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# FEM-based simulation tools for ultrasonic concrete inspection

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## Abstract

The simulation of nondestructive evaluation is a useful tool in the design of inspection procedure or the interpretation of results. In the case of the ultrasonic inspection of concrete, modeling the complex interaction of ultrasonic waves with the heterogeneous material is challenging. A module dedicated to 2D finite element computations for the inspection of concrete is being developed in the CIVA software platform. This module relies on automated meshing managed through a user-friendly interface and offers comparatively fast numerical computations. Its aims at modeling practical concrete inspection configurations, involving for example distributions of aggregates, voids and metallic objects. In this communication, we present these modelling efforts performed in a recent collaboration between CEA and EDF, and focus on configurations of interest and evaluation of the modelling performances. In particular, we show how this module can be used to estimate key descriptors of concrete materials such as effective velocity and attenuation or effects of interfacial transmission zones on wave propagation.

**Keywords:** Simulation, concrete, ultrasonic, numerical wave propagation modelling

## 1 Introduction

Ultrasonic inspection methods are widely used in the nondestructive evaluation of concrete structures. The inhomogeneous nature of concrete creates ultrasonic scattering, which affects wave velocity and causes structural noise and attenuation. This can significantly degrade inspection performances, or, in some applications, provide information concerning the concrete properties. Simulation can help gaining a better understanding of these phenomena in order to improve inspection procedures and the interpretation of their results.

For simulation purposes, concrete can be described as a random medium characterized by a distribution of aggregates in a mortar. For a given ultrasonic probe, the wave generated in a concrete structure depends on the position and the local arrangement of the aggregates. This makes it useful to introduce statistical properties of the ultrasonic field. Some modeling approaches, dating back to notions introduced by Foldy [1], use approximations to calculate the properties of the ultrasonic waves averaged over disorder. The averaged wave (or coherent wave) can be characterized by a complex wave number, which depends on frequency. Its real and imaginary parts are related respectively to velocity and attenuation. This average wave does not include fluctuations such as structural noise. Structural noise can be added to simulations by other methods. Some of them rely on empirically adjusted parameters [2].

Other simulation approaches consists in computing wave propagation through specific arrangements of aggregates, using numerical approaches such as finite element methods. Such computations tend to be more accurate than the aforementioned method, but require longer computation times. This limitation became less and less of a problem over the years with the increase in computational capabilities. Finite elements computations of wave propagation

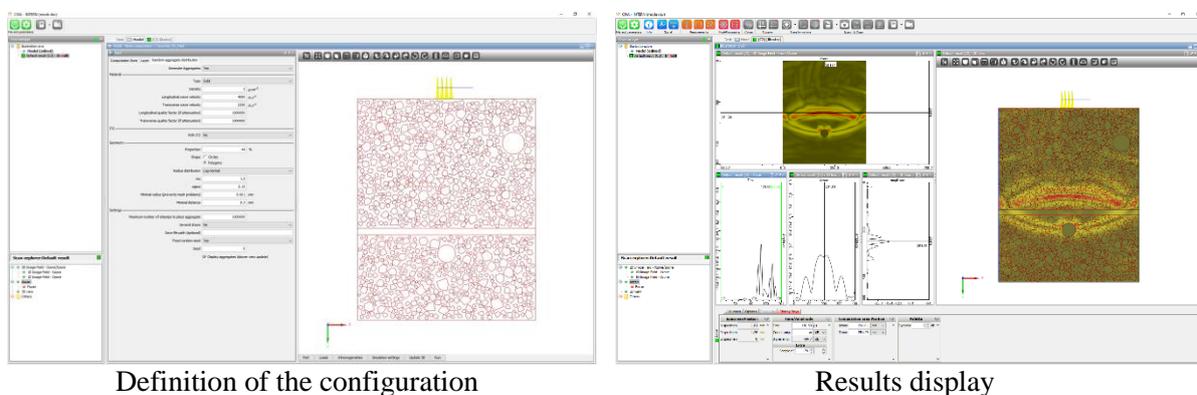
through concrete can now be ran on standard computers, especially for simplified 2D configurations.

The CEA-LIST develops the CIVA platform [3], dedicated to simulation and result analysis for nondestructive evaluation. For the simulation of ultrasonic NDE, it historically relied on semi-analytical approximations, such as the paraxial ray method for field computations [4]. It offers a homogenisation method for concrete and other granular composites. The medium is described as a matrix contained a distribution of spherical inclusions. The Waterman and Truell [5] model is used to compute the velocity and attenuation of an homogeneous medium, corresponding to the effective medium through which the average ultrasonic wave propagates. Structural noise based on a single scattering computation can be included in the semi-analytical computation, either based on empirically adjusted coefficients or by summing the echoes of individual spherical aggregates which are calculated analytically [6]. In recent years, a transient elastodynamic finite element code dedicated to the modeling of ultrasonic testing was developed by the CEA. It was progressively integrated in CIVA for various purposes, such as hybrid computations of scattering by flaws [7] and the simulation of SHM monitoring [8]. The work presented here was motivated by a CEA-EDF collaboration that aimed at evaluating the capabilities of this FEM code for concrete applications.

In section 2 we go through the main components of the complete simulation toolchain, illustrated in section 3 for a relevant configuration of ultrasonic inspection of an idealized concrete material. In section 4, we show how this FEM-based tool can be used to compute effective velocities and attenuations of the concrete materials, and to evaluate the influence of so-called interfacial transition zones. Section 5 is dedicated to gathering the main conclusions and to drawing potential perspectives of the presented work.

## 2 Features of the simulation tool

The simulation tool presented here was developed as a CIVA plug-in. It relies on CIVA for its graphical user interface framework and for its finite element computation core. Emphasis was put on allowing the simulations to be easily ran on a personal computer without high hardware requirements, and on making the process of configuring and running simulations as user-friendly as possible.



**Figure 1:** User interface

The configuration is defined through a graphical interface (Figure 1), where the various properties of the simulation can be defined, the configuration can be visualized, and the computation results are displayed.

It is possible to compute and display ultrasonic fields in a region of interest, or signals received by probes. The ultrasonic fields are the direct output of the finite element computation, and the received signals are obtained by a simple integration of the fields along the probe surface.

In its current version, simulations are limited to two-dimensional cases. It allows handling geometries relevant to practical control configurations in reasonable computation times. The simulation area is a rectangle characterized by a matrix material. Perfectly Matched Layers (PMLs) [9] can be added on each of its boundaries in order to prevent reflections of outgoing waves. An automatic meshing of the geometry as triangles is performed using GMSH [10]. The characteristic size of the elements can be either specified manually by the user, or computed automatically based on wavelengths.

Concrete is described as a mortar matrix containing a distribution of aggregates. These aggregates can be circles or polygons. It is possible to specify the shapes, positions, and materials, of each of them individually, or to use a random aggregate generator. It takes a few parameters such as the proportion of aggregates and their size distributions as entry parameter. It randomly places new aggregates iteratively, checking that the new ones do not overlap with the previous one. If polygonal aggregates are generated, random shapes are generated and the separating axis theorem is used to check non-overlap. A minimal distance between aggregates can also be specified: it helps preventing small elements that degrade computational performances from being present between two aggregates in the mesh.

Additionally to randomly generated aggregates, solid inclusions or voids can be included in the simulation. They can be circular or have arbitrary polygonal shapes. Interfacial Transition Zones (ITZ) are suspected to have a significant effect on the propagation of ultrasonic waves [11]. They can be included around aggregates and other inclusions as a thin layer with different material properties. Solid materials can be specified as viscoelastic, with an absorption specified by a quality factor and taken into account by a Maxwell model [12].

Two types of ultrasonic sources can be specified:

- Localized sources, which vibrate in a given direction. Their amplitude follows a Gaussian profile, with a maximum at the center of the probe. This amplitude profile was chosen because it was a convenient way to include thin spike-like dry point contact probes in the numerical computations.
- Plane waves that encompasses the whole domain. Such sources do not describe a practical measurement configuration, but are convenient for estimations of the velocities and attenuations of averaged waves.

Both types of sources can be set to vibrate in the plane of two-dimensional simulation, or perpendicularly to it. Depending on this, they generate longitudinal and shear-vertical waves polarized in the 2D simulation plane, or only shear-horizontal waves polarized perpendicular to it. In the first case, the ultrasonic field can be described as a two-dimensional vector, while in the second case it can be described as a scalar that obeys different equations. That scalar

formulation allows for extremely fast computations. Both vector and scalar computation have been accelerated in several ways, notably with the use of higher order element and mass lumping techniques [13].

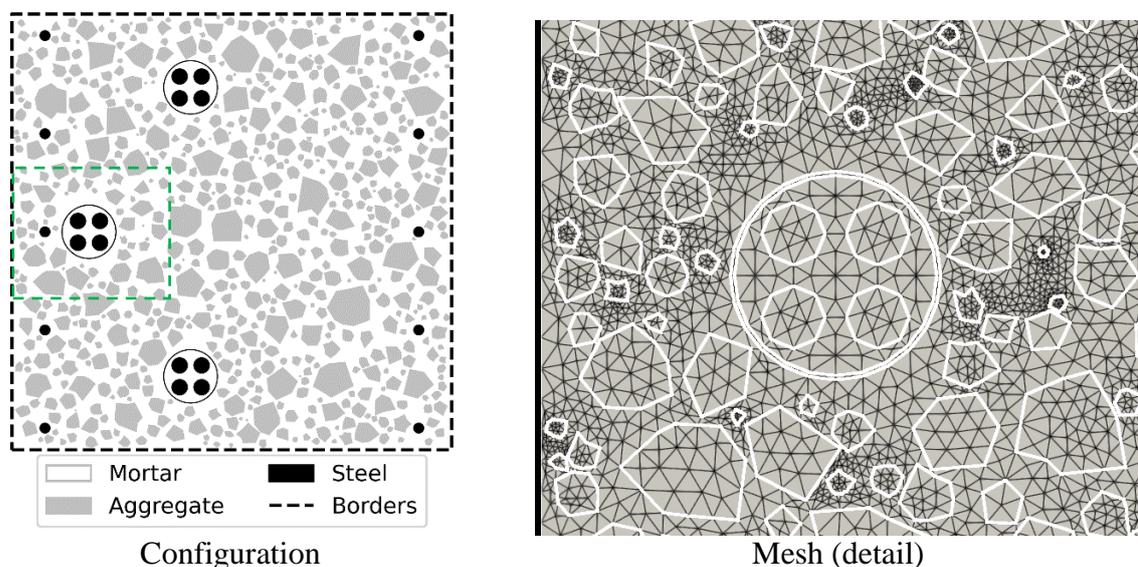
After the computation is ran, the results are displayed in the CIVA interface, as shown in Figure 1. Options are also available to save them as vtk or text files, in order to use other visualization tool or to post-process them. Additionally, automatic post-processing tools are also made available. In particular, attenuation and velocities can be computed automatically for an incident plane wave.

The simulation module was tested by comparing its results to those of analytical calculations [14], and to numerical results obtained using other codes. They were found to be in good agreement. An example of a comparison to another code made concerning velocities and attenuation is shown in section 4. Computations times were also tested and found to be relatively short.

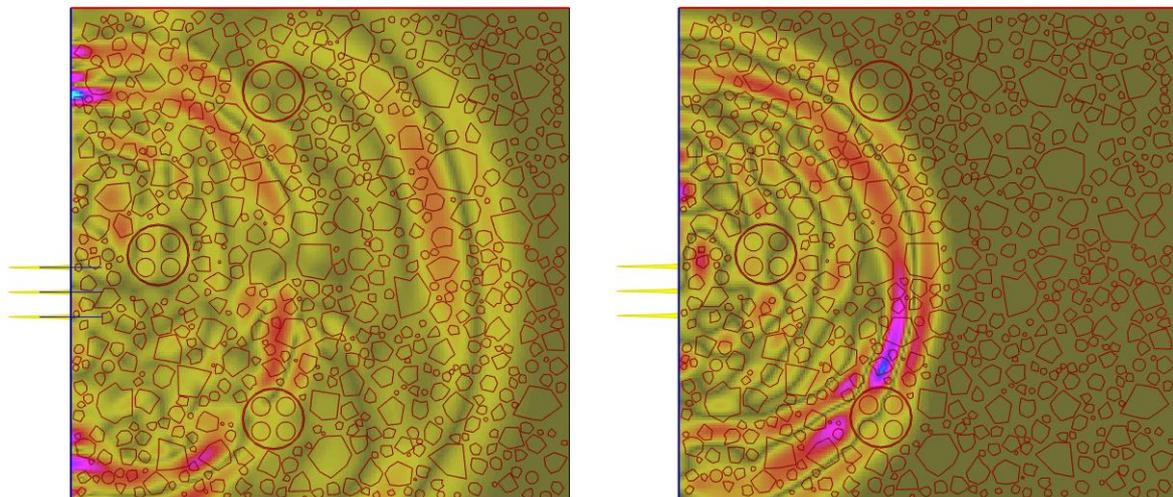
### 3 Simulation of ultrasonic testing configurations

Figures 2 and 3 show an example of a computation taking advantage of various capabilities of the simulation tool. The area of interest contains circular and polygonal inclusions of various materials. Two simulations were performed for a dry point contact array probe in two different direction: perpendicularly to the surface (generating primarily longitudinal waves), or perpendicularly to the inspection plane (generating shear-horizontal waves). Perfectly matched layers were set on all borders of the domain except the one were the probe is located.

The computation area is a 400 mm side square, without counting perfectly matched layers. The central frequency of the emitted wave is 50 kHz and the computation was performed for 200  $\mu$ s of propagation. With these parameters, the computation took 7 minutes for the horizontal displacement case and less than 2 minutes for the out of plane displacement one, on a laptop computer with a height core Intel i9 processor and a 32 Go RAM.



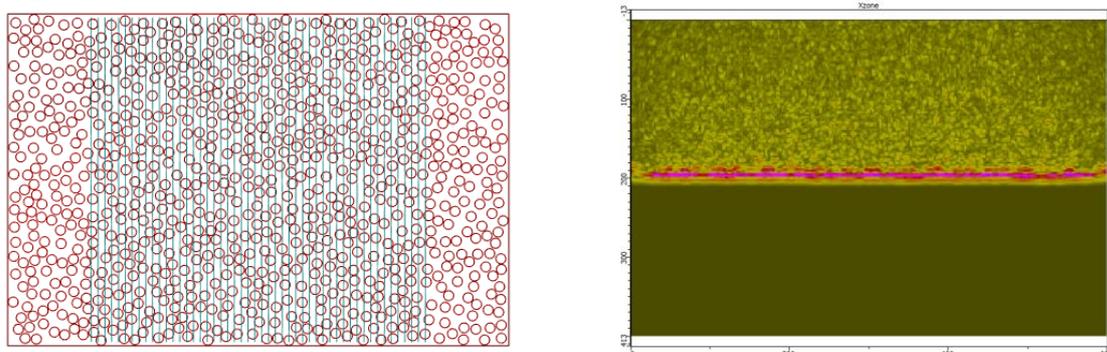
**Figure 2:** Example of a simulation configuration



Field after 100  $\mu$ s for horizontal displacement      Field after 100  $\mu$ s for out of plane displacement  
**Figure 3:** Example of simulation results

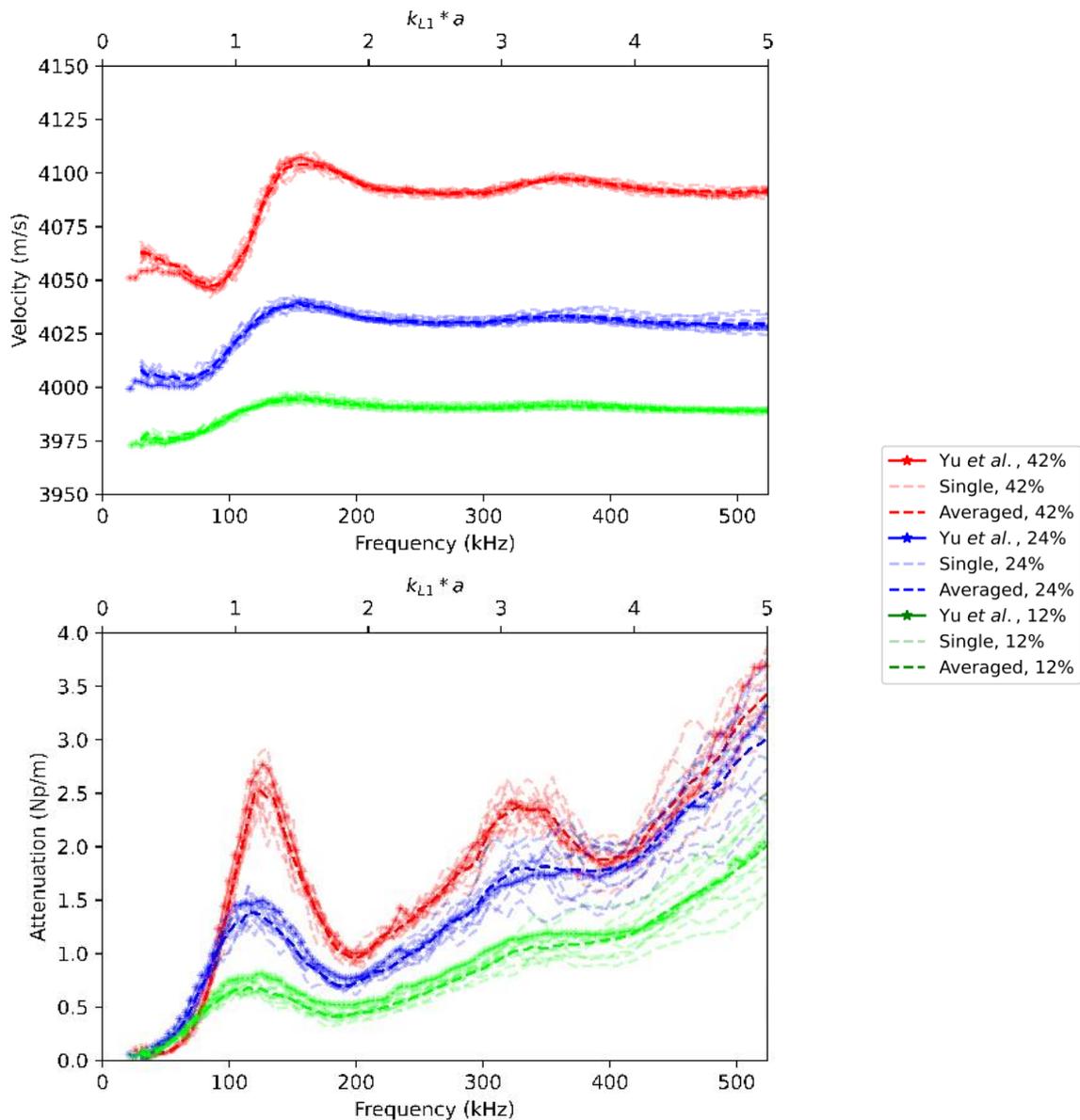
#### 4 Computations of ultrasonic velocities and attenuations

The built-in post-processing options offered in the module relies on computations such as the one illustrated Figure 4 to compute ultrasonic velocities and attenuations. A plane wave is transmitted through the inhomogeneous medium, which is surrounded by absorbing PMLs. Velocities and attenuation are obtained using a method similar to the one described by Yu *et al.* [15]. It relies on a grid of observations points, visible in green on the left of Figure 4. The ultrasonic fields along the polarization direction of interest are averaged perpendicularly to the propagation direction of the wave. It yields a series of signals that correspond to the wave front averaged over disorder for a series of propagation distances. Their Fourier transform is then considered in order to calculate velocities and attenuation for several frequencies in the bandwidth of the incident signal. Velocities are obtained based on the evolution of their phases, and attenuation based on the evolution of their amplitudes. An option is available to run a computation with the same input parameters for multiple random generations of the aggregates: in that case, velocities and attenuations are provided for each random generation and for an average of them.



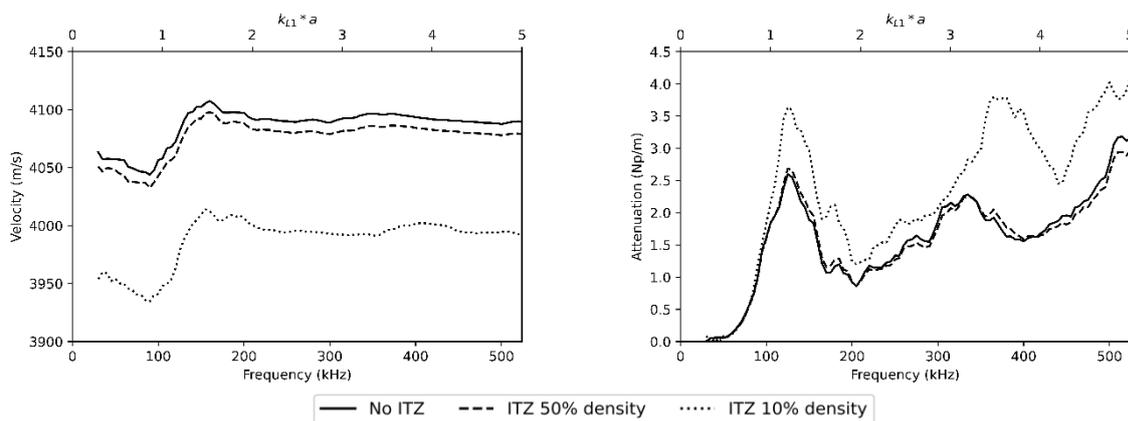
**Figure 4:** Simulation configuration and computed field for velocity and attenuation computation

Figure 5 shows results obtained for a 600 mm \* 400 mm model of mortar containing 6 mm diameter circular aggregates at various concentration, imitating one of the configuration studied using the finite element code SPECFEM2D [16] used by Yu *et al.* [15]. Their results are reproduced here. We performed 10 computations with different randomly generated aggregates for each concentration. Each individual computation (for one aggregates distribution) took approximately 20 to 30 minutes. The computations for higher densities of aggregates tend to be slower, because they require smaller mesh elements. These computations were slower than the ones at 50 kHz presented in the previous section because they were performed at a higher frequency of 250 kHz, which requires smaller mesh elements. Results for each computation and for their averages were automatically calculated by the built-in post-processing tool. A single computation allows for post-processing over a large frequency range. The SPECFEM2D results are within the possible variations obtained with CIVA.



**Figure 5:** Estimated velocities and attenuation for 10 random generation of aggregates, compared to those obtained by Yu *et al.* [15]

The simulation module also allows running several computations for a set distribution of aggregates with different parameters, in order to eliminate the variations due to the randomness of aggregates and focus on other effects. Figure 6 shows a comparison made at constant aggregate distribution for different ITZ parameters, based on the 42% aggregate concentration from the previous example. ITZs have been described as layers surrounding aggregates with a typical thickness of 50  $\mu\text{m}$ , a Young's modulus between 10% and 90% of the mortar, and a Poisson's ratio equal to the one of the mortar [11]. To be consistent with that description, we chose for that particular computation to affect the same ultrasonic velocities to the mortar and to the ITZ, and to reduce the density of the ITZ material to 50% and 10% of the one of the mortar. This is not meant to be a precise description of an ITZ, but to provide a qualitative illustration of its effect on ultrasonic propagation. When an ITZ is specified, it is added as a layer in the inside border of the aggregate. This is to ensure that an aggregate with ITZ occupies the same space as its equivalent without ITZ, and to allow adding ITZ to a set aggregate distribution without risking overlapping between the ITZs of neighboring aggregates.



**Figure 6:** Examples of velocities and attenuations obtained at constant aggregate distribution for different ITZ parameters

These results highlight a significant effect of the ITZ at 10% density compared to the one at 50% density. The simulation modules offers tools that could allow investigating this effect in a more extensive parametric study, though this is beyond the scope of this communication. The computations with ITZ took up to 55 minutes, which is approximately twice the time taken by computations without ITZ for the same parameters. This is explained by the fact the current version of the software meshes the thin ITZ layers explicitly, producing very small mesh elements.

The results presented here were obtained for circular inclusions of constant diameter in order to facilitate comparisons and reproducibility. However, polygonal inclusions as well as log-normal size distributions are available in the module and allow producing geometries that are more representative of actual concrete.

## 5 Conclusion

The simulation tool presented here aims at making FEM simulations for the ultrasonic inspection of concrete available to non-experts. It is geared towards two distinct types of applications: simulating actual inspection procedures, or estimating the velocities and attenuation of a wave propagating through a sample. All the simulations presented here are reasonably short, each taking under an hour on a laptop computer.

This tool is still under development and not yet available in a commercial version of CIVA. The implementation of additional functionalities is planned, including the implicit meshing of ITZ layers which should shorten computation times for thin ITZ layers. The possibility of 3D computations is also being considered.

Computation times limit the applicability of FEM to large 3D problems. However, the insight they provide can be useful to other methods. Faster semi-analytical methods such as the ones historically proposed in CIVA require the knowledge of velocities and attenuation in the material. FEM-based estimations of these quantities can be used as entry parameters. Additionally, FEM computations can serve as a reference for the development and validation of other models. The simulation module is intended as tool for theoretical research as well as practical applications.

## Acknowledgements

A part of the Figure 4 data is reprinted from *Ultrasonics*, vol. 92, Author(s), “Simulations of ultrasonic wave propagation in concrete based on a two-dimensional numerical model validated analytically and experimentally”, pp. 21–34, Copyright (2019), with permission from Elsevier.

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