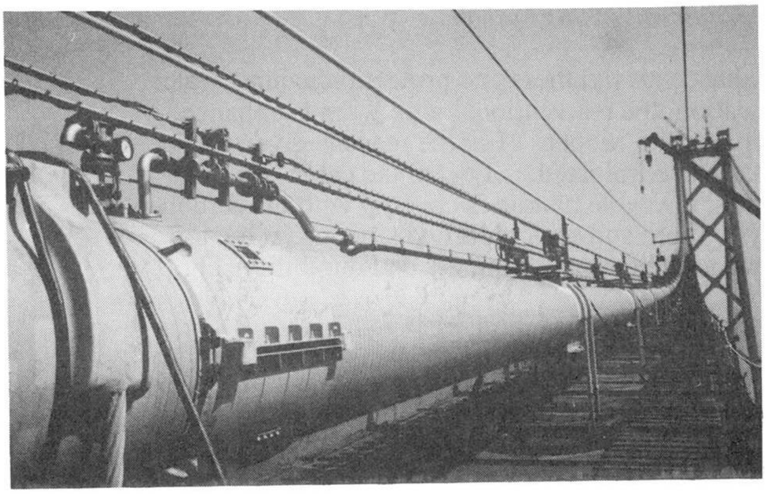

Photo 1 Dry air injection (exhaust) cover

Conclusions

This is the first-ever attempt to use a dry-air injection to protect suspension bridge cables. Further studies will be necessary to make the system more effective.

The cable sheathing on the Akashi-Kaikyo Bridge consists of wrapping the bundle with conventional wires and then rubber. A wire with an S-shaped cross section was developed to improve air tightness; after being tested in practical use on the Hakucho Bridge, it is now being tested by the Authority to verify its usability. A two-liquid very-fast-hardening urethane sheathing sprayed on in the field as a thick, flexible film is also being tested. Further, the interval between air-injection covers is being increased. Taking these changes into account, further studies will lead to a plan for protecting the cables of the Kurushima Bridge against corrosion. At the same time, policies will be developed for improving conventional corrosion protection systems already in use for suspension bridges.

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