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# Towards passive ultrasonic sounding of a steel-concrete-steel containment structure using embedded optical fibers

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## ABSTRACT

We present a Steel-Concrete wall model equipped with several embedded fiber Bragg Gratings (FBGs) and several embedded and surface piezoelectric accelerometers (PZAs). We compare the performances of these embedded sensors for several ultrasonic sources disposed on the surface of the wall and emitting at frequencies between a few tens and a few hundreds of kilohertz. We observed that a significant part of the wave energy can be transmitted to the concrete through the surface liner, despite the high mechanical contrasts between steel and concrete. Using a collection of random hammer impacts applied on the steel surface, we further attempted to reconstruct empirical Green's functions between pairs of sensors buried into the structure using passive seismic methods.

Keywords: Steel-concrete structures, Non-destructive evaluation, Embedded ultrasonic sensors, Optical Fibers, Bragg gratings.

## 1 Introduction

Steel-Concrete-Steel (SCS) structures are made of concrete poured between two metal plates (liners), serving both as a form-work and a mechanical reinforcement. Metal spikes anchored to the liner can be used to provide the coupling between the concrete and the steel plates. These structures are used in confinement structures in nuclear power plants. Because of the liner, visual inspection of the surface of the concrete is not possible. Non Destructive Testing and Evaluation methods (NDT, NDE) are therefore required to probe the concrete. The transmission of ultrasonic waves from the liner to the internal part of the structure is difficult due to the high mechanical contrasts between steel and concrete or when local detachments of the liner occur. This may alter the efficiency of the standard NDE approaches involving ultrasonic waves [3, 7].

In this project, we attempted to overcome this difficulty by using acoustic sensors embedded in the concrete part of a SCS module, which allows us to reduce the distance to the external sources (disposed on the liner). In particular, we focused on the use of Fiber Bragg Gratings (FBGs). This sensing technology based on state-of-the-art optoelectronics allows us to measure the dynamic strain at the location of the Bragg gratings along the fiber axis. These sensors can be used at ultrasonic frequencies over broad frequency ranges, and have proven their potential in Structural Health Monitoring applications based on passive diffuse noise correlation techniques [4, 6]. The deployment of FBGs embedded in concrete provides numerous advantages [5], their footprint on the structure is negligible, one can have several measurement points on the same fiber and the fiber are resistant to challenging environments (temperature or radiations).

We built a reduced scale model of a Steel-Concrete structure, in which we embedded several FBGs together with more conventional PZAs. Our main objectives were (a) to characterize the signals recorded with embedded FBGs, and to improve our understanding of their response in comparison to PZAs, (b) to evaluate the transmission of ultrasonic waves in the concrete for sources placed on the metal plates, and (c) to test the feasibility of using noise correlation methods in order to approximate the Green's function between pairs of embedded receivers using random sources applied on the liner.

## 2 Methods

### 1.1 Samples

A reduced scale model of a Steel-Concrete confinement wall (25 x 120 x 135 cm<sup>3</sup>) was designed and built for the project. During the casting, 5 traversing optical fibers with a total of 36 Bragg gratings were buried in the wall, as well as 8 PZAs (Brüel & Kjær 4393). Only one side of the wall was covered with a steel liner, but studs were inserted on both sides of the wall (Fig. 1). A few additional PZA sensors were glued outside the structure, on both sides of the wall.

### 2.1 Sources

Several piezoelectric sources (Ultran GC30 30 kHz, Panametrics V1011-100 kHz, V1012-250 kHz, V106-2.25 MHz) were applied to the faces of the wall to test the following source functions

- a Ricker function with a center frequency incremented from 10 to 300 kHz,
- a sweep function covering all frequencies between 150 and 350 kHz

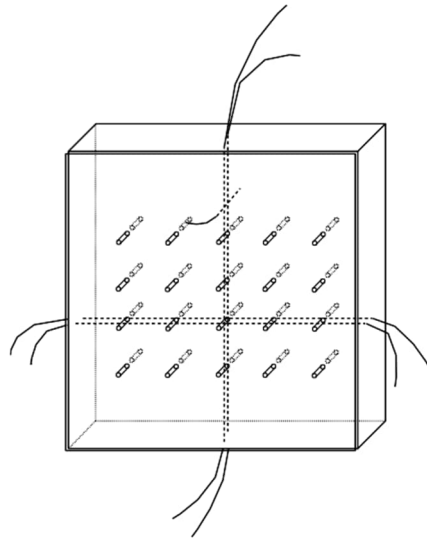
Additionally, random impacts were made with a hammer or with a robot-controlled impactor able to cover all the surface of the metal plate. The spectrum of the latter sources extended from about 5 to 70 kHz.

## 2.2 Data analysis

The recorded signals were visualized in the temporal and spectral domains. For the random hammer sources applied on the liner face, we implemented a correlation method initially designed to process ambient acoustic or seismic noise to recover the empirical Green's function of a medium between a pair of receivers according to the following relation [1]

$$\frac{\partial C_{AB}}{\partial t} \approx G_{A \rightarrow B}(-t) - G_{B \rightarrow A}(t) \quad (1)$$

In this method, the signals must be pre-processed using spectral and/or temporal normalization [2] in order to balance the contribution of every sources and to approach the ideal case of an uniform distribution of the sources or a diffusive wave-field.



*Figure 1: Scheme showing the geometry of the Steel-Concrete wall model built in this project. The front side is equipped with the steel liner. The concrete is bare on the back, lateral and upper faces of the wall. Studs were installed on both sides of the wall. The dashed lines denote the traversing optical fibers.*

## 3 Results

### 3.1 Comparison of an embedded FBG and PZA

A first series of measurements was carried out using sources glued to the concrete on the upper face of the wall, in order to avoid issues related to the transmission of waves through the liner. The emitted source was a Ricker pulse, whose center frequency was gradually increased from 50 to 300 kHz (Fig. 2, red).

The longitudinal dynamic strain measured with the embedded FBG named "V2B4" (Fig. 2, blue signals) and the particle acceleration measured with the embedded PZA "A2" (Fig. 2, black signals) had a good signal to noise ratio and allowed us to identify the first arrivals clearly. The shape of the spectrum obtained with the FBG was in good agreement with the source one, while the PZA had a peak near its resonance frequency (at 55 kHz for this sensor).

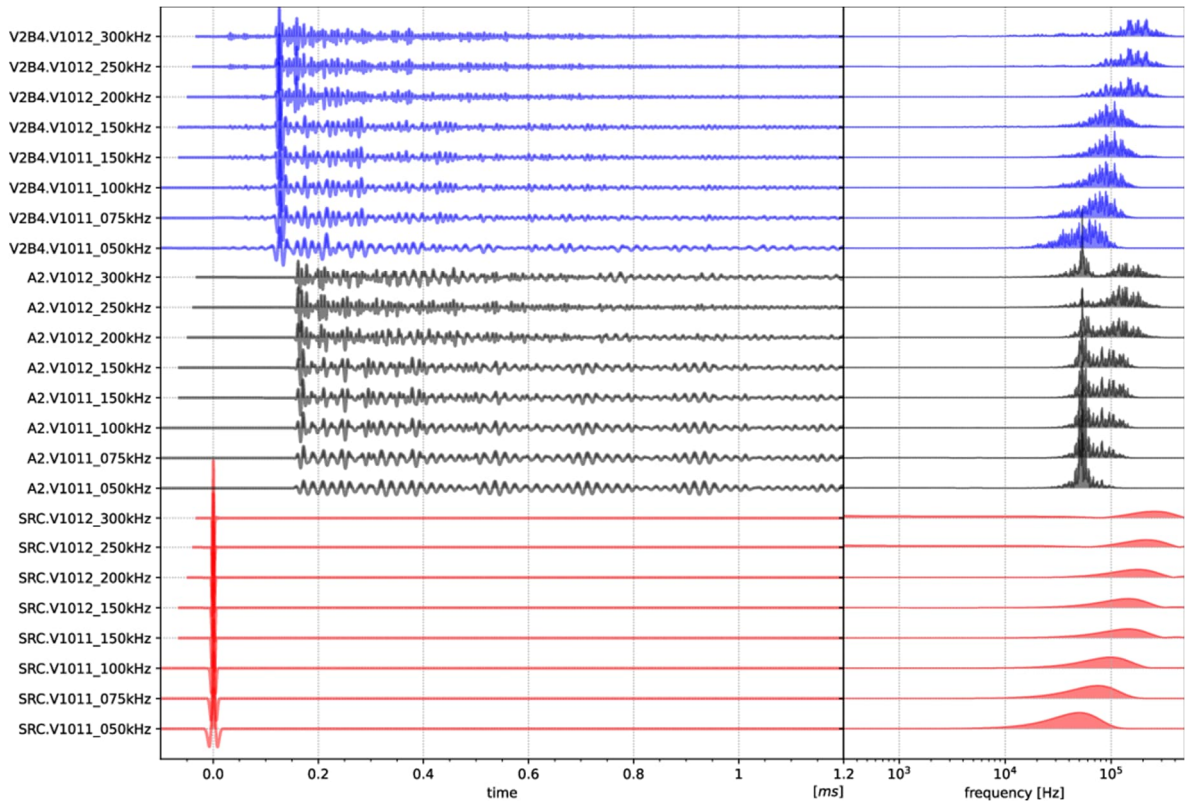


Figure 2: Signals recorded inside the wall by two nearby FBG (V2B4, blue) and PZA (A2, black) for several Ricker source functions (SRC, red) centered between 50 and 300 kHz. The signals are shown in time (left) and spectral domains (right).

### 3.2 Transmission of ultrasonic waves to the concrete

A second series of measurement was carried out in order to evaluate the transmission of ultrasonic waves in the concrete despite the high contrasts of impedance at the steel-concrete interface. We deployed a source emitting a sweep ranging from 150 to 350 kHz on either faces of the test wall, covered or not by the liner (Fig. 3, see source points named "B2a" for the concrete side of the wall and "M2a" for the liner side). The input sweep was correlated with the recorded signals in order to remove its temporal signature and to return to an impulsive record. This test showed that acoustic signals can be recorded with embedded receivers (FBGs and PZAs) at frequencies between 150 and 350 kHz. A reduction of the signal to noise ratio was observed when the source is placed on the liner (especially for the PZAs), but this did not seem to affect the waveform and the shape of the spectrum significantly.

Another potential limitation of ultrasonic methods for this application comes from the presence of local detachments of the steel plate. A possible alternative consists in placing the sources at the emerging end of the studs (Fig. 3, the source point "ST21" corresponds to the source placed on a stud, on the concrete side of the wall and "MST21" corresponds to the source being placed on a stud on the liner side). Here also, no clear changes in waveform and spectral shape could be observed between the two source locations. A complementary experiment in which the liner would be deliberately decoupled from the concrete would help concluding on the usefulness of placing sources at the extremity of the studs.

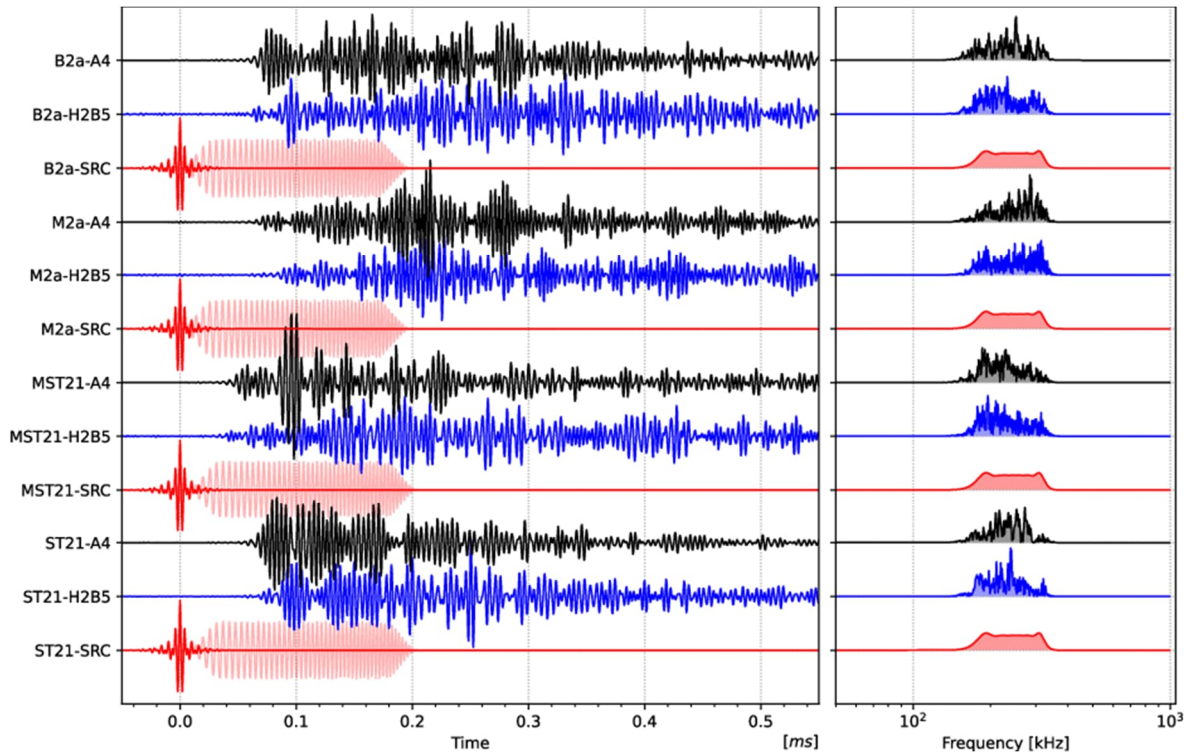


Figure 3: Signals recorded inside the wall by two nearby sensors: a Bragg grating (H2B5, blue) and a piezoelectric accelerometer (A4, black) for a source placed at various positions on the wall and emitting a sweep between 150-350 kHz (red). The signals are shown in time (left) and spectral (right) domains after correlation with the input sweep (shown in light red). The source is placed on the liner or concrete side (M2a/B2a), at the extremity of a stud on the metal or concrete side (MST21/ST21). The amplitudes are normalized for each trace individually.

### 3.3 Noise source correlation

Finally, we tested the possibility to obtain empirical Green's functions between pairs of embedded acoustic sensors for a collection of hammer impacts randomly distributed at the surface of the liner. Some pre-processing steps were applied to the recorded signals for each sensor individually. These steps implied spectral normalization (whitening) and the clipping of the largest amplitudes of the signal in the time domain. The signals were then correlated between pair of sensors, stacked and derivated temporally following equation 1.

For frequencies between 5 and 15 kHz, we obtained an anti-symmetrical correlation function (as expected from eq. 1), which suggests that both causal and anti-causal estimates of the Green's function are in good agreement, and that the wave-field is nearly equipartitioned. For a pair of PZAs, a good similarity between the correlation functions of each individual shot was obtained (Fig. 4a), which reveals a fast convergence of the correlation function toward the approximate Green's function. For a pair of FBGs, the signal to noise ratio is lower, but a clear pattern emerges by stacking all the source contributions (Fig. 4b).

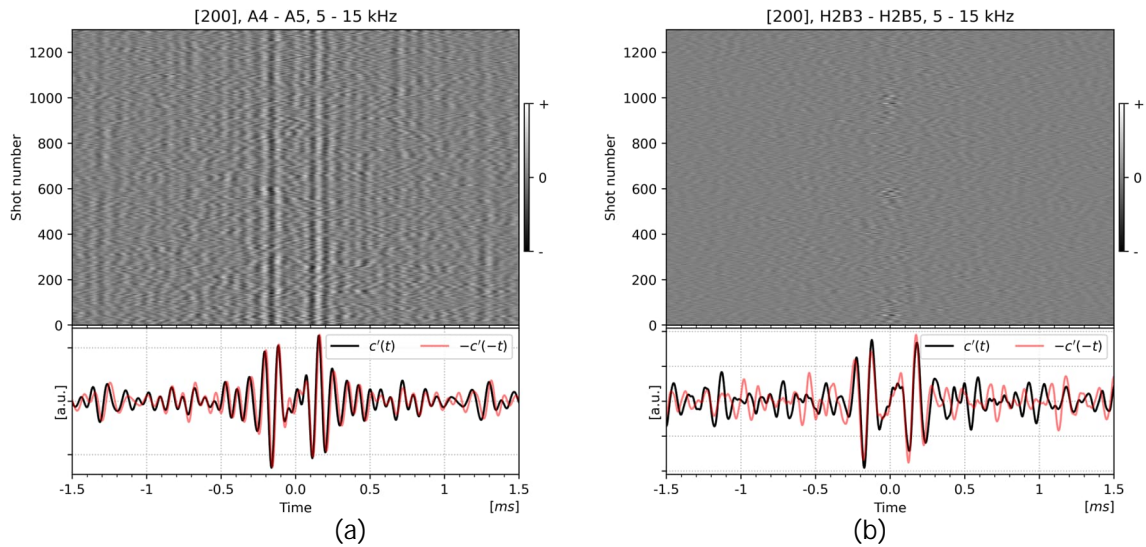


Figure 4: Estimates of the empirical Green's function by correlation of hammer shots, for a pair of PZAs (a) or FBG sensors (b). The upper part of the figures indicate the correlation functions obtained for each source individually. The stack function (black) and a reversed version of it (red) are shown at the bottom of the figures.

## 4 Conclusions

In this work, we evaluated our ability to acquire signals using acoustic sensors embedded in concrete for the non-destructive evaluation of a Steel-Concrete-Steel module. We tested a large panel of sources with known source functions (Ricker and sweep) emitting at frequencies from 10 to 350 kHz, as well as random hammer sources applied on the liner, whose spectrum extended from 2 to 70 kHz.

Our experiments carried out in a transmission regime revealed that a significant part of the energy emitted by a source positioned on the liner can be recorded inside the concrete with both PZA and FBG sensors, which suggests that this methodology can be used to evaluate the health state of a SCS module even though only the liner is accessible. An advantage of FBG lies in the shape of the spectra, which accurately reproduces the source one in the frequency range of interest. The signals obtained with embedded FBGs are usually more noisy than those of embedded PZAs. When the source term is well known and sufficiently repeatable, this can be easily addressed by direct summation of the records. For sources with an un-controlled or weakly repeatable source function, summation of the source contributions can be achieved through the correlation method usually employed for the processing of passively acquired noise wave-fields. Using this approach, we were able to approximate the Green's function of the medium between pairs of PZAs or Bragg gratings at frequencies between 5 and 15 kHz. Future efforts will concentrate on the possibility to extend this result to ultrasonic frequencies (above 20 kHz) and to use these signals in a non-destructive evaluation process.

## 5 Acknowledgments

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