Flexural behaviour of RC and PC beams strengthened with external pretensioned FRP laminates

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ABSTRACT: In this paper some results of an experimental investigation on real-scale RC (Reinforced Concrete) and PRC (Pre-stressed Reinforced Concrete) beams strengthened in flexure with FRP laminates developed at Material Testing Laboratory of the Department of Constructions and Transportation Engineering of the University of Padova are shown. Externally bonded FRP reinforcement is applied with different modalities, using different types of end-anchorage devices and, in some beams, with pre-stress transfer. After the characterisation of the single materials, four points bending tests are executed and failure and cracking modes are studied with particular attention to the behaviour of the anchorages made both with resins and different types of mechanical devices.

1 INTRODUCTION

Externally bonded Fiber Reinforced Polymer (FRP) sheets are currently used to repair and strengthen existing Reinforced Concrete (RC) and Pre-stressed Reinforced Concrete (PRC) structures.

Structural behaviour of FRP strengthened RC elements has been widely studied over the last few years and some studies have resulted in the first design guidelines for strengthened concrete. American ACI 440-02 (ACI Committee 440 2002), European fib –bulletin 14 (fib T.G. 9.3 2001) and Italian Recommendations (CNR-DT 200, 2004) are examples of such guidelines.

Experimental investigations about flexural behaviour of RC beams strengthened with FRP materials have been usually developed on reduced-scale specimens with ordinary FRP laminates/sheets. Few experimental tests (Brena et al. 2003, Chahrour and Soudki 2005, El-Hacha et al. 2003, El-Hacha et al. 2004, Tan et al. 2003, Triantafillou et al. 1992, Wight et al. 2001, Yu et al. 2004) have been developed on real-scale specimens strengthened with pretensioned FRP laminates.

A number of experimental programs have been developed in the last years at Material Testing Laboratory of the Department of Constructions and Transportation Engineering of the University of Padova about flexural, shear, axial and bond behaviour of FRP strengthened elements (Pellegrino and Modena 2002, Pellegrino and Modena 2006, Tinazzi et al. 2003, Pellegrino et al. 2004, Pellegrino et al. 2005, Boschetto et al. 2006).

In the present paper, main results of an experimental program about real-scale RC and PRC beams strengthened in flexure with ordinary and pretensioned FRP laminates developed at the Material Testing Laboratory of the Department of Constructions and Transportation Engineering of the University of Padova, are shown. Failure and cracking modes are observed and efficiency of different types of mechanical end-anchorages (Pellegrino et al. 2005, Boschetto et al. 2006, El-Mihilmy and Tedesco 2001, Malek et al. 1998, Taljsten 1997) is studied.

2 EXPERIMENTAL PROGRAM

2.1 *Test setup*

Five real-scale beams (four RC beams and one PRC beam with pre-tensioned internal strands) have been tested. Load scheme, dimensions and details of the internal reinforcement of the beams are shown in Figs. 1 and 2.

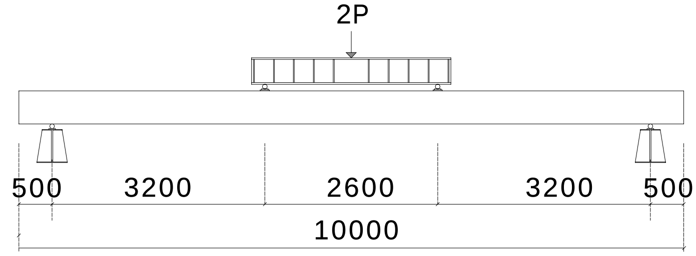
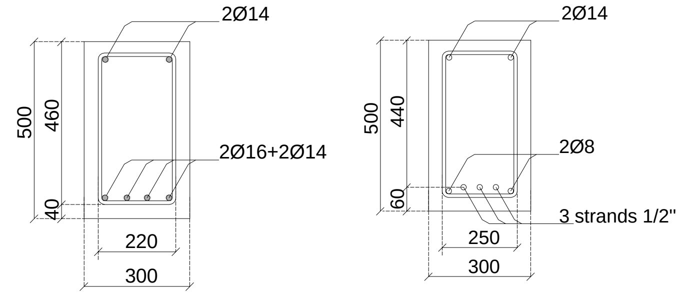


Figure 1. Load scheme of the beams



Cross section of RC beams   Cross section of PRC beam

Figure 2. Cross-sections of the beams

Shear reinforcement consists in stirrups 8mm diameter with 20cm spacing (always designed to obtain flexural failure of the specimens). Strands are pre-tensioned with initial stress equal to 1400MPa.

Beams are instrumented with three strain-gages in the middle cross-section at the upper and bottom face and laterally at the longitudinal reinforcement position and three linear variable differential transformers (LVDT) at midspan and bearings position.

The typical beam before the execution of the test is represented in Fig. 3.

Figure 3. Typical beam before the execution of the test.

2.2 *Materials*

Test on the basic materials (concrete, reinforcing and pre-stressing steel) have been developed. The results of the tests are listed in Tabs. 1, 2 and 3.

Table 1. Mechanical properties of concrete

Mean cubic compressive strength	R_{cm} = 71 MPa
Mean tensile strength	f_{ctm} = 5.2 MPa
Mean elastic modulus	E_{cm} = 38060 MPa

Table 2. Mechanical properties of reinforcing steel

Mean yielding stress	f_{ym} = 536 MPa
Mean ultimate stress	f_{tm} = 633 MPa

Table 3. Mechanical properties of pre-stressing steel

Mean yielding stress	f_{ym} = 1693 MPa
Mean ultimate stress	f_{tm} = 1895 MPa

Unidirectional Carbon Fiber Reinforced Polymer (CFRP) pultruded laminates with 1.2x100mm and 1.2x80mm areas were respectively used for ordinary and pre-tensioned strengthening.

Tensile tests on CFRP laminate have been also developed. The results of the tests are listed in Tab. 4.

Table 4. Mechanical properties of CFRP laminate

Ultimate stress	f_{fu} = 2780 MPa
Elastic modulus	E_f = 166000 MPa
Ultimate strain	ε_{fu} = 1.8 %

In Fig. 4 the execution of the tensile test on CFRP laminate is shown.

Figure 4. Tensile test on CFRP laminate (configurations before and after the test)

2.3 *Characteristics of the specimens*

RC-C beam was the control beam without strengthening.

RC-N beam was strengthened with ordinary CFRP laminate. For all strengthened specimens the concrete surface was initially cleaned with an iron brush and then the surface was covered with a layer of primer. Then the CFRP laminates were applied to the concrete prisms with two-component epoxy adhesive with a relatively uniform thickness of about 1mm. Specimens were prepared in laboratory conditions of constant humidity and temperature. One end of the laminate was "U"-jacketed with CFRP sheets for RC-N beam (see Fig. 5).

RC-EA beam was also strengthened with ordinary CFRP laminate at bottom position but mechanical steel bolted plate anchorages were used at both ends (see Fig. 6).

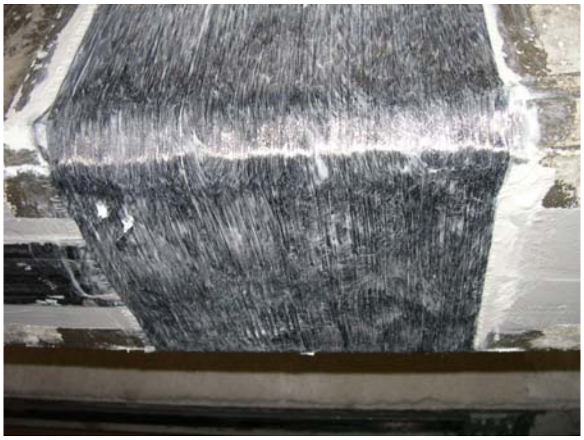


Figure 5. “U”-jacketing at one end of RC-N beam.

Figure 6. Steel bolted plate anchorages at both ends of RC-EA beam.

RC-PrEA beam was strengthened with pre-tensioned CFRP laminate. Prestressing was applied with hydraulic jack at one end of the beam (see Fig. 7) while the other end was anchored with a steel bolted plate (see Fig. 8).

Figure 7. Hydraulic jack for pre-stressing CFRP laminate

Figure 8. Steel bolted plate anchorage for RC-PrEA and PRC-PrEA beams.

When the desired level of pre-stressing was reached the other end of the laminate was also anchored with steel plate. Pre-stressing strain equal to 0.6% was applied to the laminate for RC-PrEA beam.

PRC-PrEA beam (the only PRC beam) was pre-tensioned with the same technique of the previous one applying pre-stressing strain equal to 0.4%.

3 MAIN RESULTS

In Fig. 9 load vs. midspan deflection diagrams are represented for the five beams.

RC-C diagram showed the typical flexural behaviour of RC beams with (I) pre-cracked, (II) cracked and (III) plastic stages.

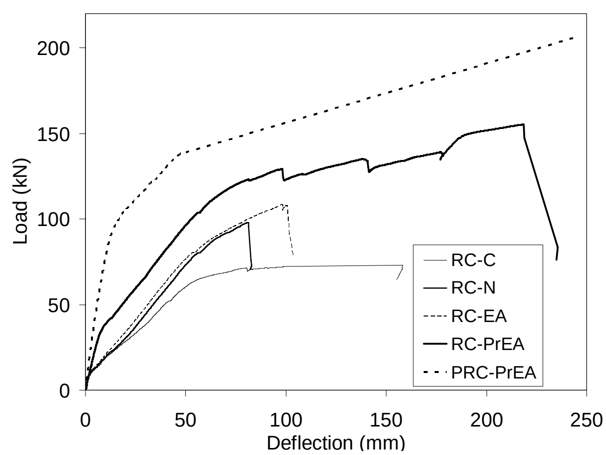


Figure 9. Load vs. deflection diagrams for the five beams.

RC-N diagram showed a brittle behaviour due to sudden delamination of the CFRP laminate starting from the free end and propagating towards the other.

RC-EA diagram showed a similar behaviour with a higher value of the ultimate load due to end anchorage devices. Intermediate delamination of the CFRP occurred in this case with failure of end anchorage (see Fig. 10).

Figure 10. Failure of end anchorage (beam RC-EA).

Failure of beams RC-PrEA and PRC-PrEA was still due to delamination of the CFRP but the action of the anchorages delayed the complete failure. Not only a relevant increment of the ultimate load but also an increment of the load at which the first crack appears, occurred for beams with pre-tensioned laminates (RC-PrEA and PRC-PrEA) with respect to control beam (RC-C).

In Fig. 11 the delaminated CFRP after failure of PRC-PrEA beam is shown.

Figure 11. Failure of beam PRC-PrEA.

In Tab. 5 ultimate values of load and deflection are listed for the five beams.

Table 5. Ultimate load and maximum deflection for the five beams

Beam	Ultimate load (kN)	Maximum deflection (mm)	CFRP area (mm^2)
RC-C	72.1	158.2	--
RC-N	98.0	81.1	120
RC-EA	107.9	100.4	120
RC-PrEA	155.3	219.2	96
PRC-PrEA	206.1	--	96

In Fig. 12 cracking patterns at failure are shown for the five beams in the zone between the concentrated loads.

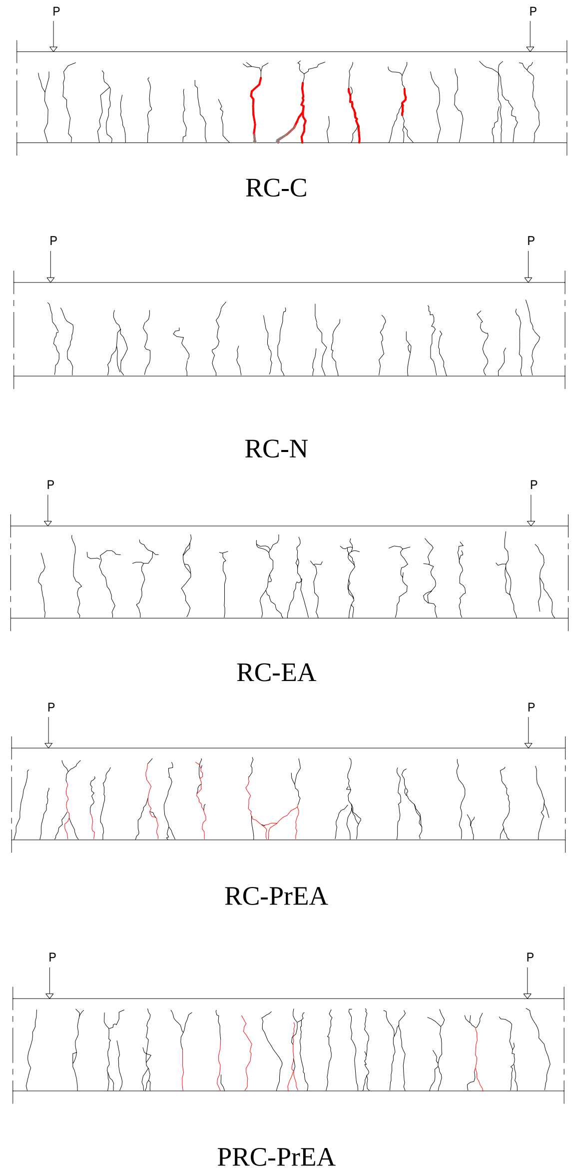


Figure 12. Cracking patterns at failure.

More uniform distribution and smaller crack amplitude were detected for strengthened beams with respect to control beam. These effects are more evident for beams with pre-tensioned laminates.

In Fig. 13-17 load vs. midspan strain diagrams are shown for the five beams. In particular strain at superior edge, lateral position at longitudinal reinforcement level and inferior concrete edge are plotted for RC-C beam; strain at superior edge, lateral position at longitudinal reinforcement level, inferior concrete edge and inferior CFRP laminate are plotted for RC-N, RC-EA and RC-PrEA beams; strain of CFRP is plotted for PRC-PrEA beam.

Strain of CFRP laminate (including pre-stressing strain if present) is equal to 0.43% (24% of the ultimate strain) for RC-N beam, 0.58% (32% of the ultimate strain) for RC-EA beam, 1.17% (65% of the ultimate strain) for RC-PrEA beam and 1.35% (75% of the ultimate strain) for PRC-PrEA beam. Therefore pre-tensioning allows a better utilization of the material characteristics with strain values very near to the ultimate.

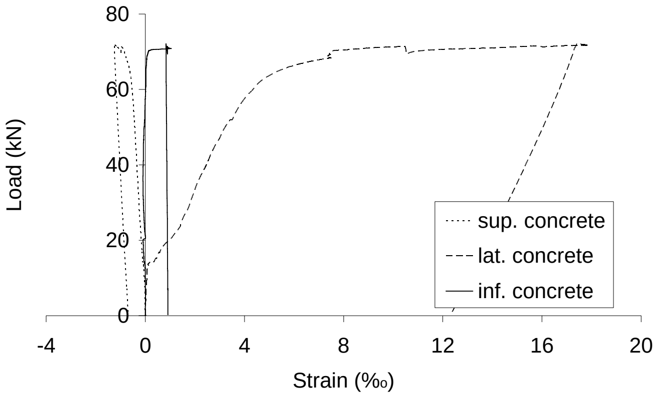


Figure 13. Load vs. strain diagram for beam RC-C.

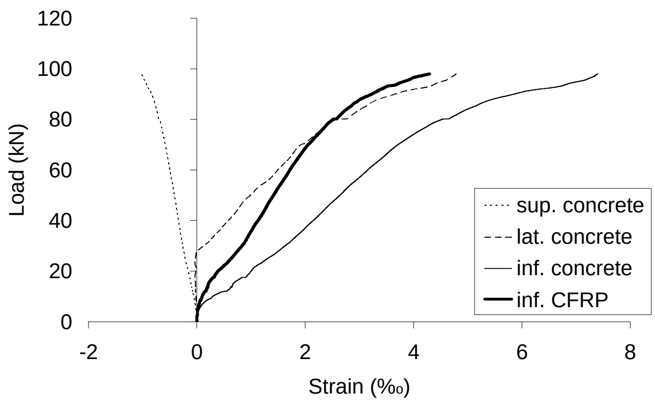


Figure 14. Load vs. strain diagram for beam RC-N.

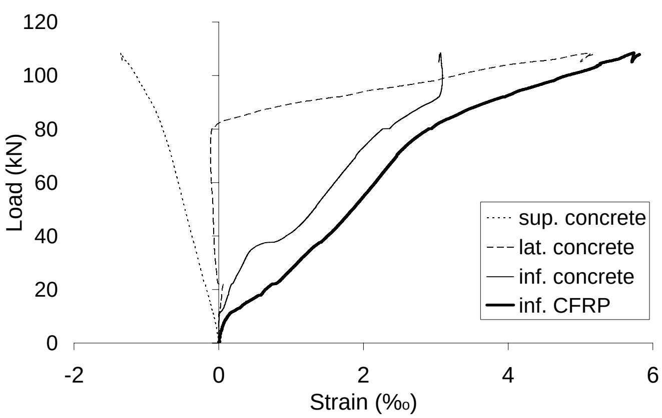


Figure 15. Load vs. strain diagram for beam RC-EA.

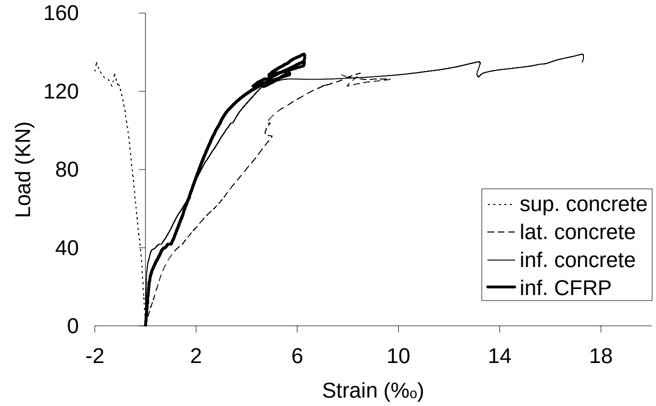


Figure 16. Load vs. strain diagram for beam RC-PrEA.

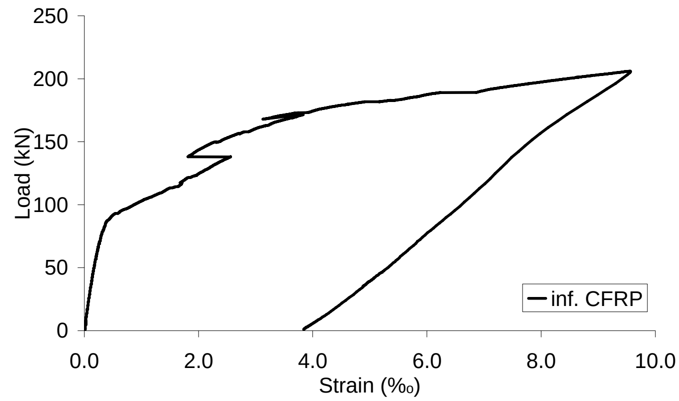


Figure 17. Load vs. strain diagram for beam PRC-PrEA.

4 CONCLUSIONS

First results of an experimental investigation on real-scale RC and PRC beams strengthened in flexure with ordinary and pre-tensioned CFRP laminates are shown. The experimental results show that the increments of ultimate capacity vary on the basis of many parameters. In particular, mechanical anchor devices increase ultimate capacity of the structural element delaying delamination.

CFRP pre-tensioning

- increases ultimate capacity of the structural element and load at which first cracking occurs;
- allows reduction of crack amplitudes and more uniform distribution of the cracks;
- allows a better utilization of CFRP material characteristics with strain values very near to the ultimate.

Further investigation is necessary especially about quantification of the increment of capacity given by end anchor devices for which the indications of the principal guidelines (ACI Committee 440 2002, fib T.G. 9.3 2001, CNR-DT 200, 2004) are very scarce or null.

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