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Estimation of reinforcing effects of FRP-PCM method on degraded tunnel linings

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Abstract

Fiber-reinforced plastic (FRP) is a practical alternative construction material that has been extensively adopted in the reinforcement of concrete structures. The reinforcing effect of FRP grids needs to be quantitatively estimated when the grids are applied to degraded tunnel linings to assist with the maintenance design. In the present study, the reinforcing effect of FRP grids embedded in Polymer Cement Mortar (PCM) shotcrete (the FRP-PCM method) on degraded tunnels was estimated. Laboratory direct shear tests and bending tests were carried out on specimens reinforced with various grades of FRP grids to obtain the mechanical properties of the bonding surfaces between the PCM and the concrete reinforced by FRP grids. The bending test results showed that the bearing capacity of beams reinforced by FRP grids subjected to bending loads improved by around 40%. A numerical modeling of the reinforced tunnels by the FRP-PCM method was performed using the properties obtained from these laboratory tests to investigate the reinforcing performance of the FRP-PCM method on degraded tunnel linings. Numerical models with different loosening pressures acting on the tunnel lining, ground classes, degrees of lining deterioration, and degrees of tunnel health were considered, and the suitable conditions under which the application of the FRP-PCM method could effectively reinforce tunnel linings were proposed.

Keywords: Degraded tunnel lining; FRP-PCM method; Direct shear test; Bending test; Numerical simulation

1. Introduction

Repairing and reinforcing existing concrete structures, which represent a substantial portion of current infrastructure and building stocks, have become a major part of civil engineering activities, especially in developed countries. Damage, such as cracking, spalling, and water leakage, occurs frequently in degraded tunnels and can significantly undermine the safety of tunnel operations. In most repair works, since degraded lining concrete cannot be easily replaced, the tunnel linings must be reinforced by the addition of external reinforcement materials.

Various methods have been developed to improve the integrity of the lining concrete, typical ones being the

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grouting reinforcement method, the fiber reinforced shotcrete (FRS) method (De la Fuente et al., 2012; Chiaia et al., 2009; Chryssanthakis et al., 1997; Jeng et al., 2002; Franzén, 1992), the carbon fiber sheet (CFS) method (Lee and Lee, 2002; Miyauchi, 1997), the steel board method (Kiriyama et al., 2005), and the fiber reinforcement plastic (FRP) method (Erki and Rizkalla, 1993; Hensher, 2013; Asakura and Kojima, 2003; Clarke and Waldron, 1996). Compared to other methods, FRP grids have several favorable properties such as high tensile strength, low weight, easy handling and application, immunity to corrosion, and minimal occupancy of space (Lau and Pam, 2010; Bournas et al., 2015). Past research has indicated that FRP grids bonded to the tensile side of flexural members can help increase the flexural capacity of reinforced concrete (RC) structures (Hensher, 2013). Therefore, in the past few decades, FRP has been increasingly utilized in engineering practices as a strengthening material for concrete structures.

To fully explore the potential of FRP reinforcement, the reinforcing effect of FRP grids has been extensively investigated. Chen and Teng (2003) and Yao et al. (2005) conducted single shear pull tests and used an anchorage strength model to estimate the effective bond length between FRP and concrete. Täljsten (1997) conducted double shear pull tests on FRP reinforced concrete and the results showed that the strain limit of the concrete was the governing factor for the debonding failure. Based on a finite element analysis, Pešić and Pilakoutas (2003) predicted the load level at which FRP-plated concrete beams fail due to plate-end debonding. They found that the extent of strengthening was limited by the shear capacity of the concrete beams. Investigations of the flexural capacity of concrete reinforced by FRP have also been reported in literature. Toutanji et al. (2006) developed a moment deflection model to evaluate the load-carrying capacity of RC beams. Several other studies showed that beams strengthened by FRP were able to avoid debonding failure when a carefully designed anchorage was applied, resulting in a good flexural performance in terms of strength and ductility (Ceroni, 2010; Esfahani et al., 2007; Chajes et al., 1994; Wang and Li, 2006). Arduini and Nanni (1997) and Buyukozturk and Hearing (1998) numerically studied the load-deflection behaviors as well as the failure mechanism from ductile to brittle of pre-cracked RC beams. Berg et al. (2006) and Nystrom et al. (2003) focused on the FRP reinforcement of concrete structures from the cost-effective perspective. They concluded that FRP reinforcements could be cost-effective given the savings in construction time, their potential long-term durability, and maintenance benefits in the engineering fields, such as for bridge decks. Although extensive research efforts have been made to understand the shear and flexural strengthening effect of FRP materials, studies focusing on the reinforcing effect of FRP on degraded tunnel linings have not been reported.

In the present study, an FRP-PCM method is proposed and the conditions under which it is applicable are estimated experimentally and numerically. Firstly, direct shear tests are performed to determine the mechanical properties of the interface between PCM and concrete bonded with an FRP layer. Then, two-point bending tests and their numerical simulations are conducted to investigate the effects of the FRP-PCM method on the bearing capacity of concrete beams. Lastly, numerical simulations based on the Finite Difference Method (FDM) are performed to systematically analyze the reinforcing effects of the FRP-PCM method on degraded tunnel linings, taking into account the influence of the ground class, the loosening pressure, the concrete strength, and the degree of deterioration of the lining concrete. Favorable conditions for applying the FRP-PCM method to degraded tunnel linings are investigated and discussed.

2. Direct shear tests

2.1. Experimental setup

The direct shear test is one kind of typical testing method for investigating the mechanical properties of different engineering materials. It provides direct and reliable estimations of the shear behaviors especially of the shear strength of tested materials. In the present study, a digital-controlled shear testing apparatus is adopted to estimate the shear behavior of FRP-PCM reinforcement. An outline of the fundamental hardware configuration of this apparatus is given in Fig. 1, which consists of three units: a hydraulic-servo actuator unit, an instrument package unit, and a mounting shear box unit. This apparatus employs a nonlinear feedback of control and measurement on a PC through a multifunctional analog-to-digital, digital-to-analog, and digital input/output board (Jiang et al., 2004). The apparatus has been adopted for a great number of shear tests in previous studies, and has helped accurately estimate the shear behaviors of different materials (e.g., Jiang et al., 2004, 2006). The purpose of conducting direct shear tests here is to obtain the mechanical properties of the interface between the concrete layer, representing the lining concrete of tunnels, and the FRP-PCM layer that serves as a reinforcement component.

Three types of FRP grids (CR4, CR6, and CR8) that were made from identical material, but have different cross-sectional areas of meshes, were tested as shown in Table 1. The material properties of the FRP grids and the PCM tabulated in Table 1 were obtained from the unpublished reports of a company that manufactures FRP grids. The procedure for sample preparation is as follows. Firstly, concrete specimens, with a length of 200 mm, a width of 100 mm, and a depth of 50 mm, were manufactured by pouring a mixture of paste and aggregates into a rectangular metal mold along with vibration, and were cured for 14 days. The weight ratio of water, cement, fine aggregate, and coarse aggregate was 1:1.70:5.08:3.75. In order to remove the top layer of paste to ensure a good