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Simulation of Non-destructive Testing Methods of Ultrasound in Concrete Columns

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Among the processes that are conducted to perform the inspection of the internal reinforcement of concrete structures, to study the component it is destroyed directly, in most cases some partial and total. By means of a sustained theoretical approach, several objectives were established to evaluate through modeling and simulation methods that could be useful for non-destructive testing in structural concrete columns. Given these variables (positions and diameters of reinforcements) were established mathematical models of the physical principles that constitute the operation of the respective non-destructive testing methods and computational models were made of reinforced concrete column, finally the data were interpreted from simulations into a graphic reconstructions which representing an approximation to the column being analyzed. The result was a conceptual design which was the product of the information gleaned from the simulations of the two methods worked, longitudinal transmission and pulse echo, corresponding to the ultrasonic non-destructive testing. This research describes theoretically non-destructive testing methods based on ultrasound, which can be used to build devices that claim to prevent partial or total destruction of the structure to be studied, and imaging techniques that are useful to identify the reinforcement positions of the concrete column based on the collected data from the simulations.

Keywords: Reinforced concrete columns, NDT, Pulse-echo method, longitudinal transmission method, Acoustic wave propagation, Ultrasound.

1. INTRODUCTION

This work presents the description, modeling and simulation of physical principles of methods that can be used to perform non-destructive testing on reinforced concrete columns, aimed at identifying the positions of the reinforcements on such structures. The study aimed to evaluate through modeling and simulations useful methods to conduct non-destructive testing on reinforced concrete structural columns, obtaining the computational model of the column, the mathematical models that represent the performance of the methods chosen and applying them through simulations on the model of column and then using signal processing tools, to finally interpret and reconstruct the values obtained on an image of the interior of the column, where it can identify the positions of the reinforcements.

The present Investigation evaluated, through simulations using the Toolbox for Matlab K-Wave, two non-destructive testing methods based on ultrasound (longitudinal transmission method and pulse-echo method). To perform the simulations, we established a computational model of the column on which a perturbation was applied (ultrasonic wave) through k-wave toolbox. Subsequently using the information gathered by the sensors, we performed the reconstruction of the column through the time-reversal algorithm, generating an image, in which after conducting the respective processing, it was possible to identify the reinforcements within the structure.

2. SELECTION OF NON DESTRUCTIVE TESTING METHODs

The ultrasound-based assay (UT) is the Non-destructive testing that provides higher performance for a possible implementation, the term ultrasonic refers to sound waves whose frequency is above the threshold of human listener. Most methods based on ultrasound testing using frequencies in a range between 1MHz and 10MHz. Additionally, along with radiographic testing, provides an accurate use on ceramic materials such as concrete, and because of its ease and convenience of use becomes the test of the present study (Table 1).

Table 1. Selection of non-destructive testing methods

Material submitted for testing	Type of discontinuity	VT	RT	ET	UT	PT	MT	AE	IR
Ferromagnetic Metallic	Cracks on the surface	x	x	x	x	x	x	x	
	Internal Cracks		x	x	x		x	x	x
Nonferromagnetic metallic	Cracks on the surface	x	x	x	x	x		x	
	Internal Cracks		x	x	x			x	x
Metallic	Pitting		x	x	x				
	Wear corrosion cracking								
	Welding (depth)		x	x	x				
	Welding (porosity)		x	x	x				
Polymer matrix composites	Delamination				x			x	x
	Porosity		x		x				x
	Damages due to impacts	x			x			x	x
Polymers	Curing				x				
	Nonadherence		x		x				x
	Porosity		x		x				x
Ceramic	Density		x		x				
	Porosity		x		x				
	Cracks on the surface	x	x		x	x			
	internal Cracks		x		x	x		x	
	VT: Visual Inspection RT: Radiographic testing ET: Electromagnetic Testing UT: Ultrasonic Testing	PT: Penetrant testing MT: Magnetic Particle Test AE: Acoustic emission testing IR: Infrared and thermal testing							

The non-destructive testing based on ultrasound can be applied by a variety of methods based on the generation and detection of mechanical vibrations or waves that propagate through the objects of study. Those are not restricted to be either metals or even have to be solid .The methods based on this test are used for material characterization studies based on the principle that the speed of ultrasound waves that travel through the material, is a function of the density of the material [1].

An ultrasound wave (in general, any type of mechanical wave), when it hits on a medium, part is transmitted and part is reflected. From this fact, two methods are derived from this non-destructive testing, respectively each based on the propagation of the transmitted wave and the collection of the reflected wave [2]. The non-destructive testing based on ultrasound (UT) provides a variety of methods for implementation, of which, the Longitudinal Transmission method and Pulse-Echo method were chosen.

2.1. Longitudinal transmission

As the name implies, the method evaluates the ultrasound which is transmitted through the medium. The form of implementation is performed, placing on one side of the piece, a transmitter of ultrasound in complete contact with the surface, and on the opposite side of the piece, also a receiver in full contact with the face and exactly aligned with the transmitter position (figure 1). [2]

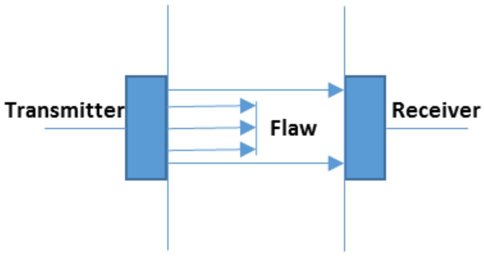


Figure 1. longitudinal transmission

When a defect stands between the transmitter and receiver, the sound intensity decreases because of partial reflection, or becomes zero in the case of total reflection. In this method, can be used either a pulse train or continuous sound, since the transmitter and receiver operate independently and are electrically separated. [2]

2.2. Pulse – Echo

This method uses the part of the wave that is reflected when it interacts with a defect. The wave propagates in the material until it finds a defect at this point is performed partial or total reflection. The form of implementation in this case is carried out by placing one probe bicristal (transmitter-receiver, the two crystals are isolated acoustically) in complete contact with the surface of the object (Figure 2). [2]

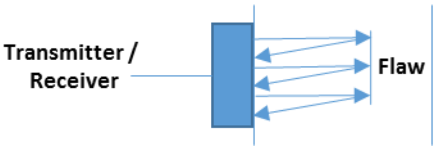


Figure 2. Pulse - Echo

In this case, a train of pulses should be used, which allows the receiver to perform the measurement, since the received signal is smaller than the signals sent by the sender. [2]

2.3. Model of the physical principle

Acoustic waves are longitudinal waves, the molecules move back and forth in the direction of wave propagation, causing adjacent regions of compression and refraction. As a result, the pressure change that occurs is the only restoring force capable of propagating a wave [3]. On Solids, the propagating waves, in addition to longitudinal waves, can also be transmitted shear waves and combinations of these with the longitudinal. Neglecting the transverse components which propagate in the solid, the wave propagation in the solid can be described with a model of longitudinal pressure wave, which depends on the density and velocity of phase [4], Eq (1).

$$\nabla \cdot \left[\frac{1}{\rho(r)} \nabla p(r,t)\right] - \frac{1}{\rho(r)\, c(r)^2} \frac{\delta^2 p(r,t)}{\delta t^2} = 0 \qquad (1)$$

Where $\rho(r)$ represents the density at any point, $p(r,t)$ the pressure wave at a given point *r* and time *t*, and *c* indicates the phase velocity of the wave. [5] The present equation is valid for any medium that has sound velocities and densities as functions of space.

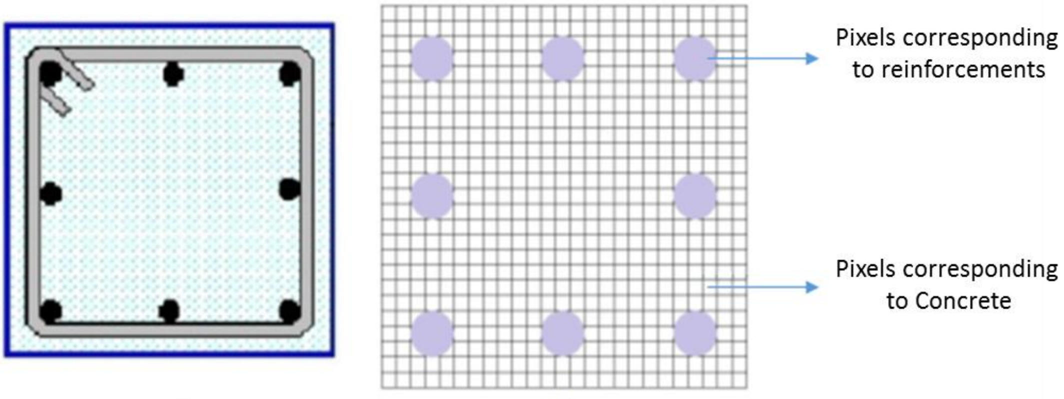
3. COMPUTATIONAL MODEL OF CONCRETE COLUMN

The reinforced concrete column has 3 main components, gravel, concrete and reinforcements. Each component has certain characteristics of interest such as the density and the phase velocity of waves as they propagate through these. Reinforcements density was set to a value of $7850\frac{kg}{m^3}$. The densities corresponding to the gravel and concrete were taken with the values of $2648\frac{kg}{m^3}$ [6] and a magnitude oscillating between $2200\frac{kg}{m^3}$ and $2800\frac{kg}{m^3}$ [6] respectively. This heterogeneous mixture is considered as a homogeneous mixture with a density corresponding to $2200\frac{kg}{m^3}$, this value was taken as a parameter for the density of the concrete. In [7] was conducted a study of the quality of concrete with respect to the measurement of the phase velocity of an ultrasound pulse that propagates through a section of the material. It was then decided to take as parameter of phase velocity a value of $4000\frac{m}{s}$ which is intermediate between a good and excellent quality concrete. On the other hand, it was established the phase velocity of the reinforcement as $5100\frac{m}{s}$, corresponding to steel value. Given the properties, and looking for an ideal model, the column is considered as a homogeneous layer with outstanding concrete reinforcements. The characteristics of ideal column materials with their respective characteristics were defined according to Table 2.

Table 2. Characteristics of the column materials

Material	Phase Velocity $\frac{m}{s}$	Density $\frac{kg}{m^3}$
Concrete	4100	2200
Reinforcement	5100	7850

Generally, smaller buildings (three floors or less) use square structural columns, whose faces are measured in a range between 20 *cm* and 25 *cm* and reinforced with rods half inch to one inch in diameter. Given these constraints, we decided to perform a computational model of a cross section of a square column of reinforced concrete, 20 *cm* face, reinforced with 8 rods whose diameters are 1 inch. The model was implemented by creating a matrix that represents the column, each pixel of the array represents the value of the parameters defined above (phase velocity and density) it means that each pixel of the array symbolizes a piece of material forming of the column (Figure 3).



a) b)

Figure 3. a) Cross-section of a real concrete column b) computational model of a cross section of a reinforced concrete square column of 20 cm of face.

4. SIMULATIONS

To perform the simulations of the physical principle in the computational model of reinforced concrete square column, we used the toolbox for Matlab, K-Wave [8-17], which implements the discrete equations from equation 1, that represent the speed of propagation of the wave U and respective pressures in x and y, Eq (2), Eq (3) Eq (4), Eq (5) Eq (6), Eq (7) , Eq (8).

$$u_x(r_1,t^+) = e^{-\alpha_x(r_1)\frac{\Delta t}{2}}\left[e^{-\alpha_x(r_1)\frac{\Delta t}{2}}u_x(r_1,t^-)\right] - e^{-\alpha_x(r_1)\frac{\Delta t}{2}}\left[\frac{\Delta t}{\rho(r_1)}\left[\frac{\partial\left(p_x(r,t)+p_y(r,t)\right)}{\partial^{(c_0\Delta t)}+x}\right]\right] \quad (2)$$

$$u_y(r_2,t^+) = e^{-\alpha_y(r_2)\frac{\Delta t}{2}}\left[e^{-\alpha_y(r_2)\frac{\Delta t}{2}}u_y(r_2,t^-)\right] - e^{-\alpha_y(r_2)\frac{\Delta t}{2}}\left[\frac{\Delta t}{\rho(r_2)}\left[\frac{\partial\left(p_x(r,t)+p_y(r,t)\right)}{\partial^{(c_0\Delta t)}+y}\right]\right] \quad (3)$$

$$p_x(r,t+\Delta t) = e^{-u_x(r)\frac{\Delta t}{2}}\left[e^{-u_x(r)\frac{\Delta t}{2}}p_x(r,t)\right] - e^{-u_x(r)\frac{\Delta t}{2}}\left[\frac{\Delta t}{k_\infty(r)}\left[\frac{\partial u_x(r_1,t^+)}{\partial^{(c_0\Delta t)}-x}\right] - \sum_{i=1}^{n} v_i^x(r)S_i^x(r,t^+)\right] \quad (4)$$

$$p_y(r,t+\Delta t) = e^{-u_y(r)\frac{\Delta t}{2}}\left[e^{-u_y(r)\frac{\Delta t}{2}}p_y(r,t)\right] - e^{-u_y(r)\frac{\Delta t}{2}}\left[\frac{\Delta t}{k_\infty(r)}\left[\frac{\partial u_y(r_2,t^+)}{\partial^{(c_0\Delta t)}-y}\right] - \sum_{i=1}^{n} v_i^y(r)S_i^y(r,t^+)\right] \quad (5)$$

$$S_i^x(r,t^+) = e^{-\frac{\Delta t}{[2\tau_i(r)]}}\left[e^{-\frac{\Delta t}{[2\tau_i(r)]}}S_i^x(r,t^-) + \Delta t\frac{p_x(r,t)}{\tau_i(r)}\right] \quad (6)$$

$$S_i^y(r,t^+) = e^{-\frac{\Delta t}{[2\tau_i(r)]}}\left[e^{-\frac{\Delta t}{[2\tau_i(r)]}}S_i^y(r,t^-) + \Delta t\frac{p_y(r,t)}{\tau_i(r)}\right] \quad (7)$$

$$\alpha(\cdot) = A\frac{c_0}{\Delta(\cdot)}\left[\frac{(\cdot)-(\cdot)_0}{(\cdot)_{max}-{\cdot}_0}\right]^4 \quad (8)$$

Where α indicates the absorption parameters in x or y, k the compressibility of the medium, v the effective source dependent of the velocity, τ the relaxation time, s the wave state variable, and A its amplitude.

4.1. Simulation of the longitudinal transmission method

The frequencies of the probes, which are on the market, vary in a range between 1MHz and 22MHz. The contact probes that have the lowest frequency provide better penetration, property that becomes the best choice to use in considerable thicknesses materials, granular materials or materials that have large attenuation. Given the characteristics of penetration of the contact probe, we chose a nominal frequency of 2 MHz respect to the amplitude, we define a value of 400mV (amplitude A), a value that provided one of the best behavior in the propagation of the wave ultrasound in the medium. To avoid an extensive number of steps in the simulation to make the sweep, we assumed a single source, whose length is equal to the extent of the face of the column. This source completely covers the whole medium and therefore is analogous to send ultrasonic waves at multiple positions. The same assumption was made for the receiver. Given the two sources then ready and the two sensors on the medium, the simulation was performed (Figure 4), two pulses are sent with origins in the face of the column parallel to the x axis and whose passage was performed on the z axis, and the face of the column parallel to the axis z whose passage was performed on the x-axis.

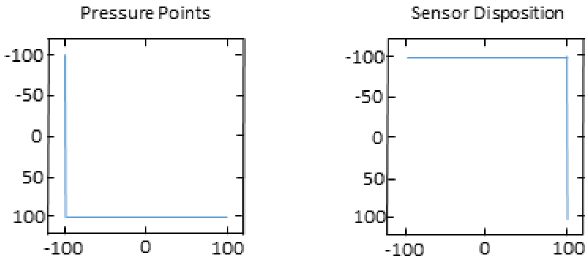


Figure 4. source and sensor arrangement in the medium

After ending the propagation of the wave, the points collected by the sensors are reassigned as initial points of pressure to perform the image reconstruction algorithm using Time Reversal [8-16]. In the reconstructed image that is obtained, it is possible to visually determine the reinforcements positions (Figure 5).

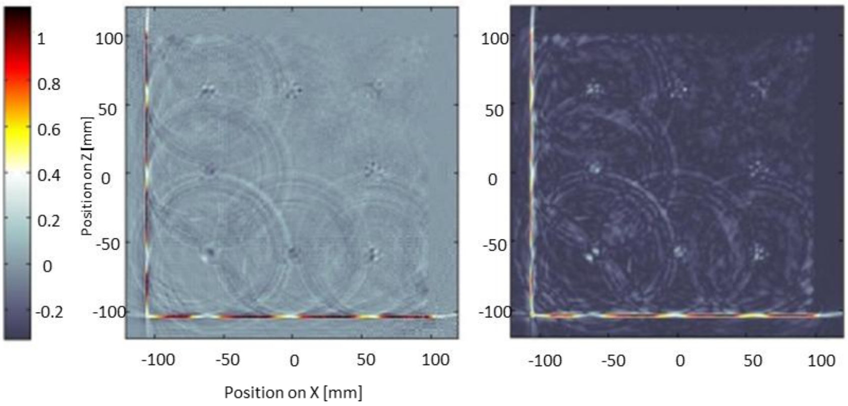


Figure 5. average reconstructed image using *Time Reversal*

To overcome the need to identify the reinforcements only with visual examination, it was performed an image processing by applying a Sobel filter using two thresholds to remove the edges with high and low intensity, 0.3 and 0.05 respectively, this filtering made possible to obtain an image in black and white with several regions of high concentration of pixels, regions corresponding to the reinforcements, this filtered image was swept using a circular mask, which determines the regions of higher concentration, keeping its coordinate. At the end of the swept, the resulting coordinates are overlayed on the original image reconstruction and then were highlighted with a circle; finally, the coordinates of the reinforcements are obtained as well as an image where those are identified (Figure 6).

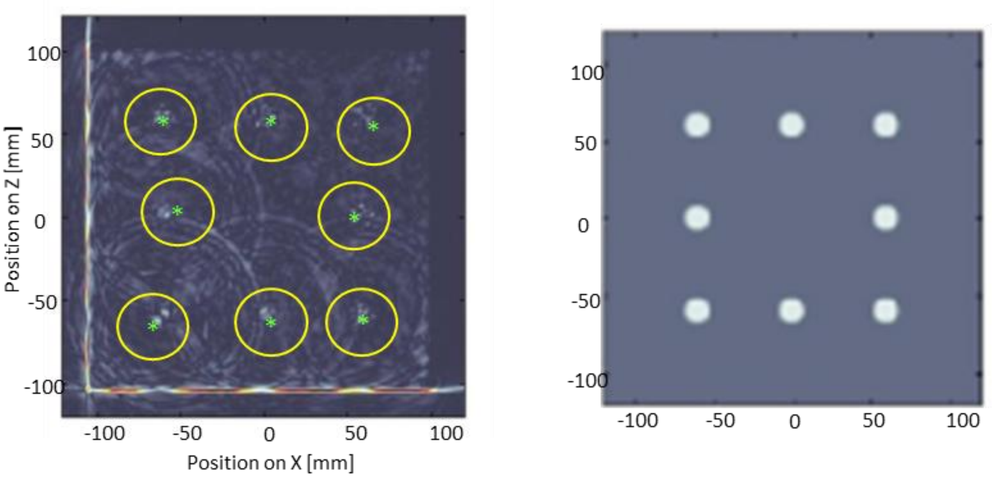


Figure 6. Comparison of the results of identification of the reinforcements with the original medium

4.2. Simulation of the pulse-echo method

The signal used was defined in the same manner as the longitudinal transmission method (2MHz frequency and amplitude of 400mV). The same consideration is made to simulate a single source of a size equal to the length of the face. Since the collection of echoes is performed by the same probe, also assumed the same length to the sensor, and additionally placed on the source, in order to simulate the operation of bicristal probe (Figure 7).

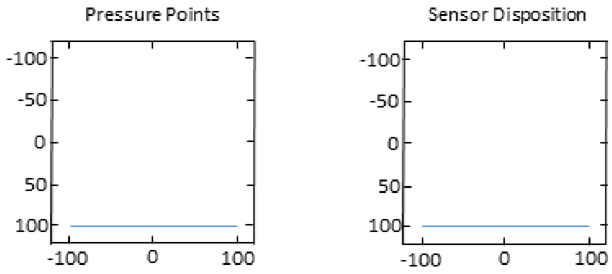


Figure 7. Layout of source and sensors

The source was configured to send 8 bursts of ultrasound in a single pulse. After sending the pulse, the source is switched off in order to receive echoes from the discontinuities. When the ultrasound wave interacted with the discontinuities of the medium (reinforcing bars), a fraction of the incident wave reflected to the sensor, this reflection effect causes the rod can be considered as a secondary source seen from the sensor, then the rod is "generating" echo waves. Following the steps in the longitudinal transmission method is assumed echoes received by the sensor pressure as initial points. With these points we applied the algorithm Time Reversal. The reconstruction of the medium is shown in figure 8.

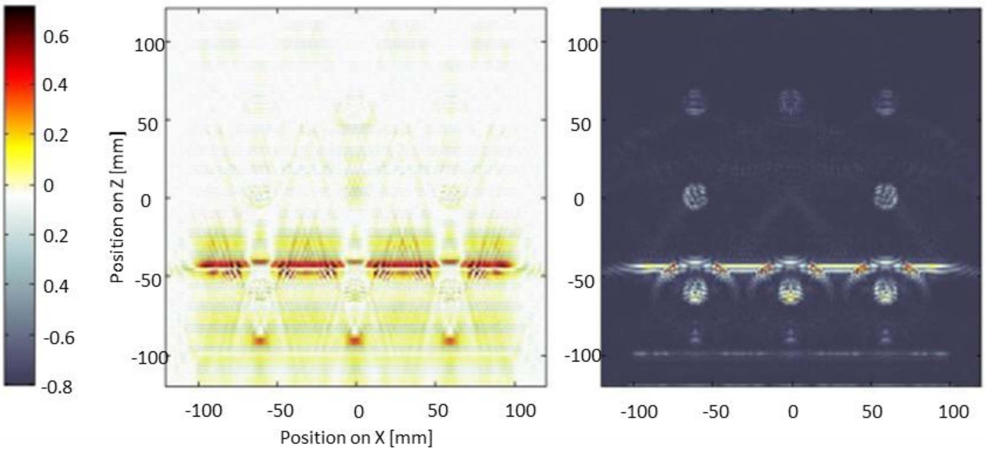


Figure 8. Image of the medium, reconstructed by Time Reversal (Pulse-Echo method)

The image was subjected to a filtering process using the Sobel operator. Was carried out using two thresholds for removing higher and lower edges intensity, 0.01 and 0.03 respectively, and then an image was obtained where it is possible to identify several regions where there is a high concentration of pixels, regions that correspond to the reinforcement . The filtered image is swept using a circular mask, which identified regions with higher concentration of pixels keeping its coordinate. After completing the course, the stored coordinates are superimposed on the original image reconstruction, where are highlighted and enclosed by a circle, thus obtaining a visual representation of the location of the reinforcements and their position within the medium (Figure 9).

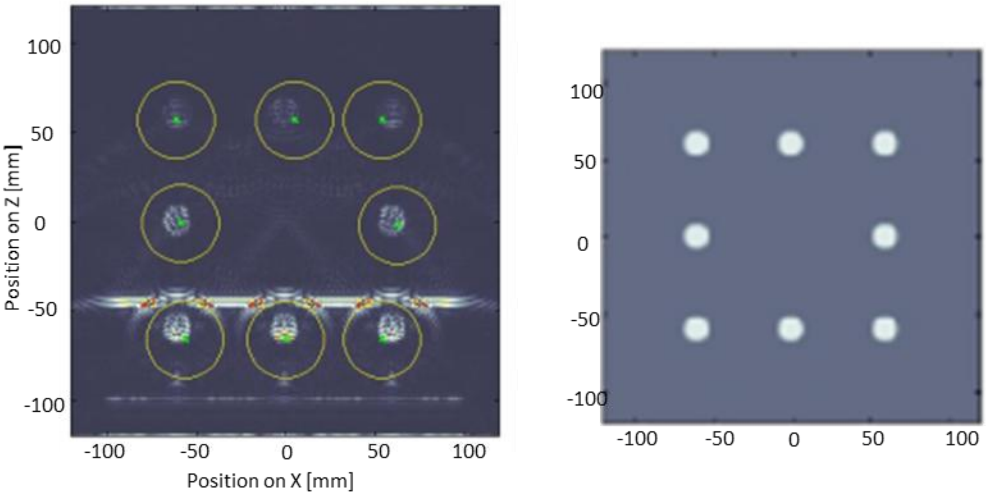


Figure 9. Identification of reinforcements compared to original medium

4.3. Visual identification of strapping steel

Reinforced concrete columnapart from the vertical reinforcement and the concrete also has reinforcements known strapping horizontally. They wrap and ensure vertical reinforcements remain in position. Thus, their detection is important when evaluating the structural condition of the building. Since the method that yielded the best results was the pulse - echo at the time of finding the position of the reinforcements, using this, we performed a new simulation of the column including narrow strip. For this simulation were defined segments corresponding to narrow strip with a diameter of 3/8 " in the computational model. (Figure 10).

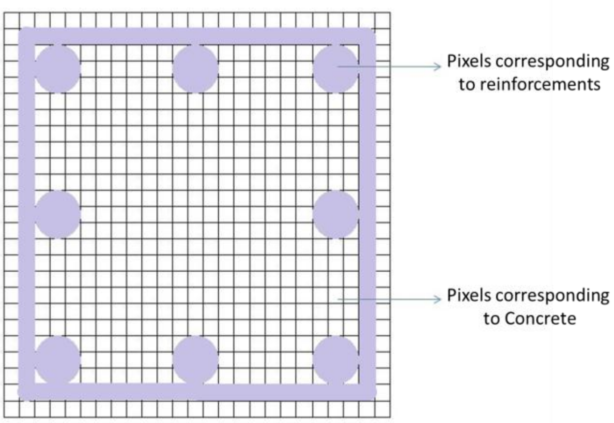


Figure 10. computational model of a cross section of a square column

With K-Wave software, the model of the medium depending on the density and velocity of phase was configured as shown in Figure 11.

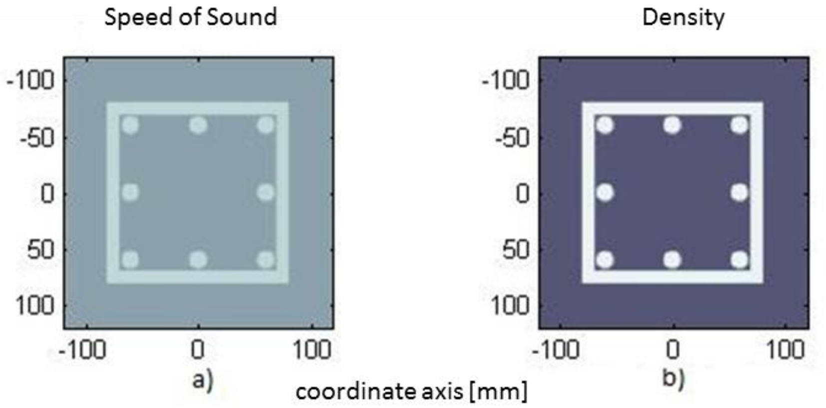


Figure 11. Pattern of media using K-Wave tool a) in terms of speed of sound b) in terms of the density

After defining the computational model was simulated propagation of ultrasound wave into the medium. When finished the simulation cycle, we proceeded to perform image reconstruction of the medium, in which by a visual inspection is possible to determine the existence of narrow strip (Figure 12).

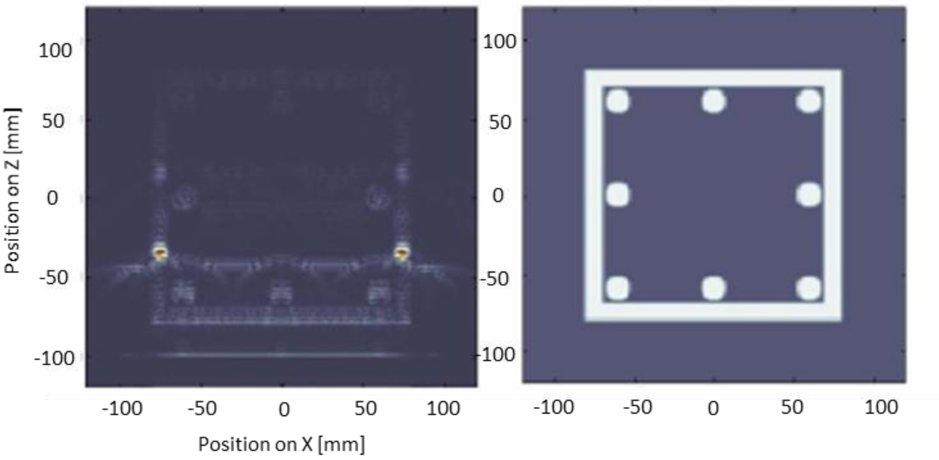


Figure 12. Image of the medium with strapping reconstructed by Time Reversal

5. CONCLUSIONS

The work allow to obtain a representation of the steps of applying ultrasonic non-destructive testing of reinforced concrete square columns of faces of 20 cm (sending and receiving high frequency waves, sampling and processing of the received signal).

Idealizations made on the concrete allowed to establish a computational model representing an approximation to the cross section of a square column of concrete.

Obtaining propagation mathematical model high frequency longitudinal waves, which is implemented by the toolbox found Matlab K-Wave, allowed by modifying the parameters of density, phase velocity, performing an Ideal simulation of the propagation of an ultrasonic pulse into a solid heterogeneous medium such as in the case of reinforced concrete.

Simulations of the propagation inside a heterogeneous medium of high frequency waves, allowed to represent two ideal methods of non-destructive testing based on ultrasound (longitudinal transmission and pulse - echo), in which it was possible to simulate the emission of an ultrasonic pulse and sampling the signal generated by the interaction of said pulse with the reinforcements inside the medium.

The simulation of the sampling of the signal generated by the interaction of the ultrasound pulse inside the medium reinforcements allowed, using the algorithm Time Reversal, a reconstruction of an image in which the reinforcements can be identified within the column.

Image processing obtained from algorithm Time Reversal allowed to perform the automatic identification of the reinforcements disposed within the column. Evaluation methods based on ultrasonic non-destructive testing, indicates that both the longitudinal transmission method as the method of pulse - echo square columns are applicable over reinforced concrete faces 20 cm in order to identify the position of the reinforcements that are within the column.

The simulation of the longitudinal transmission method, indicated that the clarity with which reinforcements are identified within the column is proportional to the diameter of these, ie the bigger the diameter, the more clearly we can identify.

The simulation method of pulse - echo proved simpler to implement, since to perform the measurement only required the provision of a point source on only one side of the reinforced concrete column, contrasting the transmission method longitudinal which demanded the independent use of a source and a receiver opposite and perfectly aligned.

The simulation method of pulse - echo demonstrated that if it is required to find the strips within the column, they can be found by visual examination in the image reconstructed from the pressure points collected by the bicristal probe.

The histograms extracted from the images generated from the algorithm Time Reversal allowed comparisons between the two worked methods, which it was determined that the method of pulse - echo was more effective in the task of identifying reinforcements concrete column armed.

The results of the simulations allowed defining a conceptual design, which gave the instrument requirements to be able to carry out the identification of reinforcements within concrete square columns of faces of 20 *cm*.

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