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A reflection on the application of vibration tests for the assessment of cracking in PRC/RC beams

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ABSTRACT

Occurrence of cracking damage in a structural, reinforced, concrete element leads to changes in its dynamic response. Nevertheless, the typical non-linear behavior of prestressed reinforced concrete (PRC) and reinforced concrete (RC) beams is characterized by cracking, due to the low tensile strength of concrete. It is necessary to take adequate account of cracking effects, in vibration-based monitoring of PRC/RC beams' structural health, by distinguishing cracking of tensile concrete due to bending moment under service loads; which does not reduce the structural availability of beams although it modifies their dynamic response, from real damage deriving from defects, loss of integrity and cracking due to overloading during service life.

This paper deals with cracking effects through an investigation of PRC/RC beam models in real scale, subjected to increasing static loading and natural vibration tests. Degradation of stiffness and development of cracking were related to frequency values measured in a frequency range through vibration tests on free end beams. The results are compared with theoretical values and discussed.

1. Introduction

The durability of prestressed reinforced concrete (PRC) and reinforced concrete (RC) structures deteriorates due to the continuous accumulation of structural damage during artefacts' service life. Reinforced structures may also be subjected to damage as a result of insufficient reinforcement, large deflections, poor quality concrete, corrosion of steel reinforcement or insufficient capacity [1,2]. Structural monitoring has undergone an acceleration during the last decades with numerous applications on civil constructions, bridges, towers, frames and beams, and in new, vibration analysis based researches.

The basic concept underlying damage analysis of reinforced concrete frames or beams with vibration-based monitoring is that dynamic characteristics are functions of structures' physical properties therefore any change caused by damage, results in change in dynamic response [3].

The possibility to assess structures and detect damage in its earliest state is considered of great interest in the domain [4]. Many methods have been reported in literature, most of these, based on the vibration characteristics of structures, analyze damage as a result in the changes in natural frequencies and mode shapes [5–9]; the change-in modal strain energy method [10], the change-in-flexibility method and the structural model updating method [10,11].

Damage is usually conceived as one or more open cracks, as the decay of the mechanical properties of part of a structural element, as a decrease of stiffness. A number of efforts have been made to consider the influence of cracked beams on vibrations. When damage is concentrated, a rotational spring can model the dynamic behavior of a damaged element [12,13]. One of the models used is the reduced Young's modulus and moment of inertia [8,14]. Other cracked beam models have been developed to properly represent crack effects using the stress or energy approach [15–17]. A crack model which considers stiffness loss at crash locations and the ineffectiveness of material around crack locations, is developed using energy formulations and fracture mechanics [18]. In general, damage due to cracking in reinforced concrete beams, interests a part of beam with many diffused cracks. In this case, concentrated springs do not allow accurate damage modeling. A number of authors have defined theoretical methods for detecting damage using a beam model where three quantities are needed to represent diffused damage: location, extension and magnitude [19,20].

There is abundant reporting, in scientific literature, on the use of vibration data for locating damage in controlled conditions or in numerical simulations of beams built using homogeneous material. Although some works have addressed the influence of cracking in the dynamic response [21–24] of nonhomogeneous beams, many theoretical aspects require additional investigation. Further experimental results are needed to improve vibration-based

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Nomenclature

^{U,D}	index for uncracked state; index for cracked state	λ	eigenvalue
A	cross section area of beam	ω	circular frequency value; angle of phase
L	length of beam	$f, \Delta f$	frequency value; difference between undamaged and damaged frequencies
H, B	beam height; beam width	M, M_y	bending moment; bending moment at yield point
I	moment of inertia of beam	M_{cr}, M_u	bending cracking moment; bending ultimate moment
EI	bending stiffness of beam	χ, χ_y	curvature of RC section; curvature at yield point
P	radial force due to prestressing steel	D_i	cracking degree
N_p	precompressive load	DC	damage coefficient
S	shear internal force	A_{sp1}, A_{sp2}	prestressing steel area
φ	inclination of beam axis	E_s, E_c	modulus of elasticity of reinforcement; modulus of elasticity of concrete
v	deflection of beam axis; vertical displacement of the middle of beam axis		
r, f	index of vibration mode, index for free end		
exp, th	index for experimental value; index for theoretical value		

monitoring know how. In the case of PRC/RC beams, the presence of cracks on concrete's surface is due to concrete's low tensile strength; cross sections change their resistant geometry from uncracked for low tensile stresses, to micro-cracking under service loads, to large cracks close to yield of steel bars with irreversible damage. Cracking of PRC/RC beams as an equivalent damage may be investigated by vibration tests, although cracking under service loads does not reduce structural availability. The paper presents a comparison between theoretical and experimental results, thus distinguishing dynamic changes due to cracking damage in the elastic behavior of beams from permanent cracking damage in the inelastic phase.

The paper's main goal is to relate the changing of dynamic responses in PRC/RC beams to different bending moment while evaluating the suitability of the vibration monitoring technique in the assessment of damaged PRC/RC beams. In order to obtain this objective, the experimental research was developed on real scale PRC/RC beam models using vibration tests at different bending loading levels, measuring frequencies in a frequency range and evaluating mode shapes directly through tests on free end beams. The experimental values obtained are compared with data obtained by theoretical analysis and discussed.

2. Experimental beam models and tests

2.1. Experimental test on PRC beam

One undamaged PRC simple supported beam model with a double T shape cross section (Fig. 1) was subjected to increasing bending load by three cycles with the following values of moment at mid length [25]: M_1 = 1.20 kN m (M_1 is almost equal to $M_{cr,th}$ = 1.165 kN m, first cracking moment of prestressing cross section) that represents the first cracking degree D_1; M_2 = 1.81 kN m ($M_2 > M_{cr,th}$), second cracking degree D_2; M_3 = 2.26 kN m, third cracking degree D_3.

The geometric dimensions of the section and the main mechanical parameters of the PRC beam are shown in Table 1. As shown in Fig. 2, the behavior of the mid length cross section of the PRC beam is non linear due to cracking of concrete in the tensile zone although, as known, the presence of a prestressing tendon allows the closing of cracks up to high loading values. The theoretical ultimate moment of section is equal to $M_u \approx$ 4.3 kN m, also taking into account one steel bar measuring 8 mm in diameter in proximity of A_{sp1}, equipped with a glued, strain gauge that is capable of measuring strain during the bending tests.

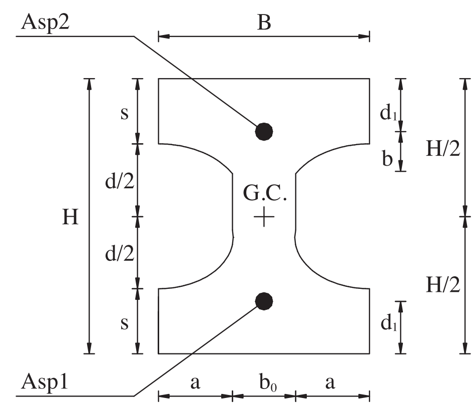

Fig. 1. Cross section of experimental PRC beam.

The beam was subjected to free vibration both at the uncracked state, before the bending test, D_0 degree, and after each cycle of loading. Natural frequencies were measured for the first four vibration modes. During the dynamic tests, the beams are hung by flexible springs with stiffness equal *to* k = 1.5 N/mm which simulate the free-free boundary conditions as illustrated in Fig. 3a. The beams were excited by impulsive load using an impact hammer (*Brüel & Kjær Impact Hammer Type 8202*) and the response was measured at 27 different points, at 87.5 mm intervals, using an accelerometer. The impact hammer can exert a maximum force of 5 kN, with a 122 gm mass addition and the use of rubber bit. Frequencies were extracted by transformed signals in frequency domain using the Fast Fourier Transform (FFT) technique [24,25]. Table 2 contains the experimental results of the PRC beam's bending test. Two sets of frequency measurements were acquired at the end of each loading cycle (Table 3). The various sets of frequency measurements were acquired in a frequency range of 0–800 Hz, with a 0.5 Hz resolution, by exciting the beam with the impact hammer on point 1 on an edge and subsequently varying the position of the accelerometer along each of the 27 fixed points along the beam.

2.2. Experimental tests on RC beams

Dynamic tests developed using the same, aforementioned procedure were carried out on three RC beams [25]. Beams B1 and B2 were reinforced with four longitudinal steel bars measuring 10mm and 14mm in diameter, respectively; B3 was reinforced with two steel bars measuring 10 mm and 2 of 16 mm in diameter.