SHM Based on Modal Analysis: Accelerometer and Piezoelectric Transducers Instrumentation for Civil Engineering in Heterogeneous Structures

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Andrés BELISARIO-BRICEÑO [1,2], Sabeha ZEDEK [1,3], Thierry CAMPS [1,2], Raoul FRANÇOIS [3,4], Christophe ESCRIBA [1,3], Jean-Yves FOURNIOLS [1,3]

[1] *LAAS – Laboratoire d'Analyses et d'Architecture de Systèmes – 31077 Toulouse*
[2] *UPS – Université Paul Sabatier – 31062 Toulouse*
[3] *INSA Toulouse – Institute National des Sciences Appliquées – 31077 Toulouse*
[4] *Université de Toulouse, UPS, INSA, LMDC – Laboratoire Matériaux et Durabilité des Constructions de Toulouse – 31077 Toulouse*

belisario@laas.fr

ABSTRACT

This paper presents a strategy for the detection of mechanical damage of a reinforced concrete beam strengthened by Carbon Fiber Reinforced Polymers (CFRP) sheets (TFC ©) based on the joint use of piezoelectric sensors and conventional accelerometers. The beam is subjected to repeat impacts that may represent the action of vehicles on a roadway joint of a bridge, at different levels of damage induce by bending of the reinforced concrete beam. The results show that piezoelectric sensors provide a much wide response those accelerometers allowing a study in the high frequency range (above 2 kHz). The spectral response appears largely affected by mechanical damage on the beam and suggests a possible use for SHM in Civil Engineering structures.

KEYWORDS : *SHM, Piezoelectric, Modal Analysis, Heterogeneous Structures.*

INTRODUCTION

One way to address the understanding and modeling of large complex systems is to develop a distributed instrumentation based on multiphysic sensors, combining low energy versatile computing architecture to diagnose weaknesses of the observed system. We focus for several years on methods and technologies able to analysis vibrations propagation in heterogeneous materials. In this article we demonstrate how distributed instrumentation onto surface can benefit on the vibrations induced by road traffic on a civil engineering work to diagnose, by a frequency signature variation, identifying structural changes in the structure synonym of potential defects.

Owed to the growth of traffic on the bridges and environmental attacks such as deicing salt, progressive damage could occur and lead to premature end of service life. We offer a case study where a concrete member is subjected to mechanical damage due to over-loading in flexure. The structure studied and characterized is a reinforced concrete beam strengthened with Carbon Fiber Reinforced Polymer (CFRP). To perform a wide-band spectrum analysis, we compare sensor response provided by a silicon accelerometer and piezoceramic transducer.

Such an approach with large-scale frequency response is worth of interest for successful prognosis damage detection. The experiment's principle is compare efficiency and complementarity of piezoelectric and accelerometer frequency response. The methodology presented in the final paper demonstrates as beam's harmonics frequency changes before and after mechanical stress – pressure and impulsive shocks.

EXPERIMENTAL BENCH

The beam tested is a reinforced concrete element with dimensions of 150 x 280 x 3000 mm. As reinforcement two high bond (ribbed) rebars with 12 mm diameter were embedded (cover depth 20 mm) and the beam is strengthened by a carbon sheet (TFC©) on tension surface. The beam is subjected to 4-point bending and instrumented with two ends and mid range *Fig. – 1*.

Such an approach with large-scale frequency response is worth of interest for successful prognosis damage detection. The experiment's principle is compare efficiency and complementarity of piezoelectric and accelerometer frequency response. The methodology presented in the final paper demonstrates as beam's harmonics longitudinal frequency changes before and after mechanical damage.

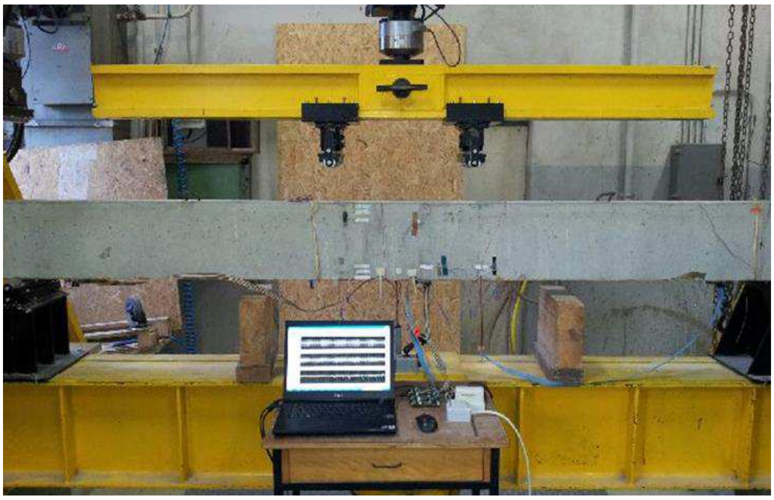

Figure – 1: Test setup 4-point bending bench and instrumentation

Loading consists of a bearing of 20kN above cracking level and a loading of 30 kN after yielding of tension reinforcement followed by a total unloading of the beam *Fig. – 2.* The impacts made on the end of the beam are obtained by a jackhammer with a slightly curved cylindrical tool steel to avoid damaging the concrete and impacting the beam at a rate of about 24 strokes per second.

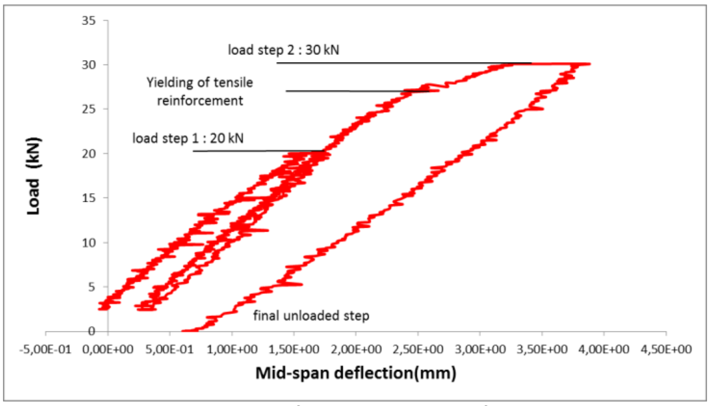

Figure – 2: load versus deflection and levels of measurement

The acquisition system comprises a measurement three-node zone with an accelerometer (XYZ) and a piezoelectric transducer –PZT–. These sensors are robust and low cost which can allow installation on large structures such as bridges. The use of accelerometers in three directions of the beam will verify the accuracy of information delivered by the PZT sensors *Fig. – 3*.

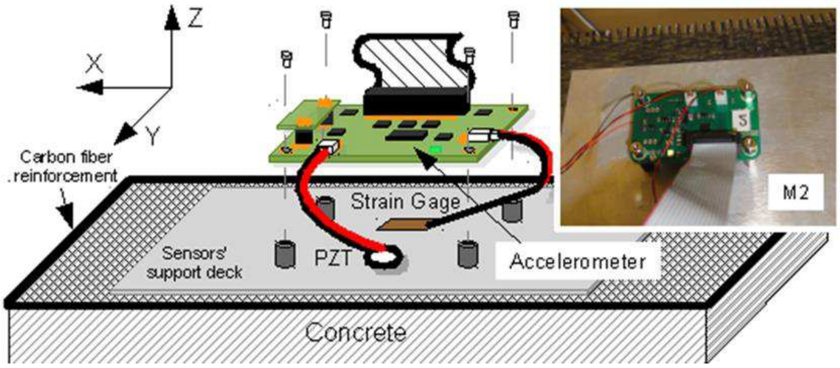

Figure – 3: Detail of the instrumentation architecture of measurement

The piezoelectric transducer is used for acoustic emission detection. The piezoelectric material we chosed in $PbZrTiO_3$ alloy, graded PZT-5A. This sensor has an excellent electro-mechanical coupling with |D31| = 175 pC/N. The associated charge amplifier with the PZT was designed to eliminate the low frequency waves, under 100 Hz, and it provides a steady gain up to 20 kHz and a total gain of 220 dB V/C. An 8 th order low pass filter limits the bandwidth of the system to 20 kHz with a rapid cutoff. Lastly, the accelerometer is based on the MMA7361. As specified in its data-sheet, the accelerometer is limited to 1.6 kHz with a double 1st order filter. It features a selectable sensitivity of 1.5G or 6G and a bandwidth of 1.6 kHz on three axes.

ANALYSIS OF EXPERIMENTAL RESULTS

The *Fig. – 4* shows the response of sensors. The accelerometer incorporates the vibrations along the axes X and Y, *Fig. – 4.a*. The PZT is omnidirectional in the plane longitudinal and transverse, *Fig. – 4.b*. In addition, we also find that the PZT sensors are used to obtain a high response, (rate>1kHz), which is not the case of accelerometers.

This is the last show a reduced bandwidth (~2kHz), but also and especially a limited signal to noise ratio 40dB which does not allow them to measure vibration in more than two decades. For its part, the PZT sensor is not limited by its frequency response and allows measurements over a dynamic signal than four decades. This is valuable for signal analysis beyond the kilohertz or the signal amplitude is attenuated rapidly, from 3 to 4 order of magnitudes. Thus, we clearly see the presence of vibrations up to about 10kHz (50µS).

In the figure below – *Figure 4.b* –, we can see that the difference between the spectra of the piezoelectric sensor and accelerometer. We can perceive as the rich spectrum of the PZT contains more information beyond the 2 kHz, as a perspective for the progress of this research work this will be the area of interest for data exploitation.

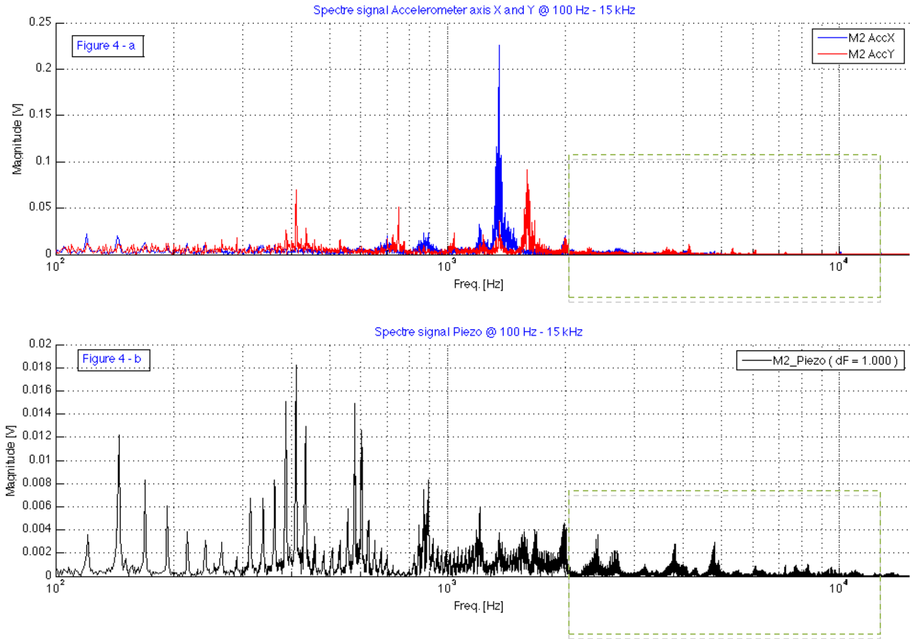

Figure – 4: Comparison of spectral profiles accelerometers X and Y with the PZT

To analyse the behavior of the beam, it will be based on the excitation imposed by the jackhammer and simplify the spectrum by discretizing frequency. For example, we cover the spectrum after damage to 30 kN *Fig. – 5* by restricting the analysis to 2 kHz. The discretized signal is studied in the frequency of stimuli beyond 2kHz as show in *Figure 5b*. According to a mathematical approximation a script we find the spectral signal profile.

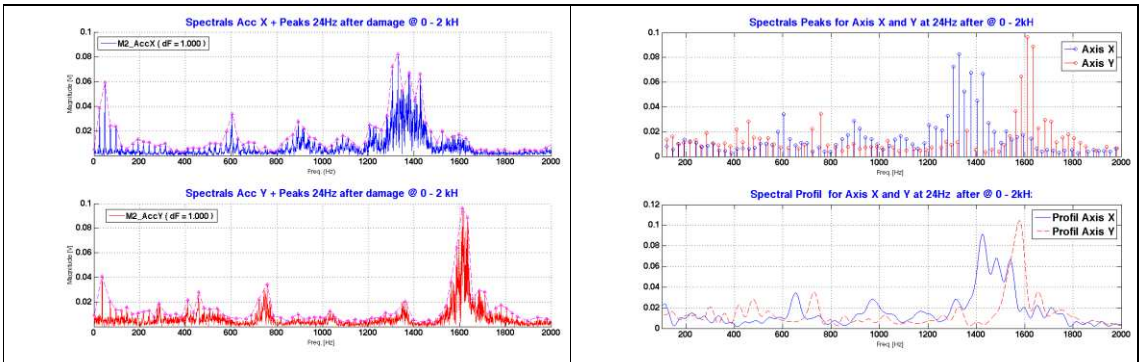

Fig. 5.a

Fig. 5.b

Figure – 5: (a) Signals Accelerometers Raw and peaks excitation rate (b) Discrete Peaks and Spectral Profile

After an acquisition time of 5 seconds with sampling at 50 kHz, there are 250,000 points. The first two seconds, corresponding to the transitional regime are removed, and reduces the acquisition to three seconds in regime-established, 150000 pts. This score is very high and in the perspective of achieving an autonomous system and compact, it's necessary in our pre-treatment drastically reduce these numbers point to a few hundred points.

To analysing the waveform, we used the *Discrete Fourier Transform* –DFT– of the time signal gives a spectrum ranging from 10 to 20 kHz, with high resolution – 0.33 Hz– and it is still ready to treat 60,000 pts. Instead of full spectrum, we prefer the discrete spectrum is limited to keep the points in the spectrum corresponding to multiples of the excitation rate impact – 24.17 Hz, this decimated FFT consists of only 827 points in accordance with our expectations *–Fig. 5.b* – and – *Fig. – 6 for the PZT–*. Although this seems coarse spectrum envelope, it's still relevant to the degradation of quantization.

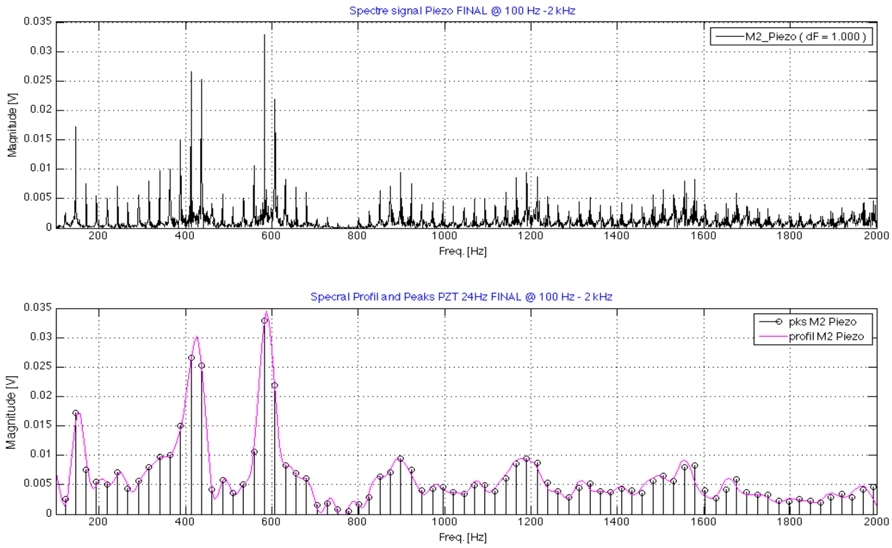

Figure – 6: Spectral profile of PZT and Harmonics at Stimuli's frequency

To better visualize the change in spectral response, the relationship between the track amplitude spectrum before and after damage due to the load (30kN) beyond the bearing steels plasticity tensioned. This amplitude ratio gives information about the irreversible damage suffered by the beam. In the below images we can note the spectral changes in two frequency bands. We divided the frequency into two groups, low -0 Hz @ 2 kHz- and high for -2 kHz @ 15kHz.

This visual method *Fig.* – 7 will allow us to look at changes in spectral level of the initial state of the structure. We can quantify several methods for treating the mechanical phenomena of the signal from structure. One of the easiest to implement analyses is to find how the are responses to frequency change in amplitude and own frequencies.

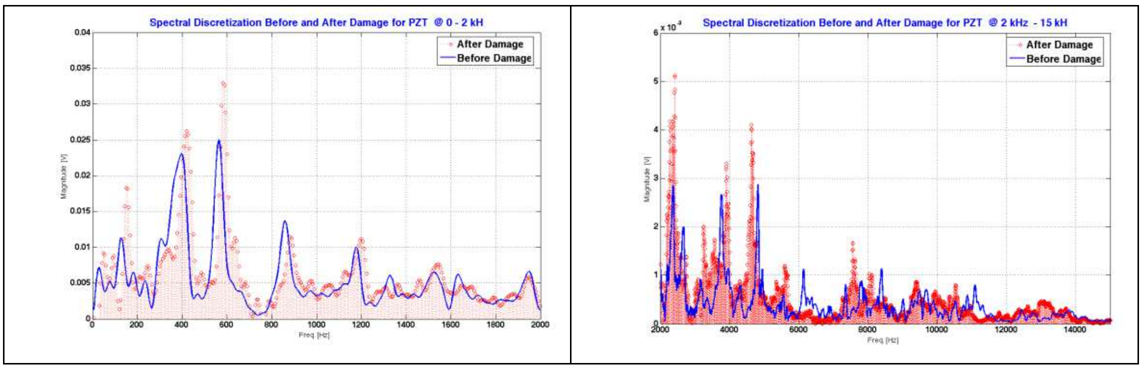

Figure – 7: Spectral Profile before damage and Spectral Harmonics after damage

We noted how the spectral change of the signal recovered after damage is shifted in frequency. The spectral profile in high frequency is shifted in frequency and magnitude.

It is thus possible propose a method of monitoring the work in relation to a certain definition of the level of damage. And setting a threshold can control the level of damage and launch control when this threshold is reached. In practice, it may be more appropriate to define the damage threshold compared to an area rather than level.

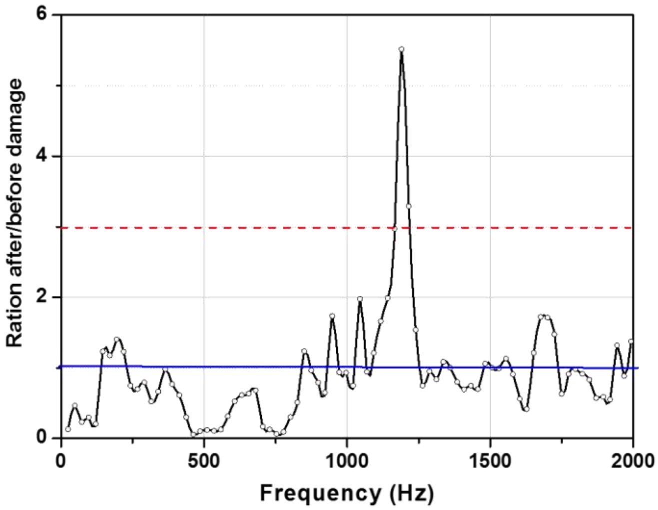

Figure – 8: Evolution of the amplitude spectrum before and after damage by a load 30kN

A possible solution in our analysis is triggered some value amplitude value as we saw previously demonstrated the frequency-displacements and the voltage gain after the degradation of the health of structure.

It remains to quantify the level of mechanical damage measured by the amplitude ratio. Furthermore the frequency domain where the threshold is exceeded likely to learn about the size and nature of the damage. This will be a series of tests at different load levels and type of irreversible damage on reinforced concrete elements and then be quantified by approaches based on learning by neural networks

We are interested to develop an autonomous and intelligent system for the calculation and estimation points for the signal dynamics with the help of software acquisition of data and signal processing.

CONCLUSIONS AND PERSPECTIVES

The analysis of the spectral response of a reinforced concrete beam requested by longitudinal vibrations that can simulate the traffic on the bridge deck shows that its spectral response is sensitive to irreversible mechanical damage undergone by the beam. A first analysis based on the difference in amplitude of the harmonic response of the request indicates that it is possible to quantify damage by spectral analysis. It remains of course to progress on the meaning and classification of damage by correlating the spectral evolution to mechanical damage.

In addition, *Fig.* – 9 shows spectral responses of beam for a range from 0 Hz to 2 kHz (9.a) and from 2kHz to 15kHz (9.b) before and after degradation. For the first range, spectrum are quite similar and the second one spectrum are distinctly separate (appearance of new resonances) and we believe that it is in this range it will be investigated to extract a spectral fingerprint of the degradation.

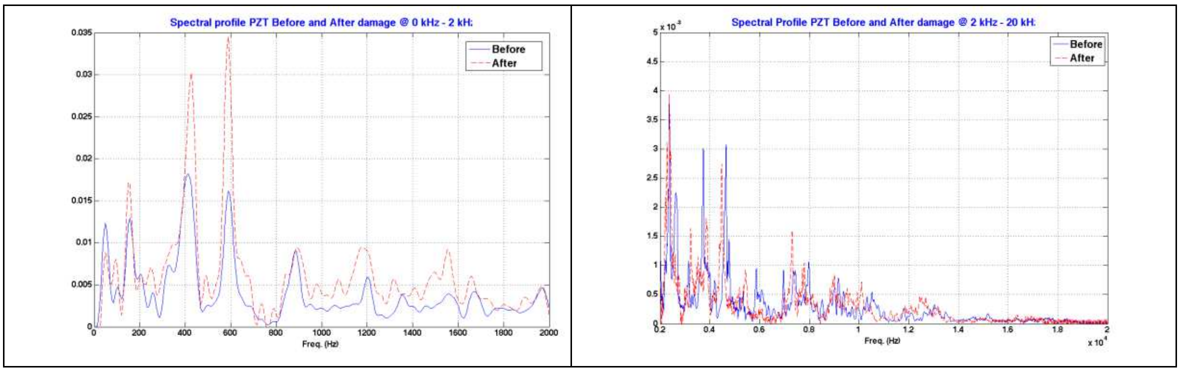

Figure – 9: Evolution of the spectra measured by the PZT in the range 1kHZ to 20kHz damage before and after a loading 30kNw

To achieve this we must have, by changing the first floor "charge amplifier" integrate a high pass filter to (FC ~ 2kHz), and thus reduce the amplitude of low frequency high amplitude signals (longitudinal mode)! This will amplify particular advantage before the A/D conversion and the time signals will also reduce acquisition time to 0.3 seconds while maintaining good accuracy.

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