Study on Reinforcing Effects of FRP-PCM Method under Seismic Load

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Abstract. The aim of the present study is to estimate the reinforcing effects of fiber reinforced plastic (FRP) grids embedded in polymer cement mortar (PCM) shotcrete (FRP-PCM method) on tunnel linings, under the seismic load. Direct shear test was conducted to investigate the mechanical properties of bonding surfaces between the PCM concrete and concrete specimens sandwiched by a FRP layer. Numerical modelling was performed to analyze the reinforcing effects of FRP-PCM method quantitively, taking into accounts the influences of cavity position and construction method of tunnels, which could provide valuable guidance for the reinforcing of underground structures.

1. Introduction

Although the seismic behaviour of underground structures, such as tunnels, is assumed to be better than that of surface structures, some existing tunnels were severely damaged by earthquakes in recent years (Suzuki 1996; Yoshida 1999; O’Rourke et al. 2001; Wang 2001 and Kontogianni et al. 2003). Cracking, spalling and water leakage occurring during earthquakes would significantly affect the safety of tunnel operation. Repairing and reinforcing the existing concrete underground structures have become a major part of civil engineering activities. A series of methods have been adopted to effectively improve the integrity of concrete structures in existing tunnels, typical ones of which are grouting reinforcement method, fiber reinforced shotcrete (FRS) method (De la Fuente et al. 2012; Chiaia et al. 2009; Jeng et al. 2002 and Franzén 1992), carbon fiber sheet (CFS) method (Lee et al. 2002 and Miyauchi 1997), steel board method (Kiriyama et al. 2005) and fiber reinforcement plastic (FRP) method (Erki et al. 1993; Hensher 2013 and Asakura et al. 2003).

Due to the favourable properties such as high strength, low weight, easy handling and application, immunity to corrosion and etc., FRP as a strengthening material for the reinforcement concrete (RC) structures has become commonly used in engineering fields. In recent years, extensive researches have been carried out to investigate the reinforcing effects of FRP grids under seismic load. Sheikh et al. (2002) conducted an experimental program in which 12 column specimens were tested under constant axial load and cyclic lateral load that were used to simulate the earthquake loads, and found that the strength, ductility and energy absorption capacity of columns can be improved by utilizing FRP. Zou et al. (2007) proposed an optimization technique for the performance-based seismic FRP retrofit design of RC building frames, and the effectiveness of this proposed procedure was discussed and...
certified by a numerical example. Antoniades et al. (2003) conducted cyclic tests on seismically damaged reinforced concrete walls strengthened with FRP reinforcement, and the test results showed that the strength of specimen reinforced by FRP strips increases up to approximately 30% with respect to a conventional repair method. Lam et al. (2006) experimentally studied the behaviours of FRP-confined concrete under cyclic compression test, and a number of significant conclusions were drawn, including the existence of an envelope curve and the cumulative effect of loading cycles.

Despite a large amount of researches on the behaviour of RC structures reinforcing with FRP were put forward, few researches were conducted on the reinforcing effects of FRP-PCM method on tunnel lining under seismic load. In the present study, the seismic resistance of tunnel lining reinforcing with FRP-PCM method was estimated experimentally and numerically. First, direct shear tests were performed to determine the mechanical properties of the interface between PCM and concrete specimens, bonding with a FRP layer. Then two-point bending tests and their numerical simulations were conducted to investigate the effects of FRP-PCM method on the bearing capacity of concrete beams. At last, numerical simulations based on finite difference method (FDM) were performed to quantitatively analyse the reinforcing effects of FRP-PCM method on tunnel linings under seismic load, taking into accounts the influences of cavity position and construction method, and those analytic results could provide valuable guidance for the reinforcing of underground structures.

2. Direct shear test

Three types of FRP grids (CR4, CR6 and CR8), which were made from identical material but different cross-sectional area of meshes, were investigated as shown in Table 1. The fabrication procedure for sample preparation is as follows. First, concrete specimens with a length of 200 mm, a width of 100 mm, and a depth of 50 mm were manufactured by pouring the mixture of paste and aggregates into a rectangular mental mold along with vibration for 1 minute, and cured for 14 days. The weight ratio of cement, water and aggregate are summarized in Table 2. Secondary, the surface of concrete specimens was grinded. Then, FRP grids with the same dimension of 200 × 100 mm² were bonded to the concrete specimens with Sikadur-30 epoxy adhesive. At last, the specimens were again installed in another rectangular metal mold with the surface bonded with FRP grids facing upwards, and PCM was then poured into the mold to accomplish the PCM-concrete specimens sandwiching an FRP layer. Figure. 1 shows an example of specimen utilized in test. All these specimens were cured in a tank for another 14 days with a constant room temperature and humidity.

Shear tests under a constant normal load (CNL) were put forward with a shear rate of 0.5 mm/min until the state was reached. The tested normal stresses were 1 MPa, 2 MPa, and 3 MPa for the three types of FRP grids, respectively. In order to minimize the errors caused by the variability of specimens, each case was tested on 2 or 3 specimens.

Figure. 2 shows the relationship between peak and residual shear stresses with normal stress for all cases tested. Linear regression was applied to these test results, and the shear stress and residual stress envelopes were obtained as follows:

\[ \tau_{\text{peak}} = 0.32\sigma + 2.22 \]  \hspace{1cm} (1)
\[ \tau_{\text{res}} = 0.29\sigma + 0.43 \]  \hspace{1cm} (2)

It is critical to identify that \( \tau_{\text{peak}} = 2.22 \text{ MPa}, \varphi_{\text{peak}} = 17.7^\circ; \) and \( \tau_{\text{res}} = 0.43 \text{ MPa}, \varphi_{\text{res}} = 16.1^\circ. \) The cohesion of bonding surface diminished dramatically after failure, while the friction angle showed a slight decrease. All these test results were later utilized in the numerical simulations.
Figure 1. Photographs of specimen after bonding FRP grids to concrete layer (a), and after constructing the PCM layer (b).

Figure 2. Test results of shear stress and residual stress vs. normal stress.

Table 1. Properties of FRP grids and PCM material.

|          | Elastic modulus $E$ (MPa) | Compressive strength $\sigma_c$ (MPa) | Tensile strength $\sigma_t$ (MPa) | Cross-sectional area of meshes (mm$^2$) |
|----------|--------------------------|--------------------------------------|----------------------------------|----------------------------------------|
| FRP grids | $1 \times 10^5$          | ----                                 | 1400                             | 6.6                                    |
| CR4      |                          |                                      |                                  |                                        |
| CR6      |                          |                                      |                                  |                                        |
| CR8      |                          |                                      |                                  | 17.5                                   |
| PCM      | $2.6 \times 10^4$        | 59.3                                 | 4.6                              | ----                                   |

Table 2. Weight ratio of mixture of paste and aggregates.

|       | Water | Cement | Fine aggregate | Coarse aggregate |
|-------|-------|--------|----------------|------------------|
|       | 1     | 1.7    | 5.08           | 3.75             |

3. Numerical analysis

3.1. Numerical models

The numerical model of tunnels, which were constructed by the Fore-piling Method (FM) and the New Austrian Tunnelling Method (NATM), were established based on FDM, as shown in Figure. 3. The tunnels constructed by FM are shown in Figures. 3(a)-(c), while the one by NATM is shown in Figure. 3(d). Mountain tunnels constructed by the FM typically encounter an unfavourable condition that cavities exist between lining and surrounding rock masses. In order to investigate the impacts of cavity positions on the reinforcing effects of the FPR-PCM method, a cavity was presumed to exist on the crown (see Figure. 3(a)) or at the right shoulder (see Figure. 3(b)) of the numerical models with an arc angle of $60^\circ$ and a thickness of 30 cm. In Figures. 3(a)-(b), the thickness of lining was typically 45 cm, which was reduced to 15 cm at the central position of the cavity. The thickness of shotcrete and secondary lining was selected as 15 cm and 30 cm as in Figure. 3(d), respectively. The reinforcement region with the FRP-PCM method for all the four cases covered an arc length of $180^\circ$ on the upper wall of tunnel as shown in Figure. 4, and the back-filling was conducted to the tunnels with cavities. The tunnel lining was reproduced by the finite element mesh, while the reinforcement effects of the FRP-PCM method were investigated by the liner element (Itasca 2002).
3.2. Boundary conditions

In order to reduce the computational time and ensure the calculation accuracy, the horizontal distance from the wall of tunnel to the boundary of model was determined as 2D (D is the excavation width of tunnel that is equal to 10 m) based on the pre-computation. The free-field boundary was selected during the seismic analysis as shown in Figure 5. The lateral boundaries of the main grids are coupled to the free field grids by various dashpots to simulate a quiet boundary, which can ensure the simulation results identical with those in an infinite model (Itasca 2002).
3.3. Mechanical properties

Two classes of ground (CI and CII) were selected as the host rock masses in the numerical simulations, which are typical ground encountered in tunnel constructions in Japan (The Ministry of Public Works Research Institute Tunnel Laboratory 1994). Since the quick hardening properties and high strength, the urethane materials were selected as the back-filling materials, and the mechanical properties of ground, lining and back-filling materials are shown in Table 3. The numerical analysis cases are summarized in Table 4.

| Table 3. Properties of ground, lining and back-filling material. |
|---------------------------------------------------------------|
| Property | Ground class | Lining | Back-filling material |
|          | CI | CII | CI | CII |
| $\gamma$ (kN/m$^3$) | 23.5 | 22.6 | 24.0 | 9.8 |
| $E$ (MPa) | 1960 | 980 | 24500 | 12.0 |
| $\nu$ | 0.3 | 0.30 | 0.20 | 0.13 |
| $c$ (MPa) | 1.96 | 0.98 | 6.99 | 0.50 |
| $\varphi$ (deg) | 45 | 40.0 | 40.0 | 10.0 |
| $\sigma_t$ (MPa) | 0.39 | 0.42 | 3.0 | 0.20 |

| Table 4. Numerical analysis cases. |
|-----------------------------------|
| Simulation case | Construction method | FRP grid | Ground class | Cavity |
| 1 | FM | × | CI | Crown |
| 2 | FM | × | CI | Shoulder |
| 3 | FM | × | CI | × |
| 4 | FM | × | CII | Crown |
| 5 | FM | × | CII | Shoulder |
| 6 | FM | × | CII | × |
| 7 | FM | CR8 | CI | Crown |
| 8 | FM | CR8 | CI | Shoulder |
| 9 | FM | CR8 | CI | × |
| 10 | FM | CR8 | CII | Crown |
| 11 | FM | CR8 | CII | Shoulder |
| 12 | FM | CR8 | CII | × |
3.4. Input motion

Figure 7 shows the history of the horizontal acceleration applied at the base of the numerical model during the seismic analysis. The input motion was recorded at the observation site of Ojiya City during the Chuetsu-Oki earthquake occurred on July 16, 2007 in Niigata Province, Japan. The maximum acceleration was observed at about 27.8 s, with a value about 330 Gal. Since the stability of underground tunnel is mainly controlled by the maximum acceleration during the earthquake, in order to reduce the computational time, the input motion at the interval from 20.8 s to 30.8 s was extracted and utilized in the numerical analysis.

![Figure 6. Input motion.](image)

3.5. Numerical results

3.5.1. Reinforcement effect of lining deformation. Figures 7-8 show the simulation results of lining deformation for the ground class type of CII in the cases of unreinforced and reinforced with the CR8 grids, respectively. For tunnels constructed with the FM as shown in Figures 3(a)-(c), the plastic failure occurred at the shoulder of tunnels, regardless the position of cavities. However, the tunnel with a cavity on the right shoulder exhibited an extremely larger failure region. Since the existence of cavity, the cross section of tunnel lining was decreased, which resulted in the stress concentration at the location of cavity. All these failure regions almost occurred at the inner side of tunnel linings. The reinforcement effects with CR8 grids are plotted in Figure 8. For tunnels constructed in the FM, plastic failure only occurred in the case with the cavity on the right shoulder of lining as shown in Figure 8(b). Due to the reinforcement with FRP grids, the flexural stiffness at the inner side of the lining increased, which led to the failure occurring on the outside of lining concrete. For the one in NATM, failure region decreased dramatically, revealing that a good reinforcing effect was obtained with CR8 grids. The lining concrete in rock class type of CI shows almost no damage during the seismic analysis.
3.5.2. Axial force distribution on lining concrete. Based on the numerical results, the stresses that perpendicular to tunnel lining are two orders of magnitude less than those axial ones, thus, in the present study, the axial stress was selected to evaluate the reinforcing effects of FRP-PCM method. Figures 9-10 depict the axial force distribution on lining concrete in the cases of unreinforced and reinforced with CR8 grids for the ground classes of CII.

In these Figures, the positive denotes the compression stress, while the negative denotes the tensile stress. A great compression stress occurred at the inner side of lining concrete, regardless the position and existence of cavities, tunnel shapes. Tunnel with cavity on the right shoulder showed a larger compression stress compared with the other two constructed in the FM. Compared with the FM, the lining concrete in the NATM showed a great bending capacity, which was generally improved by the closure of invert.

In order to estimate the reinforcing effect of FRP-PCM method quantitatively, an axial force reduction rate $R_\sigma$ was defined as

$$R_\sigma = \frac{\sigma_{wr} - \sigma_r}{\sigma_{wr}} \times 100\%$$

where, $\sigma_{wr}$ is the axial acting on the unreinforced lining (MPa), and $\sigma_r$ is the axial stress obtained in the reinforced cases (MPa). The axial stress is the principal stress oriented parallel to the wall of the tunnel lining, and the axial force reduction rate represents the degree the axial force is reduced by reinforcement.

Figure 11 shows the axial stress with various ground class types and position of cavities. The axial force reduction rates for the cases of cavities on the crown and shoulder of tunnel linings with ground class of CII are 27% and 52%, respectively, revealing that the performance of reinforcement was greater with a cavity on the shoulder.

Figure 12 shows the axial stress with various ground class types and construction methods. The axial force reduction rates for the cases constructed by the FM and the NATM are 31% and 49%, respectively, indicating that a greater reinforcement effects could be obtained for tunnels in NATM.

It can be concluded that the FRP-PCM method showed a great reinforcement effect for tunnels in seismic loads, especially for the one constructed in the FM method with a cavity on the shoulder lining concrete.
4. Conclusion
In this study, first, a series of direct shear tests were conducted on the PCM-concrete specimens embedded with an FRP layer with various types, and the mechanical properties of FRP-PCM reinforcement such as the cohesion, friction angle were obtained. Then, numerical simulations under seismic load were performed, taking into accounts the cavity position and the construction method of tunnel. Based on the experimental tests and numerical simulations, the following conclusions are drawn:

(1) The performance of various types of FRP grids was systematically investigated confirmed utilizing the direct shear test, and the typical values of cohesion and friction angle of PCM-concrete specimens sandwiched by a FRP layer were obtained as 2.22 MPa and 17.7°, respectively.

(2) The bearing capacity of concrete beam reinforced with CR8 grids obtained from bending test was improved around 60% comparing to the unreinforced one. These experimental results indicated that the FRP-PCM method has a good performance in the reinforcement of concrete structures. In addition, the proposed numerical method was proved to be reasonable to reproduce the loading procedure of bending test.

(3) A good reinforcement performance was observed for the case of cavity on the shoulder of tunnel, comparing with the one on the crown. Although tunnels constructed in the NATM showed a better bearing capacity comparing with the one in the FM, a greater reinforcing effect was obtained for tunnels in the NATM.
Only the CR8 grids were taken into accounts during the numerical simulations under seismic load. In the future, various types of FRP grids, such as CR4 and CR6 should be discussed to investigate the reinforcing effects of the FRP-PCM method.

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