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Tensile Test of Corroded Strand and Maintenance of Corroded Prestressed Concrete Girders

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Abstract**—**National bridge inventory in Korea shows that the number of old prestressed concrete (PSC) bridgeover 30 years of service life is rapidly increasing. Recently tendon corrosion is one of the most critical issues in the maintenance of PSC bridges. In this paper, mechanical properties of corroded strands, which were removed from old bridges, were evaluated using tensile test. In the result, the equations to express the mechanical behavior of corroded strand were derived and compared to existing equation. For the decision of tendon replacement, it is necessary to evaluate the effect of corrosion level on strength and ductility of the structure. Considerations on analysis of PSC girders were introduced, and decision making on tendon replacement was also proposed.

Keywords**—**Prestressed concrete bridge, prestressing steel, corrosion, strength, ductility.

I. Introduction

SEVERE corrosion failure in post-tensioned tendons has been found in a bridge. Corrosion of tendons in post-tensioned structures is mainly due to incomplete filling of the ducts, penetration of chlorides through defects of the ducts, and poor grout quality. The incomplete filling of the ducts was reported mainly in the highest parts of external tendons of concrete box girder bridges. Corrosion of post-tensioned strands has been reported in Niles Channel Bridge and Mid Bay Bridge [1]. Segregated grout lets failure of one of the external tendons of a bridge after less than two years from the construction [2].

Corrosion of prestressing steel results in the following possible fracture cases: (1) brittle fracture due to exceeding the residual load capacity, (2) fracture as a result of stress corrosion cracking, and (3) fracture as a result of fatigue and corrosion influences [3]. Therefore, service-life prediction of concrete structures is vital for the maintenance of PSC structures.

ISO proposed a framework of maintenance of concrete structures. Concrete structures are designed by requirements of performance. During the service life, the structure needs to be inspected and assessed. For the assessment, prediction of deterioration progress is essential part for decision making [4]. Inspection methods for grouted tendons are borescope inspection, visual observation after removing duct and grout test. Observed corrosion ranged from no corrosion, minor corrosion, moderate corrosion and severe corrosion [5]. Sason provided visual standards by photographing samples of strand with varying degrees of rust [6]. PTI specification classified the corrosion condition into six classes. The pit depth for Class 4 is 0.002 inch. Physical deficiency of strand for PD5 is defined as the section loss greater than 5% [7].

In this paper, corroded strands were collected from two bridges with replacement of tendons due to severe corrosion. Tensile tests were conducted, and the effects of corrosion on the mechanical properties of strand were discussed.

II. Inspection of Corrosion for Tendon Analysis

A. Inspection of Tendons

The first phase of the inspection of post-tensioned bridge is desk-top study to review design and construction details, previous inspection and maintenance record. Grout inspection consists of duct sounding, borescope inspection, grout sampling and non-destructive testing. In the practical maintenance work, there are several non-destructive evaluation (NDE) methods to inspect the corrosion of tendon such as Magnetic Flux Leakage (MFL), Electro-Impedance Spectroscopy (EIS), Impact Echo/Impulse Response (IE/IR), and so on [8]. Fig. 1 shows the corrosion inspection procedure with NDE. Once the suspected part to have corrosion is detected from the NDE, the corrosion state and speed should be evaluated by opening the duct. The corrosion state will account for the performance of corresponding tendon, and speed which is quantity of corrosion divided by time will be used to expect the performance change in the future. In the practical maintenance work, use of pit depth gauge is simple method to quantify the performance reduction of strand according to PTI specification [7], and maintenance method will be decided thereby. However, the use of pit depth has possibility to underestimate the corrosion of a tendon, because inner invisible strands are hard to be measured and considered to be not defective. For severe corrosion part, therefore, detailed corrosion inspection is required.

In case of corrosion speed, there are several suggested methods. ASTM G 102-89 [9] shows one of those methods, which suggests calculation equation based on electrochemical method.

$$CR = K\frac{i_{corr}W}{n\rho} \quad (1)$$

where CR is the corrosion speed in mm year^{-1}, K = 3.27 x 10^{-3}, mm g μA^{-1} cm^{-1} year^{-1}, i_{corr} is the corrosion current density, ρ is the density in g cm^{-3}, W is the atomic weight of the element, and n is the number of electrons required in the corrosion reaction. This equation has limitation that it cannot stand for all

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environmental condition and represents average value of corrosion area. Therefore, the mechanical property change of real corroded strand can be quite different from expected strand with ASTM equation because it is governed by most corroded section.

B. 3D Model of Corroded Strand

From the geometric data acquired from inspection, 3D model of corroded strand can be built as shown in Fig. 2. This detailed cross section evaluation is important because it enables to measure section loss due to corrosion accurately, and this will account for the strength and ductility reduction. Furthermore, this model can be used for analysis. The mechanical properties of corroded strand are varied with the number of corroded wire and amount of section loss due to corrosion. These behavior changes can be defined by either tensile test or finite element analysis with the 3D model.

Fig. 1 Inspection procedure for corroded tendon

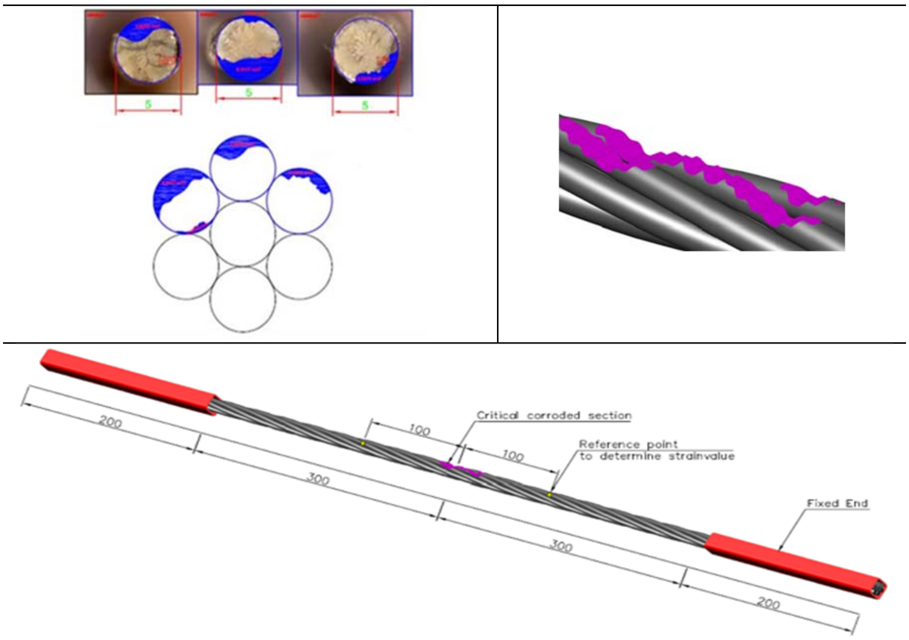

Fig. 2 3D model of corroded strand

C. Bridge Level Analysis for Decision Making

The anticipated remaining life of the PSC girder with corroded tendons can be analyzed if the mechanical properties of the corroded strand are taken from detailed inspection above. Fig. 6 shows schematic view of the bridge level analysis using the corroded tendons, and the procedure is below.

1. Once grout conditions are evaluated to check possibility of corrosion, corrosion state and speed can be expected by previous experience or suggested equations.
2. Current reduction of a strand by the corrosion is used to estimate the remained tensile strength, ductility, and fatigue life. These changes of mechanical properties are considered in the analysis of the bridge.
3. Sensitivity analysis of the bridge on corrosion speed can be conducted. This means remaining life of the bridge can be estimated, and it will be used for decision making for maintenance of the bridge.

III. Tendon Tensile Test

Corroded strands were collected from real bridges. After clearing corroded part of the strands, section reduction of the strand was evaluated as shown in Fig. 3. The section loss of most corroded part and measured mechanical properties from tensile test are listed in Table I. The ‘RT’ means reference strand which has no corrosion, and ‘CT’ means corroded strand. The section loss is calculated from corroded section area divided by gross section area. The used specimens are seven wire strands with nominal diameter of 15.2 mm and nominal area of 138.7 mm^2. The nominal strength is 1,860 MPa.

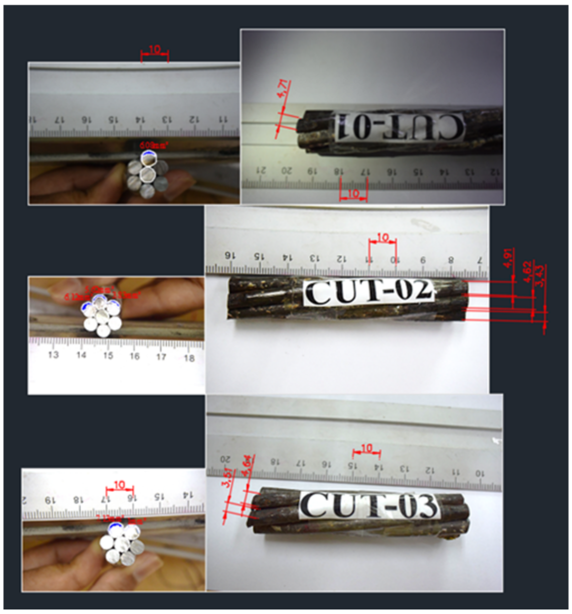

Fig. 3 Evaluation of corroded section

Wu and Li [10] suggested some equations to expect strength and ductility of corroded strand based on corrosion degree. The corrosion degree can be calculated as (2)

$$\eta_s = \frac{M_0/L_0 - M_1/L_1}{M_0/L_0} \times 100\% \quad (2)$$

where η_s is the corrosion degree, M_0 and L_0 are the weight and length of bare strand, M_1 and L_1 are the weigh and length of corroded and cleaned strand.

The equations for ultimate force and strain of corroded strain can be expressed as (3) and (4). These were derived from regression analysis of test result with human-induced corroded strands.

$$F_{uc} = (1 - 1.42\eta_s)F_{u0} \quad (3)$$

$$\delta_s = (1 - 9.91\eta_s)\delta_0 \quad (4)$$

where F_{uc} and F_{u0} are the ultimate forces of corroded strand and bare strand, respectively. δ_c and δ_0 are the ultimate strain of corroded strand and bare strand, respectively.

Figs. 4 and 5 show tensile test results of corroded strands according to section loss comparing to expression equation from Wu and Li. There are two differences from Wu and Li expression. One is corrosion degree which will be calculated as (5), because most corroded section will govern the behavior of the strand.

$$\eta_s = \frac{A_c}{A_0} \quad (5)$$

where η_s is the corrosion degree, A_c and A_0 are the cross section area of the most corroded part and bare strand, respectively.

The other is naturally induced corrosion that has occurred over a couple of decades, while corrosion in the study of Wu and Li has occurred over 10 weeks. Therefore, the equation for ultimate strain shows much difference from test specimen. As mentioned above, most corroded section will govern the behavior of the strand; however, corrosion degree calculated based on weight loss can overestimates it because quantity of corrosion is accumulated along the length of a strand. That is the reason that equation from Wu and Li shows lower force comparing to the linear regression equation of test result.

TABLE I
MEASURED SECTION LOSS AND MECHANICAL PROPERTIES OF SPECIMEN

Specimen	Section loss (%)	E (GPa)	Tensile stress (MPa)	Tensile strain (%)
RT-01	0	194.2	1863.1	6.70
RT-02	0	194.6	1868.7	6.66
RT-03	0	194.6	1864.2	6.50
CT-01	8.93	176.5	1597.8	0.78
CT-02	4.86	195.8	1886.6	3.99
CT-03	4.95	190.0	1799.6	3.59
CT-04	7.54	176.2	1593.6	0.81
CT-05	9.70	157.7	1315.3	1.08
CT-06	14.88	184.6	1718.9	2.39
CT-07	10.26	167.4	1460.3	1.01
CT-08	19.56	178.6	1629.5	1.50
CT-09	9.48	182.7	1690.4	1.59
CT-10	16.40	171.2	1518.6	0.72
CT-11	10.96	178.0	1619.0	1.80
CT-12	14.30	151.1	1216.4	0.56
CT-13	19.70	162.7	1390.0	0.79
CT-14	31.28	138.2	1022.3	0.3

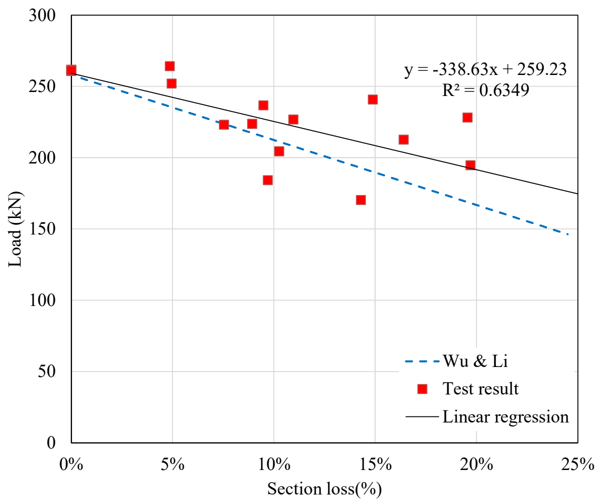

Fig. 4 Test result of corroded strand

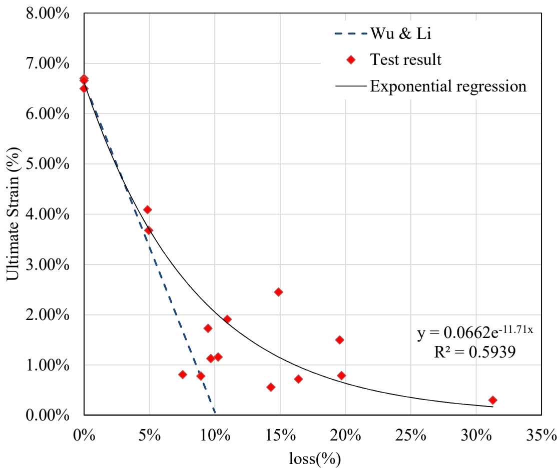

Fig. 5 Evaluation of corroded section

In this paper, different expression equations for corroded strand are suggested based on regression analysis of test result.

The ultimate force and strain of corroded strand can be modified from Wu and Li as (6) and (7).

$$F_{uc} = (1 - 1.31\eta_s)F_{u0} \tag{6}$$

$$\varepsilon_s = \varepsilon_0 e^{-11.71\eta_s} \tag{7}$$

where F_{uc} and F_{u0} are the ultimate forces of corroded strand and bare strand, respectively. ε_c and ε_0 are the ultimate strain of corroded strand and bare strand, respectively. η_s is the corrosion degree based on section loss. Equations (6) and (7) correspond to the strand with nominal strength of 1,860 MPa, therefore, further test and research are required for general use.

IV. Maintenance Decision

Decision of corroded tendon replacement depends on several aspects. Physical deficiency of tendon, quality of grout and corrosive environment are the main considerations. Due to uncertainty of the inspection, the assessment needs to be conservative. In a duct of common precast segmental box girder bridges, there are more than 15 strands with length of around 60 m. Full prestressing concept is normally used for design of serviceability.

Through the tensile tests and derived equation of corroded tendons above, engineer can evaluate the reduced strength of tendons. Based on the condition of grout deficiency, corrosion speed can be expected such as 1mm/year. The following actions can be decided by the inspection, assessment and structural evaluation considering current and future corrosion condition.

1. Re-inspection in certain period or monitoring of tendon corrosion
2. Repair of deficiency
3. Structural evaluation including check of serviceability and load rating considering tendon fracture
4. Installation of additional tendons using spare anchorages
5. Immediate traffic closure or tendon replacement

For the case of a bridge with 20 years of service life, remained prestress of a tendon is about 60% of its ultimate strength. Reduction of tendon strength or fracture of corroded wires results in transfer of tendon force to the other strand. Total fracture of tendons in a duct occurs when the increased tendon force exceeds the remained strength of whole tendons.

Tensile stress at the precast joints is not allowed for the bridge designed by full-prestressing. Once the joints are opened by decrease of prestressing force, it will be difficult to repair the joint cracking. Through structural analysis considering tendon fracture cases, decision should be conducted in terms of replaced tendons and the time of replacement. In order to compensate the prestress losses, new strands can have higher strength if the anchorage allows the increased force.

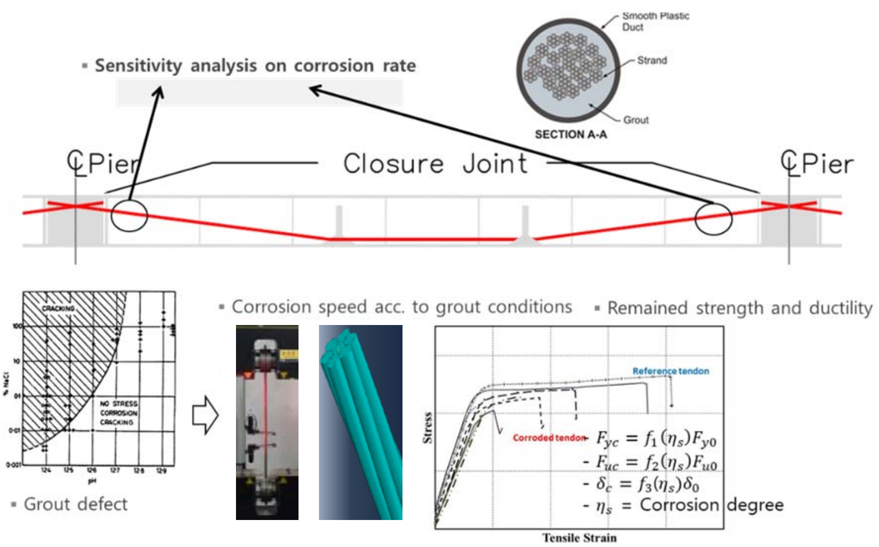

Fig. 6 Schematic view of the bridge level analysis

V. Conclusion

Aging bridges are new challenges for structural engineers. Due to much uncertainty and lack of well-organized records on existing structures, maintenance process including inspection, assessment, decision making process requires greater understanding and awareness of critical aspects. In this paper, corroded tendons in PSC bridges are dealt with and the following conclusions were derived.

1) Detailed inspection and considerations on corroded strand and their analysis were introduced.
2) Tensile test of corroded strand was conducted, and the empirical equations were derived based on section loss due to corrosion rather than weight loss.
3) Considerations for decision making of maintenance on PSC girder were introduced. The reduced strength and ductility need to be determined according to derived equation, and the corrosion speed is used to future performance change.

Based on this preliminary study on tendon corrosion, systematic information on the tendon corrosion will be accumulated in next several years through observation of existing bridges. Evaluation of current structural performance as well as it expectation will be provided based on the database and emerging technology of artificial intelligence.

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