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Corrosion-induced flexural behavior degradation of locally ungrouted post-tensioned concrete beams

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HIGHLIGHTS

- Material property of corroded strand is tested for constitutive law development.
- Flexural behavior of corroded, locally ungrouted PT beams is experimental studied.
- Analytical model is proposed to predict the flexural behavior of corroded PT beams.

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ABSTRACT

Strand corrosion within the insufficient grouted duct has become a serious problem affecting the durability of bridge structures. The residual flexural behavior of the locally ungrouted post-tensioned concrete beams after strand corrosion is investigated in the present study. Two experiments are performed: corroded strand test for the constitutive law development and beam test for the flexural behavior investigation. An analytical model is proposed to predict the ultimate strength, the deformation, and the strain response of corroded beams under external loadings. The proposed model considers the strain compatibility between strand and concrete, material mechanics deterioration of strand, and the asymmetric deflection due to local corrosion in ungrouted duct. The accuracy of the model is verified by the experimental observations. Results show that corrosion loss has less effect on the yield strength and elastic modulus than that on the ultimate strain of strand. It is also observed that light corrosion has little effect on the beam cracking and the load-deflection behavior before beam cracking. Severe corrosion degrades significantly the flexural capacity and the local post-cracking stiffness of beams, which leads to the asymmetric deformation and crack formation.

1. Introduction

Grouting is an important procedure for the construction of post-tensioned (PT) concrete structures, which is used to protect the strand from environment attack and improve the compatible strain between strand and concrete. Due to the poor construction, evaporation of bleed water, and trapped air pockets, some unwanted voids are formed inside the tendon ducts [1,2]. These grouting defects are widely found in some aging PT bridges [3–6]. The insufficient grouting reduces the protection of strands from rainwater, seawater, salt-fog, and de-icing salt. This condition can accelerate the corrosion of strand and degrade the structural performance [7–10]. The damages of the Bickton Meadows bridge and the Ynys-Y-Gwas bridge in UK are caused by this type of degradation [11]. Corrosion has become a serious problem affecting the durability of the insufficient grouted PT structures.

Strand corrosion subjected to the high stress is very complex, which is usually accompanied with stress-corrosion cracking and hydrogen embrittlement [11,12]. In these cases, some hydrogen could appear and diffuse during the corrosion processes, leading to micro-cracking on strand surfaces and deteriorating the material properties of strands [13]. Corrosion decreases significantly the material ductility and tension capacity of strands [9,14–16]. Many studies have been performed to observe the stress-strain response of corroded wires. Li et al. [17] reported that corrosion has little effect on the elastic modulus and yield strength of wires, but decreases the ultimate strain significantly. Vu et al. [18], however, found that corrosion decreases not only the ultimate strain, but also the elasticity modulus and yield strength of wires. Nowadays,

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the corrosion effects on the stress-strain response of the single wire have not reached the consensus yet. For the twisted strands, the mechanical behaviors are much more complex than that of the single wire. More works is required to investigate the stress-strain response of strand after corrosion.

Strand corrosion is very harmful for structural safety, which leads to prestress loss, strength degradation, and dangerous brittle failure of structures [19–22]. It has been reported that 25 percent of strength reduction of strand can reduce the live-load capacity of structures by 50 percent or more [23]. The insufficient grouting not only accelerates the corrosion of strand, but it also leads to the incompatible strain between strand and concrete. This will degrade further the flexural behavior of structures. Wang et al. [24] reported that locally ungrouted duct within the shear-flexural region can decrease about 10 percent of the flexural capacity of beams. Worse more, the insufficient grouting can also lead to the corrosion of steel duct sheath, resulting in structural cracking and strength degradation [25,26]. Many experimental tests and analytical models have been performed to study the effects of strand corrosion on structural behaviors [15,27–30]. Most of these works focused on the fully grouted or ungrouted structures. Very few attentions have been performed on the locally ungrouted PT beams with strand corrosion. Strand corrosion in insufficient grouted duct has been widely reported in existed bridges overall the world. There is a dire need to understand the residual behavior of these structures.

In the present study, two experimental tests and an analysis model are proposed to assess the residual flexural behavior of locally ungrouted PT concrete beams after strand corrosion. First, a tension test is performed on the corroded strand to investigate its material property deterioration. A simplified constitutive law is developed for corroded strand based on the test results. Following, the residual flexural behavior of the locally ungrouted PT beams with strand corrosion is observed through the beam test. Then, an analysis model is proposed and verified for flexural behavior prediction for these locally ungrouted PT structures after strand corrosion. Finally, some conclusions are drawn based on the proposed study.

2. Tension test on corroded strands

2.1. Tension test design

Ten 15.2-mm-diameter seven-wire strands (three uncorroded strands and seven corroded strands) were tested in the present study. The length of strand was 1.0 m. The elastic modulus, the yield and the ultimate strengths were 1.95×10^5 MPa, 1830 MPa, and 1938 MPa, respectively. The strands were tensioned to a steel frame with 1395 MPa initial stress, details are shown in Fig. 1 (a).

The specimens were exposed in an artificial climate box with salt fog (5% saline solution) to accelerate corrosion. The fog was generated in the climate box by the spray nozzle, as shown in Fig. 1 (b). The temperature and the humidity kept constant at 20 °C and 70% in the climate box, respectively. The corrosion times were different for each specimen to obtain various corrosion losses, which are listed in Table 1.

After corrosion, strands were removed from the steel frame and were subjected to an electro-hydraulic testing machine for tensile test. It was taken 200 mm long at each end of the strand to fix the strand on the testing machine. The force was monitored by a load cell and the deformation was measured by an axial extensometer attached along the strand. The gauge length of the extensometer was 500 mm recommended by the code [31], as shown in Fig. 1 (c). The loading process was controlled by 1 mm/min until the first wire rupture [31]. Following this, the loading was accelerated by 2 mm/min to investigate the residual capacity. It was found that the strand reaches to the maximum tension force as the first wire ruptured. Therefore, that case was considered as the ultimate state of the strand.

After the tension test, the strands were separated to wires, cleaned by 12% hydrochloric acid solution and neutralized by alkali. Then, these wires were cut to pieces at the three position (marked by I, II and III in Fig. 1 c) within the extensometer gauge length. The cross-section loss of the each wires were determined respectively by a contour gauge [32]. The contour shapes of the wires were transferred to graph paper and scanned into the computer (see Fig. 1 d). The residual areas of wires were determined by an aided drafting program. The cross-section corrosion loss of strand at these three sections were determined and listed in Table 1. There were some variations for these corrosion losses along the strand. The maximum one was employed to represent the corrosion loss of strand since the capacity of strand was controlled by the minimum section.

2.2. Tension test result and discussion

Fig. 2 shows the stress-strain curves for the specimens. The stress was the ratio of the monitored load to the residual area of strand determined by the maximum cross-section loss. The strain was the ratio of elongation monitored by extensometer to the gauge length. Specimen S0 was chosen as the control one since the three uncorroded specimens had similar stress-strain curves. The control specimen failed after a large deformation. Its stress-strain curve consisted of three stages: elastic stage, yielding stage, and hardening stage. The slightly corroded specimens ($\rho \leqslant 11\%$ – S1–S4) had also these three stages, but their ultimate strains decreased with the increase of corrosion loss. The severely corroded specimens ($\rho > 11\%$ – S5–S7), however, failed immediately after the elastic stage. The ultimate strain was almost equal to the yield strain of control one. Corrosion decreases significantly the ductility of strand.

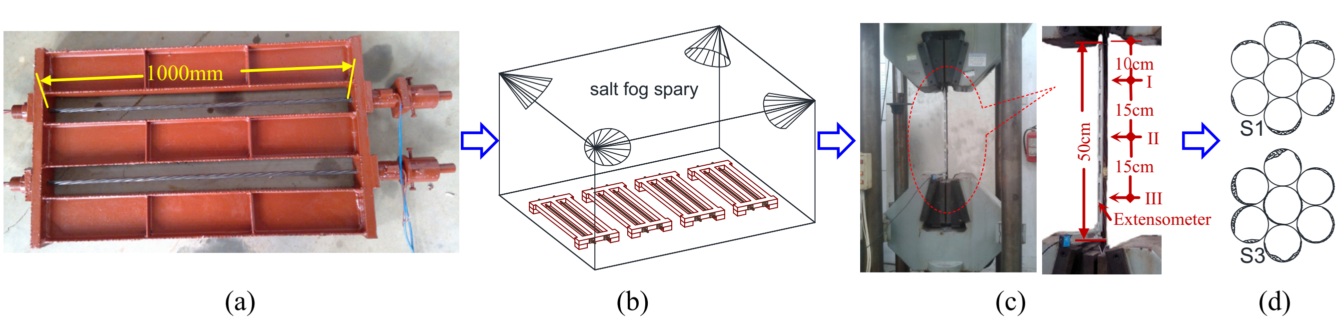

Fig. 1. Details of the tension test on corroded strands: (a) strand specimens; (b) accelerated corrosion; (c) setup of tension test; (d) contour shapes.