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RAPID REPAIR SOLUTION FOR CHINESE RC BRIDGES TO IMPROVE PLASTIC DISSIPATION, DUCTILITY AND SHEAR STRENGTH ACCORDING CAPACITY DESIGN CRITERIA

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ABSTRACT

A rapid repair and seismic upgrade solution for reinforced concrete (rc) bridges designed according to Chinese code (JTG D60-2004 [1], JTG D62-2004 [2] and JTG/T B02-01-2008 [3]) but with insufficient transversal steel reinforcement, damaged by a strong earthquake, is proposed and tested. This solution is an upgrade of the one tested with very good results during a previous research (Lavorato et al. [4]) on bridge designed according to old Italian code (‘86) [5] without proper seismic details. In particular some improvements are given for damaged rebar substitution. Cyclic tests are carried out on pier specimens (in scale 1:6) of the most stressed pier of the Chinese rc bridge at Fuzhou University lab (China) to evaluate the effectiveness of the proposed repair technique. These specimens have been built simulating the substitution of the damaged portions of the rebars using rebar turned at the pier base to have a smaller diameter. The turned rebar ensures the concentration of the plasticity at the base of the pier. A C-FRP wrapping is applied to increase the insufficient shear strength and guarantee the necessary ductility in the plastic hinge sections. Different turned rebar configurations are considered to optimize the intervention.

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Rapid repair solution for Chinese rc bridges to improve plastic dissipation, ductility and shear strength according capacity design criteria

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ABSTRACT

A rapid repair and seismic upgrade solution for reinforced concrete (rc) bridges designed according to Chinese code (JTG D60-2004 [1], JTG D62-2004 [2] and JTG/T B02-01-2008 [3]) but with insufficient transversal steel reinforcement, damaged by a strong earthquake, is proposed and tested. This solution is an upgrade of the one tested with very good results during a previous research (Lavorato et al. [4]) on bridge designed according to old Italian code ('86) [5] without proper seismic details. In particular some improvements are given for damaged rebar substitution. Cyclic tests are carried out on pier specimens (in scale 1:6) of the most stressed pier of the Chinese rc bridge at Fuzhou University lab (China) to evaluate the effectiveness of the proposed repair technique. These specimens have been built simulating the substitution of the damaged portions of the rebars using rebar turned at the pier base to have a smaller diameter. The turned rebar ensures the concentration of the plasticity at the base of the pier. A C-FRP wrapping is applied to increase the insufficient shear strength and guarantee the necessary ductility in the plastic hinge sections. Different turned rebar configurations are considered to optimize the intervention.

Introduction

Rapid repair methods for quick opening of the bridge to emergency response are very interesting solutions. The repair and retrofitting of damaged reinforced concrete (rc) bridge after an earthquake is possible using different repair techniques as concrete jacketing, steel jacketing and FRP (fiber reinforced polymer composite) wrapping.

Just to cite some techniques and relative references: concrete jacketing (Teran et al., 1992) [6]; Sabnis et al., 1996 [7]; Vandoros et al. 2008 [8]), steel jacketing and steel cage (Priestley et al., 1994 [9]; Aboutaha et al.1999 [10]; Dritsos et al., 1994 [11]; Georgopoulos et al, 1994 [12]; Nagaprasa et al., 2009 [13]) and FRP (fiber reinforced polymer composite) wrapping in continuous or discontinuous configurations (Triantafillou, 2001 [14]; Cheng et al., 2006 [15]). Their effectiveness, based on experimental evidence, is discussed for example by Priestley, Seible and Calvi, 1996 [16], Kawashima, 1990 [17] and in FIB bulletin, 2001 [18].

In particular rapid repair interventions are presented in literature by Sun et al. [19], He et al. [20] and Cheng et al. [21]. Lavorato and Nuti 2013 [4] have proposed and tested by an experimental study a new rapid repair technique. This technique was applied on damaged

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Italian old style Bridges [5]. These bridges were seriously damaged during the previous pseudo-dynamic (PSD) and cyclic tests until failure carried out by De Sortis et alt. 1996 [222223] in Italy. These Italian bridges had insufficient seismic details and their seismic behavior was compared with the one of proper seismic designed bridges according Eurocode 8 [236]. After the failure test the damaged pier specimens were repaired and retrofitted recovering the damaged concrete and rebar parts only. This intervention guarantees cost saving, very short time of intervention and very good safety level (Lavorato and Nuti [24]). The effectiveness of the intervention was validated by new PSD tests on rc bridge at the Department of Architecture at Roma Tre University (Lavorato 2009 [25]). This rapid repair technique results very effective as the original pier strength is recovered without the original unwanted shear failure. However some improvements are necessary. In fact great local plastic demand was required on welding connection between the original anchorages and the new rebar parts during the PSD tests and failure of this connection was observed.
In the present research the new rebar portions are turned with smaller diameter to ensure the distribution of the plasticity in the plastic hinge zone. Cyclic tests on pier specimens (in scale 1:6) of the most stressed pier of the Chinese rc bridge are carried out at Fuzhou University lab (China). These pier specimens have been built simulating the substitution of the damaged portions using turned rebars at the pier base (plastic hinge zone). A C-FRP wrapping is applied to increase the insufficient shear strength due to a design error and guarantee the necessary ductility in the plastic hinge sections. Different turned rebar configurations are considered to optimize the intervention.

The proposed rapid repair and seismic upgrade solution

Repair and retrofitting of seriously damaged rc piers to restore the original resistance and improve the seismic performance in terms of ductility and shear strength, can be a valid alternative and a more sustainable solution respect to reconstruction.
A rapid repair and retrofitting solution proposed by some of the authors ([4], [25], [1]) and shown in Figure 1Figure 1, consists of damaged rebar part substitution by stainless steel rebars which increase the durability and concrete restoration by self-compacting concrete (SCC) that simplifies the cast. Finally retrofitting by C-FRP (carbon fiber reinforced polymer composites) is a quick solution to increase the shear and ductility of the pier with insufficient transversal steel reinforcement. This insufficient seismic detail is very common in the Old Italian bridges [5].

(a) (b) (c)

Figure 1 Proposed rapid repair and seismic retrofitting solution for damaged Italian pier: a) damaged rebar part substitution, b) concrete restoration and c) seismic retrofitting by C-FRP wrapping.

The PSD (pseudo-dynamic test) tests on the repaired and retrofitted bridge carried out by some of the authors ([4], [25]) ([25], [1]) show that the proposed repair and retrofitting intervention is effective. In fact the original pier resistance is recovered without the original shear failure mechanism. However construction details concerning rebar connection systems have to be improved. In particular, the longitudinal reinforcement represents a complex technological problem since the connection between new and original rebars must be made in the critical zone (where there is the plastic hinge) at the base of the pier ensuring the development of the ductility demand. The improvement of the connection between new longitudinal rebars part and original anchorages and a technical solution for the new rebar part to assure a distribution of the plastic demand in plastic hinge zone only, can increase the effectiveness of the seismic upgrade. The solution for the connection between the new rebar portions and the original anchorages is the use of head welding. This connection is simple to realize in situ and excludes the negative effect of the eccentricity between the rebar axis which was observed in case of the side welding connection used for the repair of the Italian pier ([4], [25])([25], [1]). This connection results more effective.

The new rebar portions can be properly turned to reduce the original longitudinal rebar diameter and assure the distribution of the plastic demand along these new rebar part only in plastic hinge according capacity design rules. In fact also a new rebar of the same steel type and diameter of the original ones, can be statistically more resistant than the original anchorages. For that reason the plastic demand can focus on the original anchorages along a short rebar part with great plastic local demand. Furthermore the great local plastic demand can cause the rupture of the welding connection with construction defects as it was observed during the Italian PSD test ([4], [25]).([25], [1]).

Bridges

The bridge analyzed in this research, has an irregular configuration (Figure 2Figure 2Figure 2) and is the same studied in De Sortis et alt. [222223] and in Lavorato et alt [41]. The steel reinforcement has been designed according to Chinese codes ([1], [2], [3]). The Chinese design spectrum is calibrated properly to obtain a seismic design action on the bridge very similar to the one used in the design of the EC8 bridges [222223]. In this way it is possible a good comparison between European bridge, already studied by PSD test by De Sortis et al. [222223], and Chinese bridges performance. The parameters used to define the Chinese spectrum in accordance with the seismic Chinese code JTG/T B02-01-2008 [3] are given in Table 1Table 1Table 1.

Bridge Type	Design Intensity	Basic Horizontal Design Seismic Acceleration A	Ground Type	Eigenperiod T_g	Damping Ratio ξ
B	8	0.2g	III	0.65s	0.02

Table 1 Parameters used to calibrate the design spectrum according the seismic Chinese code JTG/T B02-01-2008 [3].

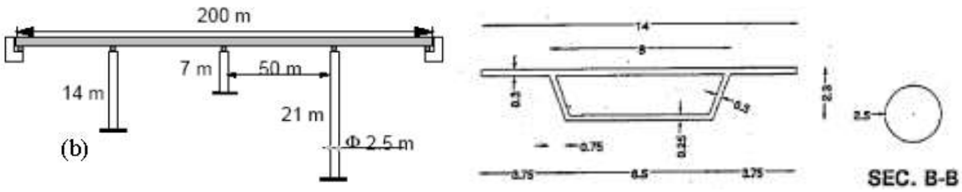

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Figure 2 Chinese rc bridge with irregular configuration; deck and pier sections geometries

The dead load on the bridge deck is 200kN/m, the same load used to design Italian and EC8 bridges [222223]. The materials used for the bridge design are: the Chinese steel types HRB335E for longitudinal reinforcement and R235 for transversal reinforcement with standard value of tensile strength of 335 and 235MPA respectively and the Chinese concrete class C30 with characteristic axial compressive strength of 20MPa. A finite element bridge model is built in MIDAS [29] to obtain the actions to design the piers according to Chinese code loads and prescriptions ([1], [2], [3]). In particular the details of the longitudinal and transversal steel reinforcements and the concrete geometries of the most stressed pier of the bridge are given in Figure 3Figure 3Figure 3a. The transversal steel reinforcement is insufficient to sustain the capacity design shear actions according the Chinese code [3] due to design error. Several Oold Chinese bridges have insufficient transversal reinforcement. In these cases a retrofitting intervention by C-FRP wrapping, much used in real applications in the world, increases the pier shear strength.

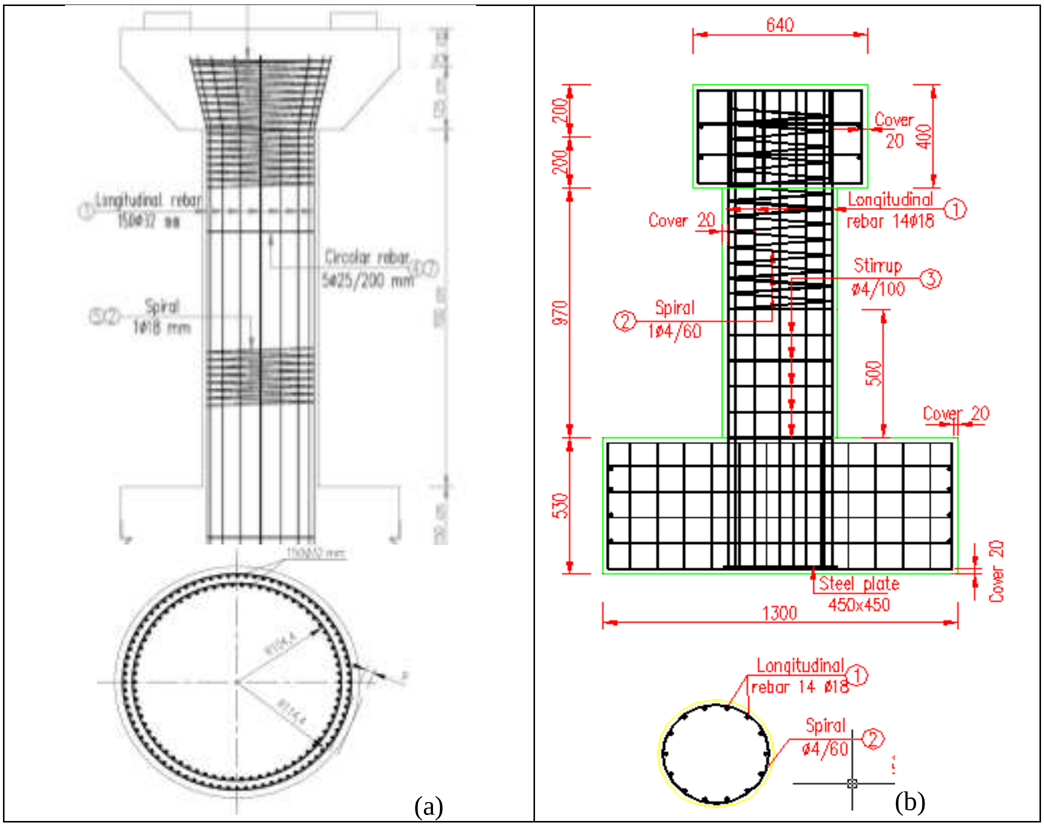

Figure 3 Chinese rc bridge: a) most stressed pier geometries and longitudinal and transversal steel reinforcements; b) pier specimen (scale 1:6) geometries and longitudinal and transversal steel reinforcements.

Pier specimens

This research campaign focuses on rapid repair and seismic retrofitting interventions on

seriously damaged rc bridge and piers after an earthquake. In particular the repair technique is the one described above. The present study focuses on the improvement of the longitudinal rebar substitution intervention. This intervention is a critical issue for the entire repair and retrofitting operations as it is experimentally shown by previous research campaign performed by some of the authors [41]. The improvement consists in the use of turned new rebar parts connected at the pier original anchorages and to the upper undamaged original rebar parts by head welding connection as above described. The improved repair and retrofitting technique is applied on the most stressed pier of the Chinese rc bridge described above (Figure 3Figure 3a). The effectiveness of the proposed intervention is tested experimentally by cyclic tests on 1:6 scaled pier specimens which have been built at Fuzhou University lab. The intervention of rebar substitution is simulated during the construction of the pier specimens by using turned rebar at the pier specimen base (Figure 3Figure 3b, Figure 4Figure 4).
Scale factors for the construction of the specimen consider costs, feasibility and apparatus capacity. Similitude criteria between model and prototype are guaranteed in terms of global quantities: flexural and shear strength, confinement effect [27]. The post-elastic buckling and the pull-out of rebars are not considered in the scale reduction. However the buckling of the longitudinal rebars is avoided by the C-FRP wrapping applied to increase the shear strength. The pull out of the rebars has effect on the strain penetration which is important in the elastic deformation range only and it can be critically considered during the results analysis. The perfect geometrical scaling of materials is not necessary allowing the use of commercial ordinary concrete mixing and commercial steel bars.
The pier specimens in scale 1:6 have diameter equal to 420mm and height of 1170mm. The geometries and steel reinforcement are given in Figure 3Figure 3b. A C-FRP wrapping (Figure 6Figure 6Figure 6c) is applied on pier specimens to increase the shear strength due to the insufficient transversal steel reinforcement. The C-FRP mechanical properties used for the wrapping design are: thickness of 0,167mm, elastic modulus 242GPa and maximum deformation of 0,005 in accordance with CNR DT 200/2013 [28] Italian guideline. Ten 1:6 scaled pier specimens have been built. Three pier specimens (P26, P36 and P46) have turned rebar with three different configurations (Figure 4Figure 4) and the same C-FRP wrapping with 3 layers of C-FRP to increase the shear strength according to Chinese capacity design prescription [3].
Five pier specimens (P16-1A, P16-1B, P16-2, P16-3A, P16-3B) do not have turned rebars and different C-FRP wrapping configurations with one, two or three layers of C-FRP (as indicated in the specimen label; (i.e. P16-3A has three layer of C-FRP) are applied to increase the shear strength. The specimens with character A or B have the same geometries, steel and C-FRP reinforcements. The specimens P16A and P16B do not have turned rebar and C-FRP wrapping. The specimens without turned rebar are useful to check the shear seismic upgrade of the piers specimen. In fact three layer of C-FRP are necessary according to design guidelines [28] considering the coefficient of safety. However it is interesting to evaluate the possibility of reducing the number of C-FRP wrapping to optimize the intervention of retrofitting. The longitudinal rebars of specimens P26, P36 and P46 have different turned configurations (Rebar 1, Rebar 2, Rebar 3, Figure 4Figure 4) in correspondence of the base of the pier:

- Rebar 1: turned rebar diameter reductions from 18 mm to 15mm and turned rebar lengths equal to 250mm
- Rebar 2: turned rebar diameter reductions from 18 mm to 15mm and turned rebar lengths equal to 125mm
- Rebar 3: turned rebar diameter reductions from 18 mm to 14mm and turned rebar

lengths equal to 240mm

The turned rebar length is assumed equal to the theoretical plastic hinge length (theoretical length according Priestley [16~~1617~~]) or equal to half of this length to optimize the intervention cost reducing the rebar part substitution and concrete removal. However the smaller plastic hinge length produces greater plastic section curvature demand to guarantee the same horizontal displacement for the three pier specimens with turned rebars. A C-FRP wrapping can guarantee the increasing of the section ductility. The rebar diameter reduction by turning assures that the maximum strength moment at the anchorages section, where there are rebar with diameter 18mm, is greater than the one on the section above the anchorages with turned rebar. Furthermore the rebar diameter reduction is chosen to assure that when the maximum strength moment is reached in the section with turned rebar, the anchorages section remains in elastic range only. In this way the plasticization of the anchorages with great plastic local demand is excluded. The turned rebar part is about 30mm above the pier foundation to simulate the real substitution intervention with head welding connection between the anchorages and the new rebar portion placed in correspondence of this zone. The spacing of the transversal steel in the plastic hinge zone is 100mm to simulate the space required for the intervention of concrete restoration to assure quick, effective and ~~the~~ simple passage of ~~the~~ concrete between the reinforcement (modest space; damaged concrete cover and more external part of concrete core of the pier are removed only).

Rebar 1	Rebar 2	Rebar 3

Figure 4 Chinese pier specimens with turned rebars: three different (Rebar 1, Rebar 2 and Rebar 3) longitudinal turned rebar configurations

Experimental cyclic tests

Cyclic tests have been carried out on specimens P13-3A and P26 at the Fuzhou University Lab. These specimens have the same C-FRP wrapping configurations with three C-FRP layers but P13-3A specimen does not have turned rebar whereas P26 has turned rebar at the pier base. In this way the effect of the turned rebar only is studied by comparing the responses of these specimens. The constant axial load applied during the test on the top pier specimen is equal to 266kN according to the design dead load applied on the most stressed pier and considering the scale factor for the force equal to 36. Two horizontal displacement histories in one direction only are applied on the top of the specimens in sequence (Figure

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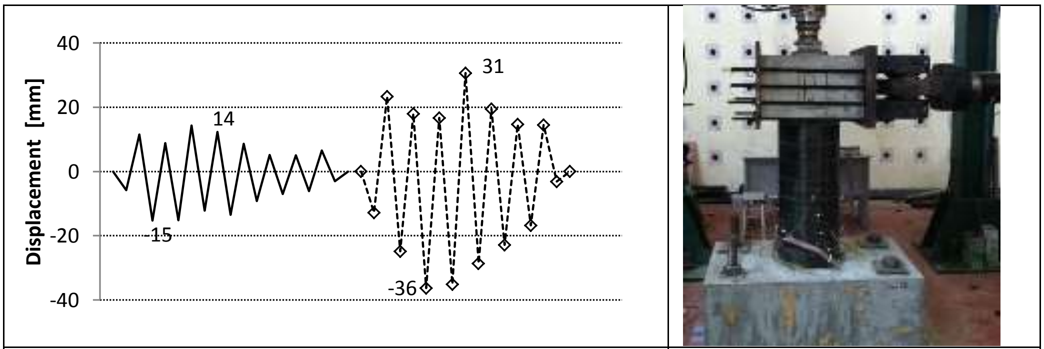
5~~Figure 5~~a)). These displacement histories are the ones recorded on the top pier specimen tested during the PSD test on the repaired and seismic upgraded Italian bridge [4~~1~~]. The first displacement history is the one recorded on top of the pier specimen applying on the bridge the Tolmezzo accelerograms during the PD1 test. The second history is obtained on top of the specimen pier applying Tolmezzo scaled to double during the PD2 test.~~ (Figure 5).~~ These two displacement histories (Figure 5~~Figure 5~~a) will be labeled as PD1 and PD2 in the text below for the cyclic test results explanations.



(a) (b)

Figure 5 Cyclic test on pier specimens: a) Displacements histories applied on top pier specimens during the first (PD1, Tolmezzo; continuous line) and the second (PD2, Tolmezzo x 2; dashed line) cyclic tests; b) test apparatus.

Test Apparatus

Test apparatus for the application of the vertical load and horizontal displacement is shown in Figure 5b. The pier specimen foundation is blocked on the lab floor by four strong steel rods to exclude pier foundation displacements and rotation. The vertical load equal to 266kN is applied by 1000kN hydraulic jack sustained by a vertical steel frame on the specimen top. A steel hinge is placed between the actuator and the pier specimen top part. The horizontal displacements are applied by a 500kN MTS actuator. This actuator is connected by a steel frame to the top of the pier. The acquisition system consists of:

- Two different acquisition systems with commercial software for strain gauges and potentiometer or for LVDT recording
- 7 LVDT for horizontal displacements
- 14 (7 on each more stressed pier side) and 26 (13 on each more stressed pier side) on steel rebars at the pier specimens base for specimens P16-3A and P26 respectively (turned rebar have 3 strain gauges on the turned rebar part for the more stressed rebar)
- 15 potentiometers for the acquisition of vertical, diagonal and horizontal displacements (Figure 6~~Figure 6~~a and b)
- 32 strain gauges on C-FRP strips (Figure 6~~Figure 6~~c)

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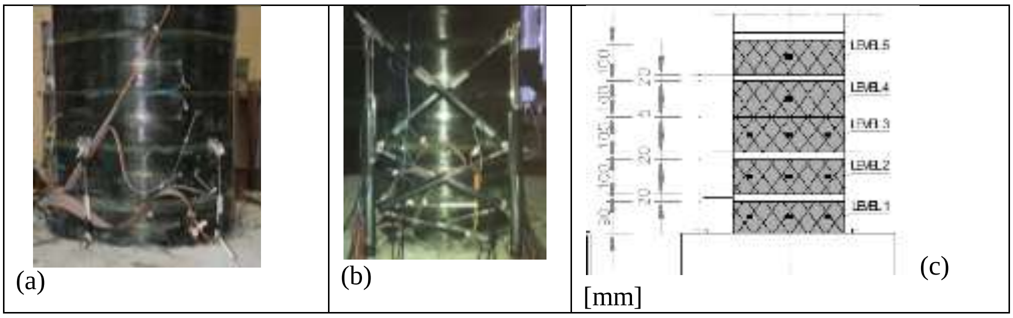
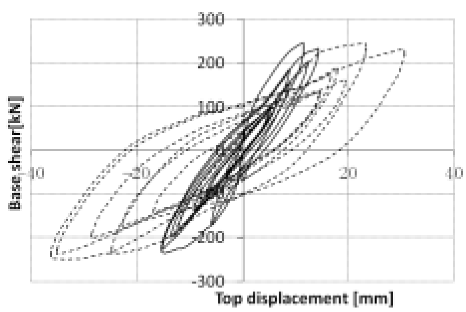
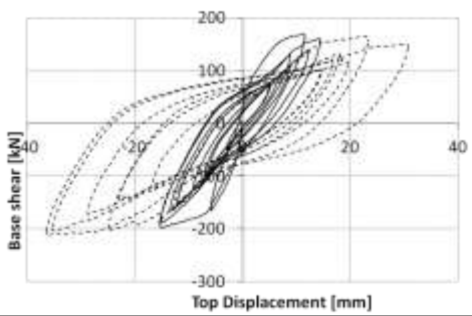


Figure 6 Pier specimen acquisition system: a) vertical potentiometers on one pier side; b) vertical and diagonal potentiometers on the other pier side; c) C-FRP configuration and strain gauges positions

Experimental results

The base shear Vs top displacements histories during cyclic test for the specimens P16-3A and P26 are shown in Figure 7~~Figure 7~~. The two displacement histories PD1 and PD2 are applied in sequence. The continuous curve line and the dashed curve line represent for each specimen the responses during the first and the second cyclic tests respectively. The specimen P16-3A without turned rebar has a yielding shear of 177kN, maximum positive shear of 247kN for a displacement of 11,5mm~~ (second test step)~~ and maximum negative shear of -230kN at a displacement of -15,33mm during the cyclic PD1 test. The maximum shears are 243Kn at 23,30mm and -247kN at 36,33mm during the PD2 cyclic test. There is not a sensible increment of the resisting force even if the displacements are greater. The specimen P26 with turned rebar has a yielding shear of 128kN, maximum positive shear of 161kN for a displacement of 11,5mm (second test step) and maximum negative shear of -186kN at a displacement of -15,33mm during the cyclic PD1 test. The maximum shears are 164 kN at 23,30mm and -206kN at -36,33mm during the PD2 cyclic test. There is not a significant increment of the resisting force even if the displacements are greater.

P16-3A (without turned rebar)	**P26 (with turned rebar)**
	

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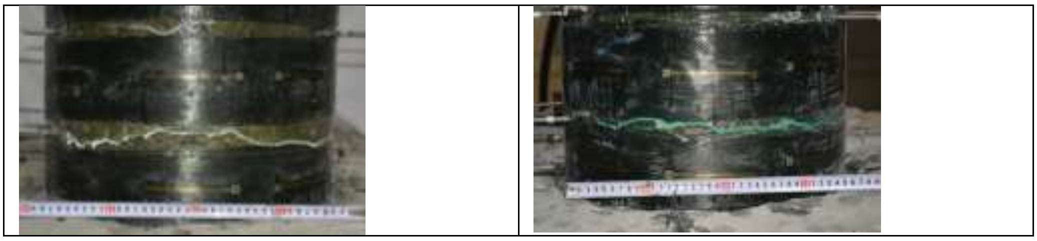

Figure 7 Chinese pier specimens: base shear VS top pier displacement histories during cyclic tests PD1 and PD2 and damage at the pier base after the tests.

The results of the pier specimens P26 with turned rebars show that the rebar plasticization happens on the turned rebars parts in plastic hinge only as design target. However the pier behavior is asymmetric maybe due to a concentration of the damage on one pier side.
The maximum shear strength of the P26 specimen with turned rebar is smaller than the one of the P16-3A specimens but it is obvious as the turned rebar have a diameter smaller than the original ones. This shear strength reduction is balanced by the distribution of the plasticity in the turned rebar as evident by strain gauges on steel rebars (it does not reported here), which permits the use of a greater coefficient to reduce the design action. The pier P26 elastic stiffness is approximately the same stiffness of the pier P16-3A but during subsequent stages, the lateral stiffness degraded slowly with the same ratio between the pier P16-3A and the P26. Finally the specimens P16-3A and P26 show exactly the same dissipated energy behavior both during PD1 and during PD2 cyclic tests.
Damage at the pier base is shown in Figure 7. Two main horizontal cracks appear at the pier base and increase the dimension during the two successive cyclic tests. The first crack is near the pier foundation. The P26 pier with turned rebar shows a crack in the correspondence of the pier base. The plasticization of the turned rebar is evident also by strain gauges measures not presented here.

Conclusions

A rapid repair and seismic upgrade solution for reinforced concrete (rc) bridge designed according to Chinese code [**1**], [**2**], [**3**] but with insufficient transversal steel reinforcement, damaged by a strong earthquake, is proposed and tested. This solution is an upgrade of the one tested with very good results in Lavorato et al. [41].
Ten pier specimens in scale 1:6 of the most stressed pier of the Chinese bridge studied, have been built simulating the substitution of the damaged portions of the rebar with new portions of turned rebars with smaller diameter to ensure the distribution of the plasticity in the plastic hinge zone at the pier base. A C-FRP wrapping is applied to increase the insufficient shear strength and guarantee the necessary ductility in the plastic hinge sections. Different turned rebar configurations are considered to optimize the intervention. The turned rebar length is reduced in one configuration to optimize the intervention.
Cyclic tests have been carried out at Fuzhou lab (China) on two 1:6 scaled pier specimens without (P16-3A) and with (P26) turned rebar at the pier base. First interesting conclusions can be drawn on the base of these first experimental results.
The C-FRP wrapping excludes the shear failure of each specimen as flexural specimen failure only is observed. The C-FRP maximum experimental deformation is similar to the design strain limit of 0.005. The comparison between the responses of the specimens without (P16-3A) and with (P26) turned rebar at the pier base, shows that the rebar plasticization happens on the turned rebars parts as it shown by strain gauges placed on the turned rebars. Damage of the column is controlled and constrained within the hinge zone according to correct

seismic design criteria. However the pier behavior is asymmetric maybe due to concentration of the damage on one pier side. It is possible to optimize the turned length and the diameter reduction to obtain a better behavior. The maximum shear strength of the P26 specimen with turned rebar is smaller than the one of the P16-3A specimens but it is obvious as the turned rebar part has diameter smaller than the original one. This shear strength reduction is balanced by the distribution of the plasticity along the turned rebar as it is evident by strain gauges on steel rebars. A better plasticization distribution permits the use of a greater coefficient to reduce the design action and therefore the smaller shear strength can be accepted as the seismic actions are reduced. Finally the specimens P16-3A and P26 show exactly the same dissipated energy behavior both during PD1 and during PD2 cyclic tests but the specimen with turned rebar presents plasticization in the plastic hinge only.

Acknowledgments

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