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Ultrasonic evaluation of a steel-concrete structure using embedded Bragg gratings and piezoelectric sensors

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Abstract

We present a Steel-Concrete wall model equipped with several embedded fiber Bragg Gratings (FBG) as well as several embedded and surface piezoelectric (PZT) sensors. We compare the performances of these embedded sensors for several sources of ultrasonic waves applied on the surface of the wall for frequencies ranging from a few tens to a few hundreds of kHz. The signals obtained reveal 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 investigate the feasibility of reconstructing 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 Fibres, 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.



26 Because of the liner, visual inspection of the surface of the concrete is not possible. Non
27 Destructive Testing and Evaluation methods (NDT, NDE) are therefore required to probe
28 the concrete. The transmission of ultrasonic waves from the liner to the internal part of
29 the structure is difficult due to the high mechanical contrasts between steel and concrete
30 or when local detachments of the liner occur. This may alter the efficiency of the standard
31 NDE approaches involving ultrasonic waves [3, 7].

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

43 We built a reduced scale model of a Steel-Concrete structure, in which we embedded
44 several FBGs together with more conventional piezoelectric (PZT) accelerometers. Our
45 main objectives are (a) to characterize the signals recorded with embedded FBGs, and to
46 improve our understanding of their response in comparison to PZT accelerometers. (b)
47 to evaluate the transmission of ultrasonic waves in the concrete for sources placed on
48 the metal plates, and (c) to test the feasibility of passive correlation methods that aims to
49 approximate Green's functions between pairs of embedded receivers using random sources
50 applied on the liner.

51 **2 Methods**

52 **2.1 Samples**

53 A reduced scale model of a Steel-Concrete confinement wall ($25 \times 120 \times 135 \text{ cm}^3$) was
54 designed and built for the project. During the casting, 5 traversing optical fibres with a
55 total of 36 Bragg gratings were buried in the wall, as well as 8 PZT accelerometers (Brüel
56 & Kjær 4393). Only one side of the wall was covered with a steel liner, but studs were
57 inserted on both sides of the wall (Fig. 1). A few additional PZT sensors were glued
58 outside the structure, on both sides of the wall.

59 **2.2 Sources**

60 Several piezoelectric sources (Ultran GC30 30 kHz, Panametrics V1011-100 kHz, V1012-
61 250 kHz, V106-2.25 MHz) were applied to the faces of the wall to test the following source
62 functions

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

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

68 **2.3 Data analysis**

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

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

73 In this method, the signals generally needs to be pre-processed using spectral and/or tem-
74 poral normalization [2] in order to equilibrate the contribution of every sources and to
75 approach the ideal case of an uniform distribution of the sources or a diffusive wavefield.

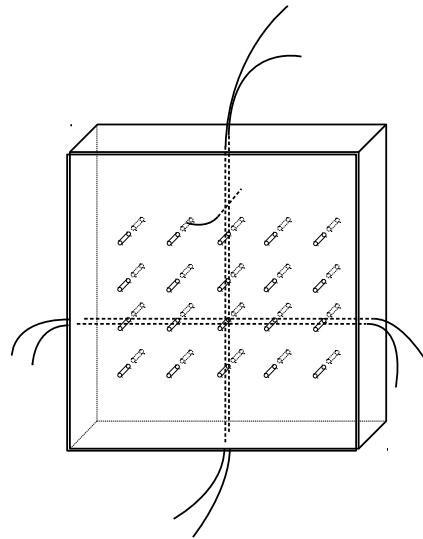


Figure 1: Scheme showing the geometry of the Steel-Concrete wall model built in this project. The front side is equipped with the steel liner. The concrete is bare on the back, lateral and upper faces of the wall. Studs were installed on both sides of the wall. The dashed lines denote the traversing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

76 **3 Results**

77 **3.1 Comparison of an embedded FBG and PZT accelerometer**

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

82 The longitudinal dynamic strain measured with the embedded FBG named "V2B4" (Fig.
83 2, blue signals) and the particle acceleration measured with the embedded PZT accelerom-
84 eter "A2" (Fig. 2, black signals) have a good signal to noise ratio and allow us to identify
85 the first arrivals clearly. The shape of the spectrum obtained with the FBG is in good
86 agreement with the source one, while the PZT accelerometer has a peak near its resonance
87 frequency (at 55 kHz for this sensor).

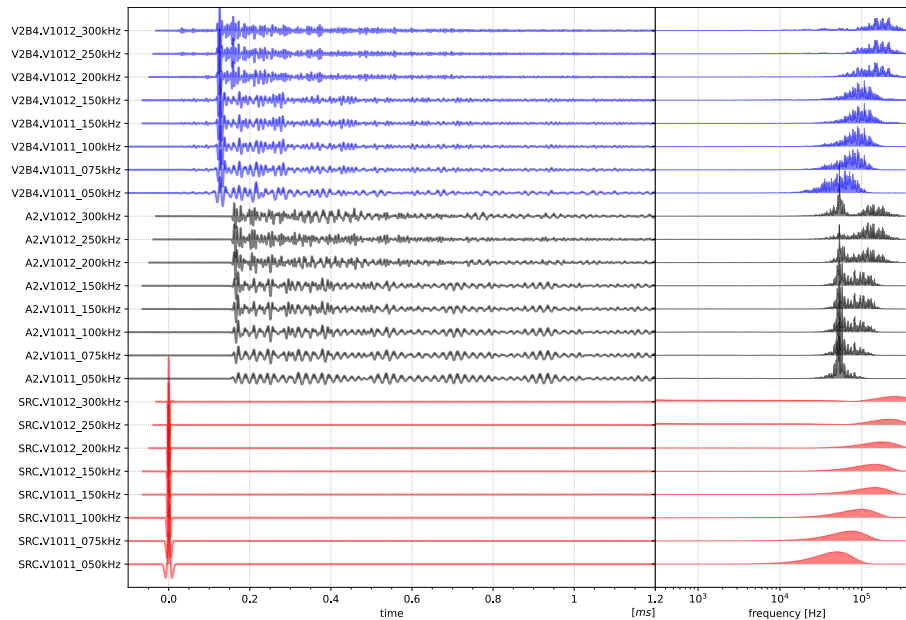


Figure 2: Signals recorded inside the wall by two nearby FBG (V2B4, blue) and PZT accelerometer (A2, black) for several Ricker source functions (SRC, red) centered between 50 and 300 kHz. The signals are shown in time (left) and spectral domains (right).

88 3.2 Transmission of ultrasonic waves to the concrete

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

100 Another potential limitation of ultrasonic methods for this application comes from the
101 presence of local detachments of the steel plate. A possible alternative consists in placing
102 the sources at the emerging end of the studs (Fig. 3, the source point "ST21" corresponds
103 to the source placed on a stud, on the concrete side of the wall and "MST21" corresponds

104 to the source being placed on a stud on the liner side). Here also, no clear changes in
105 waveform and spectral shape could be observed between the two source locations. A
106 complementary experiment in which the liner would be deliberately decoupled from the
107 concrete would help concluding on the usefulness of placing sources at the extremity of
108 the studs.

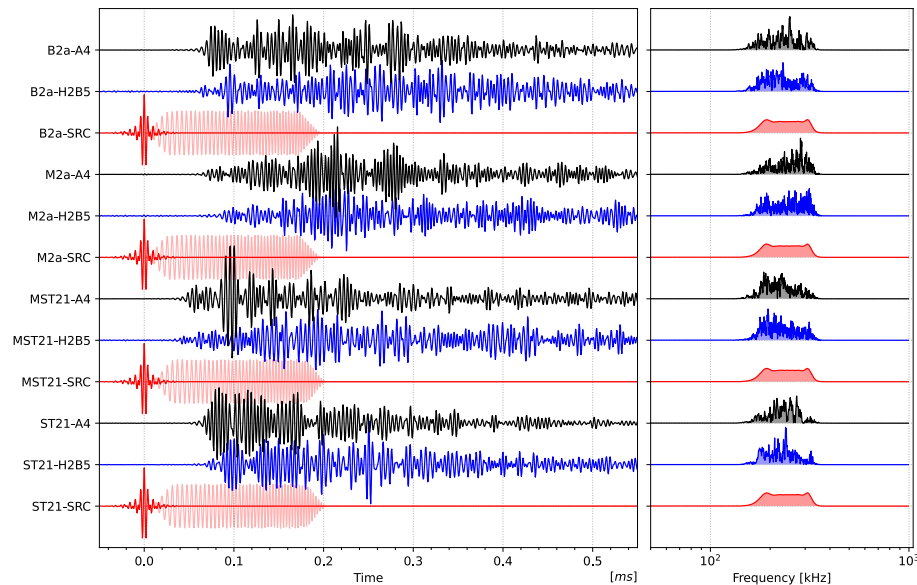


Figure 3: Signals recorded inside the wall by two nearby sensors: a Bragg grating (H2B5, blue) and a piezoelectric accelerometer (A4, black) for a source placed at various positions on the wall and emitting a sweep between 150-350 kHz (red). The signals are shown in time (left) and spectral (right) domains 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.

109 3.3 Noise source correlation

110 Finally, we tested the possibility to obtain empirical Green's functions between pairs of
111 embedded acoustic sensors for a collection of hammer impacts randomly distributed at the
112 surface of the liner. Some pre-processing steps were applied to the recorded signals for
113 each sensor individually. These steps implied spectral normalization (whitening) and the
114 clipping of the largest amplitudes of the signal in the time domain. The signals were then
115 correlated between pair of sensors, stacked and derivated temporally following equation
116 1.

117 For frequencies between 5 and 15 kHz, we obtain an anti-symmetrical correlation function
118 (as expected from eq. 1), which suggests that both causal and anticausal estimates of the
119 Green's function are in good agreement, and that the wave-field is nearly equipartitioned.
120 For a pair of PZT accelerometers, a good similarity between the correlation functions
121 of each individual shot was obtained (Fig. 4a), which reveals a fast convergence of the
122 correlation function toward the Green's function. For a pair of FBGs, the signal to noise
123 ratio is lower, but a clear pattern emerges by stacking all the source contributions (Fig.
124 4b).

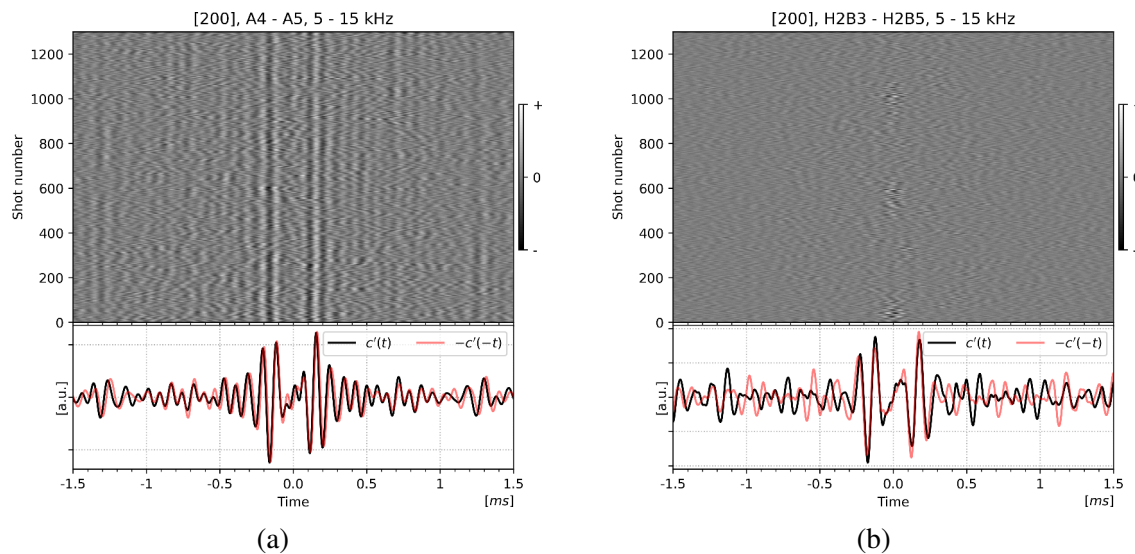


Figure 4: Estimates of the empirical Green's function by correlation of hammer shots, for a pair of PZT accelerometers (a) or FBG sensors (b). The upper part of the figures indicate the correlation functions obtained for each source individually. The stack function (black) and a reversed version of it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

125 4 Conclusions

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

131 Our experiments carried out in a transmission regime revealed that a significant part of the
132 energy emitted by a source positioned on the liner can be recorded inside the concrete with

133 both PZT and FBG sensors, which suggests that this methodology can be used to evaluate
134 the health state of a SCS module even though only the liner is accessible. An advantage
135 of FBG lies in the shape of the spectra, which accurately reproduces the source one in the
136 frequency range of interest. The signals obtained with embedded FBGs are usually more
137 noisy than those of embedded PZT accelerometers. When the source term is well known
138 and sufficiently repeatable, this can be easily addressed by direct summation of the records.
139 For sources with an un-controlled or weakly repeatable source function, summation of the
140 source contributions can be achieved through the correlation method usually employed for
141 the processing of passively acquired noise wave-fields. Using this approach, we were able
142 to approximate the Green's function of the medium between pairs of PZT or Bragg gratings
143 at frequencies between 5 and 15 kHz. Future efforts will concentrate on the possibility to
144 extend this result to ultrasonic frequencies (above 20 kHz) and to use these signals in a
145 non-destructive evaluation process.

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