Dynamic response of RC beams strengthened with near surface mounted Carbon-FRP rods subjected to damage

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Abstract. Near surface mounted (NSM) technique with fiber reinforced polymer (FRP) is becoming a common method in the strengthening of concrete beams. The availability of NSM FRP technique depends on many factors linked to materials and geometry - dimensions of the rods used, type of FRP material employed, rods’ surface configuration, groove size – and to adhesion between concrete and FRP rods. In this paper detection of damage is investigated measuring the natural frequency values of beam in the case of free-free ends. Damage was due both to reduction of adhesion between concrete and carbon-FRP rectangular and circular rods and cracking of concrete under static bending tests on beams. Comparison between experimental and theoretical frequency values evaluating frequency changes due to damage permits to monitor actual behaviour of RC beams strengthened by NSM CFRP rods.

1. Introduction

In the last years, the strengthening of reinforced concrete (RC) beams using fiber reinforced polymers (FRPs) has become a significantly common technique in the practice of civil engineering. In general, the use of two different strengthening techniques is adopted: FRP sheet/strips glued on the concrete surface as external bond composite materials; FRP rods with various types of sections, for example circular and rectangular, inserted into grooves on concrete covers. This last method is known as the near surface mounted (NSM) technique. The NSM FRP technique appears capable of solving a number of aspects which may threaten the strengthening with composite materials on the external surface: their susceptibility to damage deriving from collision, high temperature, and fire. The NSM method has been proven to be a promising one for increasing the capacity of RC beams \cite{1-3} although many factors may affect the bond between FRP rod, resin and concrete: the bond length, the diameter of the rods, the type of FRP material employed, rods’ surface configuration, and groove size \cite{4-5}. NSM FRP rods are prone to exhibit greater slips than steel reinforcement due to FRP materials’ potentially lower bond shear stress because of the presence of surrounding adhesive layers and local

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cracking in the cover concrete. In this paper the assessment of strengthened RC beams with NSM CFRP rectangular and circular rods under cracking concrete has been experimentally treated by analysing dynamic response of beams. Natural frequency measures were obtained through dynamic tests on free-free beams both strengthened and un-strengthened with NSM CFRP rods. The beams were subjected to different levels of static loading with increasing damage due to cracking of concrete. The basic concept of vibration analysis is that dynamic characteristics are functions of structures’ physical properties, therefore any change caused by damage results in change in dynamic response [6]. In the NSM method actual bond-slip may be influenced by the cracking of concrete and loss of adhesion of rods, which can modify frequency values and beams’ modes of vibration. Over the years, many studies based on frequency measures have been developed to detect damage in uniform beams [7,8] and significant researches have been carried out in the last years with RC beams. Below, the results of dynamic tests on beams are used to assess the availability of NSM strengthening with the reduction of bond increasing the damage due to bending loading.

2. Static and dynamic tests

2.1. Beams with CFRP circular rods

Static and dynamic tests were planned for two RC beams; one was reinforced with steel bars (Beam B0) while the B1 beam was reinforced inserted with steel bars and two CFRP circular rods into rectangular grooves of 20mm·20mm of section (Fig.1). Dimensions of beam section are 150mm·220mm and length 1700mm. Steel reinforcement was 4 bars of diameter 10mm and stirrups of diameter 6mm at interval of 60mm. The beams were characterized by concrete having, a tested, average cylinder strength equal to \( f_{c,av} \sim 44.3 \text{N/mm}^2 \) (Young’s modulus \( \sim 36.0 \cdot 10^3 \text{N/mm}^2 \)) and steel bars with an average yielding stress equal to \( f_{y,av} \sim 500 \text{N/mm}^2 \) (Young’s modulus about \( \sim 2.1 \cdot 10^5 \text{N/mm}^2 \)). CFRP rods with nominal diameter 8mm and section 65.04 mm\(^2\) were glued to the concrete using epoxy resin. The strength of CFRP rod is \( f_{av} \sim 2153.27 \text{N/mm}^2 \); Young’s modulus \( E_{b,av} \sim 142 \cdot 10^3 \text{N/mm}^2 \).

![Figure 1 Section of RC beam with NSM CFRP circular rods](image)

| Table 1 – Exp. cycles of loading \( P_i (\text{kN}) \) at damage degrees \( D_i \) for tested beams. |
| B0 | B1 |
|-----|-----|
| \( D_1 \) | \( P_1 = 7.2 \text{kN} \) | \( D_1 \) | \( P_1 = 7.1 \text{kN} \) |
| \( D_2 \) | \( P_2 = 14.3 \text{kN} \) | \( D_2 \) | \( P_2 = 14.3 \text{kN} \) |
| \( D_3 \) | \( P_3 = 31.5 \text{kN} \) | \( D_1 \) | \( P_3 = 31.4 \text{kN} \) |
| \( D_4 \) | \( P_4 = 39.0 \text{kN} \) | \( D_1 \) | \( P_4 = 39.0 \text{kN} \) |
| \(-\) | \(-\) | \( D_3 \) | \( P_5 = 87.5 \text{kN} \) |
| \(-\) | \(-\) | \( D_6 \) | \( P_6 = 105.0 \text{kN} \) |
| \( D_5 \) | Failure load: \( P_u = 47.7 \text{kN} \) | \( D_7 \) | Failure load: \( P_u = 115.0 \text{kN} \) |
Static tests were carried out on beams by bending, increasing the load \( P \) applied in two points measuring 300mm from the middle of beam (Table 1).

The theoretical natural frequencies for free vibration of an undamaged beam with deflection, \( v \), function of point, \( x \), and time, \( t \), may be obtained from the following equation:

\[
EI \cdot \frac{\partial^4 v}{\partial x^4} + \rho \cdot A \cdot \frac{\partial^2 v}{\partial t^2} = 0
\]  
(1)

where: \( \rho \) = density of beam material; \( A \) = the cross-sectional area.

The solution of Eq. (1) must be a harmonic function of time i.e.:

\[
v(x, t) = V(x) \cdot \sin(\omega t + \alpha)
\]

Introducing Eq. (2) in Eq. (1), assuming \( \lambda^2 = \frac{\rho \cdot A \cdot \omega^2}{EI} \), applying the following boundary conditions:

\[
V''|_{x=0} = 0; \quad V''|_{x=L} = 0; \quad V'''|_{x=0} = 0; \quad V'''|_{x=L} = 0
\]

an algebraic linear system in the unknown constants \( B_i \) may be obtained. A non trivial solution exists when the determinant becomes:

\[
\cos \lambda L \cdot \cosh \lambda L - 1 = 0
\]

The expression of circular frequency for undamaged free-free beam at the \( r \)-mode is:

\[
\omega = \left( a_r \cdot \frac{r \pi}{L} \right)^2 \cdot \sqrt{\frac{EI}{\rho A}}
\]

with coefficients \( a_r = 1.506, 1.25, 1.167 \), respectively, for the first three modes \( (r=1, 2, 3) \) [...].

The first three frequency values evaluated for undamaged beams B0 and B1 are shown in Table 2.

| Frequency values for undamaged beam | \( f_1 \) (Hz) | \( f_2 \) (Hz) | \( f_3 \) (Hz) | \( f_4 \) (Hz) |
|-----------------------------------|--------------|--------------|--------------|--------------|
| Theor. Euler-Bernoulli beam       | 310          | 857          | 1680         | 2777         |
| Exp. frequency value - B0         | 275          | 706          | 1274         | 1878         |
| Exp. frequency value - B1         | 284          | 723          | 1299         | 1923         |

The experimental dynamic tests were carried out on B0, B1 hanging the beams with springs to simulate the free-free condition.

**Figure 2** Set-up of free vibration text.
The free vibration tests were carried out with the impact technique using an impact hammer (Brüel & Kjær, Type 8202) able to transfer impulse in one point at 45mm from the edge; the measures were recorded with a mobile accelerometer (model 4508 – Piezoelectric CCLD accelerometer, Brüel & Kjær) located in 14 points at regular interval. A set of 10 hits was recorded at each of the different points and the average value was acquired. Frequency values were extracted by transformed signals in frequency domain through the fast fourier transform (FFT) technique using Pulse software. In Figure 2 set up of vibration is shown. In Figs. 3 and 4 the envelope of FRFs at damage degree $D_i$, respectively, for B0 and strengthened beam B1 are shown. In Figs. 3 and 4 the diagrams indicate the values obtained in two positions 1 and 3 of accelerometer. Trend of diagrams is similar for other points of measure of accelerometer. It may be noted that for both beams there is a shift on the left of diagrams due to reduction of frequency values at the increasing of damage condition $D_i$ by loading.

![Figure 3](image-url)  
**Figure 3** Envelope of FRFs at damage degree $D_i$, $i=1,\ldots,4$ for B0 recorded with accelerometer in (a) point 1 and (b) 3.
The variations of frequency values for B0 and B1 evidence that in unstrengthened beam B0 the decrease of frequency values are greater than in the strengthened beam B1. In Figs. 5(a),(b) at the different levels of loading reached during the beams’ bending tests, the variation in percent of frequency values, \( \Delta f_i = 100 \cdot \frac{f_i^{D0} - f_i^{D1}}{f_i^{D0}} \), for the first four modes \( r=1,\ldots,4 \), are indicated.

For example, at the first mode, a reduction of frequency values for B0 is equal to 34% at last loading stage, while in B1 it is almost equal to 26%. In the same way at the first damage degree D1-D0 at the first mode \( r=1 \) the variation is equal to 9% for B0 and minor than 2% in B1. Same trend of results is evident in the other modes of vibrations.
2.2. Beams with CFRP rectangular rods.

Two RC beams were built and subjected to testing in order to monitor static and dynamic behavior: beam B0R was not reinforced with CFRP rods; beam B1R was reinforced using three rectangular NSM CFRP rods inserted in rectangular grooves at the bottom of the beam (Fig. 6). The steel reinforcement consisted in 2 bars, measuring 10mm in diameter, placed in the lower area, and two other bars placed in the upper area, using 6mm stirrups every 80mm.

The bending tests for non strengthened and strengthened beams, B0R and B1R, foresaw loading cycles (damage degree D1 until P=5kN; D2 - P=20kN; D3 - P=30kN; D4 - P=40kN) with vertical load maximum equal to P= 50kN as damage degree D5 and, subsequently, the ultimate loading test until failure.
In Figs 7(b) experimental diagrams load, F, versus deflection at mid span section are shown for B0R and B1R; in the case of beam B1R, the capacity of the beam strengthened with NSM rectangular CFRP rods is higher than RC beam B0R. In reinforced beam B1R, failure is due to reinforcement delamination and not to concrete failure in the compressed zone. In particular, delamination occurred solely at the resin – concrete interface and a detachment of the concrete cover was also recorded (Fig. 7(a)). Beams B0R and B1R were analysed carrying out free vibration tests in order to obtain experimental dynamic parameters at different damage conditions due to bending loading; D0 indicates the undamaged state of the beams and with D_i with i=1,…,5 being the different levels of loading and relative damage degrees.

![Figure 7](image)

**Figure 7** (a) View of B1R beam at failure; (b) comparison between exp. diagrams load, P, vs. deflection at the midspan of B0R and B1R beam reinforced with NSM CFRP rectangular rods.

The dynamic test was conducted according to the set-up in Fig. 2. The experimental free vibration test was carried out for beams after each different level of load, P_i, hanging by flexible springs to simulate free-free condition. The dynamic responses were obtained using an impact hammer and an accelerometer at the beams’ intrados, 500mm from the end, connected to an acquisition system working in a range of frequencies between 0-2000Hz. The signals were recorded and elaborated in frequency domain through the FFT technique and FRFs were obtained using Labview software.

**Table 3**- Experimental frequency values and variation (%) for beam B0R.

| Damage degree | f_1 [Hz] | Δf_1 [%] | f_2 [Hz] | Δf_2 [%] | f_3 [Hz] | Δf_3 [%] |
|---------------|----------|----------|----------|----------|----------|----------|
| D0            | 233.6    | 0        | 1085     | 0        | 0        | 0        |
| D1            | 225.8    | 3.3      | 1074.2   | 1.0      | 939.2    | 13.4     |
| D2            | 176.8    | 24.3     | 492.8    | 18.5     | 390.4    | 25.8     |
| D3            | 158.4    | 32.2     | 429.8    | 28.9     | 805.2    | 26.5     |
| D4            | 166.8    | 28.6     | 439.8    | 27.3     | 796.8    | 24.7     |
| D5            | 167.2    | 28.4     | 445.4    | 26.3     | 816.4    | 24.7     |

Beams B0R and B1R at the end of each bending load step for damage degree D_i with i=1,…,5 were subjected to free vibration; in Tables 1 and 2 experimental frequency values and variation in percent, \( \frac{\Delta f}{f_{D_i}} = 100 \times \frac{f_{D_i} - f_{D_0}}{f_{D_0}} \), at the different levels of loading reached during the beams’ bending
tests, are also indicated. Regarding the dynamic response of beams BR0 and BR1, the frequency values decrease with a consequent increase of load and shift to the left in the diagrams of the FRF’s maximum values, which implies an increase of damage degree. In the strengthened beam B1R, the variation of frequency values is less than the values recorded for the non-strengthened beam, thus demonstrating the validity of the NSM technique for reinforced concrete beams; in fact with the NSM technique there is a reduction of concrete crack width and more limited diffusion of cracks on the surface of beam.

| Damage degree | $f_1$ [Hz] | $\frac{\Delta f_1}{f_1^{D0}}$ % | $f_2$ [Hz] | $\frac{\Delta f_2}{f_2^{D0}}$ % | $f_3$ [Hz] | $\frac{\Delta f_3}{f_3^{D0}}$ % |
|---------------|------------|-------------------------------|------------|-------------------------------|------------|-------------------------------|
| D0            | 234.8      | 0                             | 604.2      | 0                             | 1098.2     | 0                             |
| D1            | 233.4      | 0.6                           | 598.4      | 0.9                           | -          | -                             |
| D2            | 203.8      | 13.2                          | 553.6      | 8.4                           | 1057.8     | 3.6                           |
| D3            | 200.2      | 14.8                          | 532.2      | 12.0                          | 1012.0     | 7.8                           |
| D4            | 200.4      | 14.6                          | 527.6      | 12.6                          | 988.0      | 9.1                           |
| D5            | 197.4      | 15.9                          | 520.8      | 13.8                          | 964.8      | 12.1                          |

3. Conclusions

The experimental dynamic tests were found to be a convenient non-destructive method for verifying the safety of intact, damaged, and strengthened reinforced concrete beams. Once the dynamic parameters of these types of beams are known, monitoring their dynamic response at different load levels and assessing the validity of the strengthening becomes feasible.

In this paper the dynamic response of concrete beams with reinforced steel bars and reinforced also with NSM CFRP circular and rectangular rods is evaluated by experimental tests measuring the natural frequency values in the condition of free-free ends. Main results obtained are:

1. the strengthening of RC beams with NSM CFRP rods permits to improve the performance under static tests;
2. reduction of frequency values is greater in the unstrengthened beams than in strengthened NSM CFRP rods both for rectangular and circular rods;
3. the variation in percent of frequency values is smaller in the strengthened RC beams at every damage degree.

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Acknowledgments

This research was supported by research funds provided by Polytechnic University of Marche. The authors would like to express their gratitude to all the technicians and students who collaborated to develop the experimental research.