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Effect of insufficient grouting and strand corrosion on flexural behavior of PC beams

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HIGHLIGHTS

- We investigate the effect of insufficient grouting and strand corrosion on flexural behavior of beams.
- The influence of insufficient grouting including void, ungrouted duct length and position on flexural behavior is addressed.
- The flexural behavior deterioration induced by the combined effect of strand corrosion and insufficient grouting is analyzed.

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ABSTRACT

An experimental study is proposed in this paper to investigate the effect of insufficient grouting and strand corrosion on flexural behavior of prestressed concrete (PC) beams. First, experimental design is discussed with different insufficient grouting conditions and the strand corrosion in ungrouted duct. Thirteen PC beams were designed and divided into two groups: five beams with different insufficient grouting conditions; eight beams subjected to accelerated corrosion to different strand corrosion levels. Next, experimental study was performed and the characteristic of strand corrosion in the PC beams with insufficient grouting is discussed using experimental observation. The influences of insufficient grouting including void and ungrouted length and position on flexural behavior are addressed. Following this, the flexural behavior deterioration induced by the combined effect of strand corrosion and insufficient grouting is analyzed. The experimental results show that the cracking behavior of beams is sensitive to the bond between strand and insufficient grout. The effect of no grouting on beam's flexural behavior depends on its length and position. The strand corrosion in ungrouted duct can significantly decrease the ultimate strength of beam. The different levels of strand corrosion in ungrouted duct have different effects on the cracking behavior, the load–deflection curve, and the failure mode of beams.

1. Introduction

Posttensioned (PT) concrete structures are used extensively in bridges and buildings and were considered to be highly durable since prestressing strands could be protected against corrosion by filling the duct with cement grout [1]. However, in recent years, the deterioration affecting the long-term performance has been discovered in some existing prestressed concrete (PC) bridges [2]. The insufficient grouting or voids inside the duct (Fig. 1) is one of the main reasons and has been observed in the anchorage, deviator block and mid-span region due to the poor construction. The insufficient grouting would reduce protection for strands from rainwater, seawater, salt-fog and de-icing/anti-icing salt [3,4]. This defect can cause a high probability of the accelerated corrosion of strand resulting in strand failure. Some recent structural failures raised concerns over the safety of the bridges, for example the collapses due to the strand corrosion of Ynys-Y-Gwas bridge in UK [5] and Saint Stefano bridge in Italy [6].

Proper grouting is critical to the post-tensioned concrete bridges. Unfortunately, in the past decades the grouting technique was not well developed. The construction of PT concrete bridge was not be allowed by UK in the 1992 until the grouting technique was improved [7]. In China, the insufficient grouting was also treated as one of the most serious problems in bridge construction in the 1980's. The insufficient grouting in early PC bridges has been investigated. Woodward et al. [8] observed 281 PT bridges in the United Kingdom and found that the insufficient grouting ducts are 13% of all ducts. Wu et al. [9] reported that about 63% of the vertical ducts and 74.84% of the transverse ducts contain insufficient grout based on an inspection on a PC bridges. Liu et al. [10] found that the average filling degree of the duct is less than 73% in a demolished bridge in China. The insufficient grouting has significant impact on the durability and safety of bridge. Recently, the

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grouting technique has been improved and the construction flaw can be reduced. Many efforts have been made on the evaluation theory and method on insufficient grouting [11–16]. However, very few works have been reported on the long-term performance of the existing PT bridges with insufficient grouting.

Some inspections and strand failure cases in PC bridge showed that the unwanted voids, moisture, and chlorides inside the insufficient grouting duct is one of the major causes of accelerated corrosion of strand [17–19]. Thus, prestressing strands protected by insufficient grouting are very vulnerable to corrosion [20–22]. The corrosion of strand subjected to high stress level is very complex and can cause the sharp decrease of tensile capacity and ductility of strands due to stress corrosion or hydrogen embrittlement [23–27]. Pillai et al. [28] developed a time-variant structural reliability model subjected to the strand corrosion in insufficiently grouted ducts for post-tenstioned PC bridges. Many existing studies have aslo been made to asess the effect of strand corrosion on the flexural behavior of PC structures. Li and Yuan [29] assessed the flexural capacity degradation of full grouting beams under slight corrosion levels. Coronelli et al. [30] concluded that the effect of strand failure on the structural response of PC beams with bonded strands. Minh et al. [1,31] put emphasis on sheath corrosion induced by insufficient grouting and analyzed the ultimate strength deterioration of PT beams. In the open literature, few studies investigated the effect of ungrouted length and position, and the strand corrosion in ungrouted duct on flexural behavior degradation of post-tenstioned PC stucture.

The objective of this study is to investigate the effect of insufficient grouting-induced strand corrosion on the flexural behavior of post-tensioned concrete beams based on experimental approach. The paper is organized as follows. First, the experimental design including material property, grouting condition, accelerated corrosion, and loading test is introduced. Next, the corrosion characteristic of strand is discussed based on the experimental observations. Following this, the insufficient grouting-induced flexural behavior degradation is analyzed. The influence of insufficient grouting-induced strand corrosion on beam's flexural behavior is presented. Finally, several conclusions are drawn based on the proposed study.

2. Experimental program

2.1. Details of specimens

Thirteen post-tensioned concrete beams were designed with a rectangular cross section of $b \times h = 150 \times 220$ mm, 2000 mm total length, and the 1800 mm distance between supports. Two plain bars of HPB235 with 8 mm diameter at the bottom, two deformed bars of HRB335 with 12 mm diameter on the top, and stirrups with 90 mm spacing and 8 mm diameter were used in each beam. A duct with 32 mm diameter was reserved inside each beam during casting in the laboratory to ensure a single 15.2 mm diameter seven wires strand can be arranged. The details of beam are shown in Fig. 2.

The mechanical properties of the steel bars and strands are shown in Table 1. The initial strength of prestressing strand is 1395 MPa, i.e., 0.75 times of the ultimate strength. The concrete mix and the 28-day compressive strength of concrete are given in Tables 2 and 3.

2.2. Grouting conditions

The specimens were divided into two groups: group B and group PCB. Group B were used to study the effect of insufficient grouting condition on flexural behavior; group PCB were employed to analyze the flexural behavior degradation due to strand corrosion in ungrouted duct. Group B consists of 5 beams with different grouting conditions: full grouting (FG) as B1 as the baseline beam, no grouting (NG) as B2, grouting in the half cross-section of duct (GHC) as B3, no grouting in the half span (NGHS) as B4, no grouting in central region (NGC) as B5. Group PCB consist of 8 beams which have the similar grouting condition to B4. The only difference between group PCB and B4 is that group PCB beams have a full grouting region with 130 mm length near the anchorage to prevent the strand from corrosion in this area. The detailed grouting conditions are shown in Fig. 3.

As shown in Fig. 3, the lengths and locations of ungrouted duct are different in B2, B4, B5, and group PCB. An approach by putting two plugs inside the duct to control insufficient grouting lengths and locations is used in present work. The grout was designed with high fluidity and mixed by cement, water and additive to ensure it could flow along duct by gravity. Gout was injected into duct through the

Table 1
Mechanical properties of reinforcement and prestressing strand.

Type	Diameter (mm)	Yield strength (MPa)	Elastic modulus (GPa)
Prestressing strand	15.2	1830	195
Deformed bars (HPB335)	12	335	210
Plain bars (HRB 235)	8	235	210

(a) Ungrouted duct (b) Grouting in half cross-section of duct in [9] (c) Insufficient grouting along duct in [9]

Fig. 1. Strand corrosion and insufficient grouting in existing PC bridges.

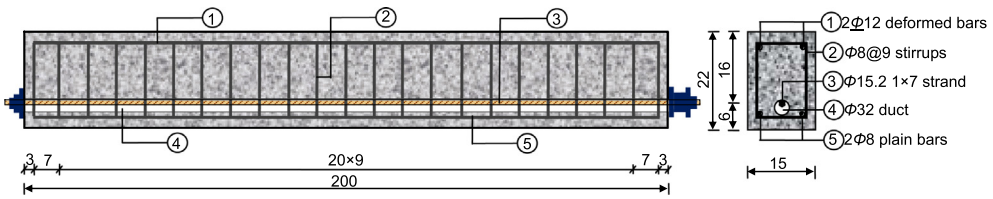

Fig. 2. Beam details (Unit: cm).