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Hydrogen embrittlement and corrosion fatigue of corroded bridge wires

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ABSTRACT

Cables of old suspension bridges and stays of cable-stayed bridges often suffer from steel corrosion. Corroded galvanized steel wires on different corrosion levels were produced at laboratories, and their mechanical properties and remaining strength were investigated. Actual tensile strength of corroded wires did not decrease with corrosion levels, whereas elongation decreased sharply after the zinc layer was partly depleted and the steel started to corrode. As the accumulated amounts of diffusive hydrogen of corrosion level-2 wires – with and without added tension – were almost the same and less than 0.2 ppm, the applied tension of steel wires did not affect the amount of diffusive hydrogen which was well below the critical concentration of 0.7 ppm to cause brittleness. This indicates that hydrogen embrittlement is unlikely to occur. Fatigue tests showed that fatigue strength did not change when only the galvanized layer was corroded, but it significantly decreased after corrosion of the steel below the galvanized layer progressed. Fatigue strength further lowered when the steel wire was cyclically stressed under wet environments when compared with the fatigue strength under dry environments. The broken wires of an old suspension bridge were also investigated. The fracture surface was similar to that caused by corrosion fatigue rather than hydrogen embrittlement. It was estimated that the wires were fractured by the mixed effects of corrosion, cyclic stresses and hydrogen.

1. Introduction

Bridge cables usually consist of high tensile galvanized steel wires. Old suspension bridges often suffer from deteriorated cables. Some of steel wires of the main-cables are heavily corroded and fractured. Wide rehabilitation works of corroded wires were carried out on the Brooklyn Bridge, the Williamsburg Bridge and other bridges [1–3]. Hanger ropes of suspension bridges and stays of cable-stayed bridges have also been severely corroded on many bridges [3].

Long-span suspension bridges are relatively new in Japan. However, it was found by field surveys that galvanized steel wires were partly corroded on several suspension bridges within ten years after the bridges were completed [4]. Wide surveys were carried out on these bridges. Water was present inside the cable and made the environment inside the cable highly humid, which caused the corrosion of wires. However, the steel corrosion was not deep and no broken wire was observed.

Although many studies have been conducted so far to clarify the mechanism to cause wire breakage, discussions are still in progress. Some researchers believe that hydrogen is accumulated while steel wires corrode and brittles and breaks wires [1,3]. Others believe that corrosion fatigue causes wire breakage, in particular, for hanger ropes that have high stress fluctuation [3,4].

In this paper fracture mechanism and remaining properties of corroded bridge wires are studied from three points of views. First, effect of hydrogen is studied. Amount of accumulated hydrogen is measured for steel wires on different levels of corrosion. Then, it is compared with the critical hydrogen amount to cause brittleness. Emphasis is placed to clarify the difference between stressed corroded wires and un-stressed wires.

Second, corrosion fatigue is investigated. The fatigue strength of corroded wires under wet environments can be lower than that in dry environments because of corrosion fatigue. Fatigue tests are therefore conducted in both dry and wet environments to clarify the corrosion fatigue strength of galvanized steel wires. Scanning electron microscopy of the fracture surface is shown and analyzed.

Third, considering the above studies on hydrogen embrittlement and corrosion fatigue, the fracture mechanism of corroded bridge wires is estimated. Investigation on the broken wire cut from an old suspension bridge is referred in the estimated fracture mechanism.

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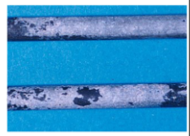
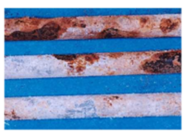
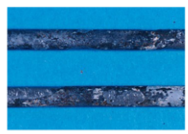
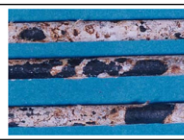
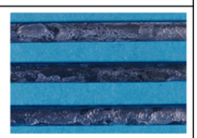
No	Corrosion Level	Appearance	
		Before removing corrosion substance	After removing corrosion substance
a	New		
b	1		
c	2		
d	3		

Fig. 1. Specimens of corroded wires (wire diameter 5 mm).

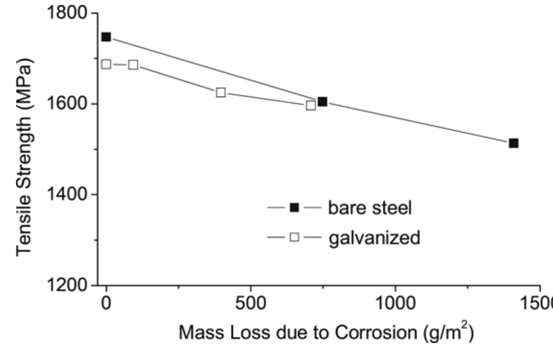


Fig. 2. Tensile strength of corroded wires.

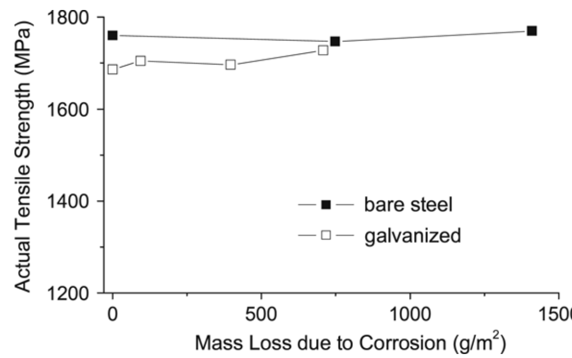


Fig. 3. Actual tensile strength of corroded wires.

2. Mechanical properties of corroded wires and hydrogen embrittlement

2.1. Corroded specimens

Nakamura, Suzumura and Tarui investigated the remaining strength of corroded steel wires [5,6]. Some results are briefly reviewed in Sections 2.1 and 2.2.

Suspension bridge cables are under severe corrosion environments; wires are wet at high temperature. To simulate this environment, galvanized steel wires are wrapped with wet gauze and kept in an enclosed box at a temperature of 40 °C. Water and oxygen are needed to corrode steel, and the wet gauze supplies both. It was proved by the past study that this simulation test with wet gauze produced the steel wires corroded in an actual corrosion environment of suspension bridge cables. The wire specimen is 5 mm in diameter, its tensile strength is 1570 MPa and the attached zinc mass is 350 g/m^2, which is equivalent to 50 μm in thickness.

The specimens were taken out from the enclosed box after 90 days, 250 days and 360 days, producing the corroded wires on different corrosion levels. Their appearances are shown in Fig. 1. The galvanized steel wires after 90 days were covered with white zinc corrosion substance (corrosion level-1), ferrous rust occurred locally in the specimens after 250 days (corrosion level-2), and ferrous rust spread widely in the specimens after 350 days (corrosion level-3).

The same simulation tests were carried out for bare steel wires. The galvanized layer was removed by immersing galvanized steel wires in H_2SO_4 to make the bare steel wire specimens. The bare steel specimen is expected to clarify the effect of the galvanized layer. The bare steel specimens after 180 days were covered with ferrous rust, and after 350 days were covered with severe ferrous rust.

The corrosion substances on the specimen surface were removed by a cloth containing 10% H_2SO_4, and the mass loss was obtained by subtracting the final mass from the initial mass. The mass loss due to corrosion increased exponentially with the elapsed days both for the galvanized specimens and the bare specimens. For the galvanized specimens, the reduced mass of about 100 g/m^2 corresponds to the level-1 corrosion (zinc corrosion), that of about 300 g/m^2 to the level-2 corrosion (steel corrosion), and that of about 600 g/m^2 to the level-3 corrosion (severe steel corrosion).

2.2. Tensile strength and elongation

Tension tests were performed with the corroded specimens [5]. Tensile strength of the specimens, the breaking force divided by the original cross sectional area, is shown in Fig. 2 with the mass loss that corresponds to the corrosion level. The tensile strength decreases with the mass loss due to corrosion both in the galvanized and bare steel specimens. Fig. 3 shows the actual tensile strength, the breaking force divided by the reduced cross sectional area due to corrosion. The actual tensile strength does not decrease with the corrosion level both for the galvanized and bare steel specimens.

On the other hand, elongation of the galvanized steel wire specimens decreases sharply after the corrosion level-1 (the reduced mass of about 100 g/m^2) and that of the bare steel decreases linearly with the reduced mass due to corrosion, as shown in Fig. 4. Elongation does not change when only the galvanized layer is corroded (level-1 corrosion) but it decreases when the steel part starts to corrode. Elongation corresponds to ductility. When the ductility of galvanized steel wires lowers, safety factor of the bridge itself is also jeopardized and should be considered carefully. It is noted that each point in Figs. 2–4 is an average of several test data.

2.3. Hydrogen embrittlement of wires corroded under tension

It is important to measure an amount of absorbed hydrogen because occurrence of hydrogen embrittlement depends on the amount of hydrogen. The absorbed hydrogen emits from the steel wire when it is heated. The specimen is therefore placed in a tube.