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Flexural behavior of bonded post-tensioned concrete beams under strand corrosion

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HIGHLIGHTS

- Flexural behavior of bonded PT beams with strand corrosion is experimental tested.
- Cracking, stiffness, ultimate strength, failure & ductility of beams are clarified.
- A coefficient is proposed to measure incompatible strain between strand & concrete.

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ABSTRACT

An experimental test is performed to investigate the flexural behavior of bonded post-tensioned concrete beams under strand corrosion. Eight beams are designed and subjected to accelerated method to different corrosion levels. The initial stiffness of beams is observed by cyclic loading-unloading test during the corrosion procedure. Corrosion effects on concrete cracking, post-cracking stiffness, ultimate strength, failure mode and ductility are then clarified by the flexural test. And, a coefficient is introduced to quantify the incompatible strain between corroded strand and concrete. Results show that the prestress force loss of strand has almost the linear relation with corrosion loss. Strand corrosion affects slightly the initial stiffness of beam before flexural cracking, but degrades significantly the post-cracking stiffness of beam as the corrosion loss exceeds 27.0%. Slight corrosion of strand has little effects on beams flexural behavior. The severe corrosion, however, decreases the number of crack, changes the failure mode form the concrete crushing to strand rupture, degrades the ductility and the ultimate strength of beams, and leads to the incompatible strain between strand and concrete. In the present test, the incompatible strain decreases about 20% of the flexural strength as the corrosion loss exceeds 27.0%.

1. Introduction

Prestressed concrete structures are considered to have high durability and were commonly used in the infrastructures, and also in the Nuclear power plant structures. In recent years, however, many degradation problems have been found, which raises serious concerns about the long-term performance of these structures. Chloride-induced strand corrosion has been identified as one of the most predominant degradation factors in these structures (Bhargava et al., 2011; Minh et al., 2008; Naito et al., 2010; Vehovar et al., 1998; Wang et al., 2014). Corrosion can decrease the tension capacity and the ductility of strand, leading to damage and even collapse of structures (Darmawan and Stewart, 2007; Gardoni et al., 2009; Pillai et al., 2010; Turnbull et al., 2006; Vu et al., 2009). The accidents of the Bickton Meadows bridge, the Ynys-Y-Gwas bridge in UK (Posten and Wouters, 1998), and the Saint Stefano bridge in Italy (Darmawan, 2009) are all induced by strand corrosion. More attention should be pay on the long-term performance of prestressed concrete structures attacked by corrosion.

Nowadays, some advanced materials have been introduced to protect the newly built structures from corrosion. For example, the functional graded material, which is a class of composite that exhibit continuous variation of material properties from the surface to inner and thus prevent the corrosion generally encountered in laminated composites (Belabed et al., 2014; Bennoun et al.,

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2016; Hebali et al., 2014; Mahi et al., 2015). For the existed structures, many researchers have investigated their residual behavior after corrosion. Rinaldi et al. (2010) performed an experimental study to observe the deterioration behavior of corroded pre-tensioned beams. It was found that a 20% strand corrosion loss can result in 60% or more reduction in the ultimate strength. Some studies also focused on the pre-tensioned members demolished from existing bridges. For example, two 45 years old concrete girders (Harries, 2009) and twenty-eight concrete panels serviced at least 25 years (Kiviste and Miljan, 2010) were tested to investigate the deterioration of flexural behavior. These works showed that strand corrosion can decrease the ultimate strength and the ductility of pre-tensioned members, and also change the failure modes.

The post-tensioned members have the different strand anchorage mechanism with pre-tensioned members. The corrosion effects of strand on the residual flexural behavior of Post-tensioned beams could also be different. Li and Yuan (2010) observed that the slight corrosion loss of strand (maximum corrosion loss $\rho = 1.98\%$) has very little effects on the flexural behavior degradation of bonded post-tensioned beams. Coronelli et al. (2009) investigated the structural response of bonded post-tensioned beams after strand fracture. It was found that the structural behavior depends on the fracture position of strand. In the open literatures, however, not many studies have been performed for the behavior of bonded post-tensioned beams with moderate strand corrosion loss. It was reported that the corrosion of prestressing strand subjected to high stress is more complex and faster than that of ordinary steel bar, which can lead to moderate or severe corrosion loss of strand (Li et al., 2011; Vu et al., 2009). There is a dire need to clarify the flexural behavior degradation of bonded post-tensioned beams with different corrosion levels.

In the present study, an experimental test is performed to overall investigate the residual flexural behavior of bonded post-tensioned beams with different corrosion levels. Corrosion effects on concrete cracking, initial stiffness, post-cracking stiffness, ultimate strength, failure mode and ductility are clarified. A coefficient is also introduced to quantify the incompatible strain between corroded strand and concrete based on the test results. These works can provide some qualitative and quantitative references for flexural behavior evaluation of bonded post-tensioned beams after corrosion.

2. Experimental program

2.1. Specimens

Eight post-tensioned concrete beams were designed and manufactured. All beams have the same dimension of $150 \times 220 \times 2000$ mm. The beams are reinforced with two 8 mm plain bars at the bottom, two 12 mm deformed bars at the top, and 8 mm stirrups with 90 mm spacing. The beams are casted with a 32 mm concrete duct and prestressed with a 15.2 mm seven-wire strand. The duct is formed by dragging out the embedded rubber rod after concrete casting. The initial prestress of the strand is 1395 MPa, which is about 0.76 times of the yield strength. The grout was injected into the duct through the channels reserved at the end of beams. The details are shown in Fig. 1.

The tensile performance of the strands and reinforcing bars was tested before the construction of beams. The average yield strength of the prestressing strand was 1830 MPa. The average yield strength of the mild steel bars was 335 MPa for the 12 mm deform bars, and 235 MPa for the 8 mm plain bars. The elastic modulus of the prestressing strand and the mild steel bars were 195 GPa and 210 GPa, respectively. The Portland cement content in the concrete mixture was 417 kg/m^3. The ratio of the coarse aggregate to the fine aggregate was 1.6 by weight. The water-cement ratio (w/c) is 0.45. The 28-day concrete compressive strength for all the beams are listed in Table 1.

2.2. Accelerated corrosion and loading-unloading test

After 28-days of concrete curing, the strand corrosion was electro-chemically accelerated to obtain different area losses. The corrosion system consisted of the direct current galvanostat, the strand anode, and the stainless steel cathode submerged in the 5% saline solution. A special corrosion tank was designed and installed along the beam to prevent the submergence of strand ends in the saline solution. The direct current flowed from the potentiostat to strand, and then through saturated concrete and saline solution to stainless steel plate, and finally back to the potentiostat. Fig. 2 shows the layout of the accelerated corrosion system.

Before the electrolytic corrosion, the beams were immersed in the saline solution for 3 days to facilitate the corrosion process. The current in the accelerated corrosion test was 0.4A. The current density herein was determined by the area of all the wires and the corresponding value was 180 μA/cm^2. The corrosion time for all the beams are listed in Table 1.

A degraded initial stiffness was reported for reinforced concrete beams during the corrosion process (Torres-Acosta et al., 2004). The corrosion effect on the initial stiffness of PT beams was still unknown. Therefore, a loading-unloading test was performed during the accelerated corrosion process to evaluate the stiffness of beam at different accelerated corrosion stages. The beams were simply supported over a span of 1800 mm. Two-point load was applied symmetrically about the midspan with a space of 600 mm. Fig. 2 shows the test set-up. The load was gradually applied up to the half of cracking load of the control beam (about 25 kN). The deflection at midspan was measured by an electronic digital dial gauge. The loading-unloading tests were cycled every ten days.

2.3. Flexural test

Corrosion results in the prestress force loss and changes the bond performance between strand and surrounding concrete. The regular approach recommended by design codes is very difficult to consider the bond degradation in predicting the flexural behavior. The static loading test was employed to study the effects of strand corrosion on the flexural behavior in the current study. After the accelerated corrosion, the beams were simply supported and

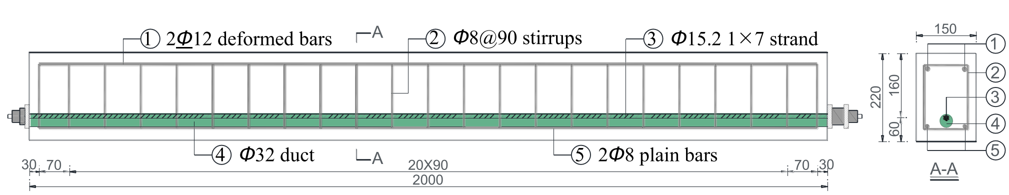

Fig. 1. Beam details (Unit: mm).