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Assessment of shear damaged and NSM CFRP retrofitted reinforced concrete beams based on modal analysis

Danilo Mascarenhas Prado *, Ivan Dario Gomez Araujo, Vladimir G. Haach, Ricardo Carrazedo

School of Engineering of São Carlos, University of Sao Paulo, Av. Trabalhador Saocarlense, 400, 13566-590 Sao Carlos, SP, Brazil

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ABSTRACT

Near Surface Mounted (NSM) Carbon Fiber Reinforced Polymer (CFRP) has shown to be a very effective technique for shear strengthening of reinforced concrete beams. Previous work showed important strength increases due to application of NSM CFRP in undamaged beams. However, few results were found in the literature to show the effectiveness of the technique for retrofitting damaged beams, especially those subjected to shear. On the other hand, several studies have shown the applicability of damage identification techniques based on modal analysis in different types of structures. No studies were found on the application of such techniques to identify damage generated by shear, which causes a cracking pattern significantly differently from flexural cracking. The purpose of this investigation is therefore to identify damages generated by shear in reinforced concrete beams through modal analysis techniques. In the same way, for retrofitted beams, to verify the changes of dynamic properties during application of NSM CFRP technique. For this purpose, reinforced concrete beams were produced and some of them were subjected to pre-loads corresponding to 40% and 70% of beam strength. These beams were then retrofitted by NSM CFRP to identify experimentally the efficiency of the procedure. Prior and after any phase of damage and retrofitting, modal analysis were performed allowing comparisons of dynamic properties. Comparisons of natural frequencies, vibration modes, Modal Assurance Criterion, Coordinate Modal Assurance Criterion, modal curvatures and damage index allowed damage identification and localization in most cases. However, it was not possible to identify significant changes of dynamic properties when the beams were retrofitted, although the important increases in strength. In light of these results it is believed that the NSM CFRP technique could not improve significantly the stiffness of the structural element while increased their strength.

1. Introduction

Concrete structures are in constant deterioration due to several causes such as moisture, pollution, chemical attack and others. The application of non-destructive tools to detect damages is an interesting evaluation strategy. Vibration-based techniques have been successfully applied for structural health monitoring (Ooijevaar et al. [1]; Hu et al. [2] and [3]; Chang and Kim [4]). These techniques have currently focused on ambient vibrations, which can be measured during the normal use of the structure, avoiding the use of a shaker or other device to excite the structure (Azenha et al. [5], Aguilar et al. [6], Russo [7]). Once the structure is vibrating due to wind, traffic, micro seismic or other event, the vibration response is measured at selected points of interest, modal properties such as natural frequencies, mode shapes and damping can be determined. These properties have shown to be very important for damage identification. Once damage affects the stiffness of the structure at some region, this local change in the stiffness can be perceived in several modal properties.

After the identification of damages, retrofitted operations should be planned in order to repair or strengthen the structure being evaluated. Carbon Fiber Reinforced Polymers (CFRP) are recognized as a very competitive solution for strengthening of reinforced concrete structures. They are noncorrosive, lightweight, have high tensile strength and elastic modulus, allow fast, simple installation and can be applied in regions with difficult access (ACI 440.2R-08 [8]). Nowadays, the main FRP-based techniques used for the strengthening of RC elements are Externally Bonded Reinforcement (EBR) and the Near Surface Mounted (NSM). According to Dalfré [9], the first applications of CFRP on the strengthening of RC structures were using the EBR (Meier [10], Kaiser [11], Triantafillou et al. [12]). From these early works,

* Corresponding author.
E-mail addresses: pradomdanilo@gmail.com (D.M. Prado), igomez19@usp.br (I.D.G. Araujo), vghaach@sc.usp.br (V.G. Haach), carrazedo@sc.usp.br (R. Carrazedo).

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several researches were performed improving this strengthening technique (Li et al. [13], Jayaprakash et al. [14], Firmo et al. [15]).

The NSM is a more recent strengthening technique whose efficiency has already been assessed by several researchers (De Lorenzis and Nanni [16], El-Hacha and Rizkalla [17], Dias and Barros [18], Zhang et al. [19], Kim et al. [20]). In Near Surface Mounted (NSM) technique, thin cuts are made on concrete cover, filled with epoxy resin and CFRP strips are inserted into them. Although this additional installation work compared to externally bonded CFRP, NSM technique has higher strengthening effectiveness due to larger bond perimeter, confinement of the surrounding concrete, higher protection against vandalism, mechanical damages and aging effects. Besides this, the appearance of the retrofitted element is practically unchanged (Dias and Barros [21]).

NSM CFRP can be successfully applied to shear strengthening of reinforced concrete beams. Dias and Barros [21] noticed that inclined laminates (bridging the cracks) are more effective in shear strengthening than vertical ones. When the behavior of strengthened and reference beams was compared, they noticed that they followed a very similar behavior until formation of the shear crack in the reference beam. Above this level of force, a significant decrease of stiffness was noticed in the reference beam, while the strengthened beam remained stiff until a much higher load. The displacement corresponding to the maximum load was larger in the strengthened beam when compared to the reference one.

The presence of pre-cracking was also investigated by Dias and Barros [21,22]. From the 44 RC beams strengthened with NSM CFRP, four were loaded up to a point when a shear crack pattern was formed, corresponding to a force between 40.1% and 47.4% of the ultimate load (this percentage depended on the beam tested). An initial loss of stiffness occurred in pre-cracked beams and the mobilization of CFRP laminates occurred just after opening of pre-cracks. On the other hand, for undamaged (not pre-cracked) beams the mobilization of CFRP laminates occurred only after shear crack formation. Although these differences found, the load carrying capacity and ultimate deflection was not affected by pre-cracking.

Few experiments of reinforced concrete beams subjected to structural damage and subsequent vibration analysis to detect damage were found in the literature, especially those concerning beams strengthened by CFRP NSM technique. Capozucca and Bossoleti [23,24], Capozucca [25] and Capozucca and Magagnini [26] tested reinforced concrete beams strengthened with CFRP NSM for flexure. They could successfully evaluate the effect of bending cracking, loss of bonding between CFRP and concrete, and notching on the CFRP rods through vibration analysis.

The present paper focused on the behavior of reinforced concrete beams damaged by shear load. The cracking configuration generated by shear differs significantly from the observed in previous research regarding flexural cracking. Besides this, a step by step analysis during the retrofitting procedure allowed evaluation of dynamic properties of beams at different states such as undamaged, pre-loaded, after grooves opening for CFRP laminates installation, strengthened and after failure. Therefore, the purpose of this research is to develop a vibration based assessment of the concrete beams during the different phases related to damage and retrofitting process.

2. Theoretical background about damage identification

Several parameters and procedures based on modal properties were developed in the last decades to help in damage identification. Allemang and Brown [27] proposed the Modal Assurance Criterion (MAC). In this criterion, a scalar constant (the MAC coefficient) evaluates the consistency of two modal vectors, $\{\psi_i\}$ and $\{\phi_j\}$, containing the coordinates of a mode shape in selected points of the structure in a reference and a modified condition (Eq. (1)). A MAC value close to zero means that the two vectors are not consistent while MAC close to unity means that they are consistent. As suggested by Allemang [28], some typical uses of MAC coefficient are the validation of experimental results by comparisons with theoretical models, quality control and damage detection.

$$MAC_{(ij)} = \frac{|\{\psi_i\}^T \cdot \{\phi_j\}|^2}{(\{\psi_i\}^T \cdot \{\psi_i\}) \cdot (\{\phi_j\}^T \cdot \{\phi_j\})} \tag{1}$$

An extension of the modal assurance criterion is the coordinate modal assurance criterion (COMAC) introduced by Lieven and Ewins [29] with the focus in identifying which degree of freedom contributes to reduce the MAC coefficients. In this method for the definition of the COMAC coefficient (Eq. (2)), modal vectors of a reference and a modified condition, $\psi_{q,r}$ and $\phi_{q,r}$, in correspondence to certain numbers L of vibration modes of interest, are used to compute for each degree of freedom a number between zero and unity that represents the correlation between reference and modified condition. A low value of COMAC for a given degree of freedom means that the modal shapes are not consistent for that position of the structure. It can give helpful information for damage localization.

$$COMAC_{(q)} = \frac{\sum_{r=1}^{L} |\psi_{q,r} \cdot \phi_{q,r}|.^2}{\sum_{r=1}^{L} \psi_{q,r} \cdot \phi_{q,r} \cdot \sum_{r=1}^{L} \psi_{q,r} \cdot \phi_{q,r}.} \tag{2}$$

Pandey et al. [30] proposed a method of damage identification named Modal Curvature Difference method (MCD) based on the changes in curvature of mode shapes evaluated for a reference and a damaged situation. They developed numerical studies with a simply supported and a cantilever beam introducing damage at specific position and noticed that the changes in curvature mode shapes were also localized in the region of damage. The MCD coefficients are obtained by averaging the curvature differences between two sets of modal curvature, $k^a_{q,r}$ and $k^b_{q,r}$, calculated from the second derivatives of vibration modes, ϕ, at each measurement point.

$$MCD_{(q)} = \frac{1}{L} \cdot \sum_{r=1}^{L} |k^a_{q,r} - k^b_{q,r}| \tag{3}$$

$$k_{q,r} = \frac{\phi_{q+1,r} - 2 \cdot \phi_{q,r} + \phi_{q-1,r}}{h^2} \tag{4}$$

Here, L is the number of vibration modes of interest in a given frequency range and h is the distance between the measuring points. In the case of a beam, the measuring points can be spaced at constant distances along its length, thus the variable h is a constant.

Also with the objective of localizing the damage in a structure, Sttubs et al. [31] proposed a procedure, applicable to beams, based on changes of stiffness at specific locations of pre-damaged and post-damaged mode shapes, and a pattern recognition technique. They showed the performance of the procedure with a Finite Element Model of a continuous beam and results from monitoring of a bridge girder. They could accurately locate the damage in the structures tested through the Damage Index (DI).

The damage index method begins by defining the change in the flexural rigidity of a sub-region j of a beam, which is represented by the Eq. (5).

$$\beta_j = \frac{EI_j}{EI_j^d} = \frac{f_{j,i}}{f^d_{j,i}} = \frac{\left[(k^d_{j,i})^2 + \sum_{i=1}^{imax}\left(k^d_{j,i}\right)^2\right]\sum_{i=1}^{imax}(k_{j,i})^2}{\left[(k_{j,i})^2 + \sum_{i=1}^{imax}(k_{j,i})^2\right]\sum_{i=1}^{imax}\left(k^d_{j,i}\right)^2} \tag{5}$$