New solutions for rapid repair and retrofit of RC bridge piers

Novas soluções para reparação rápida e reforço de pilares de ponte de BA

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Abstract

In this paper, two new rapid repair techniques for strongly damaged Reinforced Concrete (RC) bridge piers are presented. New longitudinal shaped rebar parts substitute the damaged rebar parts whereas a concrete jacket built by self-compacting concrete (SCC) or ultra-high performance fibre reinforced concrete (UHPFRC) restores the damaged concrete parts.

The shaped rebar is designed to assure the proper plastic dissipation in plastic hinge. Finally, the shear strength and ductility improvements are assured by carbon fiber reinforced polymer (C-FRP) wrapping or by the fibres contribution in case of UHPFRC jacket. These interventions are tested experimentally by cyclic tests on 1:6 RC pier specimens at the lab of Fuzhou University. The first experimental results are discussed comparing the responses of the repaired and retrofitted specimens by the two presented techniques, with the ones of the specimens before damage.

Keywords: RC bridge / Repair / Retrofitting / C-FRP / Ultra-high performance fiber reinforced concrete

Resumo

Neste artigo são apresentadas duas novas técnicas para a reparação de pilares de ponte em betão armado severamente danificados. Nova armadura longitudinal é adotada em substituição da armadura danificada, e as seções onde se observam danos no betão são reparadas recorrendo ao encamisamento em betão autocompactável (SCC) ou em betão de ultraelevado desempenho reforçado com fibras (UHPFRC).

A armadura de reforço é dimensionada de forma a garantir uma adequada dissipação de energia na região da rótula plástica. Finalmente, as melhorias de resistência ao corte e de ductilidade são asseguradas pelo encamisamento das seções com polímeros reforçados com fibras de carbono (CFRP) ou pela contribuição de fibras nos casos em que se adota o encamisamento com UHPFRC. Estas soluções de reparação e reforço foram avaliadas experimentalmente com recurso a ensaios cíclicos em provetes à escala 1:6 realizados nos laboratórios da Universidade de Fuzhou. Os resultados experimentais preliminares são discutidos comparando a resposta dos pilares reparados e reforçados recorrendo às duas técnicas em estudo com os resultados obtidos em ensaios análogos de pilares sem dano prévio.

Palavras-chave: Pontes de BA / Reparação / Reforço / CFRP / Betão de ultra-elevado desempenho reforçado com fibras

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1 Introduction

In recent years, the use of advanced technologies and materials has made the repairing and seismic upgrading of reinforced concrete (RC) bridges seriously damaged by earthquakes an increasingly valid and sustainable alternative solution to reconstruction. The time necessary to re-open a bridge damaged after a strong earthquake becomes a key issue in the selection of the proper repair and retrofitting interventions. Different solutions were presented in literature to execute rapid repair interventions on RC columns or piers ([1]-[3], [4]-[18]).

In this paper, a new rapid repair and retrofitting solution is presented to improve the repair and retrofitting interventions tested experimentally with very good results on an irregular bridge (Figure 2) at the lab of the Dept. of Architecture of the University of Roma Tre in Italy and at the lab of the College of Civil Engineering at the Fuzhou University in China ([4]-[18], Figure 1).

The previous repair and retrofitting solution consisted in: the substitution of the damaged rebar parts using new longitudinal and transversal rebar parts (Figure 1a), the restoration of the damaged concrete parts using a SCC (self-compacting concrete) concrete jacket without modify the pier dimension (Figure 1b). It is highlighted that the substitution of damaged stirrups should be limited to use of a minimum stirrups content to permit the SCC new concrete casting and so the application of an external C-FRP wrapping (Figure 1c) is necessary to increase the pier shear strength and ductility.

a) b) c)

Figure 1 Previous rapid repair and seismic retrofitting solution for damaged Italian and Chinese bridge piers [4]-[14]:
a) damaged rebar parts substitution,
b) concrete restoration and
c) seismic retrofitting by C-FRP wrapping

This repair solution is upgraded here using a UHPFRC concrete jacket to restore the damaged concrete parts: this jacket can improve the original insufficient pier shear strength thanks to the fibre contribution and so no stirrups and external C-FRP wrapping are necessary reducing the number of the repair and retrofitting operations with great time and cost saving (Figure 3). The experimental tests on some UHPFRC material specimens considering different steel fibre volume contents (1, 2 or 3%) were carried out at Fuzhou University lab. These tests permitted the definition of the correct fibre content to provide the necessary shear strength improvement on the base of the CNR-DT 204/2006 guideline formulation [29]. The new longitudinal rebar parts are shaped as in case of the previous interventions [12] assuring the proper distribution of the plastic deformation to dissipate the input seismic energy along the new rebar parts in plastic hinge only. However, the new rebar connection system used to connect the new rebar part to the undamaged original ones (anchorages and undamaged rebar part outside the plastic hinge) is upgraded. This connection system can be realized in a simple and efficient way in situ by means of a V shaped steel coupler element and two symmetric welding joints with geometries designed properly to guarantee that the connection is stronger than the connected rebar. An irregular bridge (Figure 2) was identified as critical structure inside of an infrastructures and structures network with seismic critical issues ([19]-[21]). The most stressed pier of this bridge (7 m pier, Figure 2) during the application of the seismic actions, was selected to apply the upgraded repair and retrofit solutions. Some pier specimens (scale 1:6), which are representative of the 7 m bridge pier (Figure 2), were damaged seriously in plastic hinge by cyclic test and then repaired by means of the upgraded interventions to be tested experimentally at the Fuzhou lab by ciclic test. The comparison between the experimental behaviour of the pier specimens repaired by the previous or by the upgraded solution is discussed.

2 Prototype of RC bridge

An irregular RC bridge (Figure 2) is designed per Chinese codes ([22]-[24]). The transversal pier steel reinforcement reproduced the one of some existing bridges with insufficient shear reinforcement to consider the problem of the shear and ductility retrofitting during the repair operations (common problem for many existing RC bridges) ([25]-[28]). The RC bridge geometries are shown in Figure 2, whereas the design details for the steel reinforcement of the bridge piers are described in [15]. This study focuses on the 7 m (Figure 2) pier of the bridge which is the most stressed one during the application of the seismic actions.

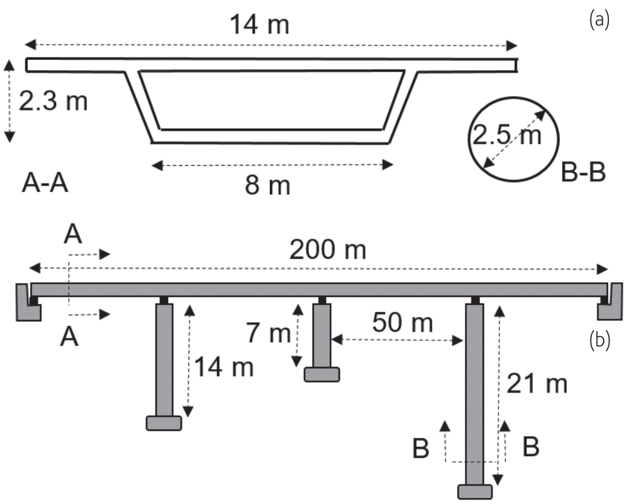


Figure 2 Irregular RC bridge geometries: a) deck and pier sections [m], b) irregular pier configuration

3 Proposed solutions for rapid repair and retrofit of RC bridge piers

The repair and retrofitting solutions presented in [4]-[14] were upgraded to reduce time and cost of the interventions guaranteeing safety, efficiency and feasibility. These upgraded repair solutions consist of: the damaged concrete and rebar parts removal along the entire pier surface in plastic hinge zone only (Figure 3a); the substitution of the longitudinal damaged rebar parts by new shaped rebar parts (Figure 3b); the damaged concrete restoration and the pier shear strength and ductility improvements by means of an UHPFRC (Ultra-High performance Fibre Reinforced Concrete) concrete jacket (CJ)(Figure 3c). The new longitudinal rebar parts are shaped reducing the rebar diameter respect to the one of the original ones, as in case of the previous interventions assuring the proper distribution of the plastic deformation to dissipate the input seismic energy along the new rebar parts in plastic hinge only. However, the new rebar connection system used to connect the new rebar part to the undamaged original ones (anchorages and undamaged rebar part outside the plastic hinge) is upgraded. This connection system can be realized in a simple and efficient way in situ by means of a V shaped steel coupler element and two symmetric welding joints with geometries designed properly to guarantee that the connection is stronger than the connected rebar. This connection can be realized in modest space (removed concrete parts, Figure 3a) and guarantees that the rebar connection is realized along the same axis avoiding local bending action on the connection. The use of strong connection systems and shaped rebar assures that the high local plastic deformations and ruptures, which were observed in some rebar welding connections in [11], are avoided.

The UHPFRC concrete jacket used to restore the damaged concrete parts improve the original insufficient pier shear strength thanks to the fibre contribution and so no stirrups and external C-FRP wrapping are necessary reducing the number of the repair and retrofitting operations with great time and cost saving. The pier geometries are not modified as the CJ substitutes the removed concrete parts only and the pier appearance does not change after repairing.

(a) (b) (c)

Figure 3 Upgraded rapid repair and seismic retrofitting solution for damaged RC bridge piers: a) damaged concrete and rebar parts removal; b) longitudinal rebar substitution using the new connection system by V-shape steel plate and symmetric welding joints; c) concrete restoration by UHPFRC concrete jacket

The UHPFRC was designed: to have a great pass-ability during the casting in very modest space with steel reinforcement (as a self-compacting concrete); to develop the maximum compressive and tensile strengths after a few days (4-6 days) for a rapid re-opening of the bridge; to assure the necessary CJ shear strength by steel fibres contribution to improve the shear strength of the repaired specimen without using stirrups and external C-FRP wrapping; to have a very good durability by the fibres that reduce the crack opening.

Three different UHPFRC mix designs were considered (Table I) using the same concrete matrix but different steel fibre volume contents (1 %, 2 % or 3 %) to evaluate the correct fibre content to provide the necessary shear strength improvement on the base of the CNR-DT 204/2006 guideline formulation [29] as it will be shown in the next section. The base concrete matrix includes: a super-plasticizer, silica fume and fine sand to guarantee high mobility and pass ability like the ones of a self-compacting concrete (SCC).

Table I Selected mix designs of the Ultra-High Fibre Reinforced Concretes (UHPFRC) developed at Fuzhou University Lab

Steel fibre content	Water/ cement (W/B)	Cement (C)	Silica fume/ cement (SF/C)	Sand/ cement (S/C)	Superplasticizer/ cement (Su/C)
1 % 2 % 3 %	0.26	1.00	0.30	1.20	0.025

The steel fibres have an ultimate tensile strength of 2000 MPa and modulus of elasticity of 200 GPa. The mechanical performance of the UHPFRC depends on the aspect ratio and the volume fraction of the fibres. The selected fibres are straight and smooth with length l_f = 13 mm and equivalent diameter d_f = 0.20 mm. Different percentage of fibres (V_f) were considered 1 %, 2 % and 3 % (volume of steel fibres to the volume of concrete) to evaluate the corresponding shear strength contribution and the fresh state properties to permit the casting of the concrete in modest space. UHPFRC specimens were made at the lab of Fuzhou University and tested by compression and flexion tests. The compression tests were executed on three UHPFRC cube specimens (100 x 100 x 100 mm) for each fibre percentage after 6 days to evaluate the cylindrical compression strength (f_{cm6}) developed by the specimens in short time (Table II). The mean value of the cylindrical compressive strength after 28 (f_{cm28}) days was also calculated per FIB model code 2010 [30] (Table II).

The comparison between cylindrical compressive strength after 6 or 28 days shows that almost the maximum strength value was exhibited after 6 days. This result confirms that the UHPFRC is a good material for a rapid concrete restoration. Finally, flexion tests were carried out on three prismatic specimens for each steel fibre percentage (100 x 100 x 400 mm prismatic specimen bended under four flexion points) with a notch size of 30 mm obtaining an equivalent flexural strength (f_{eq2}) corresponding to crack opening of 1.8 mm in agreement with the CNR-DT 204/2006 [29] (Table II). The characteristic value of the ultimate tensile residual strength (f_{Ftuk}) was also obtained from CNR-DT 204/2006 (Table II).

Table II UHPFRC mechanical properties: volume percentage of steel fibres in concrete (V_f), cylindrical compression strength after 6 days (f_{cm6}) and after 28 days (f_{cm28}); equivalent flexural strength (f_{eq2}), ultimate tensile residual strength (f_{Ftuk}); shear strength of the UHPFRC concrete jacket ($V_{Rd,UHPFRC}$), shear strength of the original pier concrete core ($V_{Rd,OC}$), total shear strength of the repaired specimen ($V_{Rd,tot}$)

Vf	f_{cm6} [MPa]	f_{cm28} [MPa]	f_{eq2} [MPa]	f_{Ftuk} [MPa]	$V_{Rd,UHPFRC}$ [kN]	$V_{Rd,OC}$ [kN]	$V_{Rd,tot}$ [kN]
1 %	84.0	99.0	12.3	4.1	137.1	49.8	186.9
2 %	91.0	108.0	15.1	5.0	149.3	49.8	199.1
3 %	97.0	114.0	16.5	5.5	156.1	49.8	205.9

4 Upgraded repair and retrofitting solution applied on RC pier specimens

The main damage of the RC bridge in Figure 2 focuses on the 7 m pier; the most stressed pier during the seismic action application. For that reason, some 1:6 scaled specimens of this pier were designed and built to apply the upgraded repair and retrofitting solutions.

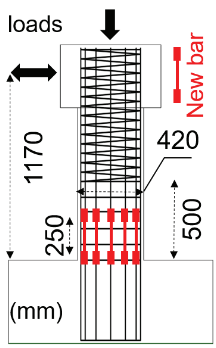
The pier specimen concrete geometries and steel reinforcement configuration were obtained starting from the ones of the full-scale pier using different scale factors. The similitude between full scale and 1:6 scaled pier behaviours in term of flexural and shear strength, stirrups confinement effect is guaranteed [31]. The perfect geometric scaling of the materials (concrete and rebars) is not necessary allowing the use of ordinary concrete mixing and commercial steel rebars simplifying the construction of the pier specimens.

Each 1:6 pier specimens have: section diameter equal to 420 mm, pier height equal to 1170 mm, longitudinal steel reinforcement composed by 14 rebars with diameter of 18 mm and transversal steel reinforcement with diameter of 4 mm and space of 60 mm (Table III). The pier specimen transversal reinforcement is insufficient to sustain the seismic shear resulting from the capacity design criteria: the pier specimen is representative of an existing bridge pier with seismic deficiencies.

In this paper, two piers specimens labelled as P-1 and P-3 were retrofitted by means of one or two C-FRP layers respectively to increase the original insufficient shear strength and ductility (Table III). The C-FRP mechanical properties are: thickness of 0.167 mm, elastic modulus 242 GPa and maximum design deformation of 0.005.

Table III Geometries and reinforcement configurations for the 1:6 scaled retrofitted pier specimens (P1, P3) and the repaired and retrofitted pier specimens (R-1, R-3): concrete jacket (CJ) material, lenght (L_s) and diameter (ϕ_{SR}) of the shaped rebar part in plastic hinge. Transversal reinforcement in plastic hinge, number (n_e) of the external C-FRP wrapping layers [mm]

Pier	CJ	Shaped Rebar part		Trans. Reinf.	C-FRP layer
		L_s	ϕ_{SR}		n_e
P-1	SCC	-	-		1
P-3	SCC	-	-	ϕ4/60	2
R-1	SCC	250	15		1
R-3	UHPFRC	250	15	No	No



Note: concrete jacket (CJ) types: self-compacting concrete (SCC); Ultra-High performance fibre reinforced concrete (UHPFRC) developed at Fuzhou University Lab.

The specimens P-1 and P-3 were severely damaged at plastic hinge zone after cyclic tests. These specimens were repaired and retrofitted (Table III) and labelled as R-1 and R-3 respectively.

The specimen R-1 was repaired by means of the previous repair and retrofitting solution (Figure 1) using 14 longitudinal shaped rebar parts (one for each longitudinal rebar), new stirrups, a new SCC CJ and an C-FRP wrapping with one layer (Table III).

Differently, the specimen R-3 was repaired by means of the upgraded solution using 14 longitudinal shaped rebar parts and an UHPFRC CJ without new stirrups and external C-FRP wrapping (Figure 3). The UHPFRC with steel fibre content equal to 2% was selected to build the CJ jacket. In fact, the UHPFRC CJ shear strength contribution ($V_{Rd,UHPFRC}$) using 2% of steel fibre content on the base of the CNR-204/2006 4.2 formulation [29] is equal to 149.3 kN (Table II). The total pier specimen shear strength ($V_{Rd,tot}$, Table II) obtained adding the CJ contribution ($V_{Rd,UHPFRC}$, Table II) to the original pier specimen core contribution ($V_{Rd,OC}$, Table II) is greater than the design shear action of about 196.3 kN.

This design shear action was evaluated on the base of the P-3 undamaged specimen experimental test. The new longitudinal shaped rebar parts, which were used for damaged rebar substitution for R-1 and R-3 had the same shaped rebar part length (L_s) and diameter reduction (ϕ_{SR}) (Table III).

5 Experimental cyclic tests on repaired and retrofitted pier specimens

Some cyclic tests were carried out on the repaired and retrofitted pier specimens R-1 and R-3 (Table III) to evaluate experimentally the effectiveness of the proposed repair operations. A constant vertical load of 266 kN (deck weight) was applied on the top of the specimens during the tests and then the same horizontal displacements history (Figure 5) was applied on the top pier specimens. This vertical ad and this displacement history (Figure 4) are the same used in case of the undamaged control specimens P-1 and P-3.

The displacement history is representative of the resulting displacement history on the central bridge pier (Figure 2) when the bridge in Figure 2 is subjected at the seismic action first equal to Tolmezzo (PD1) and then equal to Tolmezzo scaled to double (PD2) accelerograms [11].

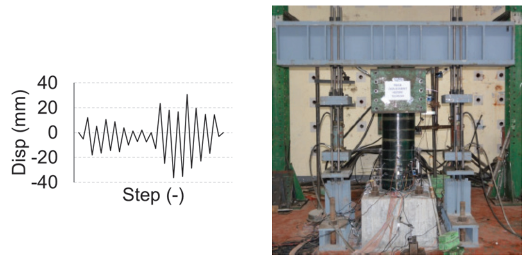


Figure 4 Cyclic tests on 1:6 pier specimens (P1, P3, R1, R3): displacements histories applied on the pier specimens during cyclic tests; cyclic test setup at Fuzhou University Lab

The force *vs.* displacement cyclic curves of the specimens R-1 and R-3 (dashed black line, Figure 5) and the ones of the retrofitted specimens P-1 and P-3 (continuous black line, Figure 5) are compared in Figure 5.

It is seen that, each repaired specimen thanks to the shaped rebar parts, shown a very good cyclic behaviour: the force- displacement cycles are wide and stable and so the proper seismic energy dissipation is guaranteed. Furthermore, the specimens did not show premature shear ruptures in accordance with the capacity design criteria.

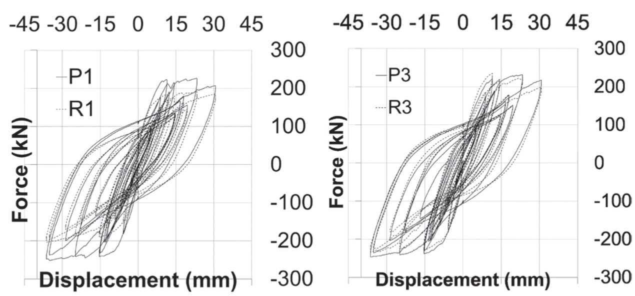


Figure 5 Cyclic tests on 1:6 pier specimens: force *vs.* displacement curves for the repaired and retrofitted specimen R-1 and R-3 (dash black lines) and for the retrofitted specimens P-1 and P-3 (continuous black lines)

The specimen R-1 shows a maximum reaction force smaller than the one of the P-1 specimen. It is expected as the longitudinal shaped rebar part in R-1 has a reduced diameter respect to the one of the specimen P-1 (Table III): it is inevitable that the maximum resisting moment of the section and the corresponding maximum reaction force is smaller.

The same reaction force reduction could be expected in case of R-3 specimens, as the longitudinal shaped rebar reduction is the same (Table III), but this specimen showed a reaction force very similar to the one of the retrofitted specimen P-3 without reduced longitudinal rebar diameter. This value of the R-3 reaction force could be due to the high strength of the UHPFRC that reduce the compressed section zone and so increase the inner section arm.

Damage at the pier specimens base are shown in Figure 6 for specimens R-1 and R-3. Some horizontal cracks appeared at the pier base of the specimen R-1 (Figure 6a) and R-3 (Figure 6b) in correspondence of the base sections where the shaped rebars are placed. The upgraded rebar connection system is efficient: no connection ruptures were observed and plastic deformation focuses along the shaped rebar parts just above the rebar connection as it is evident by concrete cracking on pier surface.

a) b)

Figure 6 Damage at the pier base of the repaired and retrofitted pier specimens R-1 (a) and R-3 (b) after the cyclic tests at the Fuzhou University Lab

6 Conclusions

Some upgrades of the repair and retrofitting techniques tested successfully in [11] are presented and applied on some 1:6 scaled damaged RC bridge pier specimens. The upgraded techniques are simpler than the previous ones and permit time and cost saving by using an UHPFRC concrete jacket. Cyclic tests were carried out on two pier specimens (P-1 and P-3) retrofitted by C-FRP wrapping to damage them. The specimens R-1 was repaired by the previous techniques and the specimen R-3 was repaired by the upgraded techniques (Table III) to be tested by cyclic tests applying the same loads and displacement histories used for the specimens P-1 and P-3. The comparisons among the experimental cyclic test results on the repaired and retrofitted specimens R-1 and R-3 and on the retrofitted specimens P-1 and P-3 show:

- The rebar connection system is simple to realize in situ and efficient as no connection ruptures were observed at the end of the tests.
- The intervention on R-1 cannot restore completely the original maximum reaction force of the pier P-1 as the new shaped rebar parts have a reduced diameter with respect to the original ones. However, the shaped rebar and the C-FRP wrapping increase the ductility and the energy dissipation capacity of the pier and so the design force may be reduced.
- The intervention on R-3 can restore the original maximum reaction force of the pier P-3 by means of the high compressive strength of the UHPFRC. The concrete high strength maybe increases the section inner lever arm and the section resisting moment and the corresponding reaction force results greater.
- The UHPFRC exhibits almost the maximum compression strength after 6 days and provides the shear strength improvement: a bridge can be repaired and retrofitted in short time with cost saving. Existing bridges are usually designed without considering the effects of the nonsynchronous actions but this design practice can be unsafe. The repair intervention can be an occasion to improve also the bridge response in case of asynchronous actions [32]-[35].

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