Microwave Non-Destructive Testing Technique for Material Characterization of Concrete Structures via Electromagnetic Waves with FDTD

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Abstract**—**Concrete is a nonhomogeneous medium that contains coarse aggregate, sand (fine aggregate), cement powder, water and porosity. Microwave non-destructive testing (NDT) technique is used to simulate three layered media that contains air gap, coarse aggregate and a two layered media that contain rebar and void is modeled as closest to the reality. Interaction of electromagnetic wave and the concrete pile is utilized for numerical simulation. A Finite-Difference Time-Domain (FDTD) method with Perfectly Matched Layer (PML) Absorbing Boundary Condition (ABC) is proposed to simulate electromagnetic wave propagation in FRP tube and composite pile. 2D simulation of a wave generated from a point source at microwave frequencies is obtained by using MATLAB®.

Keywords— cement-based samples, finite-difference time-domain simulation, layered media, perfectly matched layer, rebar.

I. INTRODUCTION

In the compositions obtained by mixing different materials, it is important for the quality of the composition to be obtained to maintain a certain level of each component quantity. The determination of the curing time in the structures that require a certain chemical activity to occur is also a condition that affects its mechanical properties [1, 2]. Compressive strength decreases if cement based samples (concrete and mortar blocks) are not cured properly. During the production of cement-based structures, the use of vibrators also is important to prevent the formation of porosity in the interior. There may be defects in concrete and mortar structures due to faults during production and improper curing, as well as disbands, delamination and interior defects due to use and external factors after a certain period of time. Cement-based structures may contain defects due to the reasons mentioned they should be inspected at regular intervals. Non-destructive testing (NDT) techniques are of great importance, as they do not affect the integrity of the structure to be inspected [1, 2]. Since microwave signals can easily penetrate into dielectric environments to a certain depth and are sensitive to the geometric and dimensional properties of a medium or a defect microwave NDT technique is used for simulation. In order to determine the thickness of concrete and mortar parts, coarse aggregates in the concrete part, air gaps between the masonry blocks on the surface, rebar and voids, the interaction of these environments and microwaves has been used for simulation with FDTD technique. For numerical application using difference equations, Maxwell curl equations and three scalar equations at the component level are given in the following section. Two dimensional geometric model to be simulated and samples that prepared according to this physical model are introduced.

II. THEORY AND NUMERICAL SIMULATION EXPERIMENTS

The Maxwell curl equations for linear, isotropic, nondispersive and lossy medium are used to understand how the electromagnetic wave interact with the cement-based environment.

In cases where the incident wave is the same in the z-direction, since all partial derivatives of fields relative to z are equal to zero, the Maxwell's equations are reduced to two-dimensional form. The two-dimensional forms containing E_x, E_y and H_z components are called TE mode and the mode containing H_x, H_y and E_z components are called TM mode. Since only TE mode waves will be used in this study, components of TE mode are given. In Cartesian coordinate system TE waves has three components as follows:

$$\frac{\partial E_x}{\partial t} = \frac{1}{\varepsilon}\left[\frac{\partial H_z}{\partial y} - \left(J_{source_x} + \sigma E_x\right)\right], \tag{1}$$

$$\frac{\partial E_y}{\partial t} = \frac{1}{\varepsilon}\left[-\frac{\partial H_z}{\partial x} - \left(J_{source_y} + \sigma E_y\right)\right], \tag{2}$$

$$\frac{\partial H_z}{\partial t} = \frac{1}{\mu}\left[\frac{\partial E_x}{\partial y} - \frac{\partial E_y}{\partial x} - \left(M_{source_z} + \sigma^* H_z\right)\right], \tag{3}$$

Thanks to FDTD the Maxwell's curl equations are discretized both space and time domains based on the Yee's algorithm [3, 4]. Central differences are applied for time and space derivatives in (1-3). Thus, the equations that will be used in the algorithm are attained and then the algorithm is implemented for 2D simulations in MATLAB®.

In numerical wave propagation computations, an artificial boundary must be defined to restrict the computation domain and absorb the outgoing waves. In PML boundary condition the waves, which have arbitrary incidence angle, frequency and polarization, are matched at the boundary [5].

The three-dimensional samples are simulated in two-dimensions and two-dimensional geometry is divided into cells of much smaller size than the wavelength. The physical models presented in Fig. 1 have 0.5 m in the x-axis and 0.25 m in the z-axis. The computational domain is a rectangular region of $0.5 \text{ m} \times 0.25 \text{ m}$. The numerical domain is obtained by dividing into 200 grids in the x-axis and 100 grids in the z-axis, $\Delta x = \Delta z = 0.0025$ m. In the first numerical experiment, namely in Case A, a three-layered rectangular computational domain is presented. The calculation domain includes masonry, mortar and concrete which contains coarse aggregate respectively from top to bottom. In the second experiment in

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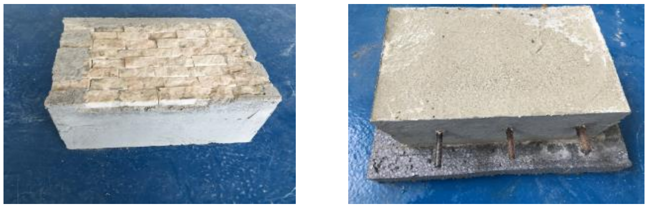
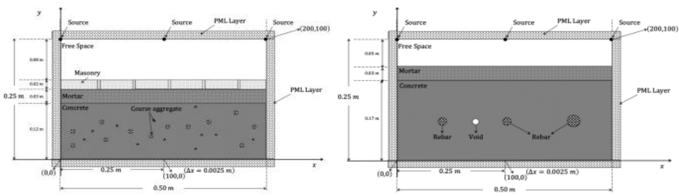
a word Case B two-layered rectangular specimen that contain mortar and concrete layer is investigated. The second sample includes a void and three rebar, two of which are of the same radius and the other one is thicker. Physical structure and numerical model of computational domains are given respectively in Fig. 1 and Fig. 2.



(a) (b)

Fig. 1. Physical structure of specimens: (a) Case A; (b) Case B.

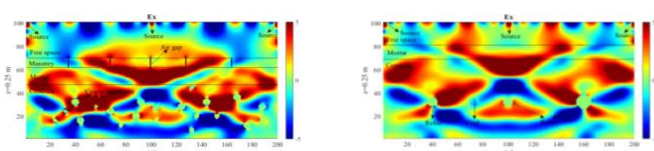


(a) (b)

Fig. 2. Numerical model of computation domain: (a) Case A; (b) Case B.

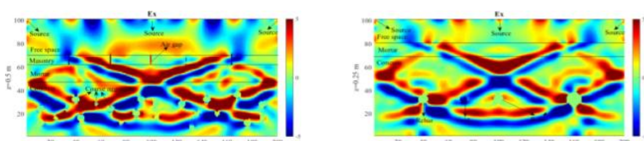
III. Simulation Results

Since the structures are excited by TE plane wave only E_x, E_y and H_z components are calculated. 1.5 GHz, 3.0 GHz and 6.0 GHz pointwise H hard sources in one dimension is used for simulation. The dielectric constants of concrete, mortar, masonry, void and rebar in Fig. 2 are $\varepsilon_{concrete} = 7.6$, $\varepsilon_{mortar} = 6.5$, $\varepsilon_{masonry} = 5.4$, $\varepsilon_{void} = 1.0$, $\varepsilon_{rebar} = 1.0$ and the conductivity of concrete, mortar, masonry, void and rebar are $\sigma_{concrete} = \sigma_{mortar} = \sigma_{masonry} 0.1\ (S/m)$, $\sigma_{void} = 0.0\ (S/m)$ and $\sigma_{rebar} = 10^7\ (S/m)$ respectively.



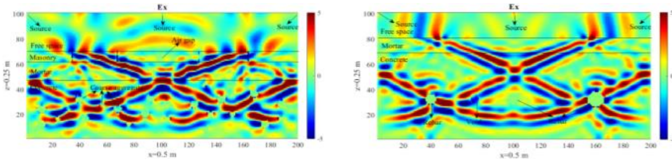
(a) (b)

Fig. 3. Simulation result for E_x at 1.5 GHz frequency: (a) Case A; (b) Case B.



(a) (b)

Fig. 4. Simulation result for E_x at 3.0 GHz frequency: (a) Case A; (b) Case B.



(a) (b)

Fig. 5. Simulation result for E_x at 6.0 GHz frequency: (a) Case A; (b) Case B.

In Figs. 3 (a)-(b) E_x field distributions at 1.5 GHz for Case A and Case B are obtained, the layers of masonry, mortar and concrete can be seen clearly and even air gaps between masonries and coarse aggregates in Case A can be seen. In Fig. 3 (b) rebars and void can be seen transparently. In Fig. 4 (a) even though the coarse aggregates are visible, the layers are almost indistinguishable so 1.5 GHz frequency is more suitable for material characterizatin than 3.0 GHz and in Fig. 4 (b) everything is seen seamlessly. In Fig. 5 (a) layers are no longer fully distinguishable but aggregates are slightly visible. In Fig. 5 (b) the mortar layer is completely blurred but the rebars remains clearly visible and thickness differences between them can be observed in all results. At all frequencies that numerical models are simulated the rebar can be clearly but higher frequency namely at 6.0 GHz rebar is more clear.

IV. Conclusions

The two different examples of civil engineering studies are designed as a numerical simulation experiment. The capability of the FDTD method for simulation of the three-layered model containing air gap and coarse aggregates and two layered media that contain rebar are investigated. The layers of the numerical model, coarse aggregate, air gap, rebar and void inside the concrete and the rebar inside it are successfully viewed. Also, rebar in the reinforced concrete is observed in such a way that the thickness of the rebar is noticeable, and the best simulation result is obtained at 1.5 GHz frequency for microwave radar NDT technique.

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