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Hydrogen Embrittlement and Corrosion Fatigue Performance of Galvanized Steel Wires for High Strength Bridge Cables

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Abstract. The research results of mechanical properties, hydrogen embrittlement and corrosion fatigue of new and corroded galvanized wires which were used in cable-supported bridges were summarized. Actual tensile strength of corroded wires did not decrease with corrosion levels, whereas elongation and torsional strength decreased sharply after the zinc layer was partly depleted and the steel started to corrode. The accumulated amounts of diffusive hydrogen of corroded wires with and without induced tension were almost the same and were well below a critical value of 0.7ppm. Therefore, induced tensions of steel wires did not affect the amount of diffusive hydrogen and below the critical concentration to cause brittleness. Fatigue strength did not change only when the galvanized layer was corroded, but it significantly decreased after the steel corrosion below the galvanized layer progressed. The corrosion fatigue life under wet conditions was shorter than that under dry conditions. The endurance life of pre-split steel wires was decreased in stress amplitude and increased in load frequency under fluctuating loading and corrosive environment, the aggressive media accelerated the growth rate of the fatigue crack.

Introduction

Cable supported bridges are famous for their capability to conquer large span. They are competitive for the span from 200m to 2000m (can be exceeded). The application range of span covers 90 percent of the bridge span which is applied in present. [1].

Cables are the chief bearing components of cable-supported bridges [2-5], and they can be classified into three categories: main cables and hanger ropes for suspension bridges, and stay cables for cable-stayed bridges [6,7]. The basic material used in cables of cable-supported bridges is made up of high-strength cold-drawn galvanized steel wires which have much higher strength than general structural steel [8,9]. The strength of cable wires has increased significantly in the recent years. The range of minimum strength had fluctuated between 1470 MPa and 1570 MPa for more than 50 years. A leap of increase to 1770 MPa has taken place with the construction of the world's longest suspension span of 1991 m, the Akashi Kaikyo Bridge in Japan. The increase in the wire tensile strength is usually accompanied by reduction in ductility and increase in the wire susceptibility to delayed fracture, also known as hydrogen embrittlement [10,11]. Inspection of cable-supported bridge cable wires has revealed deterioration with different degrees of severity [12,14]. Deterioration of cable wires take different forms; stress corrosion cracking, pitting, corrosion fatigue and hydrogen embrittlement [15,16], which compromise the strength and ductility of wires leading to a reduced service life of bridge cables. On December 1967, the Ohio Bridge which connected West Virginia and Ohio in USA collapsed suddenly. Result showed that the accident was caused by stress corrosion cracking and corrosion fatigue cracking [17]. Therefore, learning the corrosion mechanism and reassessing the remaining strength of corroded wires are helpful for predicting the life of bridge cable. It can provide basis for the decision whether the bridge cable need maintenance.

Mechanical Properties of Corroded Wires

Table 1 illustrates the progression of the corrosion of cable wires through four levels, which can easily be identified visually, and are the basis for a steel wire inspection. Cracking is possible during level-3 and can be expected in level-4. [18]

Table 1 Wires in various levels of corrosion [19]

Corrosion Level	Corroded wires	Appearance	Corrosion Level	Corroded wires	Appearance
Level-1		Wires are shiny with random signs of zinc corrosion	Level-3		Zinc is depleted with occasional spots of ferrous rust
Level-2		Zinc is partially corr-oded revealing a wh-iter corrosion product, but no ferrous corro-sion is present.	Level-4		Zinc corrosion product is largely displaced by ferrous rust.

Shun-ichi Nakamura, Keita Suzumura and Toshimi Tarui did some research on the mechanical properties of corroded galvanized steel wires [20]. The wire specimen was 5mm in diameter, its tensile strength was 1600MPa and the attached zinc was 3.43N/m^2, which was equivalent to 50 μm in thickness. The wire specimen were wrapped with wet gauze and kept in an enclosed box at a temperature of 40℃. Water and oxygen are needed to corrode steel, and the wet gauze supplies both.

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 (in table 1). Because of no change except the apparent color between the new and corrosion level-1 steel wires, the corrosion level-1 steel wire can be thought as a new steel wire. The corrosion substances and galvanized layer 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 reduced mass of about 100 g/m^2 corresponds to the level-2 corrosion（zinc corrosion）, that of about 300 g/m^2 to the level-3 corrosion (steel corrosion), that of about 600 g/m^2 corresponds to the level-4 corrosion (severe steel corrosion). The tensile strength, elongation and torsional strength were tested on different corrosion level wire specimens.

Tensile Strength

The tensile strength of the specimens, the breaking force divided by the original cross sectional area, is shown in Fig. 1 with the mass loss that corresponds to the corrosion level. Tensile strength decreases with increasing mass loss due to corrosion in the galvanized steel specimens. Fig. 2 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 corrosion level for the galvanized steel specimens. This means that the material itself does not change even when wires are corroded.

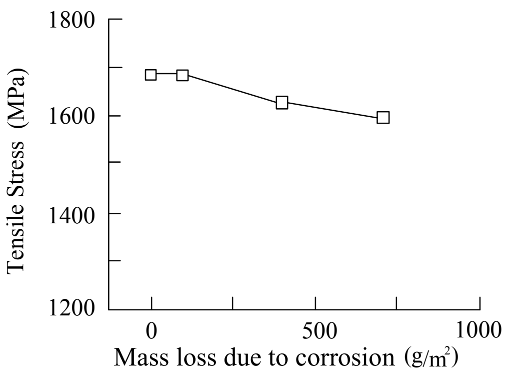


Fig.1 Tensile strength of corroded wires[20]

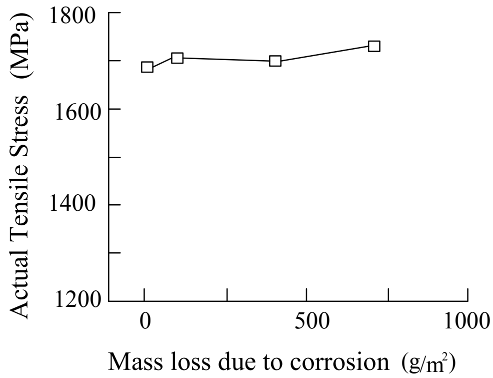


Fig.2 Actual tensile strength of corroded wires[20]

Elongation

The elongation of the corroded galvanized wire specimens decreases sharply after corrosion level-3, as shown in Fig.3. The elongation does not change only when the galvanized layer is corroded (level-2 corrosion), but it decreases when the steel part starts corroding. Elongation corresponds to ductility. When the ductility of galvanized steel wires lowers, the safety factor of the bridge itself is also jeopardized and should be considered carefully.

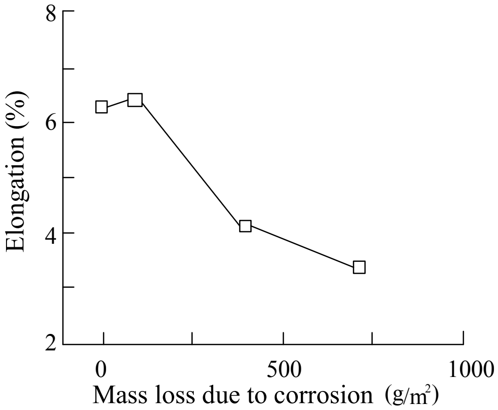


Fig.3 Elongation of corroded wires[20]

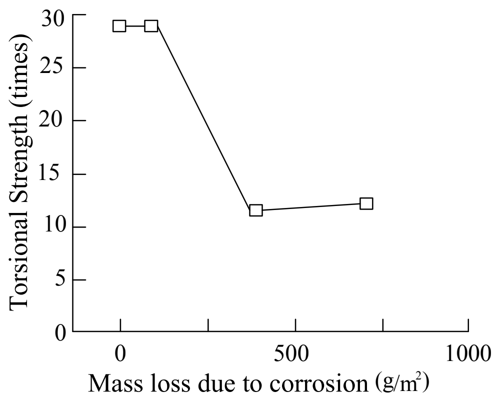


Fig.4 Torsional strength of corroded wires[20]

Torsional Strength

The torsional strength is important because it is closely related to its ductility. A specimen 500 mm long is twisted and the number of rotations is counted until it breaks. Test results are shown in Fig. 4. Torsional strength does not change at corrosion level-1 and level-2 but decreases in corrosion level-3 and level-4. This is similar to the results of the elongation of corroded wires. As ductility lowers, a crack develops along the longitudinal direction, which is called delamination. Delamination was seen in the test specimens in corrosion level-3 and level-4. It is concluded that, when a steel wire is corroded, its actual strength does not change but its ductility significantly decreases.

Hydrogen Embrittlement

Hydrogen embrittlement is a phenomenon caused by hydrogen diffusion in the metal. It leads to delayed fracture under static loading below the material yield strength [21]. The hydrogen comes in both manufacturing process and corrosion process, and it also can be divided into two types according to their existing form, diffusive hydrogen and non-diffusive hydrogen [22]. It is known by the past research that hydrogen embrittlement will occur when the accumulated amount of absorbed diffusive hydrogen is more than 0.7 ppm. This is the major reason that cause the suddenly fracture of high strength steel wires under static loading below the tensile strength. It can be said that the hydrogen embrittlement is determined by the accumulated amount of absorbed diffusive hydrogen. Therefore, it is important to know the amount of absorbed hydrogen.

Steel Wires in Stress Situation

Scholars did some research on the effect of hydrogen in galvanized steel wires [23]. The specimen is placed in a tube. When it is gradually heated with a rate of 100℃/h and hydrogen is released. Fig.5 shows a typical hydrogen evolution curve, relations between the amount of emitted hydrogen and a heated temperature. There are two peaks in the curve. The first peak is at around 100℃-150℃ and the other one is at around 250℃-300℃. The first peak associates with diffusive hydrogen and the second peak associates with non-diffusive hydrogen.

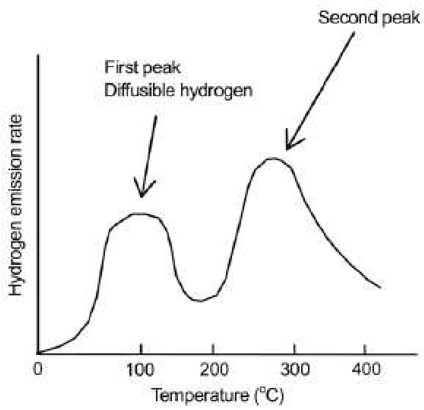


Fig.5 Typical curve of hydrogen emission rate versus heated temperature[23]

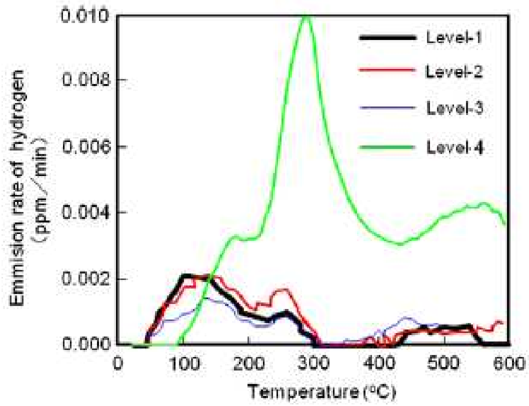


Fig.6. Emission rate of hydrogen with heater temperature[23]

Fig.6 shows hydrogen evolution curves of the galvanized steel wires on four different corrosion levels. In the hydrogen evolution curves of corrosion level-1, level-2 and level-3 specimens, the peak appears at a temperature near 150℃. However, the absorbed hydrogen of the corrosion level-4 specimen is different from others. Hydrogen is absorbed much more and the peak moved to the higher temperature of about 300℃. It is concluded from these figures that hydrogen is absorbed during the manufacturing process and not absorbed during the corrosion process of leve-1, leve-2 and leve-3.

The accumulated amount of diffusive hydrogen between 0 and 200℃is shown in Fig. 7. It is about 0.15 ppm and does not depend on the corrosion level. This accumulated amount is well below 0.7 ppm, indicating that hydrogen embrittlement is unlikely to occur. The accumulated amount of non-diffusive hydrogen, the hydrogen emitted between 200 and 400℃, sharply increases on corrosion level-3. It is known that non-diffusive hydrogen does not affect hydrogen embrittlement, although a further study is required to clarify how non-diffusive hydrogen affects fatigue strength.

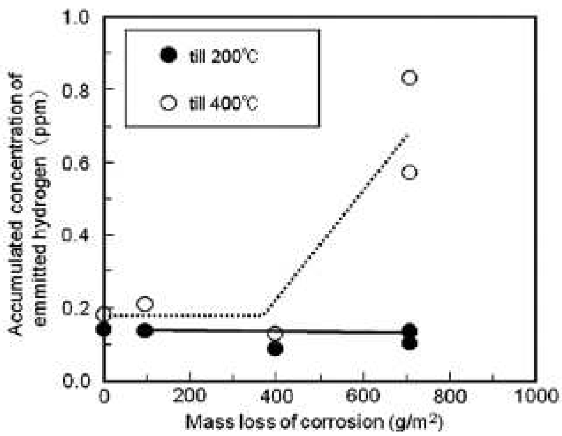


Fig.7. Volume of emitted hydrogen versus corrosion levels[23]

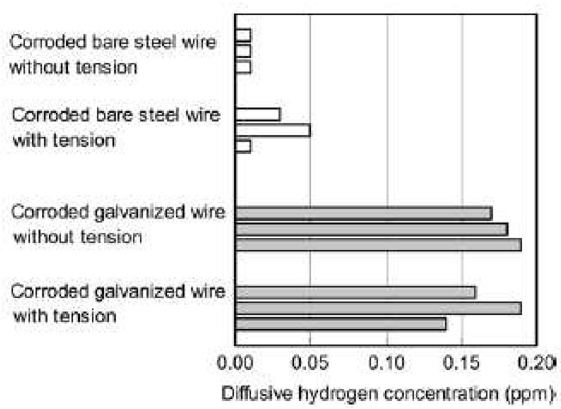


Fig.8. Diffusive hydrogen concentration (ppm)[23]

Steel Wires in Un-Stress Situation

The analysis above is keeping corroded wire specimens un-stressed. However, it is important to know the effects of the hydrogen absorption for the wire specimens while they are stressed because the cables are always in high stress situation for cable-supported bridges.

Scholars tested the accumulated amount of diffusive hydrogen of all corrosion levels [23]. It was found that the stress would not affect the amount of diffusive hydrogen. Fig. 8 shows the accumulated amount of diffusive hydrogen of corrosion level-3 wires with and without tension. The amount of bare steel wires is less than that of galvanized steel wires. This is because that hydrogen is absorbed during the manufacturing process of zinc coating. On the other hand the amount of corroded wires with tension and that without tension are almost the same and less than 0.2 ppm. It is known that tensions of steel wires do not affect the amount of diffusive hydrogen which is well below the critical concentration to cause brittleness.

Corrosion Fatigue

Corrosion fatigue is a corrosion phenomenon which is the result of cooperation of repeated stress and corrosion media. It is widely occurred in cables of cable-supported bridges. The metal can be corrosion fatigue under any corrosive environments. Fatigue cracks always initiate from the corroded parts or the surface defects. The propagation of the crack will be accelerated by the repeated stress and aggressive media. For example, the corrosion fatigue fracture is always found in the stay cables for cable-stayed bridges and the anchorage for suspension bridges.The sensibility of corrosion is increased with the increasing strength and carbon content.

Corrosion Fatigue of Pre-Split Steel Wires

J.H.JIANG did some research on the corrosion fatigue performance of galvanized pre-split steel wires [24]. The test specimens were the high-strength bridge steel wires, having a diameter of 7mm and a strength level of 1670MPa. All the specimens had a length of 300mm and a middle pre-split(0.5mm in depth) processed by digital technology for simulating surface damage. The pre-split specimens were tested to analysis their corrosion fatigue endurance life with different cyclic tensile parameters, σ_a (stress amplitude) range 200-500 MPa, R (load ratio) range 0-0.333 and f (load frequency) range 0.6-30Hz. The specimens were conducted in air, 0.5 wt% and 3.5 wt%NaCl solution, respectively.

The result shows that N_C (cycle number to failure) of specimens clearly decreases with increasing the stress amplitude under any corrosion fatigue conditions, and the depression correlates with f, R and environmental media. At the same stress amplitude, the value of N_C is lower in aggressive media than in air. However, when the load frequency reaches up to 30Hz, the N_C in 3.5 wt% NaCl solution is 20-30% lower than that in air, and 2.3 times higher than that in 0.5 wt% NaCl solution. It can be said that the interaction between aggressive media and cyclic tensile stress significantly shorten corrosion fatigue life of the bridge cable steel wires.

In order to learn the corrosion fatigue fracture deeply, J.H.JIANG observed the broken sections of samples with SEM [24]. The SEM fractographs of the samples fractured at four different stress amplitudes in 3.5 wt% NaCl solution are presented in Fig.9, where σ_a=250 MPa(a), 300 MPa(b), 400 MPa(c), 500 MPa(d), respectively.

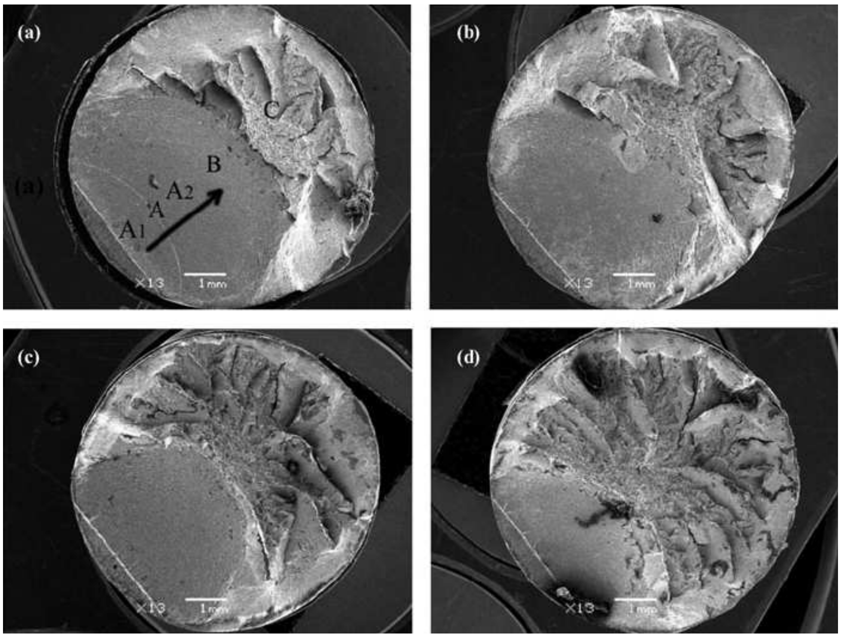


Fig.9. Fatigue-fractured sections of pre-split bridge cable steel wires tested in 3.5 wt% NaCl solution at different stress amplitudes.(a)300MPa;(b) 4000MPa; (c) 250MPa; (d) 500MPa.[24]

The fractured sections can be divided into three areas (see Fig. 9a), i.e. stable crack growth area (marked by A), rapid crack growth area (B) and instant rupture area (C). It is obvious that cracks start to stably propagate from the pre-split parts, then rapidly propagate and induce the instant interruption when the stress intensity factor(K) of the crack tip reaches the value of K_{IC} (plane strain fracture toughness). The crack growth area (A plus B) is smooth and flat, while the instant rupture area is somewhat rough with some radiating fibres and shear lips. The range of the crack growth area is bigger at the lower stress amplitude, while the propagated crack depth before instant rupture is inversely proportional to the applied load. This result means that the endurance life of pre-split bridge cable steel wires markedly decreases with increasing the stress amplitude of the applied load, consistent with that of the cycle-counting method.

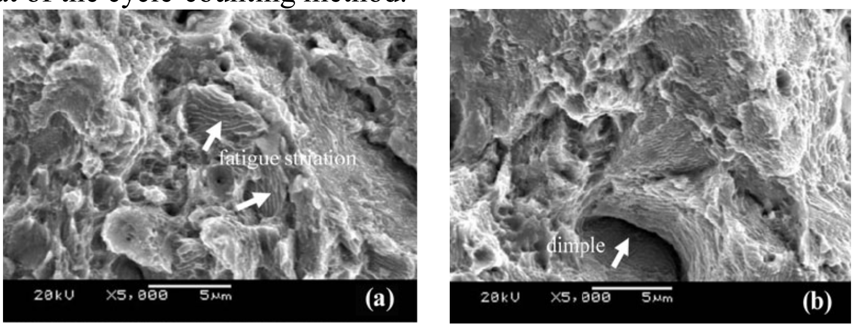


Fig.10. SEM fatigue fractographs of pre-split bridge cable steel wires tested in air (a)fatigue striation;(b) dimple [24]

Figure 10. presents SEM fractographs of the fatigue fractured samples in air (R＝0.167, f=30HZ, σ_a=500 MPa). In the initial stage of stable growth, the width and length of microcracks are very small, while plenty of fatigue striations occur in the stable crack growth area (shown in Fig. 10a). This is the typical characteristic of metal fatigue behaviour due to the transgranular fracture. More and wider microcracks present in the final area of stable crack growth and the rapid growth area. In the rapid growth area, some big dimples were formed and associated with plenty of parallel crack growth striations (as shown in Fig.10b). Plentiful intracrystalline dislocations of cold-drawn steel wires make its lattice seriously distort, therefore the crack growth in the grains becomes more difficult. Severe plastic deformation occurs at the boundaries of adjacent crystals with the crack growth, leading to the formation of tearing ridge or microporous aggregation dimples. The presence of the dimples can

reduce the fatigue crack growth rate and increase fatigue endurance with more cycle numbers to failure.

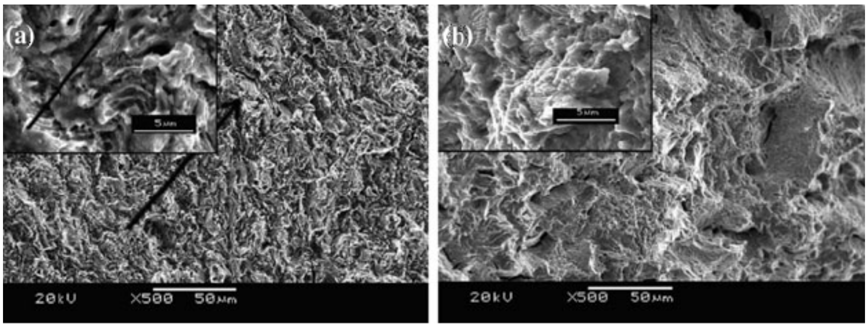


Fig.11. SEM fatigue fractographs of pre-split bridge cable steel wires tested in 3.5 wt% NaCl solution
(a) rapid crack growth area;(b) the instant rupture area [24]

Figure 11 presents SEM micrographs of fatigue-fractured sections of pre-split samples tested in 3.5 wt% NaCl solution (R＝0.167, f=30HZ, σ_a=500 MPa). The stable growth areas also show obvious brittle transgranular fracture characteristics. But the quantity of dimples in the rapid growth area (in Fig.11a) is much small in comparison with the samples broken in air. Evidently, the aggressive media can significantly reduce the toughness of the high-strength wire and increase the rate of crack growth. The fracture characteristic of quasi-cleavage is presented in the instant rupture area of the corrosion fatigue samples (in Fig, 11b). It is observed that the aggressive media can increase the rate of crack growth.

Corrosion Fatigue of Corroded Steel Wires

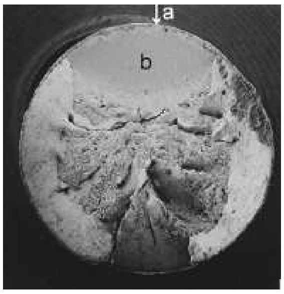
Fatigue tests were conducted for the corroded wires at corrosion levels from 1 to 4 in wet and dry conditions by scholars [23]. The specimen was held with a distance of 100mm between the grips and cyclically loaded at 64Hz. Cyclic tests were conducted keeping the minimum stress at 500 MPa and varying the stress range from 200 MPa to 600 MPa. The testes were conducted with a relative humidity under 50%.

The result shows that there is no much difference between the fatigue strength of corrosion level-1 and level-2 specimens. However, the fatigue strength of the level-3 specimen is lower than that of level-1 and level-2 specimens, and that of the level-4 specimens is further lower than above. This can be interpreted as the fatigue strength does not change only when the galvanized layer is corroded, but it significantly decreases after the steel corrosion below the galvanized layer progresses. The fatigue strength in wet environment is lower than that under dry environment.

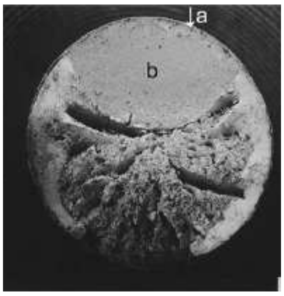
The broken positions of the level-3 and level-4 corrosion specimens agree with those of the corroded parts. Fatigue cracks initiate from the deepest corroded parts. It seems that stresses concentrate at these points and cause fatigue failure. In level-1 and level-2 corrosion specimens, as the steel corrosion does not exist and the surface is flat, stresses are unlikely to concentrate and fatigue strength is higher than those of the level-3 and level-4 corrosion specimens. There is no clear difference in appearances between the corroded specimens under dry and wet conditions.

The fractured sections are shot by SEM (Fig. 12). In all of these SEM photos, cracks initiate from the corroded parts, the top part of the wire in these photos (point a). Then the cracks propagate downwards, where is the stable crack growth area (area b). When the crack reaches about one third of the whole section, the rest of the wire section is suddenly broken. It can be seen that the broken sections of corroded wires and pre-split wires are nearly the same. All of the broken sections can be divided into stable crack growth area, rapid crack growth area and instant rupture area, and the fatigue fracture initiates from the crack parts.

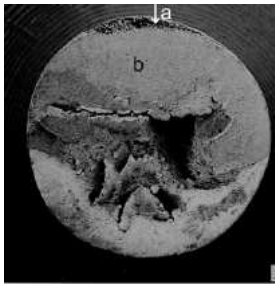
（a）



（b）

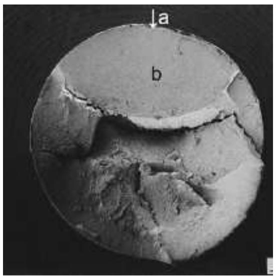


（c）

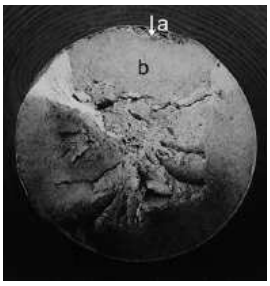


Corrosion level-1(dry condition) Corrosion level-2(dry condition) Corrosion level-3(dry condition)

（d）



（e）



（f）

Corrosion level-3(wet condition) Corrosion level-4(dry condition) Corrosion level-4(wet condition)

Fig.12. SEM photo (a: crack initiation point; b: crack propagation area)[23]

Conclusions

The corrosion of cable wires can be divided into 4 corrosion levels. Actual tensile strength of corroded wires did not decrease with corrosion levels, whereas elongation and torsional strength decreased sharply after the galvanized layer was partly depleted and the steel started to corrode.

The accumulated amounts of diffusive hydrogen of corroded wires with and without induced tension were almost the same and were well below a critical value of 0.7ppm. Therefore, induced tensions of steel wires did not affect the amount of diffusive hydrogen and below the critical concentration to cause brittleness. The hydrogen embrittlement fracture did not occur in corroded wires with and without induced tension.

The cycle number to failure of pre-split steel wires was decreased with the increase of stress amplitude. The corrosive media accelerated the growth rate of the fatigue crack. When the load frequency reaches up to 30Hz, the N_C in 3.5 wt% NaCl solution is 20-30% lower than that in air, and 2.3 times higher than that in 0.5 wt% NaCl solution. The interaction of aggressive media and cyclic tensile stress significantly shorten corrosion fatigue life of the bridge cable steel wires.Fatigue strength did not change only when the galvanized layer was corroded, but it significantly decreased after the steel corrosion below the galvanized layer progressed. The fatigue strength under wet conditions was lower than that under dry conditions.

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