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Study on seismic strengthening of railway bridge pier with CFRP and concrete jackets

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Abstract. Seismic strengthening is essential for existing bridge piers which are deficient to resist the earthquake. The concrete and CFRP jackets with a bottom-anchoring method are used to strengthen railway bridge piers with low reinforcement ratio. Quasi-static tests of scaled down model piers are performed to evaluate the seismic performance of the original and strengthened bridge pier. The fracture characteristics indicate that the vulnerable position of the railway bridge pier with low reinforcement ratio during earthquake is the pier-footing region and shows flexural failure mode. The force-displacement relationships show that the two strengthening techniques using CFRP and concrete jackets can both provide a significant improvement in load-carrying capacity for railway bridge piers with low reinforcement ratio. It is clear that the bottom-anchoring method by using planted steel bars can guarantee the CFRP and concrete jackets to work jointly with original concrete piers Furthermore, it can be found that the use of CFRP jacket offers advantages over concrete jacket in improving the energy dissipation capacity under lateral cyclic loading. Therefore, the seismic strengthening techniques by the use of CFRP and concrete jackets provide alternative choices for the large numbers of existing railway bridge piers with low reinforcement ratio in China.

Keywords: seismic strengthening techniques; CFRP jacket; concrete jacket; railway bridge pier; low reinforcement ratio

1. Introduction

In the west of China, large numbers of railway bridges have been built in the regions with high earthquake intensity. Frequent earthquakes have occurred in the west of China in recent years, e.g., Wenchuan earthquake (2008) (Jia *et al*. 2015, Parsons *et al.* 2008), Yushu earthquake (2010) (Ni *et al.* 2010), Jiuzhaigou earthquake (2017) (Wang *et al*. 2017), etc. However, most of the existing railway bridges have been designed without considering the potential earthquakes due to behindhand economic condition at that time (Zhen 2001). These existing bridges can be replaced by newly designed ones or upgraded in its strength by appropriate strengthening techniques to meet earthquake demands required by the current codes and guidelines. It is clear that the strengthening is a cost-effective alternative than replacement. Therefore, it has become an urgent need to evaluate the seismic performance of these existing bridges, and then to select appropriate strengthening techniques for deficient bridges under potential earthquakes in the future.

The bridge pier is a typical case of the vulnerable component (Abé and Shimamura 2014, Deng *et al.* 2012, Kawashima 2000). Various strengthening techniques are available to upgrade the seismic performance of existing bridge piers. One popular solution to the problem of how to strengthen old reinforced concrete structures is to place jackets around the structural elements (Chaulagain *et al*. 2015, Vandoros and Dritsos 2008). The major strengthening techniques include encasing of bridge piers with concrete, steel, fiber reinforced polymer (FRP) jacketing, etc. (Li *et al*. 2015, Mazza 2015). Among these techniques, concrete jacket is a traditional and effective method for seismic upgrading of deficient reinforced concrete bridge piers, which can be applied in full or partial height to provide increased confinement of the bridge pier (Wright *et al*. 2011). The efficiency of the concrete jacket for bridge piers is influenced by jacket thickness and the reinforcement ratio (Montes *et al*. 2015). Montes, Jara, Jara and Olmos (2015) also found that the efficiency of the concrete jacket is reduced with the pier height increase, which showed important benefits in bridges with short length piers. The steel jack*et al*so showed effectiveness in enhancing the flexural and shear performance of deficient bridge columns, which was widely used in the California and Japan (Aboutaha *et al*. 1999, Chai *et al*. 1994, Daudey and Filiatrault 2000). Although concrete and steel jackets have been widely used in seismic strengthening, other alternative materials, like the carbon fiber-reinforced polymer (CFRP) and other fiber composites, have advantages include but not limited to lightness, high mechanical performance and possibility of production in any shape, ease of installation and lesser requirement for supporting structure, controlled anisotropy, high specific strength and specific stiffness (Zaman *et al*. 2013). Therefore, these composite materials have been increasingly recognized, and widely applied in structural strengthening (Haroun *et al*. 2003, Ji *et al*.

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2016). The CFRP jacket is highly effective in confining the core concrete and preventing the longitudinal reinforcement bars of the bridge pier from buckling under cyclic loading (Kakaletsis 2016, Saadatmanesh *et al*. 1996, Smyrou 2015), and then improve both the ductility factor and the shear capacity of bridge piers (Han *et al*. 2014, Pantelides *et al*. 1999, Sun *et al*. 2017, Yeh and Mo 2005). Besides, the seismic performance of damaged reinforced concrete bridge columns can be effectively recovered after repairing with CFRP composite sheets (Chang 2010).

These research results above have laid a foundation for further study of the seismic strengthening techniques for bridge piers with different required performance criteria. It can be found that the strengthening techniques in US and Japan mainly focused on the highway bridges with the flexible piers (multi-column, hollow etc.). However, the concrete solid piers with low longitudinal steel ratio (lower than 0.5%) have been widely used in railway bridges in China (Chen *et al*. 2016, Shao and Jiang 2014, Zhen 2001). These railway bridge piers cannot be specified as the standardized reinforcement concrete in current codes and guidelines, strengthening techniques of this type of bridge piers have not received much attention in previous research. In this study, the traditional material of concrete and the composite material of carbon fiber reinforced polymer (CFRP) are employed to strengthen existing railway bridge piers with a very low longitudinal steel ratio (0.1%). The static and seismic performance of the original pier and strengthened ones using the two different techniques are evaluated by quasi-static test for 1/8-scale model piers based on a typical prototype pier widely used in quake-prone region of China.

2. Experimental design

2.1 Model pier design

A widely used type of railway bridge pier with rectangular cross section in quake-prone region of China is selected as the prototype in this study. The prototype pier height is 20 m, and the size of the cross section is 513×357 cm (length and width). Four scaled model piers (M1-M4) are designed based on a 1:8 scale of the prototype pier. Therefore, the height of the model pier is 2.5 m, and its size of the cross section is 64×45 cm (length and width), a bearing platform with a cross section size of 220×100 cm is designed at the bottom of the pier, as shown in Fig. 1. One of scaled model piers (M1) is regarded as the benchmark model without strengthening, the other three model piers are strengthened by encased jackets of carbon fiber reinforced polymer (CFRP) (M2) and concrete (M3 and M4), respectively. These model piers in this study are strengthened with CFRP and concrete by partial pier height. The CFRP jacketing of the M2 is 1.0m height from the footing of the pier, and the concrete jacketing of the M3 and M4 are 0.9 m and 1.5 m height, respectively.

The nominal cubic compressive strength of the concrete used in model piers and their bearing platforms is 30 MPa. Original scaled model piers are reinforced with 10 longitudinal deformed bars of 6mm in diameter with a yield

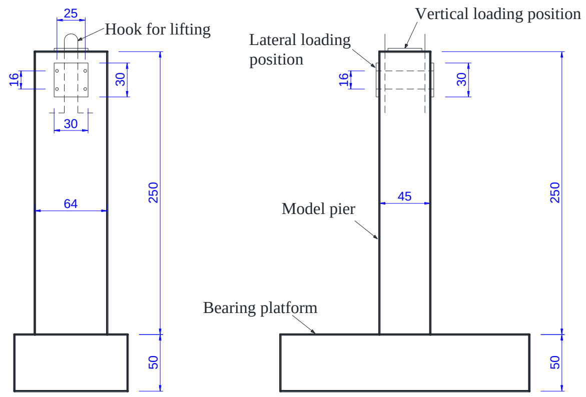


Fig. 1 Size and shape details of the model pier (unit: cm)

Table 1 Reinforcement details of original model piers

Specimen	Longitudinal steel ratio (%)	Diameter of longitudinal steel(mm)	Hoop reinforcement ratio (%)	Diameter of hoop steel (mm)	Strengthening technique
M1	0.1	6	0.1	6	No
M2	0.1	6	0.1	6	CFRP jacket (1.0m height)
M3	0.1	6	0.1	6	Concrete jacket (0.9m height)
M4	0.1	6	0.1	6	Concrete jacket (1.5m height)

strength of 335 MPa, which constitute a longitudinal steel ratio of 0.1% for the gross area of the pier section. Longitudinal steel bars are evenly distributed with a concrete cover of 20 mm. Original model piers are also reinforced with hooping steel bars of 6mm in diameter, which are spaced at 192 mm intervals in height. Reinforcement details of original model piers are listed in Table 1. According to Code for Design of Concrete Structures of China (China 2015), and using the actual strength of steel and concrete, the nominal flexural strength of the reinforced concrete bridge column is computed to be M=101 kN·m, and it will be M=41.7 kN·m if the model pier is regarded as plain concrete and considers no reinforcement.

2.2 Model pier construction

The construction processes of the original model pier are summarized in Fig. 2, the main procedure includes reinforcement frame assembling, formwork, concrete casting and curing. The rust removal treatment on surfaces of steel bars should be carried out firstly, then these steel bars can be used for assembling. The concrete casting and curing should comply with the requirements of design and terms of construction specification of China. Four embedded bolts for lateral loading and two hooks for lifting should be designed at the top region of these model piers, as shown in Figs. 1 and 2(d). Besides, the bolt fastening holes should be reserved in the bearing platform to make sure that the model pier can be firmly fixed to the ground foundation during testing.

(a) Reinforcement

(b) Formwork

(c) Concrete casting

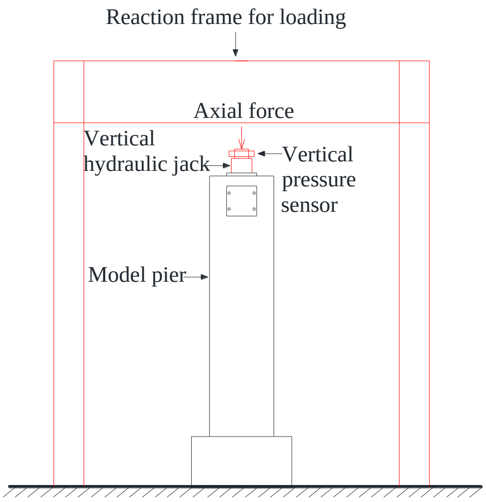
(d) Completed model

Fig. 2 Construction procedure of the original model pier

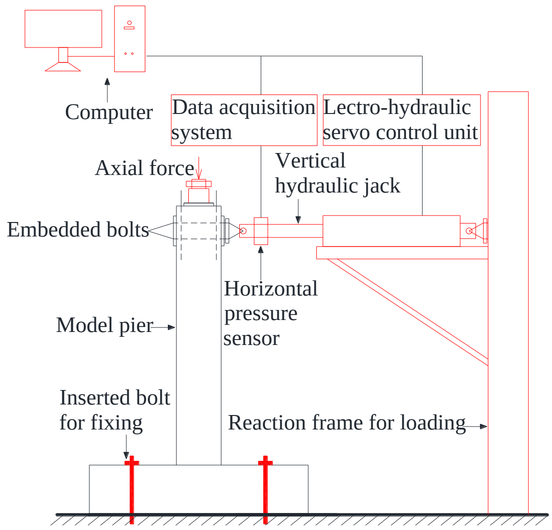
2.3 Test equipment and method

Quasi-static tests were conducted at the Structural Testing Laboratory of Lanzhou Jiaotong University. The test equipment includes the vertical loading unit, horizontal loading unit, electro-hydraulic servo control unit, and the data acquisition system. The vertical loading unit consists of vertical hydraulic jack, vertical pressure sensor and reaction frame for loading; the horizontal loading unit consists of horizontal hydraulic jack, horizontal pressure sensor and reaction wall; the vertical and horizontal hydraulic jack are controlled by the electro-hydraulic servo control unit, which can be used to apply a constant vertical axial load and lateral cyclic load to model piers; the displacement sensor, vertical and horizontal pressure sensors are connected to the data acquisition system to collect data during testing; and the electro-hydraulic servo control and data acquisition system are connected to a computer. Configure of the test equipment used in this study is shown in Fig. 3.

Firstly, the foundation bolts will be inserted into reserved holes at the bearing platform, then the model pier can be firmly anchored to the foundation by fastening the bolts. As the earthquake excitation in longitudinal direction is the major consideration for seismic design of bridges, we focus on the seismic response in longitudinal direction of the bridge (along the bridge span), which is the weak direction of the bridge pier. Therefore, the lateral load is applied in the weak direction. The lateral cyclic loading is conducted in a force control mode, the absolute maximum value of the lateral load depend on the pier concrete cracking and failure. The lateral cyclic loading is applied by a step of 5 kN, 3 times per step, the loading sequence is shown in Fig. 4. When the concrete crack expands to cause failure of the pier, the lateral cyclic loading should be stopped to increase. The applied vertical axial load (57 kN)



(a) Vertical loading unit



(b) Horizontal loading unit

Fig. 3 Configure of the test equipment

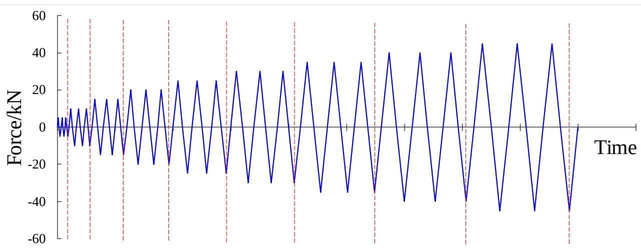


Fig. 4 Lateral cyclic loading sequence

is maintained at a constant level throughout the testing, which can be calculated by the similarity ratio of model pier to the prototype.

3. Strengthening techniques

Three of completed model piers are strengthened by using the encased jacket of CFRP and concrete materials. Previous research results showed that the monolithic factors

Table 2 Physical and mechanical properties of the CFRP material

Thickness (mm)	Tensile strength (MPa)	Tensile modulus of elasticity (MPa)	Tensile Elongation (%)	Mass per unit area (g/m^2)
0.167	3400	2.4×10^5	1.71	300

(a) Brush coating (b) Vertical CFRP (c) Horizontal CFRP

(d) Drilling (e) Planted steel bars

(f) Concrete casting (g) Completed model

Fig. 5 Construction procedure of the pier strengthened with CFRP jacket

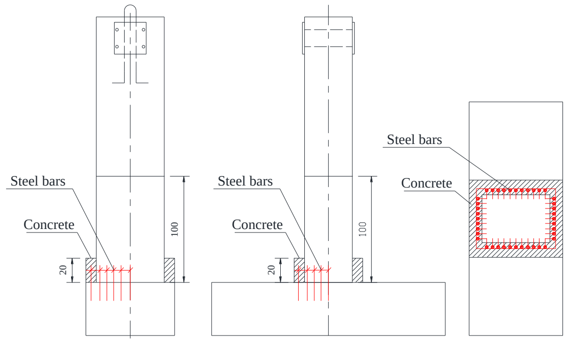


Fig. 6 Bottom-anchoring method using planted steel bars for the pier strengthened with CFRP jacket

(a) Positioning and drilling

(b) Planted reinforced bar

(c) Steel skeleton (d) Concrete casting (e) Completed model

Fig. 7 Construction procedure of the pier strengthened with concrete jacket

associated with strength, stiffness, and deformation vary greatly depending on the techniques followed in constructing the jacket (Thermou *et al*. 2007). Therefore, the construction techniques of the jacketing is a key factor to ensure the strengthening effect. In this study, a bottom-anchoring method is presented to ensure the CFRP and concrete jacketing to work jointly with original concrete piers, of which planted steel bars and new concrete jacket are employed at pier-footing region.

3.1 Strengthening techniques using CFRP material

The CFRP material used in this study is a FRP composite reinforced by unidirectional carbon fabric fiber, and its physical and mechanical properties provided by the manufacturer are listed in Table 2.

The strengthening procedures of the model pier with CFRP sheets are summarized in Fig. 5, which include clear interface and brush glue coating, CFRP pasting (vertical and horizontal), positioning and drilling for planted steel bars, assembling planted steel bars and concrete casting at pier-footing region. In this study, one layer of CFRP sheet is wrapped in horizontal and vertical direction of the model pier, respectively. CFRP wrapping in the horizontal direction can reinforce the concrete column by the lateral confinement improving (Chang *et al*.2004). Likewise, CFRP sheets wrapped in the vertical direction reinforce the concrete pier as the increasing of the equivalent longitudinal steel ratio. If there is no effective bottom-anchoring method, the improvement will not be achieved due to the premature failure caused by delamination and peeling of the CFRP sheets (Mostafa and Razaqpur 2013). The delamination of CFRP sheets might be avoided if adhesive bonding is supplemented by mechanical fastening (Chang and Tsai 2005). In this study, planted steel bars are arranged at the

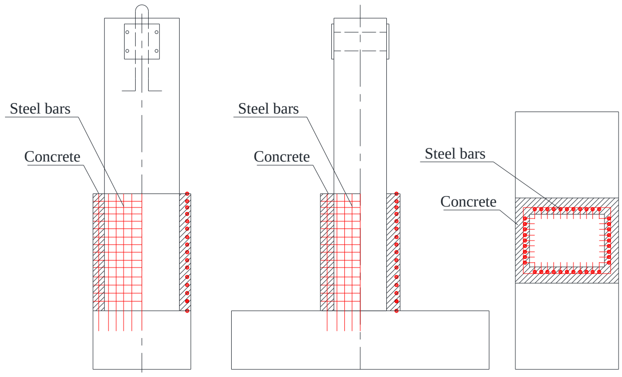


Fig. 8 Bottom-anchoring method using planted steel bars for the pier strengthened with concrete jacket

pier-footing region to prevent the delamination and peeling of CFRP sheets. In fact, these steel bars are planted into the pier and bearing platform, as shown in Fig. 6, a 20 cm-height of concrete is casted around the anchored bars and form a new reinforced concrete structure to guarantee the CFRP jacketing to work jointly with the original model pier (Figs. 5(f) and 6).

3.2 Strengthening techniques using concrete material

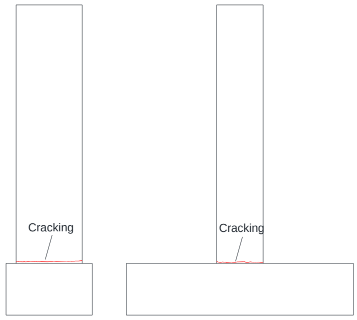
The concrete material used for strengthening is as same as that used for the original concrete. The strengthening procedures of the model pier with concrete jacketing are summarized in Fig. 7, which include positioning and drilling for steel bars, assembling and planting steel bars (vertical, horizontal and hooped steel), formwork, and concrete casting. In order to enhance the strengthening effect, reinforced steel bars in concrete jacketing should be planted into the original concrete with a certain depth, as shown in Fig. 8. The planted vertical reinforced bars can guarantee the concrete jacketing to work jointly with the basement. With the planted horizontal reinforced bars, the shear strength of new and existing concrete increases greatly. The thickness of the new concrete jacketing is 12 cm in this study.

4. Results and analysis

4.1 Analysis of fracture characteristics

The fracture characteristics of the four model piers (M1-4) are shown in Figs. 9-11. The initial horizontal crack occurs at the pier-footing region when the lateral load of the M1 increases to 34kN. It can be found that the crack expand rapidly and penetrate through the whole pier section, and the fracture plane almost coincides with the interface between the model pier and its bearing platform, as shown in Fig. 9. Therefore, the railway bridge pier with a low longitudinal steel ratio (0.1%) can be easily destroyed under lateral cyclic loading and shows the characteristics of brittle failure. The horizontal crack also indicates the failure mode is flexural failure, which related to the large aspect ratio of the model pier (pier height / section width=3.9). Based on

(a) Photo of concrete crack



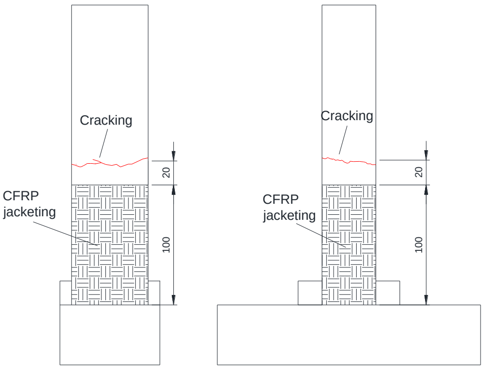
(b) Crack position and distribution

Fig. 9 Concrete crack of M1 (model pier without strengthening)

the fracture characteristics, it also can be deduced that the vulnerable position of the railway bridge pier with low reinforcement ratio during earthquake is the pier-footing region. These above results of the original model pier provide valuable guidance for corresponding pier strengthening.

Initial crack occurs when the lateral load of the M2 increases to 52 kN. The crack location of the model pier strengthened with CFRP jacketing (Fig. 10(a)) is quite different from that of the model pier without strengthening (M1, Fig. 9(a)). The main crack is shifted from pier-footing region up to the unstrengthened region of the concrete pier, about 1.2 m height from the pier footing (0.2 m height from the top side of CFRP jacketing). In contrast, the concrete at the strengthened region is still in the range of elasticity under the lateral cyclic loading. Particularly, the original vulnerable position (pier-footing region) shows a significant enhancement due to the bottom-anchoring method with planted steel bars and new concrete jacketing. It can be found that the geometrical shape of the crack is nearly horizontal and simple, which indicates that the main failure mode of the model pier strengthened with CFRP jacketing under lateral cyclic loading remains a flexural failure. As a conclusion, the bridge pier strengthened by using partial CFRP jacketing can relocate the fracture region and increase the crack load capacity of bridge piers with low initial reinforcement ratio. The actual flexural strength of the original concrete bridge pier with low reinforcement ratio is 34 kN×2.5 m=85 kN·m. It is higher than the calculated value with considering no reinforcement (41.7 kN·m), but lower than the calculated value with fully considering reinforcement (101 kN·m). Therefore, it is not appropriate to regard the concrete bridge pier with low reinforcement ratio (lower than 0.5%) as full plain or reinforced concrete structure during static or dynamic analysis.

(a) Crack photo of M2

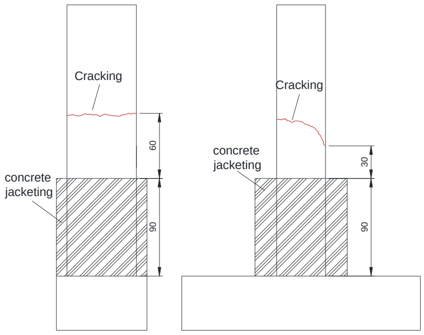


(b) Crack position and distribution of M2

Fig. 10 Concrete crack of M2 (model pier strengthened with CFRP)

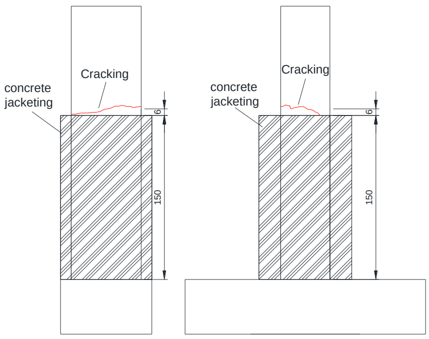
Initial horizontal crack occurs when the lateral load of the M3 increases to 58 kN. The main horizontal crack of M3 (Fig. 11(a)) appears at the region of the model pier without concrete jacketing, about 1.5 m height from the pier footing (0.6 m height from the top side of the concrete jacketing). It is clear from the photo that diagonal crack appears on the pier surface which is parallel to the loading direction and extends down to about 1.2 m from the footing of the pier (Fig. 11(a) and (b)). The concrete jacketing height of M4 (1.5 m from the footing of the pier) is greater than that of M3 (0.9 m from the pier-footing). Therefore, the ultimate lateral load of M4 (98 kN) is large than that of M3 (58 kN), increases almost 70%. However, the location of the main crack is almost unchanged. The crack of M4 also appears at the region of the pier without concrete jacketing, about 1.56 m height from the footing of the pier (0.06 m height from the top side of concrete jacketing). The horizontal cracks on the loading surface also turn to diagonal cracks when the height of concrete jacketing increases from 0.9 m to 1.5 m. This indicates that the failure mode of the strengthened model pier with concrete jacketing changes from flexural failure to shear failure. The change of failure mode is mainly due to the decrease of the aspect ratio of the column pier (unstrengthend part), i.e., M1 (3.9), M2 (2.5), and M3 (1.6), the flexural strength increases with the decrease of the aspect ratio. Therefore, it can be deduced that the height increase of the concrete jacketing can enhance the flexural strength of the bridge pier and change the failure mode, but it cannot significantly translocate the vulnerable region of the bridge pier under lateral cyclic loading. The bonding behavior between new and old concrete is critical for the strengthening technique by using concrete jacketing. The bottom-anchoring method using planted steel bars (Fig. 8) can prevent encased concrete from peeling off under lateral cyclic loading. This indicates that the anchoring method is effective for the

(a) Crack photo of M3



(b) Crack position and distribution of M3

(c) Crack photo of M4



(d) Crack position and distribution of M4

Fig. 11 Concrete crack of M3 and M4 (model pier strengthened with concrete)

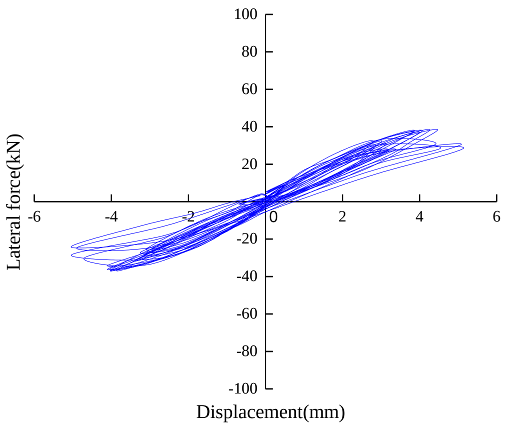


Fig. 12 Force-displacement behavior of M1 (model pier without strengthening)

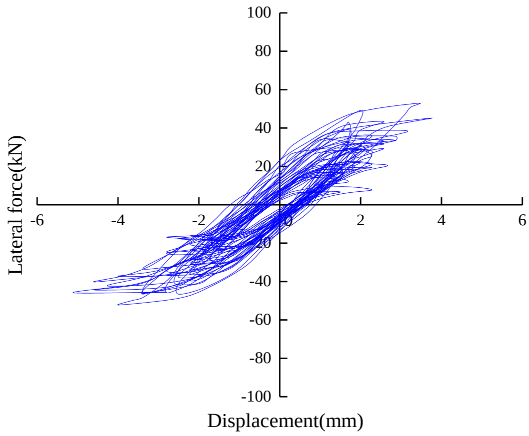
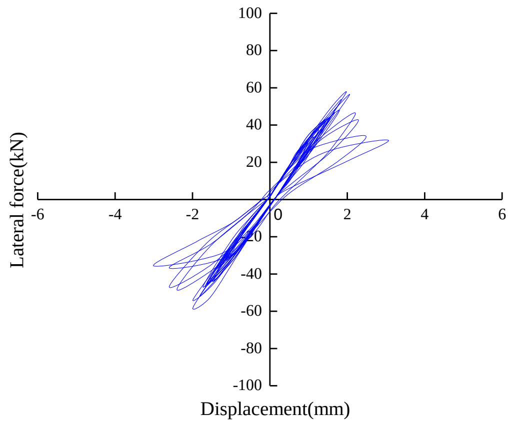
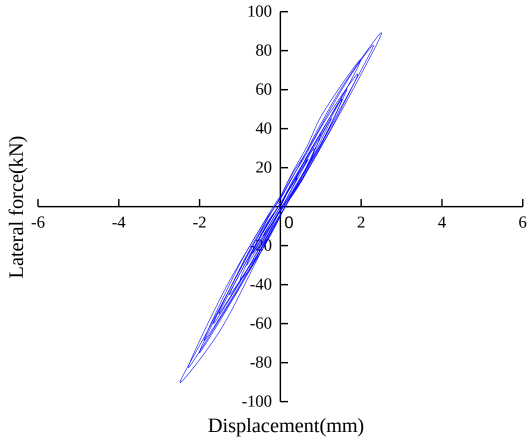


Fig. 13 Force-displacement behavior of M2 (model pier strengthened with 1.0 m height of CFRP jacketing)



(a) M3 (0.9 m height of concrete jacketing)



(b) M4 (1.5 m height of concrete jacketing)

Fig. 14 Force-displacement behavior of model pier strengthened with concrete

seismic strengthening of bridge piers by using concrete jacketing.

4.2 Analysis of the force-displacement curve

The top-of-pier force-displacement hysteretic relationships (hysteretic loops) of the different model piers (M1-4) are shown in Figs. 12-14. Fig. 12 shows the hysteretic loops of the model pier without strengthening (M1). The unstrengthened pier of M1 reached ultimate bearing capacity with lateral force of 33.87 kN and top lateral displacement of 5.15 mm (push). The thin hysteretic loops in Fig. 12 show that the railway bridge pier with a low longitudinal reinforcement ratio (0.1%) has inadequate ductility and energy dissipation under lateral cyclic loading.

Fig. 13 shows the hysteretic loops of the model pier with CFRP strengthening (M2). The strengthened pier of M2 reached ultimate bearing capacity with lateral force of 52.93 kN and top lateral displacement of -5.10 mm (pull). The top lateral displacement of M2 changed a little after strengthening, but the lateral force (52.93 kN) increased by 56% than that (33.87 kN) of M1 in the unstrengthened case; the hysteretic curves became more stable and the hysteretic loops became plump and full. Therefore, seismic strengthening technique with CFRP jacketing not only brought a significant enhancement of strength, but got a benefit of the energy dissipation for railway bridge pier. It is known that the hysteretic damping caused by plastic deformation is the major source of seismic energy dissipation in reinforced concrete bridge column (Chang 2010), so the CFRP strengthening improves the plastic deformation capacity of the bridge pier with low longitudinal steel ratio.

Fig. 14 shows the hysteretic loops of the model pier strengthened with concrete jacketing. The strengthened pier of M3 reached ultimate bearing capacity with lateral force of 57.87 kN and top lateral displacement of 3.07 mm (push), and the ultimate force and displacement of the M4 were 98.09 kN and 2.51 mm. The hysteretic loops of the two piers strengthened with concrete material (Fig. 14) were thinner and more steepened than the pier strengthened with CFRP material (Fig. 13). Therefore, the ultimate bearing capacity of the model pier strengthened by using concrete jacketing enhanced significantly; however the displacement ductility capacity decreased slightly, compared with the unstrengthened case. From the difference between the Fig. 14(a) and (b), it can be found that the height increase of the concrete jacketing increased the strength and stiffness but decreased the displacement ductility of the model pier. The force-displacement relationship of the strengthened piers was tend to linear,

Table 3 Ultimate bearing capacity and failure mode of model piers

Specimen	Ultimate load (kN)	Enhancement ratio of bearing capacity (%)	Failure location (from the foot of pier, m)
M1	33.87	-	0
M2	52.93	56	1.2
M3	57.87	71	1.2~1.5
M4	98.09	190	1.5~1.56

especially for the pier with 1.5 m height of concrete jacketing. This implied that the strengthened piers had insufficient plastic deformation capacity under lateral cyclic loading.

Through the above analysis, it is concluded that the bridge piers can be strengthened effectively by using of the encased CFRP and concrete jacketing, and the ultimate load-bearing capacity of the strengthened piers improved significantly, as seen in Table 3. The ultimate loading capacities of bridge piers strengthened with CFRP and concrete jacketing achieved a significant improvement of more than 50%, i.e., 56% for 1.0 m height of CFRP jacketing, 71% and 190% for 0.9 m and 1.5 m height of concrete jacketing, respectively. The four model piers cracked and failed at the region without strengthening jacketing, and showed the characteristics of brittle failure due to the low initial reinforcement ratio (0.1%). Therefore, it can be concluded that the strengthening techniques (CRFP and concrete jacketing with partial height) are effective in enhancing of ultimate bearing capacity of the existing railway bridge pier. However, the failure mode are still determined by the vulnerable regions without strengthening jacketing.

The skeleton curves of model piers are the maximum peak of each cycle of the force-displacement hysteresis curves, the average (push and pull) skeleton curves of the four model piers can be seen in Fig. 15. From this figure, it can be indicated that the peak values of the load-carrying capacity for the model piers increased significantly after strengthening with CFRP (M2) and concrete jacketing (M3 and M4) in comparison with the unstrengthening case (M1). However, the failure displacement at the top of the model pier decreased slightly, especially for the pier strengthened with concrete. The failure displacement also decreases with the increased height of the concrete jacketing (M3 and M4). Compared with the strengthened model pier with CFRP jacketing (M2), stiffness degradation was not obvious for strengthened model piers with concrete jacketing (M3 and M4), the phenomenon became more obvious when the height of concrete jacketing increased from 0.9 m in M3 to 1.5 m in M4.

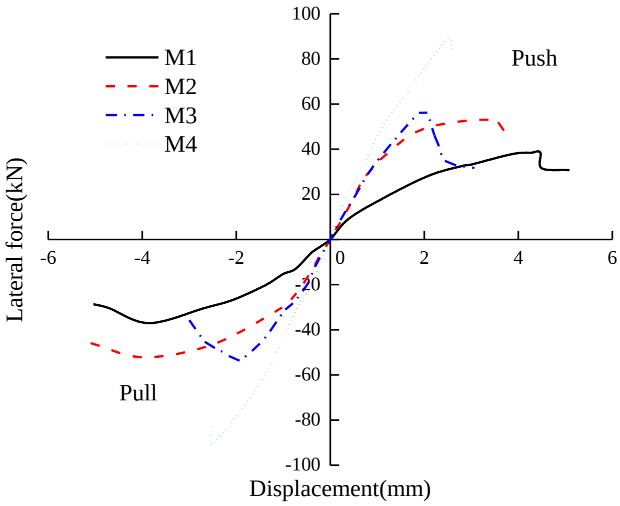


Fig. 15 Skeleton curves of the four different model piers

5. Conclusions

The CFRP and concrete materials were provided to strengthen the existing deficient railway bridge piers with low initial reinforcement ratio (0.1%) in this study. Quasi-static tests of scaled model piers were carried out to investigate the seismic performance of the original and strengthened bridge piers. Some conclusions were drawn based on these results.

- From the fracture characteristics, it can be found that the cracks of the four model piers appeared at the region without strengthened jacketing, all of them showed the characteristics of brittle failure due to the low initial reinforcement ratio (0.1%). Nonoccurrence of delamination and peeling of the strengthened materials from original pier concrete surface indicated that the bottom-anchoring method by using planted steel bars is effective for the implementation of the CRFP and concrete strengthening.
- With reference to the model pier without strengthening, the load-carrying capacity of the bridge piers strengthened with CFRP and concrete jacketing achieved a significant improvement of more than 50%, i.e. 56% for 1.0m height of CFRP jacketing, 71% and 190% for 0.9m and 1.5m height of concrete jacketing, respectively.
- From hysteretic loops of model piers, it can be found that the CFRP strengthening technique not only brought a significant enhancement of ultimate loading capacity, but got a benefit of the energy dissipation capacity for railway bridge pier with low longitudinal steel ratio. The ultimate loading capacity of the model pier strengthened by using concrete jacketing also enhanced significantly, but the displacement ductility capacity decreased slightly.

Therefore, different strengthening materials for existing railway bridge pier with low reinforcement ratio can be recommended on the basis of different seismic requirements.

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