Experimental Study on Repair Methods of Corroded Long Span Cables

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***Abstract*— The cables and hangers of old suspension bridges and the stays of cable-stayed bridges often suffer from steel corrosion. It is important to repair them by proper methods to prevent the further progression of corrosion. In this paper six repair methods were proposed and applied to cable specimens. Then, the specimens were exposed to severe corrosion environments and the effectiveness of the proposed repair methods was compared. Two different types of test cables were used in this study: parallel wire strands and spiral strands. The first test group used parallel wire strand cables consisting of 5 no galvanized steel wires. This test was aimed at the main cables of the suspension bridges. Six repair methods were applied to these cable specimens: coating with zinc-rich paint, coating with epoxy resin paint, coating with zinc powder paste, filling with epoxy resin, filling with oil, and a dehumidification method. Then, the specimens were accelerated to corrode in a laboratory. By investigating the mass loss owing to corrosion and appearance during this period, the effectiveness of the six repair methods was compared. For the surface wires, the dehumidification method was the most effective followed by the epoxy resin paint and filling, the zinc powder paste, and the zinc and epoxy resin paint on the surface. The oil filling was not very effective compared with other repair methods. The corrosion of the inside wires was much less than for the surface wires. The second group test used spiral strand cables consisting of seven galvanized steel wires. This test was aimed at the hangers of suspension bridges and the stays of cable-stayed bridges. The same repair methods and corrosion acceleration methods were used. By investigating the mass loss owing to corrosion and the appearance of both inside and surface wires during the 16-month period, most of the proposed repair methods were very effective compared with those of unrepaired strands. This study proves that even if cables are corroded proper repair work is effective in preventing further corrosion.**

Keywords—Bridge wires; Corrosion; Galvanized steel wires; Parallel wire strands; Spiral strands; Repair; Zinc paste; Epoxy resin, Dehumidification.

I. INTRODUCTION

Cables and hangers of old suspension bridges and stays of cable stayed bridges are exposed to severe corrosive environments and often suffer from steel corrosion. Some of the bridge wires break, reducing the bridge's loads bearing capacity. The mechanism of fracture of corroded wires has been widely studied in the past. Some researchers found that the wires suffer high tensile, bending, and residual stresses, which lead to stress corrosion cracking or hydrogen-assisted cracking. Others found that hydrogen concentration does not influence the loss of ductility of the wires, indicating that hydrogen absorption into the steel core is not a controlling factor in the embrittlement process.

The amount of hydrogen absorbed in the steel layer does not reach a level that causes hydrogen embrittlement and that wire breakage is more susceptible to corrosion fatigue. Although particular parts of cables and strands are sometimes vulnerable to corrosion, such as the cable collar, socket end, and anchorage, the general part of the strands is studied in this paper.

As the cables are the critical elements of cable-supported bridges, it is important to repair them by proper methods in order to prevent the further progression of corrosion. This paper describes six repair methods, proposed and applied to bridge cable specimens. The specimens were exposed to severe corrosion environments in the laboratory and the effectiveness of these repair methods was compared. Two different types of cables were tested in this study.

The first test group used parallel wire strands. Each strand consisted of 5 no galvanized steel wires. This test was aimed at the main cables of suspension bridges. Six repair methods were applied to these strands: coating with zinc-rich paint, coating with epoxy resin paint, coating with zinc powder paste, filling with epoxy resin, filling with oil, and a dehumidification method. By investigating the mass loss owing to corrosion and the appearance during this period, the effectiveness of these repair methods was compared.

The second group test used spiral strands. Each strand consisted of seven galvanized steel wires. This test was aimed at the hangers of suspension bridges and the stays of cable-stayed bridges. The same repair methods and corrosion acceleration methods were used. By investigating the mass loss owing to corrosion and the appearance of both the inside and surface wires, the effectiveness of the six repair methods was compared. In summarizing these studies, the best repair method is recommended for corroded bridge cables of suspension and cable-stayed bridges. Systematic and fundamental studies on cable repair have been scarcely reported in the literature and, therefore, this study is unique and practically useful.

II. REPAIR METHODS OF PARALLEL WIRE STRANDS

Repair methods of corroded wire

The repair of corroded wires is an important subject. Seven cases were compared in evaluating the effectiveness of various repair methods of corroded parallel wire cables (see Table 1). In Case A-1, no repair measures were taken; in Case A-2, only the surface wires were coated with epoxy resin paint with a thickness of 80 µm; in Case A-3, only the surface wires were coated with zinc-rich paint with a thickness of 50 µm; in Case A-4, the surface wires were coated and the cable inside was filled with oil containing inhibitor; in Case A-5, the surface wires were coated and the cable inside was filled with epoxy resin paint; in Case A-6, the surface layer was coated with thick paste containing zinc powder paste with a thickness of 1.0 mm; and in Case A-7, the cable inside was dehumidified at 45% relative humidity (RH). The zinc-rich paint contained about 95% zinc and the epoxy resin paint was the solvent-type modified epoxy resin paint. The inhibitor did not contain harmful oily materials and formed an anticorrosion thin coating. In the dehumidification system, the strands were placed in a chamber where the temperature and moisture were kept at constant values. A test strand consisted of 5 parallel no galvanized steel wires. Although galvanized steel wires are used for actual bridge cables, bare steel wires were adopted in order to accelerate corrosion and to compare the effectiveness of the repair methods more clearly. The wire specimen was 5 mm in diameter with a tensile strength of 1,764 MPa. A piano wire with a carbon content of about 0.8% was drawn into a wire with a pearlite microstructure. The attached mass of the zinc was 350 g/m2, which is equivalent to 50 µm in thickness. Then, the galvanized layer was removed by immersing the galvanized steel wires in H_2SO_4 to make the bare steel wire specimens. The zinc layer only increases the corrosion resistance and this removal process did not change the mechanical properties of the original wire.

The appearance and corrosion conditions of the surface and inside wires and the mass loss of these specimens were checked after certain periods.

TABLE 1

s.no	Repair methods of parallel wire strand	
	Numbers	***Repair methods***
1	A-1	Not repaired
2	A-2	Epoxy resin paint
3	A-3	Zinc-rich paint
4	A-4	Filled with oil
5	A-5	Filled and painting with epoxy resin
6	A-6	Zinc powder paste
7	A-7	Dehumidification (40% RH)

Fig 1: test strands in oven

III. TESTING OF CORRODED WIRE

Fig. 1 shows the appearance of the test strands 15 months after
the initiation of the corrosion acceleration test. The strand was
Dismantled at the same time and the corrosion conditions of both the surface wires and inside wires are also shown in Fig. 1. In Case A-1, the surface wires were heavily corroded, especially at the points where the gauze was attached to the wires. In Case A-2, steel rust came out from the coating defect of the surface wires. In Case A-3, the surface wires were covered with a white zinc corrosion product. In Cases A-1 to A-3, the inside wires were covered overall with steel rust, which was heavy at the connection lines of the adjacent wires.
In Case A-4, the oil became partly solid, producing a mixed State of steel rust and solid oil. In Case A-5, no damage was Observed on the surface and the inside wires except for light steel corrosion at the connection lines of the adjacent wires. In Case A-6, although a white zinc corrosion product was observed, the paste was still healthy and steel rust was not observed on the surface wires. Steel rust appeared on the inside wires; however, it was lighter than in Case A-3. In Case A-7, although there was very light steel rust on the wires, the wires were basically healthy. That the mass loss of the surface wires in the repaired cases (A-2 to A-7) is much less than in the unrepaired wire (Case A-1). Among the repair methods, the dehumidification method (Case A-7) was the most effective, followed by the epoxy resin paint and filling (Case A-5), the zinc powder paste (Case A-6), and the zinc-rich and epoxy resin paint (Cases A-2 and A-3). The oil filling (Case A-4) was not as effective as the other repair methods because the oil became solid and lost resistance against corrosion. the surface wires with 450 g/m2 (Fig.4). Fig. 5 also indicates that
the mass loss of most of the repaired wires after 15 months was between 40 and 70 g/m2; this was about the same amount

in the unrepaired wires. In particular, the dehumidification (Case A-7) and the epoxy resin paint and filling of the surface and inside wires (Case A-5) seem to be very effective with a mass loss of less than 15 g⁄m2.

IV. TENSION TEST RESULTS OF CORRODED WIRE

Tension tests were then conducted for some corroded wires, and the tensile strength and elongation were measured (Fig. 7). Fig. 8 shows the tensile strength of four typical groups of the tested wires:

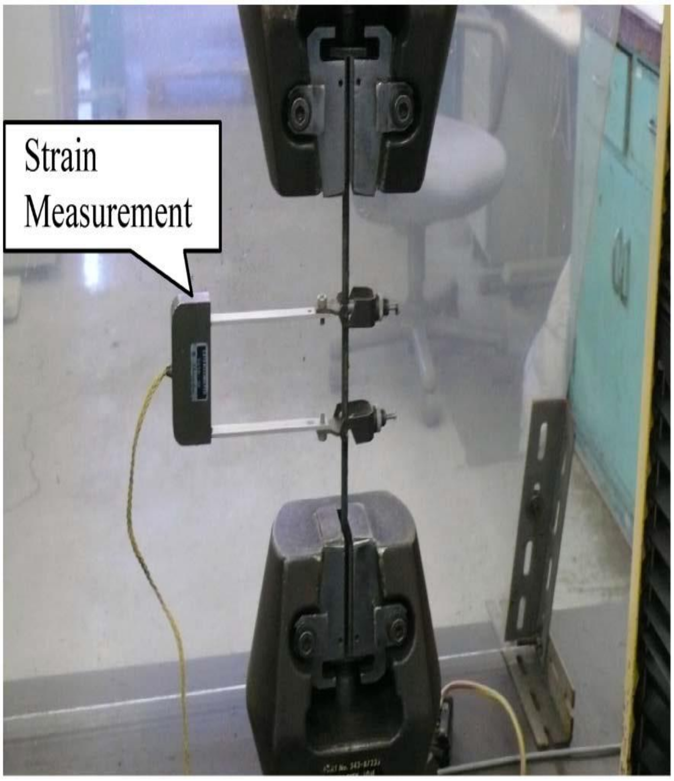

Fig 2: test strands

The surface wires of the unrepaired specimens (Case A-1), the inside wires of the unrepaired specimens (Case A-1), the surface wires with dehumidification (Case A-7), and the epoxy-filled surface wires (Case A-7). There are three specimens in each case. It is understood from Fig. 2 that the tensile strength of the surface wires in dehumidification Case A-7 was almost the same as in the original wire, whereas that of the surface wires of unrepaired Case A-1 was lower than in Case A-7 by about 75 MPa. The tensile strength of the surface wires of epoxy-filled Case A-5 and that of the inside wires of unrepaired Case A-1 are also nearly the same as the original
Strength. Fig. 3 shows the elongation of the same tested wires. Elongation of the surface wires of unrepaired Case A-1 was much less than in dehumidification Case A-7 and epoxy-filled Case A-5. It was found by these tension tests that corrosion significantly reduces the tensile strength and elongation of wires and proper repair is useful in preventing the reduction of the mechanical properties of cables.

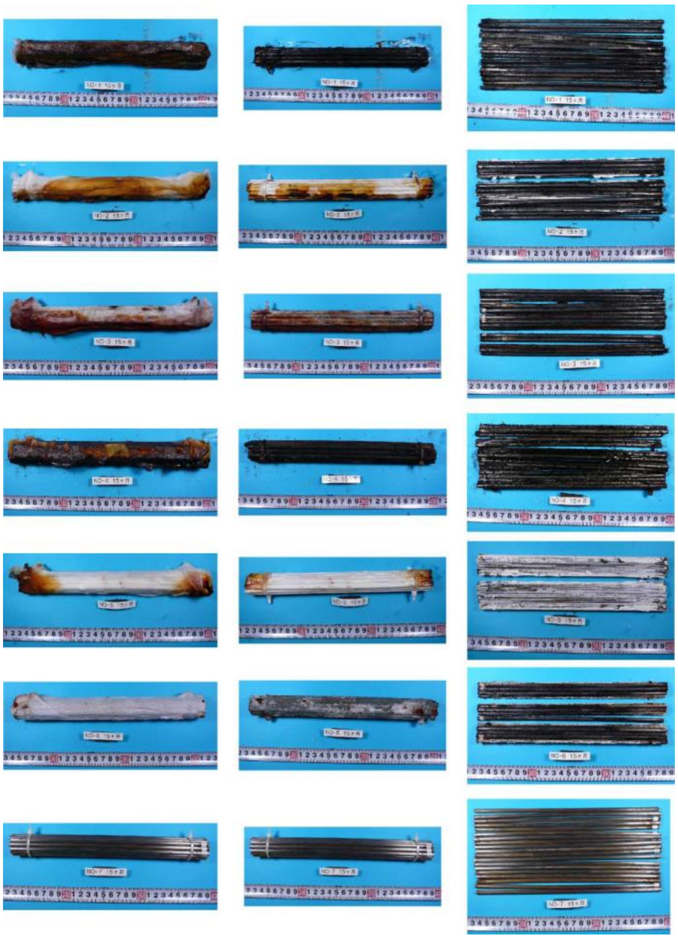

Fig 3: appearance after test

V. REPAIR METHODS OF SPIRAL WIRE STRAND

In this section, the six repair methods for spiral strands are investigated. Seven cases were compared, as in the first test group, to evaluate the effectiveness of the six different repair methods of corroded wires (see Table 2). In Case B-1, no repair measure was taken; in Case B-2, only the surface wires were coated with epoxy resin paint; in Case B-3, only the surface wires were coated with zinc-rich paint; in Case B-4, the surface wires were coated and the cable inside was filled with oil containing inhibitor; in Case B-5, the surface wires were coated and the cable inside was filled with epoxy resin paint; in Case B-6, the surface layer was coated with thick paste containing zinc powder paste; and in Case B-7, the inside of the cable was dehumidified at 40% RH. The specimen was a spiral strand consisting of seven galvanized steel wires. Each wire had a 4.0 mm diameter and a tensile strength of 1,230 MPa. The strand had an outer diameter of 12.0 mm with a cross-sectional area of 88:0 mm2 and a tensile force of 99.1 KN

TABLE 2

s.no	Repair methods of parallel wire strand	
	Numbers	***Repair methods***
1	B-1	Not repaired
2	B-2	Epoxy resin paint
3	\B-3	Zinc-rich paint
4	B-4	Filled with oil
5	B-5	Filled and painting with epoxy resin
6	B-6	Zinc powder paste
7	B-7	Dehumidification (40% RH)

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The spiral strands were corroded by the same method used for
the parallel wire strands. They were wrapped with wet gauze and kept in a chamber at a temperature of 40°C for 40 days to accelerate corrosion. After this period the corroded strands were subjected to the six repair measures explained previously. The appearance and corrosion conditions of the surface and inside wires and the mass loss of these specimens were checked in 4, 10, and 16 days after initiation. the appearance of the test strands 40 days after initiation. The corrosion condition of the seven test cables looked the same as before being repaired the specimens before the repair was applied, when the corrosion substances were removed, and after the repair method was applied. the cross section of a spiral strand consisting of seven wires after 40 days, photographed with an optical microscope, where it can be observed that the surface wires are partly corroded. The contact parts between the surface wires and the parts between the surface wires and the center wire are also partly corroded.

VI. TESTING OF SPIRAL WIRE STRAND

The appearance of the test cable 40 days after initiation of the test. The strand was dismantled at the same time, and the corrosion conditions of the surface wires and inside wires are also shown in Fig. the wires were covered with white zinc corrosion and steel rust at the surface. In Case B-2, the surface looked healthy; however, there was some zinc rust inside. In Case B-3, the surface and inside wires were locally covered with steel rust. In Case B-4, the oil became partly solid and produced a mixed state of steel rust and solid oil on the surface wires. In Case B-5, no damage was observed on the surface and the inside wires except a small amount of zinc corrosion. In Case B-6, although the white zinc corrosion product was observed, the paste was still healthy and the steel rust was light. In Case B-7, although there was very light steel rust on the inside wires, they were basically healthy.

The mass loss rate owing to corrosion of the spiral strands with the six repair methods. The mass loss rate of the strands owing to corrosion decreased sharply with time for the first 4 months. At that time, the corroded strands were repaired. After the initial 4 months, the spiral strand without repair continued to corrode. On the other hand, the corrosion did not progress further for the spiral strands, which were repaired by all of the six methods. These tension tests results show that although corrosion significantly reduces tensile strength proper repair is useful in preventing the reduction of the mechanical properties of cables.

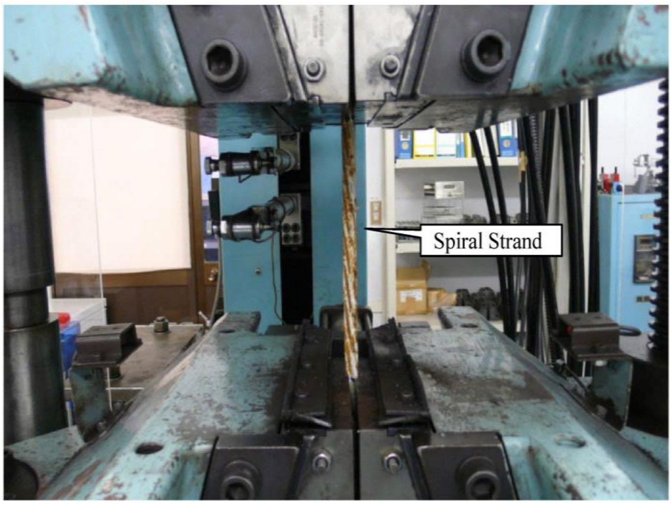

Fig 4: testing of spiral strands

VII. DISCUSSION AND CONCLUSION

Bridge cables in suspension bridges and cable-stayed bridges are under severe corrosion because of environmental factors, and some become seriously corroded. This study investigated how to repair corroded cables and the effectiveness of the repair methods. Six repair methods were proposed and applied to the cable specimens: coating with zinc-rich paint, coating with epoxy resin paint, coating with zinc powder paste, filling with epoxy resin, filling with oil containing an inhibitor, and dehumidification. Using these six repair methods, the specimens were exposed to severe corrosion environments, and the effectiveness of the methods was compared.

Two types of bridge cables, parallel wire strands and spiral strands, were studied. The specimens with parallel wire strands were no galvanized; however, those with spiral strands remained galvanized. This difference does not basically influence the results of this study because the two types of strands were studied independently. In addition, it is not the galvanized layer but the steel layer that directly affects the mechanical strength. The discussion and main conclusions about this study are as follows. Regarding the parallel wire strands, the surface wires corroded much more than the inside wires when no repair was installed. This was because more oxygen was supplied to the surface wires. The dehumidification method was the most effective in preventing the progression of corrosion, followed by the epoxy resin paint of the surface and inside wires, the zinc powder paste, and the zinc and epoxy resin paint of the surface wires. The oil filling was not as effective as the other repair methods.

Therefore, the dehumidification method can also be a promising repair method. However, it needs relatively large equipment to be installed. It is important for the dehumidification method to remove residual water and prevent water coming into the cable inside during Installation and operation. This can be achieved by continuously supplying dry air and monitoring the system. Epoxy resin filling is also promising as a repair method. It only needs compact installation equipment. It is important for the epoxy resin filling method to remove residual water and to fill inside without a void. This can be achieved by using fewer viscous materials. Other paintings and pastes are conventional materials and the installation is easy; however, the corrosion resistant effects are smaller than in the dehumidification and the epoxy filling methods. Tension tests were conducted with some corroded wires. The tensile strength of the surface wires, which were not repaired, and the most corroded specimen, was lower than that in the other repaired specimens by about 35 MPa. Elongation of the surface wires was also much less than in the other tested wires. Regarding the spiral strands consisting of seven galvanized steel wires, the specimens were corroded for 4 months, and then the six repair methods were applied and corrosion acceleration continued for another 40 days. The corrosion continued to increase when the strand was not repaired. On the other hand, corrosion did not progress further when the spiral strands were repaired. Most of the proposed methods were very effective; however, the one with oil filling was not as effective as the others. The tensile strength of the unrepaired specimen was lower than the effectively repaired specimen by about 30 MPa. As the number of specimens for the tension tests of the parallel strands and spiral strands was limited, further tests are required to estimate more accurately the stress reduction owing to corrosion. Strands and cables with various sizes and diameters are used in actual bridges. In general, epoxy resin filling is suitable for the hangers of suspension bridges and the stays of cable-stayed bridges, but not for suspension bridge main cables consisting of more than 30,000 wires. On the other hand, the dehumidification system is suitable for suspension bridge main cables but not for hangers and stays. This is mainly because the dehumidification system needs large installation equipment whereas the epoxy resin filling can be done with a compact device. This study proves that even if a cable is corroded, proper repair work is effective in preventing further the progression of cable corrosion. It should be noted that because effectiveness depends on the repair method and also the workmanship, the proper selection of the repair method and careful installation work are very important. The earlier corrosion is found, the easier and more effective will be the repair work. Periodic monitoring, such as through visual inspection, measurement of reduced cross-sectional area by electromagnetism, and estimating stresses by X-ray diffraction, is also Very useful in minimizing the risk of corrosion problems.

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