Study on Design of Tunnel Lining Reinforced by Combination of PCM Shotcrete and FRP Grid Technique

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Abstract. The purpose of this paper is to investigate the reinforcing effect of the fiber-reinforced plastic (FRP)-polymer shotcrete mortar (PCM) technique on degraded tunnel lining based on the finite difference method. One adverse condition that cavities exist between the lining and rock masses was concerned, and another adverse condition was considered, namely, that due to the existence of the cavity, the rock mass located above the cavity underwent large deformation that may have exerted excessive pressure on the lining. This pressure was defined as loosening pressure; In addition, the degree of deterioration was defined to represent the degraded level of the lining concrete compared to the original strength of the concrete. The limit state design method of the Moment-Axial force (M-N) performance curve was proposed to determine whether the structure is in a safe state. The results show that when the lining deterioration degree is 0% and 50%, the location of (M, N) is all distributed inside the corresponding M-N performance curves, which indicates that the reinforcing measures can meet the safety requirement, while when the lining deterioration degree is 80%, ten sets of cases (four cases for ground class DI and six cases for ground class DII) where the M-N values of several strengthening measures distributed outside the corresponding M-N performance curves were summarized, and these cases should be avoided in the corresponding engineering. The results of this investigation can provide a valuable reference for study on the reinforcing behavior with the FRP-PCM technique.

1. Introduction

Reinforcing degraded tunnel linings, which extensively distributed in developed countries, has become a major part of civil engineering. Damage occurs frequently in degraded tunnels, with forms of cracking, spalling, and water leakage, seriously threaten the safety of tunnel operation. Recently, the utilization of FRP composites for reinforcement to concentrate members has emerged as one of the most existing and promising technologies in structure engineering [1-5]. The reinforcement technology used FRP in degraded tunnels can be presented in Figure 1. To improve the reinforcing efficiency, evaluation of reinforcement should be conducted to optimize reinforcing parameters.

One important application of FRP composites is to strengthen or retrofit the reinforced concrete (RC) structures by making repair layers [6-8]. Concerning the investigation of reinforcing effect for FRP, Jiang et al. [9] carried out the direct shear test and bending experiments of specimen reinforced with various grades of FRP grids to obtain the mechanical properties and then estimated the reinforcing effects of FRP-PCM technique on degraded linings concrete. Guo et al. [10] revealed the bonding behavior and stress transfer mechanism of FRP grids with PCM shotcrete on RC members, and the influence of the number of FRP grid points, the interval of the horizontal grid, the existence of a vertical grid and the type of PCM on the bonding behavior of FRP grid concrete with the PCM shotcrete method.
were discussed. According to the research of Ta’ljsten [11], the strain limit of the concrete was the governing factor for the debonding failure of concrete reinforced by FRP. Chen et al and Yao et al. [12-13] conducted single shear pull tests and used an anchorage strength model to estimate the effective bond length between FRP and concrete. Yin et al. [14] focused on the influence of roughness on the shear bonding performance of the FRP-concrete interface. Ivana et al. [15] described the formulation based on the structural optimization design of a tunnel lining with the reinforcement of FRP.

With respect to the concrete beam reinforced by FRP, Guo et al. [16] evaluated the shear capacity of RC beams by using a carbon fiber-reinforced-polymer (CFRP) grid with PCM shotcrete. Pesic et al. [17] investigated the load level at which FRP-plated concrete beams fail due to plate-end debonding, and they found that the extent of strengthening was limited by the shear capacity of the concrete beams. Sumarac et al. [18] report on a study in which the flexural strength and deformability of circular concrete members with hybrid reinforcement-carbon-CFRP bars and glass-GFRP spirals—were assessed experimentally and analytically. 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 [19-22].

Although extensive efforts have been made to understand the shear and flexural strengthening effect of FRP materials, studies focusing on the reinforcing effect of FRP-PCM technique on degraded tunnel linings have been reported less. Therefore, in this paper, the reinforcing effect of the FRP-PCM technique on tunnel lining was evaluated, and the suitable conditions under which the application of the FRP-PCM technique could effectively reinforce tunnel linings were obtained.

![Figure 1. FRP reinforcement method: (a) schematic diagram of the degraded tunnel; (b) application of FRP grids on degraded tunnel; (c) use of FRP grids on road tunnel; (d) detailed component of FRP grids](image)

2. Numerical simulation of degraded tunnels reinforced by FRP-PCM technique

Mountain tunnels constructed by the fore piling method typically encounter an adverse condition that cavities exist between the lining and rock masses [23-25], which is likely to induce shear failure [26-27]. Therefore, the numerical model of a tunnel containing a cavity was established using a finite difference method (FDM) in this paper (Figure 2), the arc range of the cavity is 90 ° relative to the center point of the tunnel with a thickness of 30 cm. The excavation diameter of the tunnel is D (10m) and the horizontal distance from the wall of the tunnel to the boundary of the model was determined as 2D. Concerning the boundary conditions, the left and right sides were roller boundaries, and the bottom boundary was fixed with no rotation and displacement. For the constitutive equation, the Mohr-Coulomb failure criterion was adopted to describe the mechanical behavior of the tunnel lining. Besides, three classes of ground (CII, DI, and DII) were selected in the numerical simulations, which are composed of the medium-hard and soft rocks typically encountering in tunnel constructions in Japan. The properties of the ground, lining, and back-filling materials are listed in Table 1.
This paper aims to investigate the reinforcement effect of the FRP-PCM technique on degraded tunnel linings, so the deterioration degree should be defined to represent the degraded level of lining concrete. In this paper, the deterioration degrees were determined as 0%, 50%, and 80% respectively. In addition, another adverse condition that due to the existence of the cavity, the rock mass located above the cavity would undergo large deformation that may exert excessive pressure on the lining was also considered. This pressure was defined as loosening pressure, which represented a certain height of rock mass (loosening height) that exerted its self-weight on the lining. The properties of FRP grids and PCM material are summarized in Table 2. In this paper, the type of FRP grids was determined as CR4, CR6, and CR8, respectively. Since FRP-PCM is a combination of two materials, the parameter value of the structural unit liner is converted by the equivalent cross-section. Regarding the constitutive equation, the Mohr-Coulomb failure criterion was also adopted.

### Table 2. Properties of FRP grids and PCM material

| Materials | Elastic modulus (MPa) | Tensile strength (MPa) | Compressive strength (MPa) | Cross-sectional area of mesh (mm²) |
|-----------|-------------------|-----------------|---------------------|-----------------|
| FRP grid  |                   |                 |                     |                 |
| CR4       | 100000            | 1400            | —                   | 6.6             |
| CR6       | 26000             | 4.60            | 59.3                | 17.5            |
| CR8       |                   |                 |                     | 26.4            |
| PCM       |                   |                 |                     |                 |

### 3. Reinforcing behavior of FRP-PCM technique

Generally, the section forces in lining include axial force, bending moment, and shear stress. While the axial force and bending moment are the dominant factors to control the local failure of the lining. In many cases, part of the lining is plastically deformed. Even if the tunnel lining does not collapse due to plasticization, if a large deformation occurs inside the tunnel, it will significantly affect the function of the tunnel. On the other hand, it is not easy to check the limit state of the lining during the operation period of the tunnel. Hence, the strength characteristics of the lining concrete and the ultimate state of the reinforcing must be concentrated on.

Moment-Axial force (M-N) performance curves are regularly used to investigate the limit state design method of lining concrete. The calculation of the design section force can be shown in Figure 3, and it is assumed that it is performed by equation (1) and (2).
\[ M_{ud} = \frac{\int_2^h \sigma'_{y} \cdot y \cdot bdy}{\gamma_b} \]  
(1)

\[ N'_{ud} = \frac{\int_2^h \sigma'_{y} \cdot bdy}{\gamma_b} \]  
(2)

Where \( M_{ud} \) is the design bending strength; \( N'_{ud} \) represents the designed axial strength; \( h \) is the thickness of lining; \( b \) is the unit width; \( \gamma_b \) is the member coefficient.

The upper limit of the designed compression strength \( N'_{oud} \) can be calculated as follows:

\[ N'_{oud} = \left( \frac{0.85 f'cd \cdot A_s}{\gamma_b} \right) \]  
(3)

Where \( A_s \) is the cross-section of lining; \( f'cd \) is the designed axial compressive strength of concrete.

Thus, the M-N performance curve with 15 cm thickness of lining at the cavity can be shown in Figure 4a. In this Figure, three lining deterioration of 0%, 50%, and 80% were presented. To evaluate the reinforcing effect of the tunnel lining by the FRP-PCM technique, the axial force and bending moment of the lining are calculated for each case and then compared with Figure 4a. In other words, it is necessary to check whether it is located inside the M-N performance curve (on the safe side). If the coordinates of the axial force and bending moment are inside the performance curve, the lining is in a safe state.

In this section, the maximum axial force and moment values of the shoulder and crown cross sections are extracted for lining deterioration of 0%, 50%, and 80%. Figures 4b and 4c present the comparison between the numerical values and the theoretical values of the axial force and moment on the shoulders and the crown when the lining deterioration is 0% and 50%. It is noted that the location of the (M, N) is all situated inner the corresponding M-N performance curve, indicating that the lining is in a safe state.

As observed in Figure 4d, when the ground class is DI, the below four reinforcement conditions of "CR6-2D-120°-Crown", "CR8-2D-120°-Crown", "CR4-2D-180°-shoulder", and "CR6-2D-90°-shoulder" distributed outside of the corresponding M-N performance curve. Therefore, the above four reinforcement measurement should be avoided to maintain a safe state. Concerning the ground class DII, the below six reinforcement conditions of “CR4-2D-120°-Crown”, “CR6-2D-DII-120°-Crown”, “CR8-2D-DII-120°-Crown”, “CR4-2D-DII-90°-shoulder”, “CR4-2D-DII-180°-shoulder”, “CR6-2D-DII-90°-shoulder” are distributed outside of the corresponding M-N performance curve. Hence, the above six reinforcement measurement should also be avoided in corresponding reinforcing engineering with the FRP-PCM technique. Also, concerning other cases, the analysis values are surrounded by theoretical values, so reliability requirements can be achieved.
4. Conclusions

In this paper, the reinforcing behavior of FRP-PCM technique on degraded tunnel lining was investigated, the design method of M-N performance curve was proposed, if the coordinates of the axial force and bending moment are inside the performance curve, the lining is in a safe state. Otherwise, the corresponding reinforcing measures are considered as an adverse situation and should be avoided in the corresponding engineering. Overall, the main conclusion can be drawn as follow:

1. When the lining deterioration is 80%, for the ground class is DI, the reinforcing measures of "CR6-2D-120°-Crown", "CR8-2D-120°-Crown", "CR4-2D-180°-shoulder", and "CR6-2D-90°-shoulder" cannot meet the requirement of safety.

2. When the lining deterioration is 80%, for the ground class DII, the below six reinforcing measures of “CR4-2D-120°-Crown”, “CR6-2D-DII-120°-Crown”, “CR8-2D-DII-120°-Crown”, “CR4-2D-DII-90°-shoulder”, “CR4-2D-DII-180°-shoulder”, “CR6-2D-DII-90°-shoulder" should be avoided.

3. In the reinforcing engineering with FRP-PCM technique, the strengthening effect is closely related to lining deterioration grade.

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