Transmission Approach for Near-Field Non Destructive Characterization of Steel Fiber Reincorced Concrete at Microwave Frequencies

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Abstract

Steel Fiber-Reinforcement is a way to strengthen concrete structures which results to be more flexible and less expensive than the conventional hand-tied rebars, while still increasing the tensile strength. In order to ensure the prescribed tensile strength, the conglomerate needs to have a certain volumetric density of fibers uniformily distributed over the structure. In this paper, a novel study on microwave Non-Destructive Testing (NDT) for Steel Fiber Reinforced Concrete (SFRC) is developed, with the objective to produce an image of the fiber density distribution in the concrete. An electromagnetic model is formulated relating the electromagnetic properties of SFRC to physical properties of this conglomerate such as fiber density or humidity content. A measurement system based on two dielectric waveguide antennas working at the appropiate microwave frequency range is designed, according to the environmental constraints and subject to the electromagnetic requirements of the situation. Laboratory non-destructive measurements on real SFRC test structures and images of the fiber density distribution in the SFRC are shown in this paper. Agreement with the theoretical simulated results is achieved.

1 Introduction

Thanks to its improved mechanical properties, Steel Fiber Reinforced Concrete (SFRC) is being increasingly used in civil constructions that need to withstand heavy forces such as pavements, airport runways and subway tunnels [1]. In SFRC composites, uniform density and random orientation of fibers are crucial to ensure isotropy and uniformity of the strength properties of the material. Nowadays, destructive methods based on magnetic approaches are the most common technique used to assess the dosage and uniformity of fiber distribution, however, they provide partial information but not a pixeled image of the whole volume of the concrete structure, as it is desirable for civil engineering purposes.

To address these problems, a new non-destructive imaging technique using a microwave system for the fiber density diagnostics is proposed in this paper. In this context, microwaves, due to their capability to sense light-opaque materials with reasonable spatial resolution, penetrability and discriminability, offer an interesting approach. The presence of fibers inside the material modifies the complex dielectric permittivity of the medium and, therefore, produces variations in the propagation of microwaves through it. Consequently, the measurement of electromagnetic properties carries information about the fiber density, leading to the obtention of images of the fiber density distribution in the concrete structure. In this paper, the performance of the proposed electromagnetic imaging technology is investigated through an experiment on multiple SFRC blocks with different fiber densities arranged forming a test wall, named Lego wall.

2 Electromagnetic Modeling

In electromagnetic theory, a randomly placed steel fiber inside a dielectric host medium induces a dipole moment accounting for the additional polarization density into the host medium. Let us consider Figure 1, an arbitrary oriented thin metal wire (length l_{fib} and diameter d_{fib}) distribution iluminated by an incident x-polarized plane wave. The average dielectric polarizability value for these metallic individual wires may be obtained as [2]:

$$\alpha_p = \frac{(2l_{fib})^2}{j\omega Z_{inp}} \tag{1}$$

where Z_{inp} is the input impedance of the wire antenna and ω is the angular frequency. Under the Maxwell - Garnett approach [3], that assumes the length of the inclusion particles to be much smaller than the wavelength, the Clausius - Mossotti formula

$$\frac{\epsilon_{reff} - \epsilon_{rh}}{\epsilon_{reff} + 2\epsilon_{rh}} = \frac{n\alpha_p}{3\epsilon_{rh}\epsilon_0} \tag{2}$$

can be used to connect the relative effective permittivity ϵ_{reff} of a composite with the polarizability of the individual inclusion α_p and the number of inclusions per unit volume n. ϵ_{rh} is the relative permittivity of the host medium and ϵ_0 is the permittivity of free space.

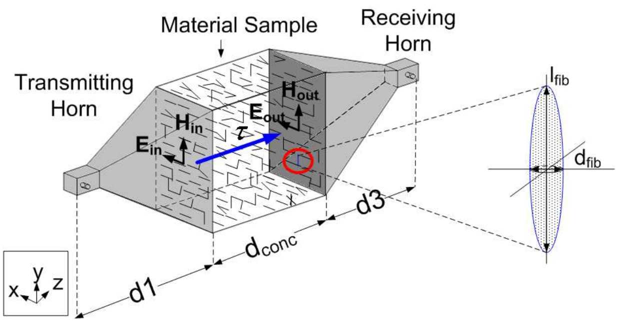


Figure 1: Randomly oriented metal wire distribution illuminated by an X-polarized plane wave.

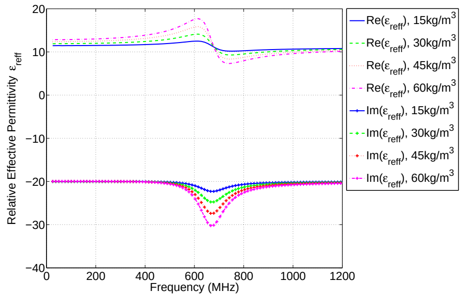


Figure 2: Real and Imaginary parts of ϵ_{reff} of PEC wires inside host medium of $\epsilon_{rh} = 11 - j20$ for different fiber densities.

Figure 2 represents the relative effective permittivity ϵ_{reff} versus frequency, of a composite material consisting of metallic wires ($l_{fib} = 50mm$ and $d_{fib} = 1mm$), in the band from $100MHz$ to $1.2GHz$. The host medium is a standard wet concrete of relative permittivity $\epsilon_{rh} = 11 - j20$. The polarizability α_p has been computed using the Numerical Electromagnetics Code (NEC) based on Method of Moments (MoM). The curves show a well behaved linear increasing variation of the permittivity with the fiber density increase until frequencies close to the resonant regime. The resonant behaviour is characterized by the dielectric properties of the material, the fiber length and the coupling between fibers [4], and produces an intense response of the fibers that alters the stable response of the system [5]. In order to properly extract the fiber density information from the measurements it is required to operate in the stable below the resonance region, which could be approximately bounded by the limits $f_{min} < f_{op} < f_{max}$, that is

$$0.3f_{res} < f_{op} < 0.8f_{res}, \qquad with \;\; f_{res} = k_{cp}\frac{c}{2\sqrt{\epsilon'_{reff}}l_{fib}} \tag{3}$$

where f_{res} is central frequency of the resonant regime and k_{cp} accounts for the reduction of the resonant frequency due to coupling effects between fibers and depends on the fiber density $f_{dens}[kg/m^3]$. This dependence is experimentaly retrieved from the electromagnetic model of Figure 2 and is expressed as $k_{cp} = 0.925 - f_{dens}0.0025$.

3 Experimental retrieval of the fiber dosage of SFRC

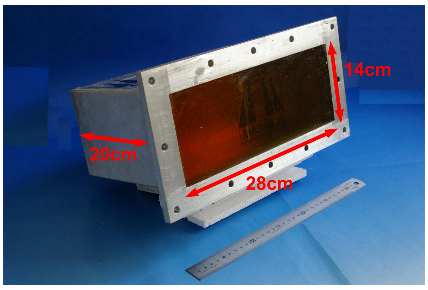


Figure 3: Dielectric waveguide antenna used in the experimental setup.

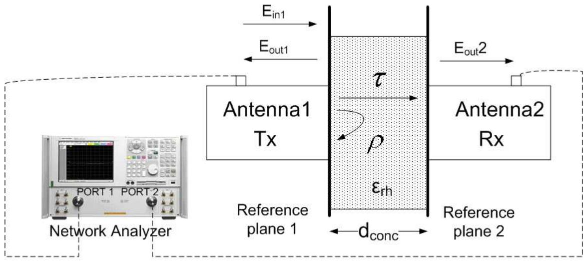


Figure 4: Schematics of the general experimental setup.

A two port measurement system is designed according to the rough operating civil engineering environment and frequency constraints for the SFRC measurements described above. The system consists of two epoxy filled waveguide antennas [5] placed into a transmission arrangement propagating an illuminating field through the material. The antennas are optimized (size versus matching) whithin the frequency range of $300MHz$ to $600MHz$, for maximum transmission into the SFRC material.

The schematics of the experimental setup is shown in Figure 4. The propagation factor, τ, can be mathematically expressed as a complex exponential accounting for attenuation, α, and phase, β, of the propagated electric field inside the material of thickness d_{conc}, as follows:

$$\tau = e^{-(j\beta+\alpha)d_{conc}} \tag{4}$$

The attenuation α is expressed in $[Nep/m]$ and β is calculated as $\beta = 2\pi/\lambda_{eff}$. Attenuation and phase of the propagation factor are obtained from the scattering parameters through

$$S_{11} = S_{22} = \frac{E_{out1}}{E_{in1}} = \frac{\left(1-\tau^2\right)\rho}{1-\tau^2\rho^2} \tag{5}$$

$$S_{12} = S_{21} = \frac{E_{out2}}{E_{in1}} = \frac{\left(1-\rho^2\right)\tau}{1-\tau^2\rho^2} \tag{6}$$

where ρ is the reflection factor and is an intermetiate step in the system of equations required to calculate τ. Thus, the complex effective relative permittivity of the material under test is related to the propagation factor through

$$\epsilon_{reff} = \frac{\beta^2-\alpha^2}{\omega^2\mu_0\epsilon_0} + j\frac{2\beta\alpha}{\omega^2\mu_0\epsilon_0} \tag{7}$$

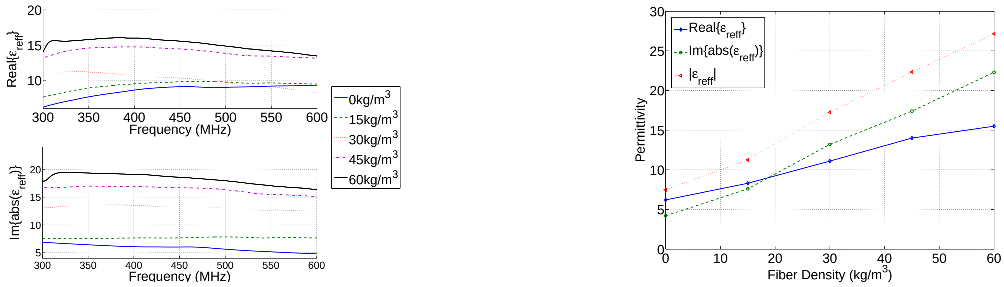
where ϵ_0 and μ_0 are the free space permittivity and permeability respectively.

Measurements in the frequency stable region of individual labeled SFRC blocks of $15cm \times 15cm \times 15cm$ size, $35mm$ long fibers and with different fiber density each, are conducted to stablish a relationship between the retrieved permittivity of a block using (7) and its fiber density, as shown in Figure 5(b). This correspondence will be used in the incoming experience as a reference for determining the fiber dosage in measurements of a complex pixeled SFRC structure.

4 Experimental SFRC Characterization

In this experience, the SFRC blocks above characterized are arranged forming a Lego wall of $3 \times 7 \times 2$ blocks $(45cm \times 105cm \times 30cm)$. The scenario of measurements is shown in Figure 6(a), where the numbers on the blocks stand for the fiber dosage of each block.

Preliminary results of measurements of a real SFRC Lego wall arrangement are shown next to numerical simulations. Figure 6(a), 6(b) and 6(c) may be compared and good similarities betwen measurements, simulations and the real scenario are observed. Difficulties on the mechanization of the

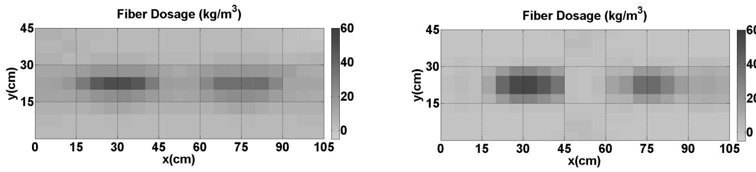


(a) (b)

Figure 5: Retrieval of the effective relative permittivity, $\epsilon_{reff}(f)$, through individual SFRC blocks measurements of different fiber densities. (a) Real and Imaginary $\epsilon_{reff}(f)$ versus frequency and (b) $\epsilon_{reff}(f)$ versus fiber density.

measurement setup may contribute to some disagreements on the measurements thay could be fixed by redesigning a new mechanization system or miniaturizing the positioning system while still mantaining its performance.

0	0	0	0	0	0	0
0	60	60	0	45	45	0
0	0	0	0	0	0	0



(a) (b) (c)

Figure 6: Lego wall results. (a) Scheme of the Lego wall scenario. (b) Intensity of fiber distribution resulting from a numerical simulation using HFSS. (c) Intensity of fiber distribution resulting from measurements.

5 Conclusions

A microwave non-destructive testing technique for monitoring the steel fiber content of SFRC has been presented. The electromagnetic model developed in this paper stablishes a nearly linear relationship between the effective permittivity of a SFRC medium and the density of fibers in that medium. A measurement system based on two dielectric probe waveguide antennas ($300MHz$ and $600MHz$) has been designed and fabricated, according to the operational constraints and electromagnetic requirements.

The performance of the proposed electromagnetic imaging technology for the fiber density diagnostics of complex pixeled SFRC structures, has been investigated in measurements of an SFRC test structure, called herein Lego wall. Results show an interesting map of the fiber content spatial distribution with good agreement with the numerical simulations.

Acknowledgments

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