1.541 Mechanics and Design of Concrete Structures
Spring 2004

TERM PROJECT

Non-destructive Evaluation of FRP-Concrete Structures using Microwave Techniques - Measuring Dielectric Properties

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Background

In today's world, civil infrastructures are one of the most important assets to a country, and in the case of the United States, the construction industry accounts for almost 10% of the Gross National Product (GNP) [4]. However, most of these structures are now approaching their service life and in need of urgent repair and retrofit. Fiber-reinforced plastic (FRP) composite jacketing systems have emerged as an alternative to traditional construction, strengthening, and repair of reinforced concrete structures. Escalating deployment of this new technology is expected, especially in seismically active regions. Assessment of the degree of damage in structural members that are confined in FRP jackets becomes problematic as the concrete core conditions cannot be fully revealed until physical removal of the jacketing system, unless the member has already been subjected to extensive damage. Based on previous studies, a concrete column may appear safe without showing any sign of substantial damage on the jacket, while the concrete core might have undergone severe cracking or crumbling [1]. Currently, several non-destructive evaluation (NDE) techniques for assessing FRP-confined concrete structures have been under development. In spite of these efforts, there is no currently available technology capable of characterizing the various forms of FRP-bonded concrete damages that is ready for real-time, large-scale damage detection on site. A reliable imaging technology is presently needed to complement the rapidly growing deployment of FRP jacketing in concrete columns and bridge piers.

Problem Statement

The objective of the 1.541 Class Project is to establish the most current understanding of NDE imaging techniques to visualize and quantify damages on FRP-confined reinforced concrete members using wideband radar. According to previous research, microwave radar technology presents several advantages other methods [3,6]. Additionally, new imaging techniques have been recently developed to better capture the electromagnetic wave propagation phenomena [2]. Numerous research tasks such as determining electromagnetic properties of materials, numerical simulations, and physical radar measurements need to be carried out in order to develop an effective radar imaging method, as shown in Figure 1. Due to the extensive character of microwave NDE research, this class project will only focus in the area of assessment of electromagnetic properties for concrete and FRP composite materials. The project will consist of an extensive literature review covering the developments in this particular area of NDE using microwave techniques, the study of the underlying physical principles of electromagnetic properties of concrete and FRP materials, and an analysis of today's research efforts in this particular area.

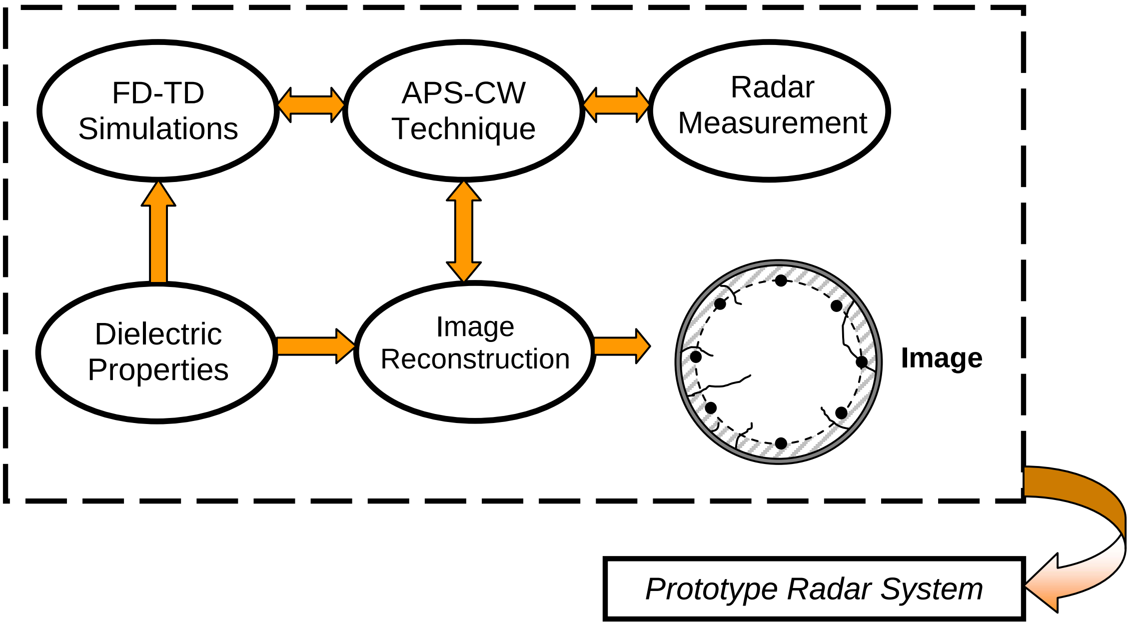

Figure 1. Schematic of a Research Plan for Developing an Effective Microwave NDE Technology

Literature Review

Review on NDE Methods

Several non-destructive evaluation techniques are being used worldwide for the assessment of civil infrastructures. Among the most important techniques are stress wave, x-ray, infrared thermography, and radar [3].

Stress wave methods are based upon elastic wave propagation in solids. They include pulse-echo, impact-echo, ultrasonic, acoustic emission, and spectral analysis of surface waves (SASW) techniques. The disadvantages of using these techniques include the need of intimate contact between the equipment and subject, the use of sound couplant, as well as the existence of multiple paths through the same subject that make result interpretations difficult [3]. X-ray techniques make use of radiation that passes through the subject and exposes it onto a film in a light-tight packet on the other side of the subject. Drawbacks of this method include the need to access both sides of the subject, the need of safety precautions, long exposure, and two-dimensional (2D) images of three-dimensional (3D) subjects [3]. Infrared thermography is based on the understanding of heat flow in the specimen in which air gaps due to delamination act as insulators, therefore blocking out the proper heat flow. Data interpretation is, however, complicated because of varying ambient temperature conditions and surface emissivity variations, which is a function of surface properties [3]. Radar technologies have been used extensively for site characterization in geotechnical engineering. The radar technique involves the generation and transmission of electromagnetic impulses into materials such as concrete with different dielectric constants [8]. Voids, delaminations, rebars, and material characteristics can be detected and interpreted from the wave reflections. The proper optimization between penetration depths and range detection capability, which are dependent on the frequencies and bandwidth of the wave, is needed. Conventional radar often makes use of low frequencies to enhance penetration but with sacrificed detectability [3]. Further developing this technique by incorporating effective imaging methods and proper characterization of dielectric properties of the materials under study could lead to enormous potential for deployment of NDE radar equipment for field applications.

Study of Dielectric Properties for Civil Engineering Materials

The first step in the developing an effective radar imaging technique is the determination of the electromagnetic properties of the investigated media. These properties become key parameters for understanding the results of both numerical simulations and physical radar measurements. Several studies have been carried to capture the variation of the properties as functions of radar frequency, moisture levels, and material density. For the purposes of this progress report, three studies will be presented, which portray the advances in dielectric property measurements of concrete and FRP composites.

Early work in electromagnetic property assessment focused in measuring the dielectric properties of concrete, mortar, and aggregates using the open-ended coaxial probe method [8]. Being concrete a dielectric material, its electromagnetic properties can be characterized essentially by the complex permittivity [6]:

$$\varepsilon = \varepsilon' - j\varepsilon''$$

where the first term is related to the dielectric constant and the second term to the loss factor. Additionally, dielectric materials are also only characterized by the real part of the complex permeability, which is very close to that of free space, $\mu_0 = 4\pi \times 10^{-7}$. Consequently, only two parameters fully describe the electromagnetic properties of concrete, FRP, and other civil engineering dielectrics. In NDE using microwaves, the dielectric constant is associated with the reduction of velocity and wavelength of the transmitted waves, which in turn increases detectability. The loss factor is associated with penetration depth of waves in the concrete medium. The open-ended coaxial probe consists of a network analyzer, and measuring probe, and a computer for data acquisition. The method is based on the principle of measuring the reflection of waves from the material along with knowledge of its physical dimensions (Figure 2). Rhim established a clear understanding of the relations between these parameters and radar frequency, moisture conditions, and penetration depths [8]. Based on his experimental work, mathematical expressions were obtained to describe the variation of the permittivity parameters with changing radar frequencies (Figure 3). It was also proven that moisture content significantly affects the permittivity parameters for concrete.

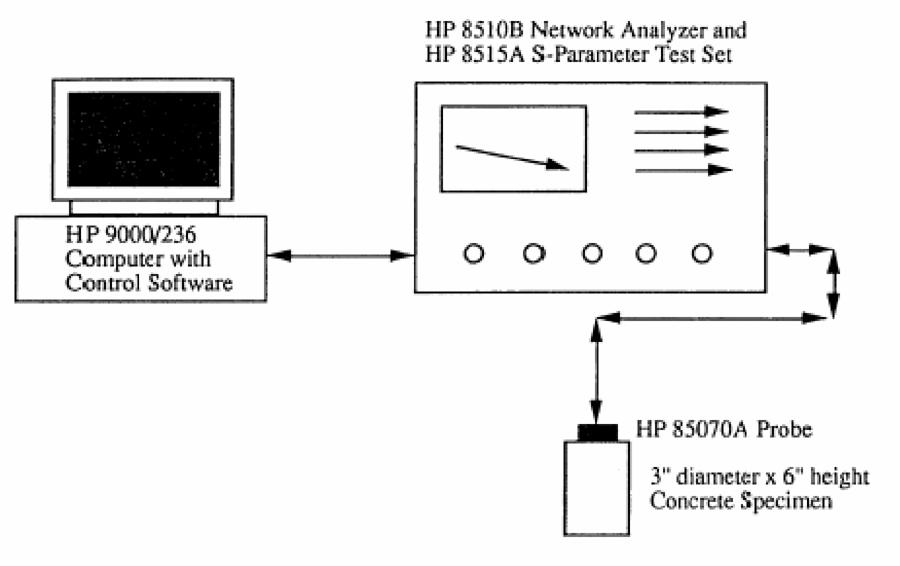

Figure 2. A Block Diagram of Dielectric Constant Measurements using the Probe Method

Additionally, a clear tradeoff between radar detectability and wave penetration depth was identified for concrete specimens.

Dielectric properties of low-density fiberglass composites were studied by Qaddoumi at microwave frequencies [7]. The main goal of the research project was to relate that information to the state of cure of the resin binder content. A waveguide method was used to study the dielectric properties of fresh and cured resin (used in the production of low-density fiberglass composite materials) in an extensive frequency range. The same method was used to determine the dielectric properties of fiberglass materials containing several curing levels of resin binder. However, the results were similar for all curing levels. Consequently, another method referred to as open-ended rectangular waveguide was used. This technique allowed for non-contact inspection. The results of the experimentation showed that dielectric property measurements served as effective tools for determining the state of cure in liquid resin binders. After optimizing the radar operating frequency and the standoff distance (related to the open-ended rectangular waveguide method), a microwave NDE imaging approach was developed to effectively distinguish among fiberglass at different levels of resin binder.

Some of the most recent work in the area of determining dielectric properties for FRP composites is in progress at the Massachusetts Institute of Technology (MIT). The Infrastructure Science and Technology Group (IST) at the Civil Engineering Department have performed extensive studies in the area of FRP retrofitting of concrete structures. One of the latest projects is currently underway, which is looking into developing effective radar NDE techniques for visualizing the condition of concrete core in FRP wrapped columns. As mentioned before, the first task in the research plan is the measurement of the dielectric properties of the materials to be tested with microwave NDE methods. However, the measurement of dielectric properties of FRP materials has become an even more difficult task than in the past due to the increasing variety of composites used in industrial applications. Typical FRP composites used in the field range from fabric sheets to plates of both glass and carbon-based materials. The mentioned variety of materials and geometries present a challenge when trying to assess their dielectric properties. With the collaboration of Lincoln Laboratory at MIT, the measurement of such properties will be performed using an innovative approach compared to previous work in this area. In particular, radar technology will be used to study the wave propagation phenomena thought FRP laminate samples. Looking at readings related to microwave power reflected and transmitted, appropriate algorithms will be developed to backfigure the dielectric constant and the loss factor for different FRP samples. The study will involve both numerical predictions based on electromagnetic wave theory and experimental measurements. The goal of the study is determining the dielectric properties of FRP composite materials as functions of several parameters such as radar frequency and sample thickness. The author of this class project is leading the mentioned research effort; and as a result, it will be used as the basis for this report.

Methodology

The IST Group at MIT is currently working in establishing the dielectric properties for FRP composite materials used for retrofitting of structures as part of a major project involving the development of efficient NDE techniques using microwaves for damage assessment of FRP confined concrete members.

Several methods are available to measure the dielectric constants such as open-ended coaxial probing (already discussed in the literature review), resistivity cell, parallel plate, and transmission line. Each method involves its specific equipment and setup, which gives them distinct levels of accuracy within the frequency range of measurement [5]. However, none of these methods is suitable to accomplish our research goal if taken into account the final geometric configuration of the FRP composite jacketing system. Figure 5 shows a cross-sectional view of a concrete column retrofitted with FRP composites. The FRP composite jacketing system is exaggerated in the sketch since typical thicknesses of FRP jackets vary between 1 to 5 mm. This reduced thickness of the FRP jacket in its final state for industry applications presents a challenge for measuring its dielectric properties if microwave radar technology is envisioned as an NDE technique. The array of methods already described required sizable samples that allow for manageable electromagnetic wave propagation. Based on the expertise of Lincoln Laboratory staff, it was decided that the dielectric properties of FRP materials will be carried out keeping the thickness of the jacketing system as similar as that when being put in place on a concrete column member. The reasoning for this approach is to

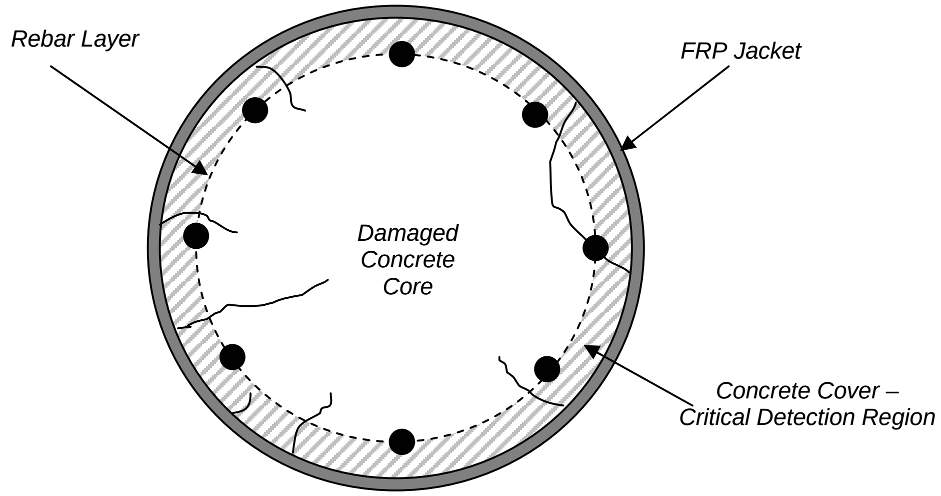

Figure 5. Geometry of FRP Jacketing System and Critical Region of Detection (shaded)

emulate experimental setup conditions for non-destructive evaluation of FRP confined concrete columns using radar equipment.

Experimental Setup

Physical measurements of electromagnetic wave propagation will be used to determine the dielectric properties of FRP composite materials used for concrete column retrofitting. For this, a network analyzer and a pair of horn antennas will be the key components of the experimental setup. A basic layout of the experimental setup is presented in Figure 6. The underlying concept for the design of this specific setup is to measure the dielectric properties of the FRP samples by back-calculating them from power transmission and reflection records of the microwave propagation through the sample. As shown in Figure 5, the FRP sample will be radiated with microwaves using two horn antennas. A network analyzer will be used to measure and analyze the electromagnetic power amplitudes and phases of the waves propagating through the sample. Conceptually, the appropriate interpretation of these measurements will allow from the determination of the transmission (T) and reflection (R) coefficients for the specific experimental setup, and finally, the dielectric properties of the FRP samples will be back-calculated from these coefficients.

Several aspects of the experimental setup have to be taken into account to ensure an accurate measurement of the proposed test parameters. Three of the most important test conditions are the far-field condition, radar aperture, and wave refraction. Far-field condition is necessary to have an appropriate handle of the recorded data, avoiding complex wave behavior in the near-field between the horn antennas and the FRP

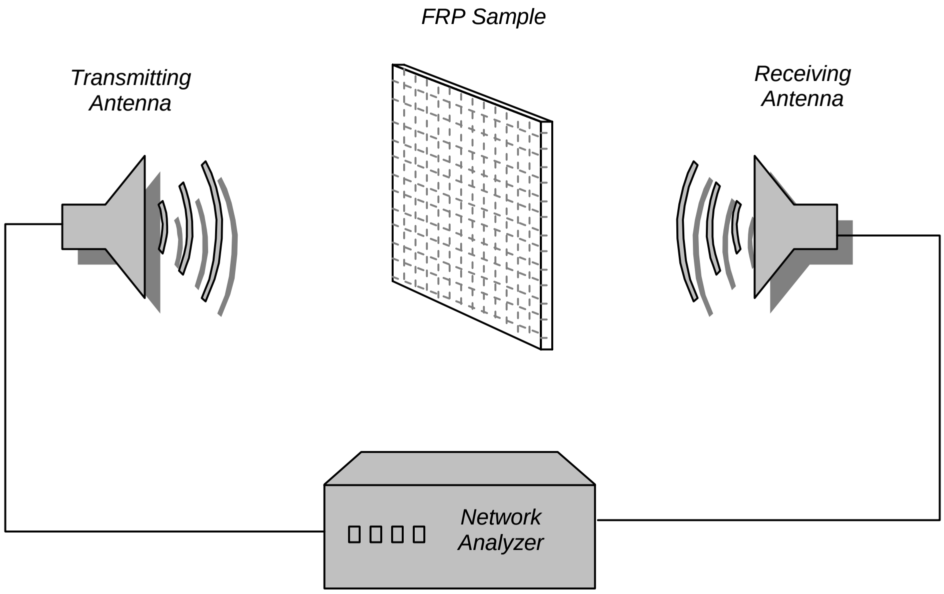

Figure 6. Experimental Setup for Measurement of Dielectric Properties of FRP Composite

sample. For the case of a horn antenna of rectangular cross-section dimensions *w* and *h*, far-field condition is guaranteed by:

$$R > \frac{2w^2}{\lambda} \quad \text{and} \quad R > \frac{2h^2}{\lambda}$$

where R is the distance from the horn antenna to the FRP sample and λ is the wavelength of the microwave. The dimensions for the horn antennas to be used are approximately 6 cm for either side. An estimate for the working frequency for the experiments is 10 GHz. Using the relation between frequency, wavelength and the speed of light in free space:

$$\lambda = \frac{c}{f} = \frac{3\times10^8[m/s]}{1\times10^9[Hz]} = 0.03m$$

we obtain the wavelength corresponding to 10 GHz. Based on these parameters, the distance R for far-field conditions is approximately 24 cm. Radar aperture is directly related to the far-field condition, as it is expressed in terms of the distance between the antenna and the sample and the aperture angle. The mathematical relationship between these parameters is then:

$$R \cdot \theta = R \cdot \frac{\lambda}{w} = 0.24m \cdot \frac{0.03m}{0.06m} = 0.12m$$

From the two mentioned conditions, we conclude that the sample should be located at least 24 cm away from the horn antennas, and the minimum dimension of the sample should be greater than 12 cm for adequate illumination. The third test condition involves the control of wave refraction, which is a phenomenon describing how much power of propagating waves that circumvent the experimental sample is captured at the receiving antenna. Assessing the amount of refraction will be achieved in our experiment by executing two independent measurements. The first measurement will be recording the power perceived at the receiving horn antenna (P_1) for a free-space scenario (no sample in between antennas). The second measurement will be recording the power perceived at the receiving horn antenna (P_2) when using a metal plate. Assuming the metal plate as a perfect conductor, no power will pass through the sample, and thus, all the power received will be due to refraction. The appropriate amount of refraction for the experimental setup could be expressed as:

$$\frac{P_1}{P_2} \gg 1$$

This power readings will be made in terms of the *Friss Transmission* equation, which relates the antenna gains for the two horn antennas, the wavelength of the microwaves used, and the distance between the antennas. the Friss equation is expressed in terms of the receiving and transmitted signals, as seen below:

$$\frac{P_R}{P_T} = \frac{\lambda^2 G_R G_T}{(4\pi)^2 d^2}$$

Sample Preparation

As expressed in the previous sections, experimental samples are to be FRP sheets made out of FRP fibers and their corresponding epoxy component. The sample dimensions are 1 ft by 1 ft, which meets the test conditions for far-field and aperture. Several samples will be made using the most widely-used FRP types for industrial applications. Two categories of samples will be manufactured: glass fiber and carbon fiber. The samples will be manufactured by first extruding 1 ft^2 squares, which are then saturated with the corresponding epoxy. Once a sample is fully saturated, it will be put on top of a metal plate wrapped with waxed paper. The sample must be pressed against the metal base using the epoxy impregnator for this will allow the sample to become flat and avoid air pocket formations. After some preliminary tests, the curing time for the FRP sample has been determined at about one week.

Numerical Model

As explained before, the proposed experimental setup will allow for the appropriate characterization of the wave propagation phenomena through a FRP sample. Using the network analyzer, two parameters will be directly measured: the transmission (*T*) and reflection (*R*) coefficients. In order to back-calculate the dielectric properties of the FRP composite sample in terms of the complex permittivity (ε), the following numerical model is proposed. Assume a semi-infinite medium where a plane incident wave in the *x*-*z* plane hits a planar boundary as shown in Figure 7. The TM (electric field is parallel to the plane of incidence) incident, reflected, and transmitted waves are characterized by the following magnetic waves [6]:

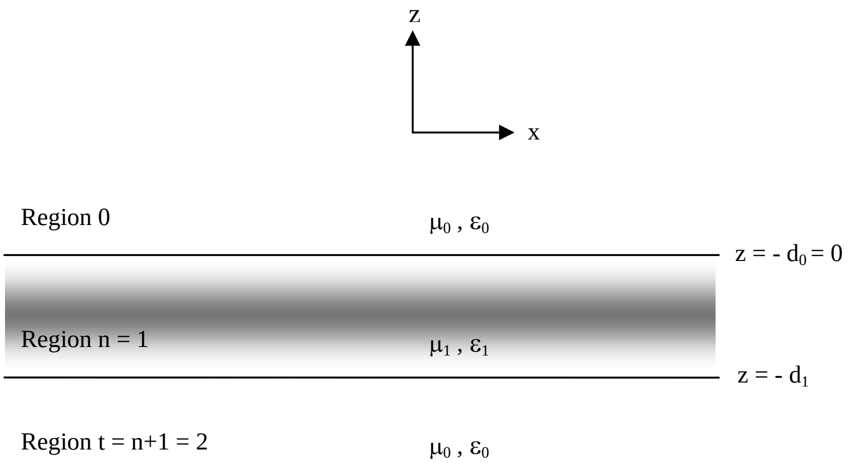

Figure 7. Layered Medium

$$\bar{H}_i = \hat{y} H_0 e^{ik_x x - ik_z z}$$
$$\bar{H}_r = \hat{y} R H_0 e^{ik_x x + ik_z z}$$
$$\bar{H}_t = \hat{y} T H_0 e^{ik_x x - ik_z z}$$

and their corresponding electric waves deduced by using Ampere's Law:

$$E_x = \frac{1}{i\omega\varepsilon_0} \frac{\partial}{\partial z} H_y$$
$$E_z = -\frac{1}{i\omega\varepsilon_0} \frac{\partial}{\partial x} H_y$$

The above expressions show plane waves traveling the *x-z* plane with known wavenumbers *k*. Let's now consider a layered medium, as in Figure 8, where three regions are identified. For the case of our problem, regions 0 and 2 will be free-space (air), and region 1 will represent the material sample. Defining both the electric and magnetic wave forms on a stratified medium as the sum of a component traveling vertically upward (+*z* direction) characterized by *A* and a component traveling vertically downward (-*z* direction) characterized by *B*, the total electromagnetic field in region *l* is:

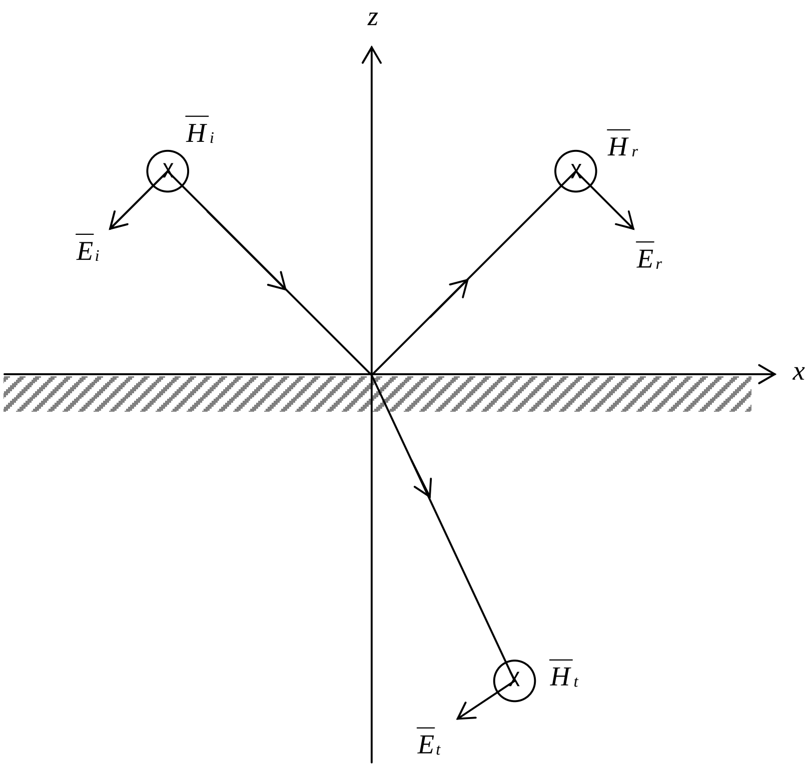

Figure 8. Reflection and Transmission of TM Waves

$$H_{ly} = \left(A_l e^{ik_{lz}z} + B_l e^{-ik_{lz}z} \right) e^{ik_x x}$$

$$E_{lx} = \frac{k_{lz}}{\omega\mu_l} \left(A_l e^{ik_{lz}z} - B_l e^{-ik_{lz}z} \right) e^{ik_x x}$$

$$E_{lz} = -\frac{k_x}{\omega\mu_l} \left(A_l e^{ik_{lz}z} + B_l e^{-ik_{lz}z} \right) e^{ik_x x}$$

Applying the dispersion relation and phase matching [6], we obtain:

$$k_{lz}{}^2 + k_x{}^2 = \omega^2 \mu_l \varepsilon_l$$

where k is wavenumber, ω is frequency, μ and ε are the permeability and permittivity of layer l. For regions 0 and 2, the boundary conditions are:

$$\text{Region 0: } \begin{Bmatrix} A_0 = RH_0 \\ B_0 = H_0 \end{Bmatrix} \qquad \text{Region 2: } \begin{Bmatrix} A_2 = 0 \\ B_2 = TH_0 \end{Bmatrix}$$

where R and T are the reflection and transmission coefficients. At $z = -d_l$ boundary conditions require that H_y and E_x be continuous. This implies:

$$\begin{aligned} A_{l+1} e^{-ik_{(l+1)z} d_l} + B_{l+1} e^{ik_{(l+1)z} d_l} &= A_l e^{-ik_{lz} d_l} + B_l e^{ik_{lz} d_l} \\ A_{l+1} e^{-ik_{(l+1)z} d_l} - B_{l+1} e^{ik_{(l+1)z} d_l} &= p_{(l+1)l} \left(A_l e^{-ik_{lz} d_l} - B_l e^{ik_{lz} d_l} \right) \end{aligned}$$

where,

$$R_{(l+1)l} = -\frac{1 - p_{l(l+1)}}{1 + p_{l(l+1)}} \qquad ; \qquad p_{(l+1)l} = \frac{\varepsilon_{l+1} k_{lz}}{\varepsilon_l k_{(l+1)z}}$$

and,

$$R_{(l+1)l} = -R_{l(l+1)} \qquad ; \qquad p_{(l+1)l} = \frac{1}{p_{l(l+1)}}$$

From these equations, we apply the concept of propagation matrices. Defining $R = A_0 / B_0$ and $T = B_t / B_0$, we then obtain:

$$\begin{pmatrix} 0 \\ T \end{pmatrix} = \overline{\overline{V}}_{t0} \cdot \begin{pmatrix} R \cdot e^{-ik_z d_0} \\ e^{ik_z d_0} \end{pmatrix}$$

where,

$$\begin{aligned} \overline{\overline{V}}_{t0} &= \overline{\overline{V}}_{tn} \cdot \overline{\overline{V}}_{n(n-1)} \cdots \overline{\overline{V}}_{10} \\ \overline{\overline{V}}_{(l+1)l} &= \frac{1}{2}\left[1 + p_{(l+1)l}\right] \begin{pmatrix} e^{-ik_{(l+1)z}(d_{l+1} - d_l)} & R_{(l+1)l} e^{-ik_{(l+1)z}(d_{l+1} - d_l)} \\ R_{(l+1)l} e^{ik_{(l+1)z}(d_{l+1} - d_l)} & e^{ik_{(l+1)z}(d_{l+1} - d_l)} \end{pmatrix} \end{aligned}$$

Applying to a two-layer system, where $d_0 = 0$:

$$\begin{pmatrix} 0 \\ T \end{pmatrix} = \frac{1}{4}[1+p_{21}][1+p_{10}]\begin{pmatrix} e^{ik_{2z}d_1} & R_{21}e^{ik_{2z}d_1} \\ R_{21}e^{-ik_{2z}d_1} & e^{-ik_{2z}d_1} \end{pmatrix} \cdot \begin{pmatrix} e^{-ik_{1z}d_1} & R_{10}e^{-ik_{1z}d_1} \\ R_{10}e^{ik_{1z}d_1} & e^{ik_{1z}d_1} \end{pmatrix} \cdot \begin{pmatrix} R \\ 1 \end{pmatrix}$$

From this expression, we can calculate the transmission and reflection coefficients:

$$R = \frac{R_{01} + R_{12}e^{i2k_{1z}d_1}}{1 + R_{01}R_{12}e^{i2k_{1z}d_1}}$$

$$T = \frac{4e^{i(k_{1z}-k_z)d_1}}{(1+p_{01})(1+p_{12})\left(1+R_{01}R_{12}e^{i2k_{1z}d_1}\right)}$$

From the two expressions above, we see that the variables defining R and T are wavenumber k, the thickness of the sample layer d_1, and the permittivity of free-space and of the material sample. For the case of a lossy medium (applicable to concrete and FRP composites), permittivity ε is a complex quantity, which was already discussed in the literature review.

Parametric Study – Special Case

As first attempt to capture trends for the different scenarios of dielectric properties of FRP materials, a simple parametric study was carried out in order to ilustrate the process for analytically understand the behavior for power transmission readings in terms of the dielectric constant. Several other variables need to be taken into account, since for a dielectric lossy medium, the wavenumber is expressed as:

$$k^2 = \omega^2\mu\varepsilon - i\omega\mu\sigma$$

which is consequently a function of the excitation frequency, the dielectric constant and permeability, and an imaginary term which incorporates the conductivity of the medium. For the case of a first approximation, we will consider the imaginary term as neglelible, as for concrete and FRP, these are not good conductive materials. Consequently,

$$k \approx \frac{2\pi f}{c} \qquad , \qquad c = \frac{1}{\sqrt{\varepsilon_0\mu_0}} = 2.998\times10^8 m/s$$

where c is the velocity of microwaves in free space.

Additionally, let's assume an incident wave of the form:

$$\bar{H}_i = \hat{y}H_0\cos(k_x x - k_z z)$$

Using Maple, a mathematical solver package, the corresponding expression for the transmission coefficient reduces to:

$$T := \frac{4\cos((k1z - kz)\, d1)}{\left(1 + \frac{\varepsilon_0\, k1z}{\varepsilon_1\, kz}\right)\left(1 + \frac{\varepsilon_1\, kz}{\varepsilon_0\, k1z}\right)\left(1 + \frac{\left(1 - \frac{\varepsilon_0\, k1z}{\varepsilon_1\, kz}\right)\left(1 - \frac{\varepsilon_1\, kz}{\varepsilon_0\, k1z}\right)\cos(2\, k1z\, d1)}{\left(1 + \frac{\varepsilon_0\, k1z}{\varepsilon_1\, kz}\right)\left(1 + \frac{\varepsilon_1\, kz}{\varepsilon_0\, k1z}\right)}\right)}$$

After some mathematical manipulation, this could be expressed as:

$$T := \frac{4\cos\left(\frac{\left(\frac{y\,\varepsilon_1}{\varepsilon_0} - 1\right) d1}{\sqrt{\varepsilon_0\,\mu_0}}\right)}{(1 + y)\left(1 + \frac{1}{y}\right)\left(1 + \frac{(1 - y)\left(1 - \frac{1}{y}\right)\cos\left(\frac{2\, y\,\varepsilon_1\, d1}{\varepsilon_0}\right)}{(1 + y)\left(1 + \frac{1}{y}\right)}\right)}$$

where:

$$y = \frac{\varepsilon_0\, f1\sqrt{\varepsilon_1\,\mu_0}}{\varepsilon_1\, f\sqrt{\varepsilon_0\,\mu_0}}$$

For the purposes of showing a schematic graph of the behavior of the transmission coefficient, let's investigate the variation of transmission coefficient *T*, as a function of thickness of the FRP sample d_1, for different values of ε_1. The following properties for the different values are stated:

$$f < f_1$$

$$\varepsilon_0 < \varepsilon_1$$

$$\mu = \mu_0$$

which mean that the frequency of the incident wave (for the case of a single frequency wave) is smaller than that after wave propagation through the material sample. This is because of the attenuation expected in the wave propagation, which leads to shorter wavelength waves. The seconds condition is that the dielectric constant of the FRP sample is to be greater than that of free space (based on previous research, ε_{FRP} is approximately three times ε_0). Finally, the permeability of FRP is assumed to be equal to that of free space, which is the case for most dielectric materials. One thing to be noticed is that the schematic graph to be presented is based in terms of relative permittivity and permeability. Although the derivation is not formally achieved in terms of dimensionless variables due to the complexity of the expression, the purpose of the plot is to illustrate the behavior of the studied variables.

Based on this observations, the relation between the transmission coefficient and the thickness of the material for different FRP dielectric constants is the following:

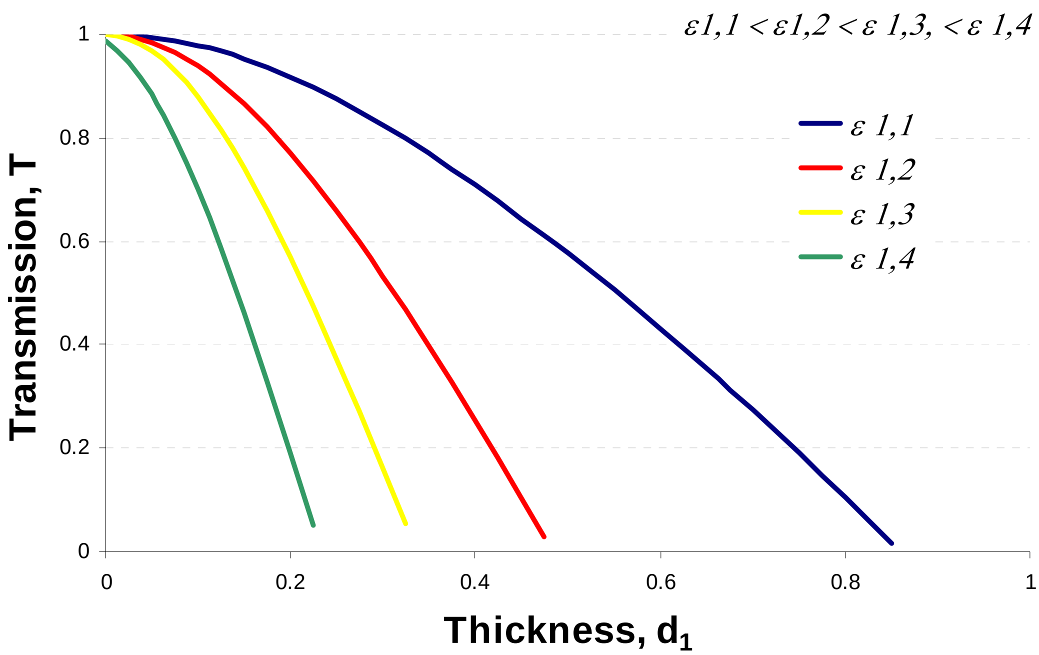

Figure 9. Schematic Relationship between the Transmission Coefficient T and the Thickness of the FRP Sample d_1 for different values of FRP Dielectric Constant

As observed in Figure 9, for greater values of dielectric constant, the range of possible FRP sample thicknesses becomes smaller for a given measured transmission coefficient. This is what it was expected, as greater values of permittivity for the FRP material would mean that the material can absorb more power for the incident wave.

Other parametric studies are to be carried out in terms of analyzing the effects of incident wave frequencies, moisture conditions, among others in order to have a clearer understanding of the wave propagation phenomena related to the laboratory measurements and thus better interpret the recorded power transmission readings.

Conclusions

This progress reports has covered several topics. The first part focused on defining the problem statement and the research goals. The second part showed the most relevant literature review pertaining to the advances in measuring dielectric properties for civil engineering materials such as concrete and FRP composites. The third section briefly described the proposed methodology for approaching the goals of the project. The fourth section referred to the numerical studies involving the numerical and analytically solutions for the expressions for reflection and transmission coefficients in terms of permittivity and wavenumber. Experimental measurements will be carried out in the future, and the results will be processed adequately using the methodology presented herein.

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