SEISMIC DAMAGED CHINESE RC BRIDGES REPAIRED AND RETROFITTED BY RAPID INTERVENTION TO IMPROVE PLASTIC DISSIPATION AND SHEAR STRENGTH

D. Lavorato(1), A.V. Bergami(2), C. Nuti(3)(7), B. Briseghella(4), A. M. Tarantino(5), S. Santini(6), Y. Huang(8), J. Xue(9)

(1) Researcher, University of Roma Tre, davide.lavorato@uniroma3.it
(2) Research fellow, University of Roma Tre, alessandro.bergami@uniroma3.it
(3) Full professor, University of Roma Tre, camillo.nuti@uniroma3.it
(4) Full professor, College of Civil Engineering of Fuzhou University, Fuzhou, China bbrise@gmail.com
(5) Full professor, Department of Engineering, University of Modena and Reggio, Italy, angelomarcello.tarantino@unimore.it
(6) Professor, University of Roma Tre, silvia.santini@uniroma3.it
(7) Visiting professor, College of civil engineering at Fuzhou University
(8) Assistant professors, College of Civil Engineering, Fuzhou University, China, yufanhuang@fzu.edu.cn
(9) Assistant professors, College of Civil Engineering, Fuzhou University, China, junqing.xue@foxmail.com

Abstract

In this paper, Chinese rc (reinforced concrete) bridges piers damaged after a strong earthquake, were repaired and retrofitted by means of some innovative interventions which guarantee the proper plastic dissipation in plastic hinge only and the shear strength improvement according to capacity design criteria. In particular, the repair and retrofitting techniques proposed and tested with very good results during previous experimental researches on Italian [4] or Chinese bridges [5], which were designed without proper seismic details (i.e. very modest shear strength), are upgraded. The upgrades consist in: new shaped rebar parts to substitute the damaged rebar parts, new strong connection systems to connect the new rebar parts to the undamaged original rebar parts and new concrete jacket built by means of Ultra High performance concrete (UHPC) with fibers which replace the damaged concrete parts and can guarantee the necessary pier shear strength improvement. The new shaped rebar parts are designed to assure the plastic dissipation along the new rebar parts only. The rebar connection systems are realized by strong steel couplers and welding chords to simplify the connection in situ. The concrete jacket was built by UHPC considering different fiber contents (1, 2 or 3%). The experimental results about these materials confirm that a concrete jacket with fibers can provide the necessary shear strength according to CNR-DT 204/2006 formulations [21]. Some rc pier specimens (scale 1:6) were repaired and retrofitted by means of the proposed interventions with and without new stirrups in the repaired zone and external wrapping (CFRP or steel). Cyclic tests will be carried out on these scaled specimens at Fuzhou University SIBERC lab (China) to evaluate the effectiveness of the proposed technique. In particular, the experimental tests on the pier specimens repaired by using the UHPC jacket with fiber without new stirrups and external wrapping could confirm if the concrete jacket only can assure the necessary shear strength increment to obtain time and cost saving.

Keywords: Fiber reinforced concrete, shaped rebar, c-frp, steel wrapping, repair, retrofitting

1. Introduction

The time necessary to re-open a bridge damaged after a strong earthquake, is a key point about the selection of the proper repair and retrofitting interventions on this bridge. In fact, the bridges are usually strategic structures and their quick opening for the emergency response is much important. Different solutions were presented in literature to execute rapid repair interventions on rc columns or piers ([13], [14], [15]). In this paper, a new rapid repair solution, which improves the repair and retrofitting interventions proposed and tested successfully by means of PSD (pseudo-dynamic) tests on seismic damaged Italian bridges piers at the Department of Architecture of University of Roma Tre lab [4] or by cyclic tests on Chinese piers at SIBERC lab (Sustainable and Innovative Bridges Engineering Research Center of the Fujian Province University) at University of Fuzhou [5], is presented. The damaged parts of the rc pier are repaired and retrofitted (plastic hinge, Fig. 2) by means of: the substitution of damaged rebar parts using new shaped rebar parts, the construction of a concrete jacket without modifying the pier dimension (Fig. 2b) to restore the damaged concrete and new stirrups in the repaired damaged zone and/or an external C-FRP wrapping to increase the pier shear strength and ductility. The substitution of the damaged stirrups was limited to the use of a minimum stirrups content to permit the new concrete casting. The effectiveness of the shaped rebar was tested successfully on pier specimens (scale 1:6) by cyclic test at Fuzhou University lab [5]. In this paper, some new technique improvements are presented about the rebar substitution, the concrete restoration and the shear and ductility improvements to simplify the interventions reducing time and cost. In particular, the shaped rebar connection with the original rebar was realized by means of strong steel coupler using symmetric side welding connections. This system is simple to perform in situ on vertical longitudinal rebar in modest space (removed concrete) and guarantees a rebar connection along the same axis avoiding local bending action on the connection. Another improvement is about the use of a fiber concrete jacket to restore the damaged concrete without modifying the pier dimension. This concrete was designed to guarantee also the shear strength improvement without using transversal steel reinforcement and external C-FRP wrapping to obtain time and cost saving. In fact, different research studies demonstrated how concrete with fibers can give an important contribution to the ductility and shear strength capacity of rc beam and columns ([18], [17], [16]). In particular, Ultra-High Performance Concrete (UHPC) with steel fibers were designed properly at Fuzhou University Lab considering different fiber content (1 %, 2 % and 3%) and tested by compression and flexural tests. Some pier specimens in scale 1:6 were repaired with and without new steel stirrups and external wrapping (CFRP or Steel) in plastic hinge only using fiber concrete to evaluate the feasibility and the effectiveness of the interventions. The use of steel tissue was considered as alternative to the C-FRP wrapping to increase shear strength and ductility of the pier specimen with external wrapping. The shear strength due to the UHPC concrete jacket was evaluated by CNR-DT 204/2006 model using the concrete experimental test results.

2. The rc bridge before the repair

An irregular rc bridge (Fig. 1) was designed according the Chinese codes [1], [2], [3]. The transversal pier 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 (a problem for many existing rc bridges). The rc bridge geometries are shown in Fig. 1 whereas the design details for the steel reinforcement of the bridge piers are described in [5]. The center pier of this bridge, the most stressed pier during seismic action application, was severely damaged at the pier base in plastic hinge and damage consisted in: concrete spalling and crushing, transversal stirrups rupture, longitudinal rebar buckling and ruptures and evident shear cracking.

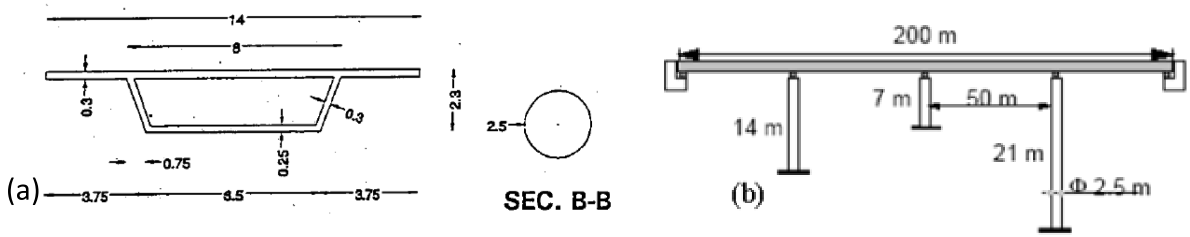


Fig. 1 Chinese irregular rc bridge geometries: a) deck and pier sections b) irregular pier configuration.

3. Rapid repair and retrofitting intervention on rc bridge piers

A rapid repair and retrofitting solution was applied on the most stressed and damaged rc bridge pier in plastic hinge only [4]. This technique consisted of: damaged concrete and rebar parts removal along the entire pier surface in plastic hinge (Fig. 2a), substitution of the damaged rebar parts by new rebar parts, damaged concrete restoration by self-compacting concrete (Fig. 2b) and shear strength and ductility improvements by the application of an external C-FRP wrapping (Fig. 2c).

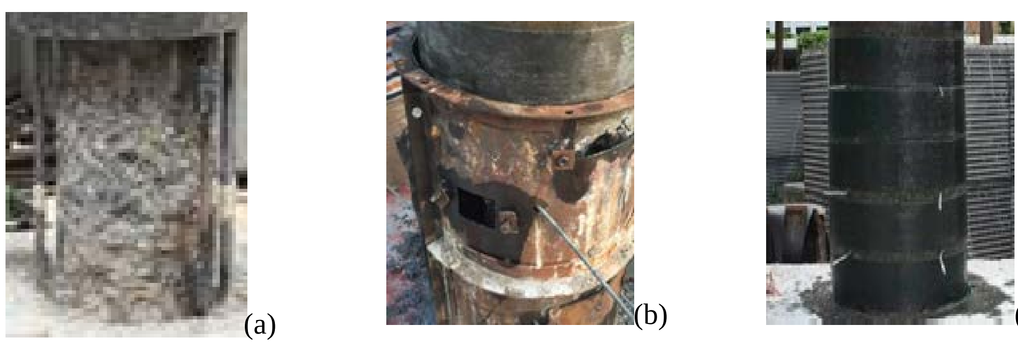


Fig. 2 Rapid repair and seismic retrofitting solution for damaged rc pier [4][5]: a) damaged concrete and rebar parts removal; b) concrete restoration; c) seismic retrofitting by C-FRP wrapping.

The previous research campaign on Italian and Eurocode EC8 bridges assures the feasibility and the effectiveness of the interventions to restore the pier strength [4]. However, high local plastic deformation was observed in some rebar welding connections between the original undamaged rebar and the new rebar parts. For that reason, a new research campaign in collaboration with the Fuzhou University [5] tested with success shaped rebar systems to replace the damaged rebar parts. The shape of this new rebar permitted a proper plastic distribution along the new rebar parts only and it was tested successfully on Chinese repaired pier specimens (scale 1:6) by cyclic tests at Fuzhou University [5]. In this paper new improvements of rebar substitution and concrete restoration are presented to simplify the intervention. In particular, the connection in situ between new and original rebar parts during the rebar substitution is analyzed and strong welding connection systems by steel coupler and two symmetric strong side welding chords were designed to connect the new shaped rebar parts with the original undamaged rebar parts in the pier. This connection system is simple to perform in situ on vertical longitudinal rebar in modest space (removed concrete). The new and original rebar parts are connected along the same longitudinal axis avoiding local rotation and plastic deformation as observed in [4].

A concrete jacket (CJ) realized by means of an UHFRC (Ultra-High Fiber Reinforced Concrete) can restore the removed concrete cover and the external parts of the core and increases the insufficient original shear strength and ductility without using new stirrups and/or external wrapping reducing time and cost of the interventions. The pier geometries are not modified as the CJ substitutes the removed concrete parts only and the pier appearance does not change after the repair. The UHFRC was designed to have: great pass-ability during the casting in the very modest space with steel reinforcement (as a fresh Self compacting concrete), the development of the maximum compressive strength after a few days for a rapid opening of the bridge, the necessary shear strength by steel fibers contribution to reduce as possible as the steel stirrups and external wrapping and great durability as the cover dimension are not changed. In particular, three different UHFRC mix designs were considered (Table 1). Each mix design includes: a super-plasticizer, silica fume and fine sand to guarantee high mobility and pass ability similar to the ones of a self-compacting concrete (SCC). In this way, the casting results simple, rapid and uniform also in modest space (cover and external part of pier core).

Table 1 Mix designs of the UHFRC developed at Fuzhou University lab to restore the damaged concrete parts of the Chinese pier specimens in scale 1:6.

Steel Fiber content	water/ cement (W/B)	Cement (C)	Silica fume/ cement (SF/C)	Sand/ cement (S/C)	Superplasticizer/ cement (Su/C)
1 %					
2 %	0.26	1	0.3	1.20	0.025
3 %					

Steel fibers were added to the UHFRC mix design to increase the durability and guarantee the necessary shear strength of the CJ without steel stirrups and external C-FRP wrapping. These fibers have an ultimate tensile strength of 2000 MPa and modulus of Elasticity of 200 GPa. The mechanical performance of the UHFRC depends on the aspect ratio and the volume fraction of the fibers. The selected fibers are straight and smooth with length l_f= 13 mm and equivalent diameter d_f= 0.20 mm. Different percentage of fibers (V_f) were considered 1 %, 2 % and 3 % (volume of steel fibers 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. UHFRC specimens were built at Fuzhou University lab to execute compression and flexion tests. In particular, the compression tests were executed on three UHFRC cube specimens (100 x 100 x 100 mm) for each fiber percentage after 6 days to evaluate the cylindrical compression strength (f_{cm6}) developed by the specimens in short time (Table 2). The mean value of the cylindrical compressive strength after 28 (f_{cm28}) days was also calculated according to Fib model code 2010 (Table 2). 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 UHFRC is a good material for a rapid concrete restoration. Finally, flexion tests were carried out on three prismatic specimens for each steel fiber 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 (feq2) corresponding to crack opening of 1.8 mm in agreement with the CNR-DT 204/2006 [21] (Table 2). The characteristic value of the ultimate tensile residual strength (f_{Ftuk}) was also obtained according to CNR-DT 204/2006.

Table 2 UHFRC mechanical properties: percentage of fibers 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}).

V_f	f_{cm6} [MPa]	f_{cm28} [MPa]	f_{eq2} [MPa]	f_{Ftuk} [MPa]
1 %	84	99	12.3	4.1
2 %	91	108	15.1	5.0
3 %	97	114	16.5	5.5

4. Repaired scaled 1:6 pier specimens

The most stressed pier of the Chinese irregular rc bridge in Fig. 1 during the seismic action application is the center one [5] and the main damage of the bridge focuses on this pier. For that reason, some 1:6 scaled pier specimens representative of this pier, were designed. Their geometries and reinforcement details were obtained using scale factors which guarantee similitude criteria between pier model and pier prototype in terms of global quantities (flexural and shear strength and confinement effect; [4][5]). The perfect geometrical scaling of materials is not necessary allowing the use of ordinary concrete mixing and commercial steel rebars simplifying the construction of the pier specimens and the tests on concrete and steel rebars specimens. Nine rc pier specimens in scale 1:6 were damaged after some cyclic tests and then were repaired with different types of repair and retrofitting interventions in plastic hinge zone only (Table 3). These pier specimens had diameter equal to 420 mm and height 1170 mm (Table 3), longitudinal reinforcement composed by 14 rebars with diameter of 18 mm and transversal reinforcement out of the plastic hinge with space of 60 mm and diameter of 4 mm. The repaired specimens have different reinforcement configuration in plastic hinge zone. In particular, there are pier specimens with and without stirrups and external wrapping. The repaired specimens have insufficient shear strength and the ductility and different retrofitting solution were evaluated.

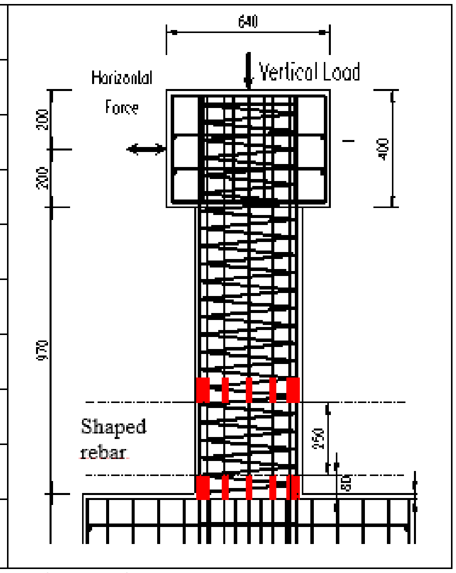
The pier specimens (5, 7 and 8) without stirrups and external confinement will be tested to evaluate the shear strength contribution of the fiber concrete jacket CJ only. Different concrete mix designs were developed to restore the specimen damaged concrete: an UHFRC with steel fiber developed and tested at Fuzhou University (it was described above) and a High Fiber Reinforced Concrete (HFRC-I) developed at Roma Tre University Lab (Italy). The HFRC-I was realized using 2 or 3 % of polymeric fibers (by ISTRICE) and a commercial repair mortar (commercial name Geolite MAGMA by Kerakoll) very fluid at fresh state with optimum compressive strength after 6 days. The HFRC-I will be not described here in details.

The pier specimens with stirrups and external confinement (1, 2, 3, 4, 6 and 9) will be tested to compare their responses with the ones of the specimens without stirrups and external confinement. An external C-FRP wrapping with one layer only (ne=1) was selected for this first part of the research campaign. The external wrapping provides ductility and shear strength enhancements. The C-FRP mechanical properties are: thickness of 0.167mm, elastic modulus 242GPa and maximum deformation of 0.005 in accordance with CNR DT 200/2013 Italian guideline. External steel sheet wrapping (by Kerakoll) will be used as alternative to the C-FRP wrapping during the second part of the ongoing research campaign to increase the shear strength and the ductility. This reinforcement combines excellent mechanical and installation properties with high durability thanks to galvanization of the individual wires and is extremely easy to handle and shape. The steel sheets represent an interesting alternative with respect to C-FRP sheet. In fact, they can be anchored and fastened on concrete elements by simple metal plates without taking particular precautions about sheet-anchorage system interactions as in case of C-FRP sheet. Furthermore, steel can be tensioned to add active confinement actions.

The new rebar parts, which were used for longitudinal damaged rebar substitution for each specimen, had the same length (L_s) and diameter reduction (Φ_{SR}) of the shaped part [5] with the exception of the control specimen 9.

Table 3 Repair and retrofitting details for Chinese pier specimens (scaled 1:6): type of concrete jacket (CJ), lenght of the new shaped rebar (Ls), diameter of the new shaped rebar (ΦSR), diameter of the sirrups (Φs), spacing of the stirrups (s), number of the external C-FRP wrapping layers (ne). [mm]

label	CJ	Ls	ΦSR	Φs	s	ne
1	SCC	250	15	4	60	1
2	SCC	125		4	60	1
3	SCC	250		4	60	1
4	HFRC-I	250		4	60	1
5	HFRC-I	250		-	-	-
6	UHFRC	250		4	60	1
7	UHFRC	250		-	-	-
8	UHFRC	250		-	-	-
9	SCC	250	18	4	60	-



Note: concrete jacket (CJ) types: self compacting concrete (SCC); High performance fiber reinforced concrete developed at Roma Tre Lab (HFRC-I), Ultra High performance fiber reinforced concrete developed at Fuzhou University (UHFRC).

5. Shear strength of repaired pier specimens without steel stirrups and external c-frp wrapping

The shear strength improvement was guaranteed by a fiber reinforced concrete jacket in case of repaired specimens 5, 7 and 8 (Table 3). The design shear action is the maximum experimental one (V_e equal to about 198 kN, Fig. 3) measured on the retrofitted and repaired pier specimens P26 and P36 during the previous cyclic tests at Fuzhou University Lab [5]. These two pier specimens were very similar and the shear strength improvement provided by stirrups and external C-FRP wrapping was calculated according capacity design rules.

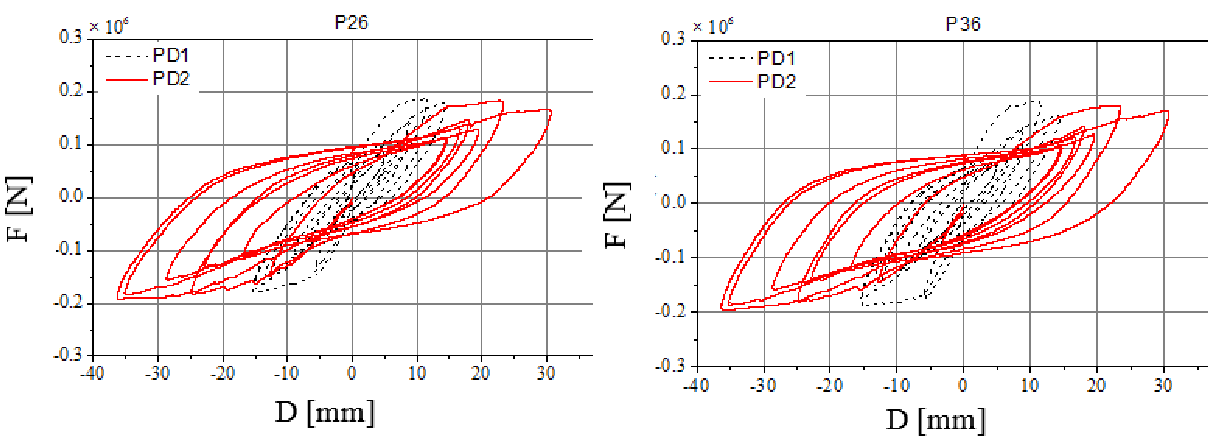


Fig. 3 Force (F) VS displacement (D) histories recorded during the cyclic tests on Chinese repaired and retrofitted rc pier specimens P23 and P36 with shaped rebar, stirrups and C-FRP wrapping (scale 1:6). Displacements history obtained by PSD tests (Lavorato 2015a, b) using Tolmezzo (PD1, dot black line) or Tolmezzo scaled to double (PD2, red line) accelerograms.

The shear strength of the repaired specimens by fiber CJ was calculated as the sum of two contributions: the shear strength of the CJ ($V_{Rd,\ UHFRC}$) and the one of the original pier specimen core ($V_{Rd,OC}$) contributions. The CJ shear strength contribution ($V_{Rd,\ UHFRC}$) was calculated according to CNR-204/2006 formulation (equ.1) substituting the shear area A_{HS} to b_{wd}. The shear area of the CJ (A_{HS}) was calculated according to Priestley [10] assuming the crown thickness equal to 100 mm (the removed concrete thickness).

$$V_{Rd,UHFRC}=\left[\frac{0.18}{\gamma_c}\cdot k\cdot(100\,\rho_1\cdot(1+7.5\cdot\frac{f_{Ftuk}}{f_{ctk}})\cdot f_{ck})^{1/3}+0.15\sigma_{cp}\right]\cdot b_w\cdot d \tag{1}$$

In equation 1, γ_c is the partial safety factor for the concrete without fibers, ρ_l is the reinforcement ratio for longitudinal reinforcement, f_{ck} is the cylindrical characteristic compression strength of the concrete, k is a factor that takes into account the size effect, σ_p is the average stress acting on the concrete cross section, f_{ctk} is the characteristic tensile strength of the concrete matrix and f_{Ftuk} is the characteristic value of the ultimate residual tensile strength. The concrete matrix tensile and compression strengths were obtained by the experimental tests on concrete specimens with different fiber contents (1 %, 2 % or 3 %) performed at Fuzhou University.

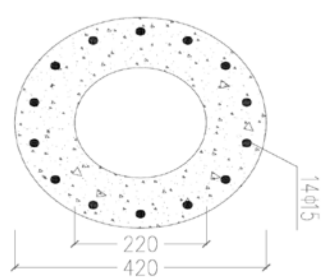
The shear strength contribution of the original specimen concrete core ($V_{Rd,OC}$) was calculated according the equ. 2 proposed by Sezen 2004 for older columns having less transverse reinforcement:

$$V_{Rd,OC}=\frac{0.5\sqrt{f'_c}}{a/d}\sqrt{1+\frac{P}{0.5\sqrt{f'_c}A_g}}\,0.8A_g \tag{2}$$

where P is the axial load, A_g the gross section area, f'_c the compressive strength of the concrete and a/d is the rc element aspect ratio. The values of $V_{Rd,UHFRC}$, $V_{Rd,OC}$ and $V_{Rd,tot}$ for different fiber contents (1 %, 2 % or 3 %) are shown in Table 4. The comparison among the total shear strength ($V_{Rd,tot}$) and the design shear action (V_e) shown that a CJ built by means of a UHFRC with a fiber content of 2 % is sufficient to improve the original shear strength without using stirrups and CFRP jacket. The pier specimens 7 and 8 repaired with a UHFRC fiber concrete jacked using 2% of fiber will be tested at Fuzhou University lab to check experimentally by cyclic tests these numerical results.

Table 4 : Retrofitted and repaired pier specimens by fiber concrete jacket (CJ): fiber content (Vf), shear strength of the CJ (VRd, UHFRC), shear strength of the original pier concrete core (VRd, OC), total shear strength of the repaired specimen (VRd, tot). Concrete jacket (CJ) section scheme.

V_f	$V_{Rd.UHFRC}$ [kN]	$V_{Rd,OC}$ [kN]	$V_{Rd,tot}$ [kN]
1 %	137.1		186.9
2 %	149.3	49.8	199.1
3 %	156.1		205.9



6. Conclusion

This paper presents a rapid repair and retrofitting technique applied on damaged rc bridge pier with insufficient shear strength. The proposed intervention was applied on the damaged concrete and steel reinforcement parts of some rc bridge pier specimens (scale 1:6) in plastic hinge only where the damage was great. The substitution of the damaged rebar parts consisted in the use of new shaped rebar parts connected with the original undamaged rebar parts by steel coupler system. These shaped rebars guarantee the distribution of the plastic deformation along the rebar in plastic hinge only and their effectiveness was tested experimentally during a previous research study [5]. The connection system among the new rebar parts and the original ones was realized using strong steel coupler elements and two symmetric side welding chords. This connection is an upgrade of the rebar substitution intervention that results simple to realize in situ on vertical longitudinal rebars in modest space. It guarantees that the connected rebars have the same rebar axis avoiding local rotation of the connection and so local bending actions. In this way, the great local plastic demand observed in some connection during the previous tests on repaired pier [4] can be avoided.

Another intervention upgrade is about the damaged concrete restoration by using concrete jacket (CJ) built with Ultra-High Performance Concrete (UHPC) with steel fibers. These CJ can guarantee the necessary shear strength without using steel stirrups and external wrapping (C-FRP or steel). A UHPC was designed and tested by compression and flexion tests on concrete specimens considering different percentage of steel fibers (1 %, 2 % and 3 %). The concrete jacket (CJ) built with this material to restore the damaged concrete parts guarantees:

- The bridge pier can be repaired in short time as this UHPC exhibits almost the maximum compression strength after 6 days
- An improvement of the pier durability without modifying the original cover dimension as the fiber restrains the concrete crack opening
- The improvement of the pier shear strength by means of the shear strength contribution of the concrete jacket with fibers also without stirrups and external wrapping. In this way, time and cost of the repair intervention are reduced.

The shear strength of the CJ ($V_{Rd.UHFRC}$) was calculated by CNR-DT 204/2006 equations relative to fiber concrete elements without stirrups, and compared with the experimental maximum shear action (V_e) measured during the previous cyclic tests performed on repaired and retrofitted pier specimens at Fuzhou University lab[5]. This numerical comparison shows that a CJ built with UHFRC using 2 % or 3% of steel fibers can provide the necessary shear strength to sustain the shear action considering also the contribution of the original core ($V_{Rd,\ OC}$). Finally, the feasibility of the proposed repair intervention was proved building some rc pier specimens in scale 1:6 with and without steel stirrups and external wrapping. Cyclic test on these specimens will be performed at Fuzhou University to evaluate the effectiveness of the proposed intervention.

7. Acknowledgements

The authors gratefully acknowledge the funding by "The Laboratories University Network of seismic engineering" (ReLUIS) thanks to the research project ReLUIS/DPC 2015. This research is also supported by the Structural Laboratory College of Civil Engineering (Fuzhou University) and the International Joint-Lab (Universities of Roma Tre and Fuzhou). Authors thank Prof. Tao Ji for the assistance in the development of the UHPRC, Kerakoll S.p.A. and ISTRICE (Fili&Forme Srl) for having provided the materials for the development of the HFRC-I at Roma Tre University.

8. References

[1] JTG D60-2004 Chinese code. General code for design of highway bridges and culverts

[2] JTG/T B02-01-2008 Chinese code. Guidelines for seismic design of highway bridges

[3] JTG D62-2004 Chinese code. Code for design of highway reinforced concrete and prestressed concrete bridge and culverts.

[4] Lavorato D., Nuti C. (2015a). Pseudo-dynamic tests on rc bridges repaired and retrofitted after seismic damage. Engineering Structures - Journal - Elsevier.

[5] Lavorato D., Nuti C., Briseghella B., Santini S., Xue J. (2015b) A repair and retrofitting intervention to improve plastic dissipation and shear strength of Chinese rc bridges. IABSE Conference Geneva, Switzerland.

[6] Sabnis GM, Shroff AC, Kahn LF. (1996) Seismic Rehabilitation of Concrete Structures. Farmington Hills, Mich.: American Concrete Institute.

[7] Teran A., Ruiz J. RC. Jacketing of Existing Structures (1992). Proceedings 10th World Conference of Earthquake Engineering, Balkema, Madrid, Spain.

[8] Vandoros KG., Dritsos SE. (2008) Concrete jacket construction detail effectiveness when strengthening RC columns. Construction and Building Materials.

[9] Georgopoulos T., Dritsos SE. (1994) A steel jacketing technique for strengthening RC columns. Proceedings of the 10th European Conference on Earthquake Engineering, Vienna, Austria.

[10] Priestley MJN., Seible F., Xiao Y., Verma R. (1994) Steel jacket retrofitting of reinforced concrete bridge columns for enhanced shear strength. Part 2: test results and comparison with theory. ACI Materials Journal.

[11] Triantafillou TC. (2001) Seismic retrofitting of structures with fiber-reinforced polymers. Progress in Structural Engineering and Materials. John Wiley & Sons, Ltd. Volume 3, Issue 1.

[12] Cheng L., Karbhari VM. (2006) New bridge systems using FRP composites and concrete: a state-of-the-art review. Progress in Structural Engineering and Materials. John Wiley & Sons, Ltd.

[13] Sun Z., Wang D., Du X., SI B. (2011) Rapid repair of severely earthquake-damaged bridge piers with flexural-shear failure mode Earthquake Engineering and Engineering Vibration.

[14] He R, Sneed LH, Belarbi A. (2013) Rapid Repair of Severely Damaged RC Columns with Different Damage Conditions: An Experimental Study International Journal of Concrete Structures and Materials.

[15] Cheng CT, Yang JC, Yeh YK, Chen SE. (2003) Seismic performance of repaired hollow-bridge piers. Construction and Building Materials, Elsevier Science Ltd.

[16] Le Huang, Lihua Xu, Yin Chi, Haoran Xu (2015) Experimental investigation on the seismic performance of steel–polypropylene hybrid fiber reinforced concrete columns. Construction and Building Materials.

[17] Foster S. and Attard M. (2001) Strength and Ductility of Fiber-Reinforced High-Strength Concrete Columns. J. Struct. Eng. (ASCE)

[18] Mansur M., Ong K., and Paramasivam P. (1986) Shear Strength of Fibrous Concrete Beams without Stirrups. J. Struct. Eng (ASCE).

[19] Albanesi T., Lavorato D., Nuti C., Santini S. (2009) Experimental program for pseudo-dynamic tests on repaired and retrofitted bridge piers. European Journal of Environmental and Civil Engineering, Paris: Lavoisier.

[20] Tao Ji, Cai-Yi Chen, Yi-Zhou Zhuang, Jian-Feng Chen (2013). A mix proportion design method of manufactured sand concrete based on minimum paste theory, Construction and Building Materials.

[21] CNR-DT 204/2006 Guide for the Design and Construction of Fiber-Reinforced Concrete Structures; Italian NATIONAL RESEARCH COUNCIL (CNR).

[22] CNR DT 200/2013 Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Existing Structures; Italian NATIONAL RESEARCH COUNCIL (CNR).

[23] Fib Model Code for Concrete Structures 2010. The International Federation for Structural Concrete (fib).

[24] Ranzo G., Priestley M J N (2000) Seismic performance of large rc circular hollow columns 12WCEE 2000 12th World Conference on Earthquake Engineering, Auckland, New Zealand.

[25] Sezen, H. and Moehle, J.P. (2004), “Shear strength model for lightly reinforced concrete columns,” J. Struct. Eng.