Assessment of RC beams strengthened with near surface mounted CFRP rods by static and dynamic tests

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SUMMARY. The assessment of RC beams damaged by bending and strengthened with carbon fibre reinforced polymer rods utilising near surface mounted method has been carried out trough experimental tests in the laboratory. Changes in the properties of RC beams such as stiffness and ductility have been investigated by bending tests and results compared with theoretical data. Dynamic response of damaged and strengthened beams has been investigated such as natural frequencies and vibration mode shapes. Finally, dynamic measures have been used to assess the strengthening method of near surface mounted carbon-FRP rods.

1 INTRODUCTION

Externally bonded FRP strips and sheets have been the most commonly used techniques for strengthening RC structures damaged by high values of loads or corrosion process of steel bars [1]. Unfortunately many tests indicated brittle failure due to the FRP debonding and concrete cover delamination. Moreover, externally bonded FRP reinforcements are susceptible to damage from collision, high temperature and fire [2]. To limit these problems, the near surface mounted (NSM) fiber reinforced polymers (FRP) rods represents a convenient method. The method of strengthening is a promising technology for increasing the flexural and shear capacity of reinforced concrete members [3,4,5,6,7,8,9]. Experimental results confirmed available of strengthening with NSM CFRP rods of damaged RC beams obtaining an increase of stiffness in the elastic field and higher capacity strength. Failure was due to collapse of concrete without detachment of CFRP rods [5,7,8]. An extensive campaign of static and dynamic tests on the behaviour of RC beams strengthened by NSM CFRP has been developed [10] and in this paper any aspects are discussed. Changes in the properties such as stiffness and ductility have been studied comparing experimental results obtained by tests on RC beams without and with CFRP rods.

To assess the safety of beams strengthened with near surface mounted CFRP rods, vibration response have been experimentally investigated such as natural frequencies and mode shapes. Over the years, many algorithms have been proposed to address the problem of locating and quantifying structural damage in RC beams using changes in the vibration characteristics of the structure [11,12,13,14,15,16]. The analysis of vibration as a non destructive method to assess the method of strengthening by NSM was experimentally used and it appears very fruitful.

1.1 *Experimental program*

In the laboratory RC beams were subjected to static bending tests (Fig. 1) and strengthened with NSM carbon-FRP rods. Assessment of strengthening was carried out by static and dynamic tests. RC beam models (B1-B2-B3) in real scale, with different reinforcement (Fig. 2), were subjected to increasing bending loads until yield of steel (Table 1). Four vertical load levels D1… D4 were assumed as damage degrees due to cracking. After the damage degree D4 the RC beams showed a diffused cracking state. Damaged beams were strengthened with two CFRP rods located into grooves of width 20·20 mm^2 at the bottom of beam; after applying the primer on the concrete, CFRP rods were embedded into adhesive epoxy resin rebuilding the cover**.**

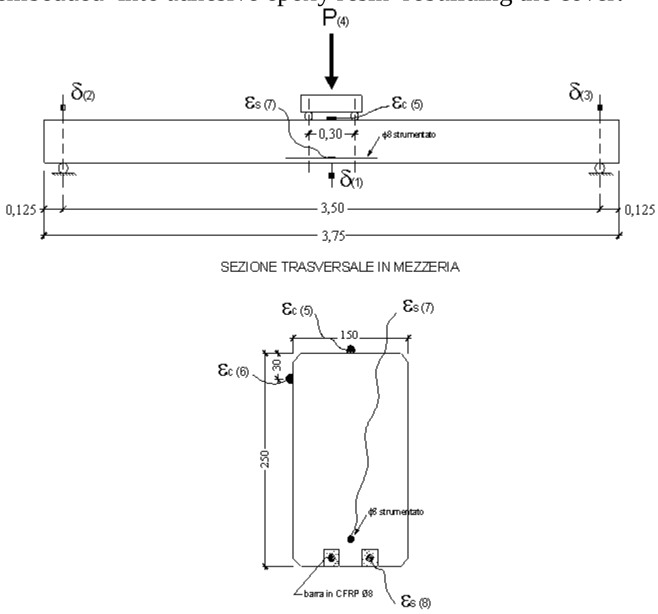


Figure 1: Experimental bending static test on RC beam models

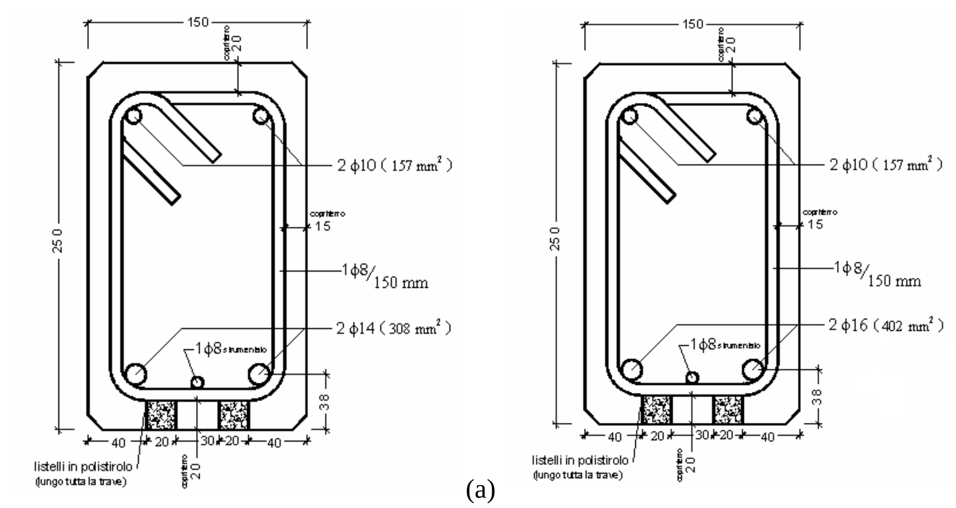


Figure 2: RC sections at mid span: (a) B1, B2 and (b) B3 beam sections.

Poultries CFRP rods were characterized by a section of fiber of 44mm^2 and diameter 7.5 mm.

Main mechanical parameters are: tensile strength 1.8kN/mm^2 ; Young's modulus 130kN/ mm^2; ultimate strain 1.8%. Strengthened beams were tested with the same loading path under cycles of vertical load P.

Table 1 – Damage degrees for B1-B2 and B3 beams under static bending test

Damage Degree	**(B1-B2)** **M$^{(*)}$** (kNm)	**(B3)** **M$^{(*)}$** (kNm)
D1	5.00	5.00
D2	15.00	15.00
D3	28.00	33.20
D4	32.44	41.60

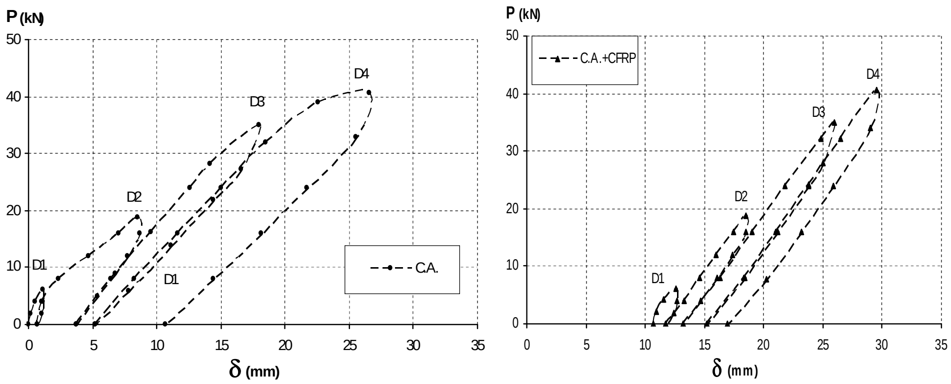
(*)Bending moment at mid span section

Further, the beams were analysed by free vibration tests to obtain experimental dynamic parameters at different conditions: before and after damage at each damage degree D1...D4 and with and without strengthening. During the dynamic tests, the beams are hung by flexible springs. The beams are excited by impulsive load given by impact hammer and the response is measured at different points using an accelerometer. The frequencies are extracted by transformed signals in frequency domain by the Fast Fourier Transform Technique (FFT). Each beam subjected to dynamic tests was divided into 21 points. The distance between each point was 180 mm with the same distance from the edge equal to 75mm. The condition of the beam with free ends was simulated by hanging the beam with elastic springs of stiffness equal to K=8N/mm. The dynamic measures were obtained utilising an impact hammer and working in a range of frequencies between 0 - 800 Hz with a resolution of 0.5 Hz [10].

2 RESULTS OF STATIC TESTS

2.1 *Static results and comparison with theoretical data.*

A comparison of experimental results obtained on RC beam B1, before and after the strengthening, is shown in Figure 3 under different levels of loading - D3 and D4 damage degrees.



(a) (b)

Figure 3: Experimental diagrams load vs deflection for B1: (a) RC and (b) strengthened beam.

The behavior of reinforced beam is characterized by an increase of stiffness with a reduction of displacements. In Figure 4 the development of strain at mid span section for concrete, steel and CFRP rods during different phase of loading is shown for B1 beam model until failure.

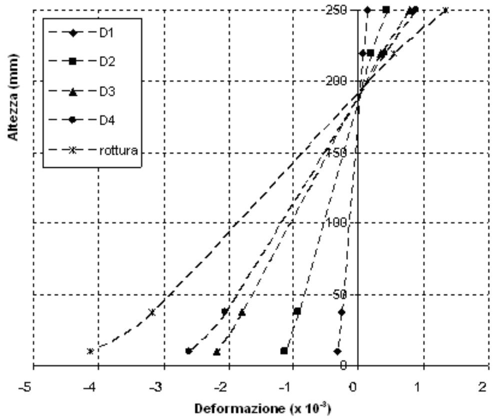


Figure 4: Experimental strain on mid span section of strengthened beam (B1).

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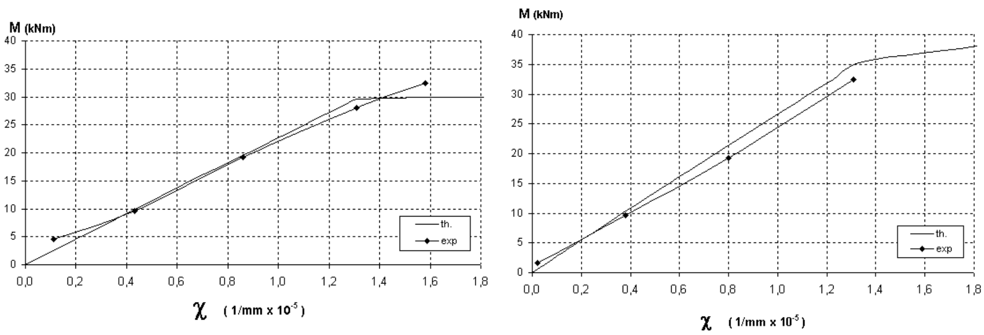
Non linear analysis of beam sections with steel reinforcement and strengthening of CFRP rods has been developed in Capozucca (2009) [10]. Theoretical moment, M, vs. curvature, χ , diagrams have been evaluated both for RC sections and strengthened sections considering the following hypotheses :

- planarity of bending section up to failure;
- perfect bond between steel and CFRP rods with concrete;
- concrete without strength under tensile stress.

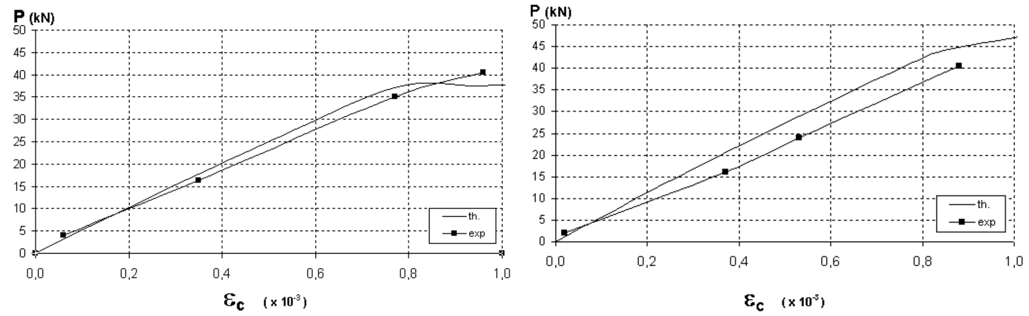
A comparison between the theoretical data and experimental results of moment vs. curvature for the mid span section of RC beam and strengthened beam are shown in the Figures 5 considering the loading path from D1 to D4 degrees of damage.



(a) (b)

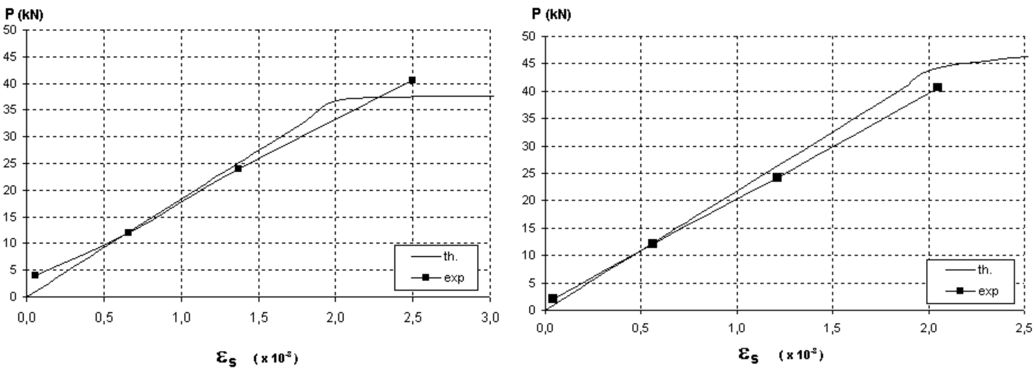
Figure 5: Theoretical and experimental diagrams moment vs. curvature for (a) unreinforced and (b) reinforced beam (B1).

In Figures 6, 7 and 8, respectively, experimental strain values on concrete edge, strain values on steel bars and strain on NSM CFRP bars at D1…D4 are shown for mid span section of RC beam and strengthened beam and compared with theoretical data. The Figures 6, 7 and 8 show a substantial theoretical and experimental close response at the four damage degrees.



(a) (b)

Figure 6: Theoretical and experimental diagrams load vs. compressive concrete strain for (a) unreinforced and (b) reinforced beam (B1).



(a) (b)

Figure 7: Theoretical and experimental moment vs. tensile steel strain for (a) unreinforced and (b) reinforced beam (B1).

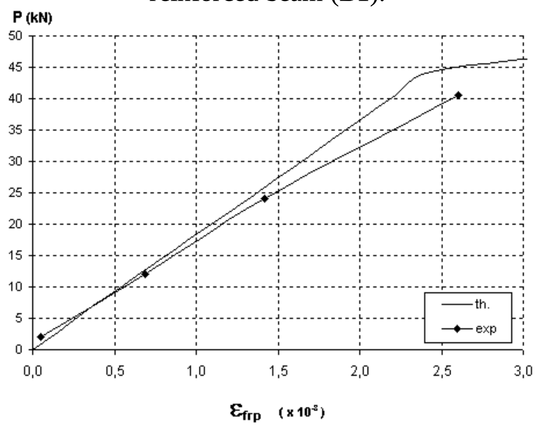
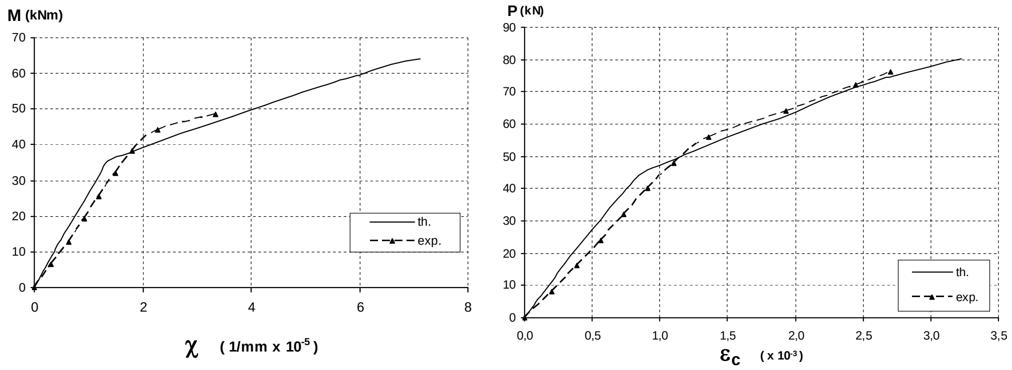


Figure 8: Theoretical and experimental load vs. strain diagrams on CFRP bars for strengthened beam (B1) subjected to different steps of damage.

Finally, in Figure 9 a comparison between theoretical and experimental results is shown until the failure load/moment for B1 model through moment vs. curvature and load vs. concrete strain at the mid span section of beam. By the diagrams shown in Figure 9, it is possible to appreciate the validity of theoretical analysis that permits to obtain values very close to experimental results in the case of strengthened RC beam with NSM CFRP bars.



(a) (b)

Figure 9: (a) Theoretical and experimental diagrams: (a) moment vs curvature and (b) load vs compressive concrete strain, for reinforced beam (B1) under bending test until to failure.

Figure 10: Failure view of strengthened RC beam (B2)

Failure damage of RC beam (B2) is shown in Figure 10. Crash of concrete developed in the compression zone at the extrados of beam where load is applied. At the bottom of beam longitudinal cracking appeared on the cover where CFRP rods are located. Cracking at the intrados of beam did not produce delamination of CFRP bars into grooves. Finally, in the following Table 2 experimental and theoretical results for B3 beam model with and without strengthening due to NSM CFRP bars are shown.

Table 2 - Experimental and theoretical results for B3

Beam Model B3 Phases of Bending Test		Load **P** (kN)	Moment **M** (kNm)	Curvature χ (1/mm·10^{-5})	Concrete ε_c (10^{-3})	Steel ε_s (10^{-3})	CFRP ε_f (10^{-3})
RC Beam	exp.	40.55	32.44	1.59	0.96	2.50	---
Damage degree:	th.	37.03	29.62	1.33	0.77	2.05	---
D4	%	-8.68	-8.68	-16.29	-20.28	-17.94	---
Strengthened	exp.	52.03	41.62	2.00	1.20	2.63	3.59
RC+CFRP	th.	44.19	35.35	1.35	0.84	2.05	2.3
at yielding	%	-15.07	-15.07	-32.53	-29.84	21.97	-32.12
Strengthened	exp.	76.03	60.82	---	2.63	---	---
RC + CFRP	th.	80.25	64.20	7.11	3.23	11.85	13.85
at failure	%	5.55	5.55	---	22.76	---	---

3 RESULTS OF DYNAMIC TESTS

The B1, B2 and B3 beams have been analysed by dynamic tests to measure experimental dynamic parameters before and after damage and, successively, with the strengthening by CFRP rods. The dynamic tests were used to monitor the behaviour of beams [15,16]. At every damage degree D1...D4, removed load, dynamic vibration tests have been carried out on beams without constraints in free-free end condition (Fig. 11). To measure dynamic parameters the following instruments were utilized:

- piezoelectric accelerometer (model 4508 Brüel & Kjær) on steel plates glued to the beam model with sensibility 100 mV/g and maximum value of measure 700 m/s^2(70 g);
- impact hammer with load cell (model 8202 Brüel & Kjær) and sensibility -1 mV/N;
- pulse system code to record dynamic values.

Figure 11: Dynamic tests of vibration on RC beam (B1) with free-free ends.

In the Table 3 for model B1, frequency values of vibration and variations in percent at different steps of damage D1…D4 are shown both in the case of un-strengthened and strengthened beam.

Table 3. Frequency values of free-free vibration of B1 model beam

	Damage	f_1 (Hz)	$\Delta f_1/f_1$ (%)	f_2 (Hz)	$\Delta f_2/f_2$ (%)	f_3 (Hz)	$\Delta f_3/f_3$ (%)
R.C.	D_0	71.774	---	194.016	---	367.299	---
	D_1	67.066	-6.56	184.908	-4.69	353.627	-3.72
	D_2	61.861	-7.76	170.673	-7.70	332.364	-6.01
	D_3	61.228	-1.02	167.207	-2.03	320.924	-3.44
	D_4	55.630	-9.14	159.185	-4.80	298.607	-6.95
R.C.+CFRP	D_0	49.287	-11.40	143.930	-9.58	279.885	-6.27
	D_1	50.541	2.54	147.031	2.15	284.930	1.80
	D_2	51.291	1.48	148.123	0.74	286.519	0.56
	D_3	52.721	2.79	151.655	2.38	291.699	1.81
	D_4	53.077	0.68	152.791	0.75	292.687	0.34

Finally, the Figures 12, 13 and 14 frequency variation ratio, $\Delta f_i/f_{D0}$, vs moment ratio, M/M_{max} , for B1 beam without and with strengthening are shown. It can be note a decrease of frequency in the case of RC beam due to increase of damage degree, from D_0 to D4 while in the case of beam with strengthening, frequency values are almost constant or with a light increase.

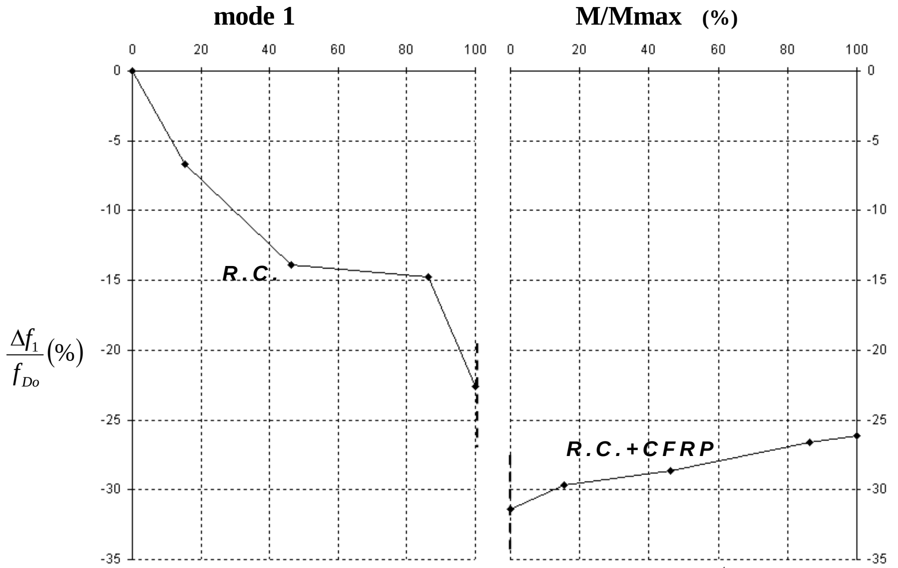


Figure 12: Variation of frequency vs. moment ratio for 1st mode of vibration.

Frequency value at D_0 for strengthened beam is lesser than that recorded after D4 for RC beam due to an increment of mass of CFRP rods.

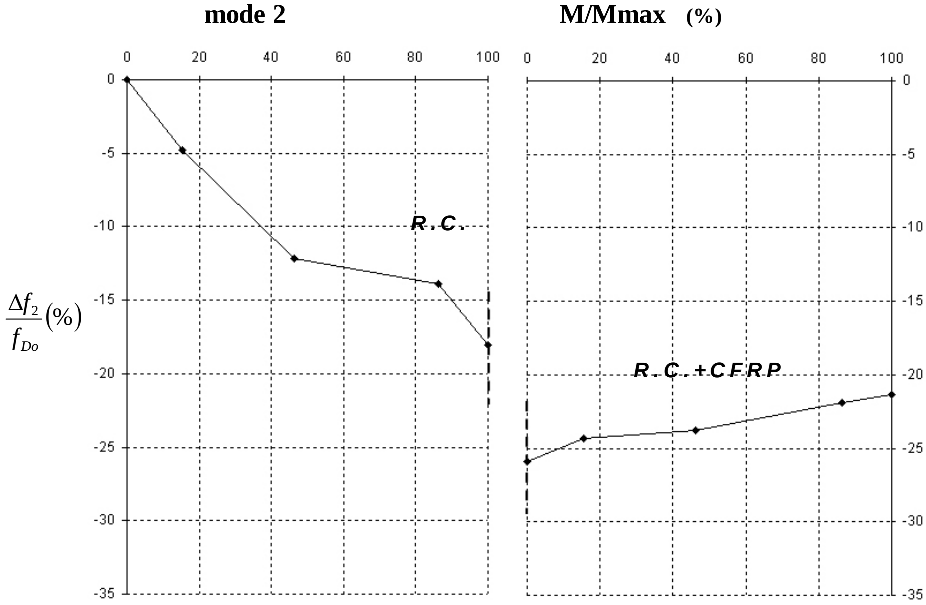


Figure 13: Variation of frequency vs. moment ratio for 2nd mode of vibration.

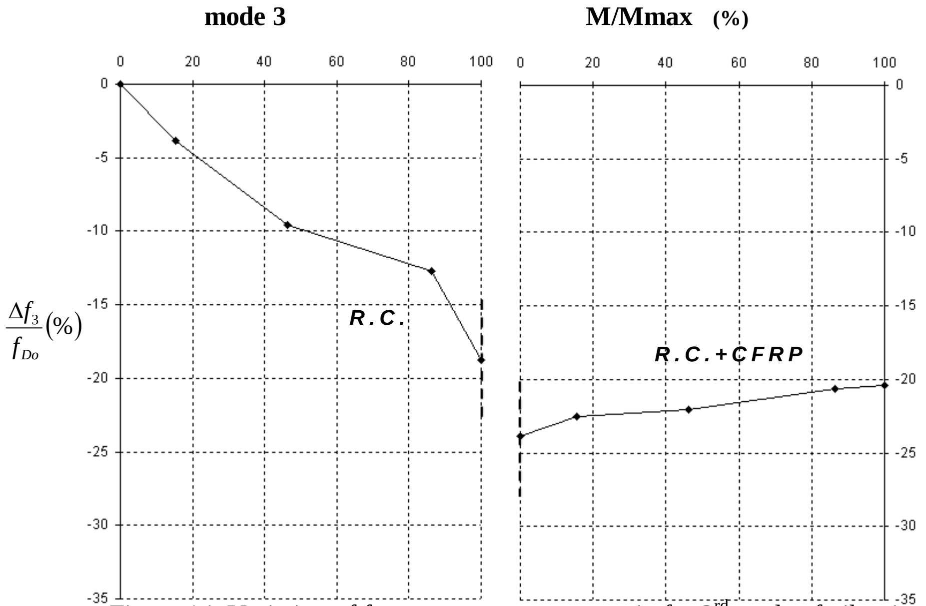


Figure 14: Variation of frequency vs. moment ratio for 3rd mode of vibration.

4 CONCLUSIONS

In this paper the experimental behavior of RC beams damaged and strengthened by the technique of NSM with CFRP has been discussed. Experimental static and dynamic tests have been carried out in the laboratory on three beam models in real scale to verify the response of RC beams strengthened with NSM technique both under service loads and until failure. Dynamic parameters and, in particular, frequency values allowed to confirm that the delamination of CFRP bars was neglecting until failure. Finally, in strengthened beams with NSM CFRP bars, the cracking state due to a damage was maintained stable under service loads.

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