# FRP reinforcement to retrofit bridge pier after repair: experimental test results

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## Abstract

Reinforced concrete (RC) bridge piers damaged after a strong earthquake are repaired. The damaged concrete and the steel reinforcement parts are replaced by rebar segments connected to the existing rebar parts by welding connections and by a self-compacting concrete jacket respectively. A modest transverse steel reinforcement, not sufficient to improve the seismic pier capacity, is used to simplifies the concrete cast in modest volumes. After the repair, a carbon fiber reinforced polymer (Carbon FRP) reinforcement is applied to enhance the pier ductility and the shear strength. Three RC circular columns, representative of piers, were repaired and reinforced by the proposed strategy to be tested in lab applying a deformation history due to a strong earthquake. The piers were able to sustain very strong seismic demand and therefore the proposed repair and retrofitting interventions are effective. The strain distribution of the Carbon FRP reinforcement was measured and discussed to increase the very modest database presented in the literature.

**Keywords:** Carbon FRP, experimental strain, bridge, repair.

## Introduction

Reinforced Concrete (RC) bridge piers can present great damage due to corrosion of the steel reinforcement, a common problem for the bridges that have reached the end of their service life, and worsened by unproper maintenance interventions, and/or due to other factors, as the seismic action (Nuti et al. 2020).

This issue requires further efforts to improve the assessment of the structural capacity of the existing structures including corrosion phenomena and to propose alternative repair and retrofitting strategies considering construction problems as well as the out-of-service time acceptable for bridges, which usually are strategic structures. For the construction of new bridges, a valid technical solution is represented by Integral Abutment Bridges (Zordan and Briseghella 2007, Caristo et al. 2018, Fiorentino et al. 2019).

Numerical models, that can simulate the response of structures including the deterioration of steel and concrete due to corrosion (Belletti et al. 2017, Lavorato et al. 2019a, Marano et al. 2017, Pellicciari et al. 2018, Pellicciari et al. 2019), can be valid tools to assess the structural capacity and to choose the proper repair interventions.

There are many repair solutions proposed in literature but usually these techniques are applied to structural elements with modest damage and consist in the restoration of the concrete cover only and the application of external carbon fiber or steel reinforcements. Some authors (Cheng et al. 2003, Cheng et al. 2006, Sun et al. 2011, He et al. 2013, Imperatore et al. 2012a, Imperatore et al. 2012b, Lavorato and Nuti 2015, Lavorato et al. 2015, 2017, 2018a,b, 2019b, Xue et al. 2018) propose to repair also the longitudinal rebars but the substitution of the damaged rebars is necessary not only in case of strong seismic damage but also in many cases for existing structures with evident corrosion of the steel rebars.

In this paper, a new rapid repair solution, which focuses on the substitution of the damaged longitudinal rebar of bridge piers (or columns) is presented. The proposed technique gives practical solutions considering also the construction problems in situ.
This strategy improves the repair and retrofitting solutions 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 (Lavorato and Nuti 2015) or by cyclic tests of Chinese piers at SIBERC lab (Sustainable and Innovative Bridges Engineering Research Center of the Fujian Province University) at University of Fuzhou (Lavorato et al. 2015).
The damaged steel and concrete parts at the bottom of a RC pier (i.e. the plastic hinge) are substituted by new rebar parts, new stirrups and a new self-compacting concrete (SCC) jacket without modifying the pier dimension. Finally, an external Carbon Fiber Reinforced Polymer (CFRP) wrapping is applied to increase the pier shear strength and ductility because a minimum stirrup content is used to simplify the new concrete casting.
The new rebar shape assures the distribution of the plastic strains along the new rebar parts only. The connection in situ between new and original rebar parts is performed by a strong connection system composed by a steel coupler and two symmetric strong fillet welds. This system is simple to realize in situ also on vertical longitudinal rebar in modest space (the removed concrete parts).
The SCC was designed to simplify the casting in modest spaces with steel reinforcement. This concrete develops the maximum compressive strength after a few days and therefore it is possible to minimize the closure time of the bridge.
The new strategy was applied to repair three piers specimens in scale 1:6. The response of one of these specimens is shown in terms of base shear versus top displacement of the specimen and strains of carbon FRP wrapping. The specimen was able to sustain very strong seismic demand and therefore the proposed repair and retrofitting interventions are effective. The strain distribution of the wrapping was measured and discussed to enrich the literature about the topic. The maximum obtained Carbon FRP strain is smaller than the design one used to evaluate by code equations the shear strength contribution.

## Repair and retrofitting procedure

The proposed repair and retrofitting strategy for RC piers consists of: removal of damaged concrete and rebar parts along the entire pier surface of the plastic hinge, substitution of the damaged rebar parts by new turned rebar parts, damaged concrete restoration by SCC concrete jacket and shear strength and ductility improvements by the application of an external carbon FRP wrapping.
The new rebar parts are machined (turned) to have a part of the rebar with a diameter smaller than the one of the original rebars. This reduction ensures the distribution of the steel plastic strains in plastic hinge only.
A strong steel coupler and symmetric fillet weld joints ensure the connection between new and existing rebar parts along the same axis avoiding local bending actions on the connection. This latter is studied to obtain a quick connection in situ of the vertical rebars. It is designed to be strong, and the steel plastic strains of the new rebar parts happen out of the anchorage zone avoiding damage there.
A modest transverse steel reinforcement, not enough to improve the seismic pier capacity, is used to simplify the concrete cast in modest volumes (the removed concrete parts).
The modest transverse steel reinforcement is not able to assure the necessary shear strength and therefore a carbon FRP reinforcement is applied to enhance the pier ductility and the shear strength. This reinforcement gives also a confinement effect that could help the collaboration between new (the restored concrete by the jacket) and the original concrete parts (core column).

## Case of study

The selected case of study is an irregular RC bridge (**Figure 1**) with reinforcement designed according to the Chinese codes (JTG D60-2004, JTG/T B02-01-2008, JTG D62-2004). The RC bridge geometries are shown in **Figure 1** whereas the design details for the steel reinforcement of the bridge piers are described in Lavorato et al. (2015). The study focuses on the central pier of this bridge because it is the most stressed one during a seismic event. The selected seismic excitation is the Tolmezzo earthquake (Italy, 1976) (it will be indicated with the label t1 in the next figures) imposing high accelerations in the natural period range of the bridge. The same earthquake scaled (doubled, i.e. Tolmezzo x 2) is then applied to consider a very strong seismic excitation (it will be indicated with the label t2 in the next figures).

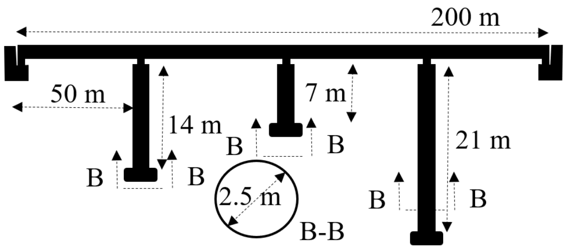



Figure 1. Geometries of the irregular RC bridge chosen as case study

## Specimen repair

The most stressed pier of the irregular RC bridge of **Figure 1** during the seismic action application is the central one (Lavorato et al. 2015) and the main damage of the bridge in concentrated in this pier.
For that reason, three 1:6 scaled specimens representative of this pier were realized. 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; Lavorato and Nuti 2015, Lavorato et al. 2015) starting from the bridge design according to the Chinese code (JTG D60-2004, JTG/T B02-01-2008, JTG D62-2004).
Scaling of materials is not necessary allowing the use of ordinary concrete mixing and commercial steel rebars: this simplifies the construction of the pier specimens and the tests on concrete and steel rebars specimens. The concrete geometries and reinforcement of the three specimens are given in **Figure 2**.
The steel used for the reinforcement has shown yield stress equal to 335MPa (Chinese steel grade HRB335E) whereas the concrete has a compressive cylindrical strength of 20.1MPa (Chinese concrete grade C30).
The pier specimens were severely damaged at the pier base (plastic hinge) applying in the lab the deformation histories depicted in **Figure 3**. These histories were obtained during the pseudo-dynamic tests on the bridge in **Figure 1** after the bridge repair in Lavorato et al. (2015).
Damage survey have shown severe concrete spalling and core crushing, some transversal stirrups ruptures, some longitudinal rebar buckling and ruptures and an evident shear cracking (Lavorato et al. (2015)).
The repair intervention steps are shown in **Figure 2**. The three specimens presented different turned rebars with the geometries given in **Table 1** to investigate the optimum length of the machined part of the new rebar segment: 250 mm equal to the plastic hinge length calculated by the well-known equation by Priestley et al. (1996) or 125 mm a reduction of the previous length that could implicate until to half of quantities of concrete and steel that have to be removed with cost saving. The variation of the machined rebar diameter is practically the same 14mm or 15mm for the three specimens.
The SCC concrete jacket restores the removed concrete parts only without modify the specimen dimension and the covers. This has shown experimental compressive cylindrical strength equal to about 20MPa. The cast of this jacked is simple and rapid and most of the strength of the material is obtained in a few days.
A discontinuous carbon FRP wrapping (three layers) was applied on each specimen to guarantee that the shear strength is surely greater than the flexural strength of the specimens. The space among the wrapping rings was 120mm and the width of the ring was 100mm.
The carbon FRP tissue mechanical properties are thickness of 0.167mm, elastic modulus 242GPa and maximum strain of 1.2% from productor datasheet.

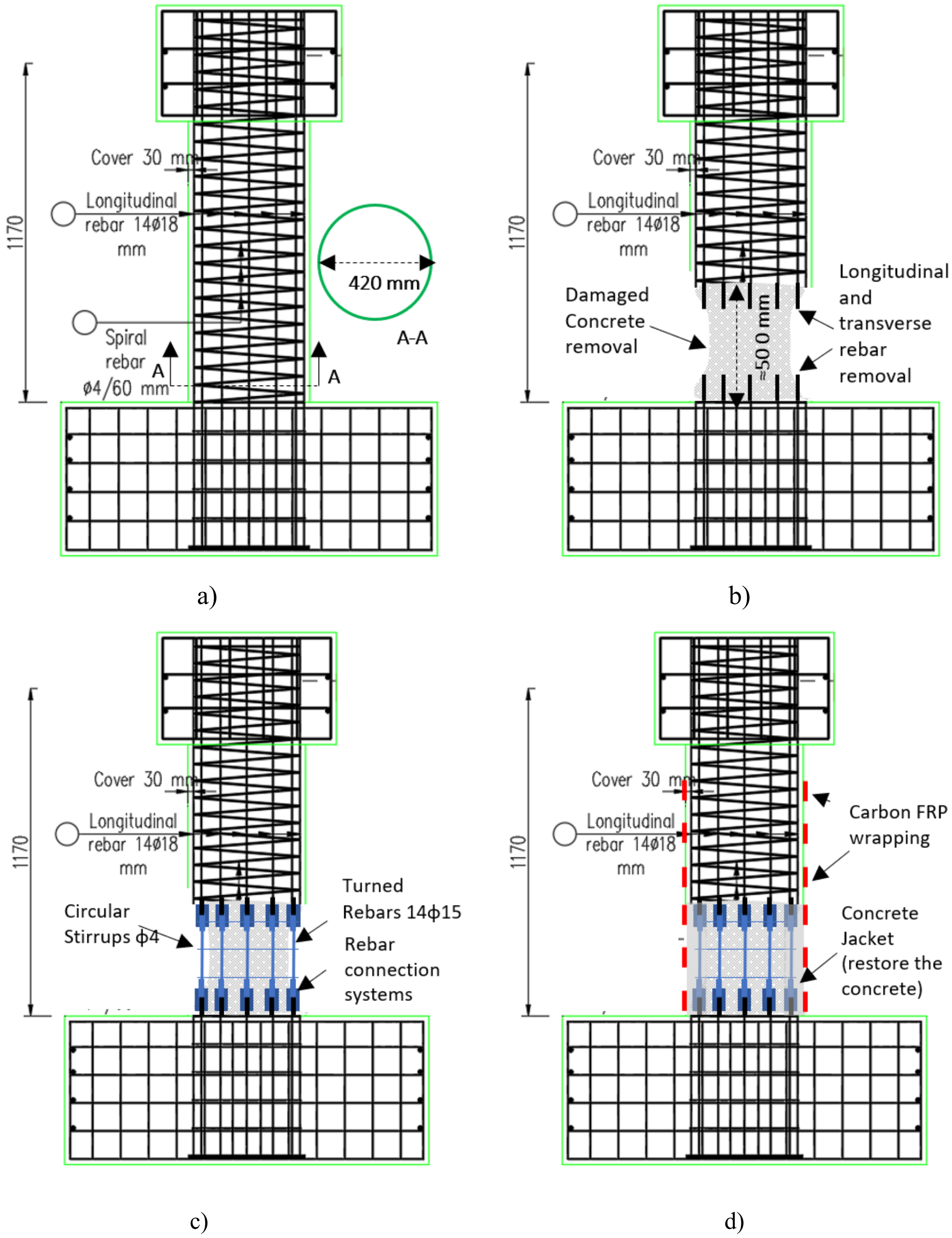



Figure 2 1:6 scaled specimens: a) before the damage; b), c), d) steps of the repair and seismic retrofitting strategies for the damaged specimens [mm]

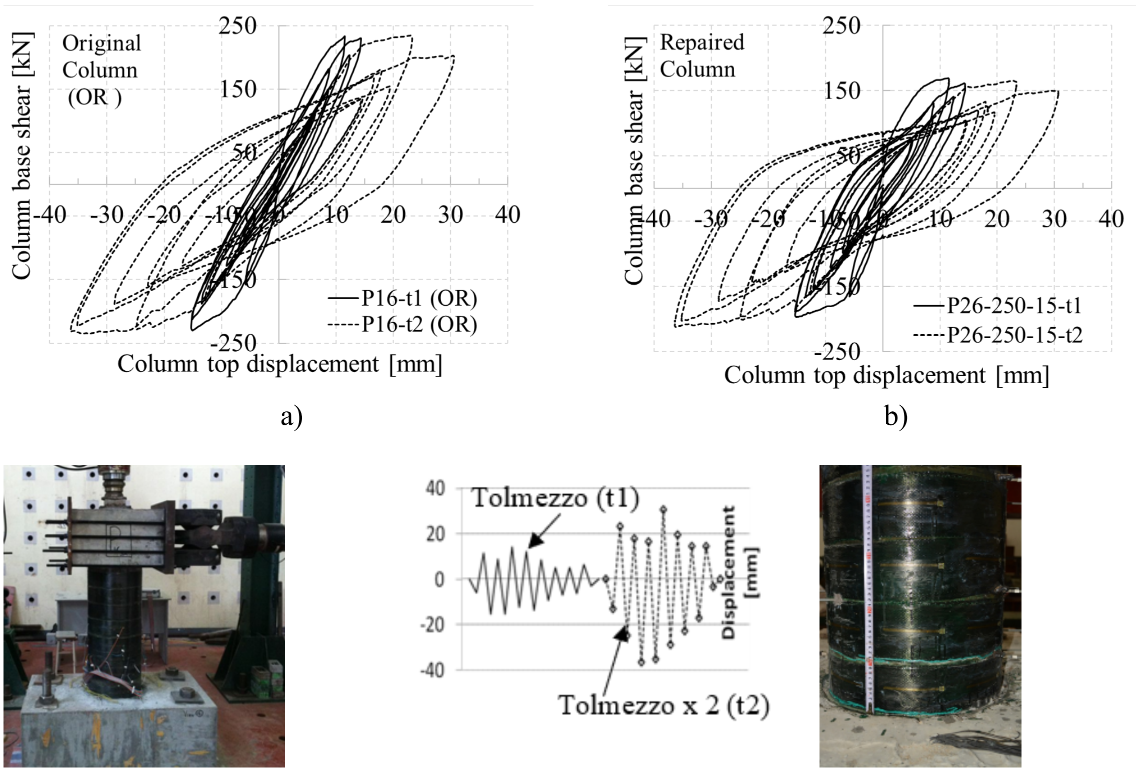
Table 1. Repair and retrofitting interventions details for each 1:6 scaled pier specimen [mm]

| Column | Turned part of the new long. rebar segments | | New circular stirrups | Concrete jacket | Carbon FRP wrapping | Welded joints for the new rebar segments |
|---|---|---|---|---|---|---|
| | length | diameter | bar diameter / space | thickness | layers | |
| **P26-250-15** | 250 | 15 | Φ4/100 | 80 | 3 |  |
| **P36-125-15** | 125 | 15 | Φ4/100 | 80 | 3 | |
| **P46-240-14** | 240 | 14 | Φ4/100 | 80 | 3 | |

# Experimental results

The seismic behavior of the undamaged and the repaired specimens was tested at the Structural Lab of Fuzhou University (China) applying a constant vertical load N = 266kN (deck load) and the same cyclic horizonal displacement history with the set-up apparatus showed in **Figure 3**.
The results are presented in term of Base shear versus top specimen horizontal displacement and Carbon FRP wrapping strains distributions.

**Base shear versus top specimen horizontal displacement**
The response of the original specimen (P16, OR) and the one of the repaired specimen (P26-250-15) in terms of base shear versus top specimen displacement are shown in **Figure 3** during the application of Tolmezzo (P16-t1, P26-250-15-t1) and Tolmezzo x 2 (P16-t2, P26-250-15-t2) displacement histories. The repaired specimen was able to sustain a very strong seismic demand without shear rupture (**Figure 3**) and therefore the proposed repair strategy seems to be effective. The cycles have shown good energy dissipation, no pinching for shear and a modest reduction of the maximum force also in case of a very strong earthquake (Tolmezzo x 2). There is not rupture of the rebar joints or of the new rebar parts because there is not an evident abrupt loss of the forces.
The fraction of the original strength in term of base shear which was restored by the repair is about 72%. This is due to the reduction of the diameter of the new longitudinal rebar segments which causes a reduction of the resisting moment of the repaired sections at the base of the bridge column. However, the behaviour of the specimen is improved because the design shear force decreases because it is related to the maximum resisting moment of the section by capacity design criteria whereas the shear strength increases by means of the FRP reinforcement. Moreover, the design force on the foundation decreases because it is related to the maximum available design base shear of the bridge pier. Reinforcement of the foundation, intervention difficult in real application on bridges, may be not necessary. At the contrary repair intervention in the literature which increases the strength of the repaired section needs of an intervention on foundation.
The ductility of the specimen is not directly investigated because the same displacement history is applied. However, it seems that there is an increasing of the ductility of the repaired specimen because the reduction of the strength for the maximum applied displacement it is smaller than the one of the original specimen.




a) b)

c) d) e)

Figure 3. a) Original and b) repaired 1:6 scaled specimens responses; c) specimen tested in the lab; d) top column horizontal displacement histories; e) pier damage at the end of the test

**Carbon FRP wrapping strains distribution**

The experimental carbon FRP wrapping strain distribution along the specimen in term of average values in the two load directions (pull and push) is given in **Figure 4.** The maximum value of the strains was 0.0035 which is smaller than the design value 0.005 indicated in the national and international structural design codes (CNR DT 200 2013, FIB 2001) to evaluate the shear strength contribution of the wrapping. This confirms that the maximum FRP strain activated in case of a very strong earthquake excitation (Tolmezzo x 2) also for a repaired specimen is smaller than the maximum available value for the Carbon FRP tissue equal to 0.012. The strain distribution shows greater values from the column base to the specimen height h1 equal to 200cm.

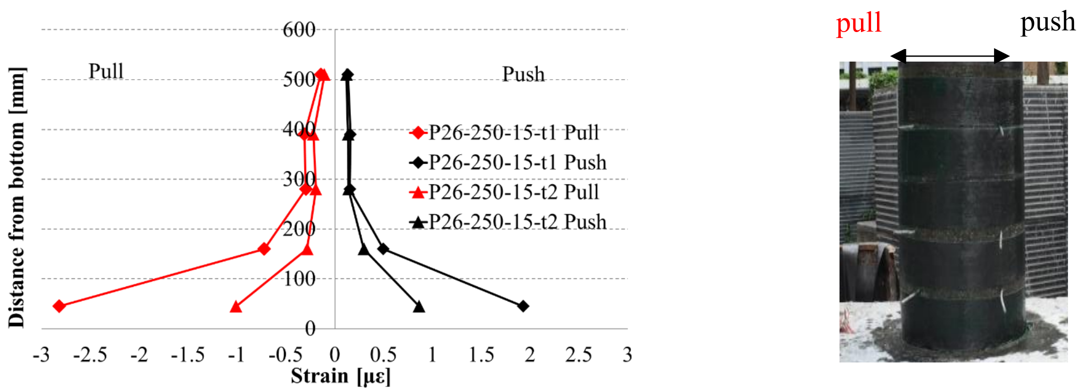



Figure 4. Test results: Carbon FRP wrapping strains along the specimen height in the push and pull load directions for the Tolmezzo(t1) and the Tolmezzo x 2 (t2) deformation histories

This means that the turned rebars has worked correctly and the distribution of the plastic strain was along the new rebars only just above the rebars connection that is located at the base of the specimen. Furthermore, the length of the machined rebars could be reduced from 250mm to 125mm because the strain of the Carbon FRP are very small after h1, the connection length is about 80mm and therefore the turned part of the new rebar could be smaller.

## Conclusions

A new rapid repair strategy, focusing on the damaged longitudinal rebar substitution for bridge pier or columns is presented. The proposed technique gives practical solution considering also the construction problem in situ giving practical solution from an engineering point of view. The strategy was applied to repair three piers specimens in scale 1:6 tested in the lab. The specimens were able to sustain very strong seismic demand without concrete shear and new rebars parts and joints rupture and therefore the proposed repair and retrofitting interventions are effective. The strain distribution of the carbon FRP wrapping shows that the design value of the FRP tissue strain proposed in the code to evaluate the FRP contribution to shear strength can be used also for the repaired columns and bridge piers. The wrapping is effective to prevent the shear rupture of the column. The distribution of the FRP wrapping strain shown that the plastic strains were distributed along the new rebar only.

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