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*Research Article*

# Detection of Cracks in Concrete Structure Using Microwave Imaging Technique

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Cracks in concrete or cement based materials present a great threat to any civil structures; they are very dangerous and have caused a lot of destruction and damage. Even small cracks that look insignificant can grow and may eventually lead to severe structural failure. Besides manual inspection that is ineffective and time-consuming, several nondestructive evaluation techniques have been used for crack detection such as ultrasonic technique, vibration technique, and strain-based technique; however, some of the sensors used are either too large in size or limited in resolution. A high resolution microwave imaging technique with ultrawideband signal for crack detection in concrete structures is proposed. A combination of the delay-and-sum beamformer with full-view mounted antennas constitutes the image reconstruction algorithm. Various anomaly scenarios in cement bricks were simulated using FDTD, constructed, and measured in the lab. The reconstructed images showed a high similarity between the simulation and the experiment with a resolution of $\lambda/14$ which enables a detection of cracks as small as 5 mm in size.

## 1. Introduction, Motivation, and Problem Statement

Many buildings and civil structures are made up of reinforced concretes or cement based materials. These structures are designed to carry certain amount of load under certain conditions and for a specific period. Environmental exposure and loadings are ways through which deterioration and damage are introduced inside a functioning civil structure or cement based materials during service. For example, a structure can deteriorate when it is loaded with more than what it has been originally designed for. This gradual deterioration and damage to the material usually appear in the form of a crack or other anomalies. The anomaly presents a great threat to any civil structures; it is very dangerous and has caused a lot of destruction and damage. Even small cracks that look insignificant can grow and may eventually lead to severe structural failure. Whatever may be the genesis of these cracks, either being micro or macro in nature, the side effects of such a defect affect not only the structural properties of such buildings but also more importantly their mechanical behaviour, integrity, and permeability characteristics [1–4]. Therefore, when cracks occur, the actual strength of such structures would be reduced.

Besides manual inspection that is ineffective and time-consuming, several nondestructive evaluation techniques have been used for crack detection such as ultrasonic technique, vibration technique, and strain-based technique; however, some of the sensors used either are too large in size or suffer from poor resolution [5]. A high resolution microwave imaging technique with ultrawideband signal in detecting cracks of millimeter scale is proposed.

In this paper, we present the results using the proposed technique for cement based bricks. A total of 16 antennas were mounted surrounding the material producing a full-view configuration. A homogeneous material with $\varepsilon = 3.8$ was assumed for the bricks. This work is deigned to use an effective means that is simple, easy, low in cost, and fast with good signal penetration for data acquisition and better image resolution through multistatic arrangement. This was achieved by experimentally assessing the performance of the P-Shaped wide-slot antenna as a sensor for cement

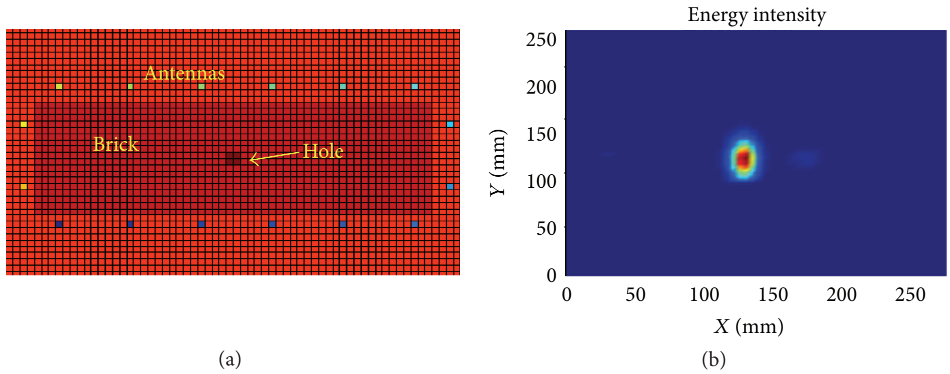



Figure 1: The FDTD simulation of a single hole with diameter of 5 mm. (a) The FDTD model. (b) The reconstructed image.

based application determining the suitable frequency range that gives better signal penetration depth through the brick structure and modeling of the time domain propagation of UWB pulses using the finite difference time domain (FDTD) method.

## 2. Problem Description

The 2D domain is considered in this work for the imaging of cracks on the bricks cross section. The 2D domain is considered in this work for the imaging of cracks on the bricks' cross section because it saves memory space optimally and demands less tasking compared to 3D domain that is computationally time demanding. The imaging space is made up of rectangular block placed at the center of the domain surrounded on every side by transceiver points numbered from 1 to 16 to give full-view scanning of the brick phantom. The brick phantom without crack in which the dielectric properties are known (homogeneous material) is used as the background for the imaging domain. As a result of this, each sensor sends UWB pulse signals to the domain and other sensors now serve as observation points with each of them recording the received signal as the resulting response from the field.

The main aim of using FDTD model is to be able to test and to also verify the capability of the imaging modality in detecting and differentiating cracks of different orientation and sizes from a brick and the constructed structure. In this work, several models with different crack size, positions, and orientation were simulated using this model. Holes of different diameters and lengths were used to characterise different crack sizes. These holes were positioned in the brick model at $(x, y)$ positions measured in millimeter. The computational domain is divided into rectangular cells in 2D with the grid size of 4 mm. The perfect match layer (PML) is composed of square of 260 mm by 260 mm to contain the size of the brick and the structure.

## 3. Image Reconstruction with Delay-and-Sum Beamformer

The image reconstruction is based on delay-and-sum beamforming technique as indicated in (1), where $I$ denotes the energy at point $x$, $m$ denotes the transmitter number, $n$ denotes the receiver number, $s$ denotes the normalized and background subtracted measured signal, $W$ denotes the integration window size, and $\tau$ denotes the propagation delay from the transmitter $m$ to point $x$ and to receiver $n$. Consider

$$I(x) = \int_0^W \left[ \sum_{m=1}^{M} \sum_{n=1}^{N} s(t-\tau) \right]^2 \mathrm{dt}. \tag{1}$$

The range resolution, $\Delta x$, of the beamformer is dictated by Rayleigh criteria as in (2), where $\varepsilon$ and $f_c$ are the permittivity and the central frequency, respectively [6]:

$$\Delta x = \frac{c}{2 \cdot \sqrt{\varepsilon} \cdot f_c}. \tag{2}$$

Based on (2), the higher $f_c$ is the higher $\Delta x$ can be achieved; however, the maximum frequency is not unlimited due to higher signal reflection and attenuation inside the material at high frequencies. After several tests we found out that optimum $f_c$ is from 1 GHz to 7 GHz. Using this frequency bandwidth together with 16 antennas in multistatic configuration, $\Delta x = \lambda/14$ can be achieved as shown in later section.

## 4. Simulation and Experimental Results

To test the resolution of the system, several FDTD models with different crack size, positions, and orientation were simulated. Firstly, a two-dimensional model of a brick with a single 5 mm or $\lambda/14$ diameter hole was simulated. Comparing between the model and the reconstructed image in Figure 1, it can be seen that the hole has been properly reconstructed at the right position; however, its shape appeared to be a little distorted with some clutter around it.

The same defect model was constructed and measured in the lab using the configuration shown in Figure 2. A 70 × 70 × 220 mm cement brick was used as the phantom. The measurement setup consists of vector network analyzer (VNA), 16 wide-slot antennas [7], 20 dB wideband amplifiers, and a multiplexer.

From the first experimental result, it can be concluded that the reconstructed image from the measurement as displayed in Figure 3(b) matches the image from the simulation. The 5 mm hole in the brick had been clearly detected.

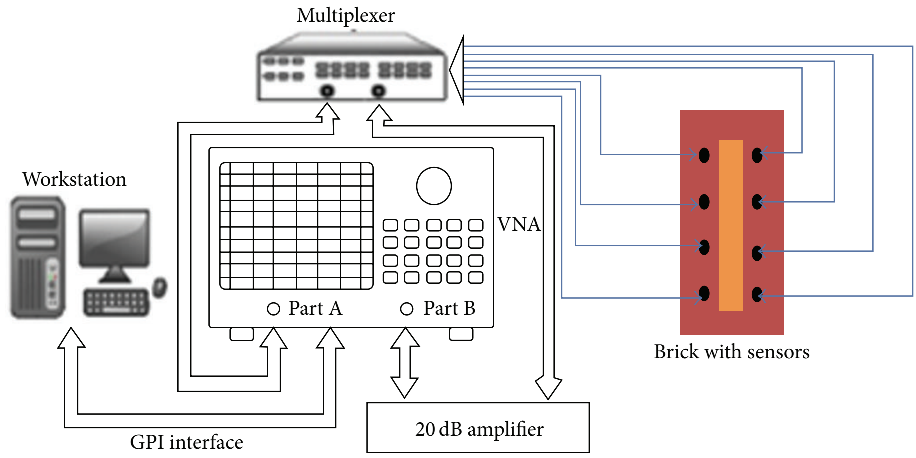
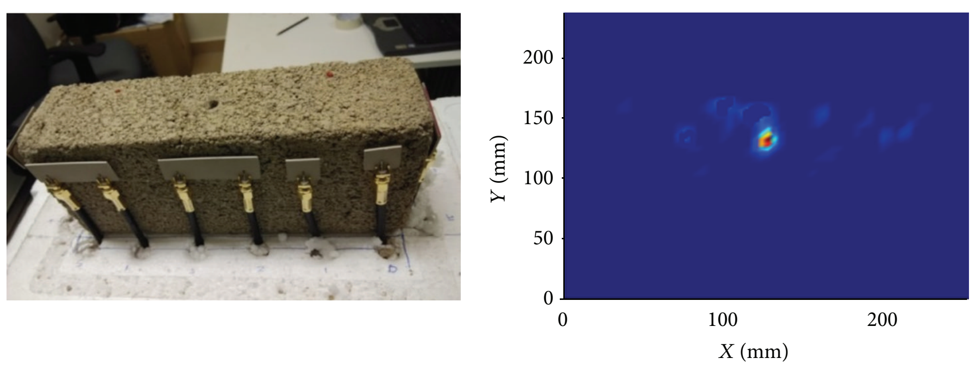



Figure 2: The experimental setup.




(a) (b)

Figure 3: The experiment of a single hole with diameter of 5 mm. (a) The brick with the 16 antennas. (b) The reconstructed image.

To study the localization performance of the system, multiple holes were simulated and measured. This time the model consisted of three holes, each with diameter of 5 mm or $\lambda/14$, and they were separated by the distance $\lambda$. From Figure 4, it can be seen that the three holes have been properly located at the right position; however, some have higher energy intensity as compared to the others. Almost similar results were obtained from the measurement, except that the holes at the edge had higher intensity than in the middle. The intensity of a point, $x$, depends on its location with respect to its distance to the antennas. An object that lies at the center or on the symmetrical line of the antennas will be more strongly detected compared to an object that lies at the sides. However, in real measurement, the antennas were mounted with a certain air gap to the brick's surface. This leads to multiple reflection between the antenna and the surface; consequently the holes at the edge appeared brighter compared to those in the middle.

A real crack in a building could be modelled with a line air gap with width of 5 mm as depicted in Figure 5(a). From Figure 5(b), it could be seen that the algorithm was able to reconstruct the line target. The similar crack model was constructed by breaking a brick into two unequal halves and putting them back together side by side. The result from the real brick shows a vague line that could match the irregular crack line of the brick. With bare eyes the line was hardly visible; however, if it would be processed further with image processing tool such as using edge detection technique, the crack could be better detected.

Since civil structures are normally made up of multiple bricks combined together and laid on each other to form a building, the next experiment is aimed at testing the ability of the signal to penetrate through a constructed building structure. The constructed structure is made of three bricks laid side by side and three bricks lay on top producing a 220 mm thick square beam which is 330 mm high. The antennas were mounted at a distance of 60 mm apart from each other with four on each side. The measurement setup remains the same as that of the single brick. A hole with a diameter of 5 mm was drilled at the center of the beam as displayed in Figure 6.

From Figure 6(c), it could be seen that the resolution for the beam has deteriorated as compared to a single brick. This might be caused by the dispersion effect of the signal which is more glaring as the thickness increases [8]. This effect could be compensated by filtering technique or using enhanced delay-and-sum algorithm [9].

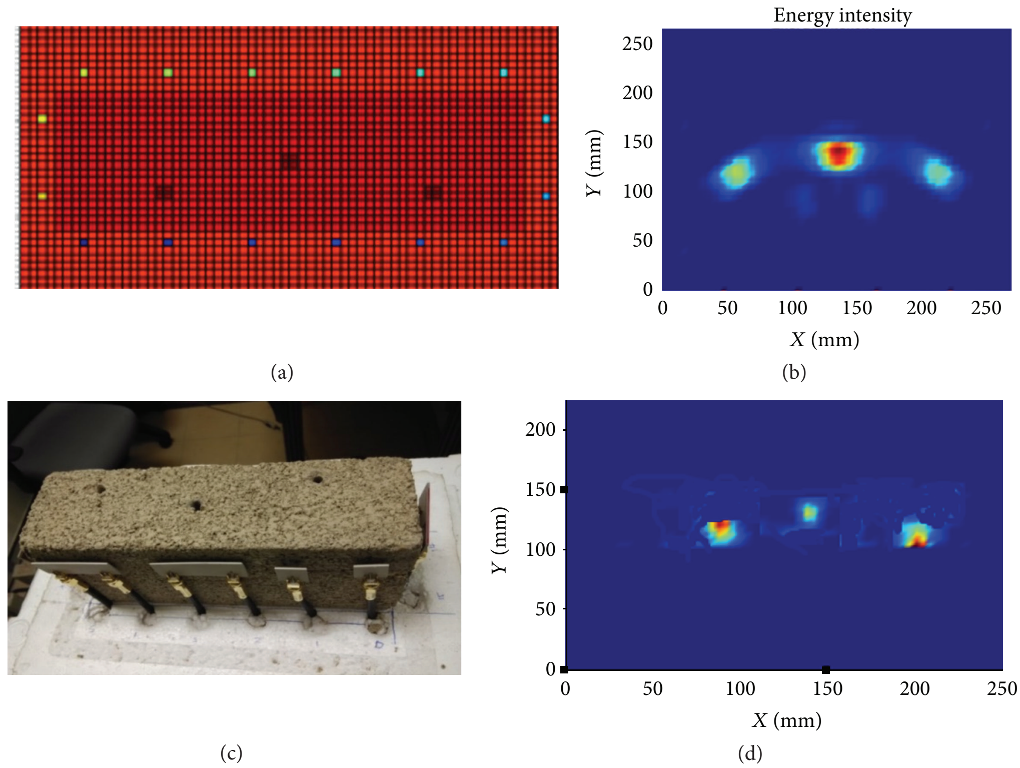



FIGURE 4: (a) The FDTD model with three holes. (b) The simulation result. (c) The brick with three holes. (d) The experimental result.

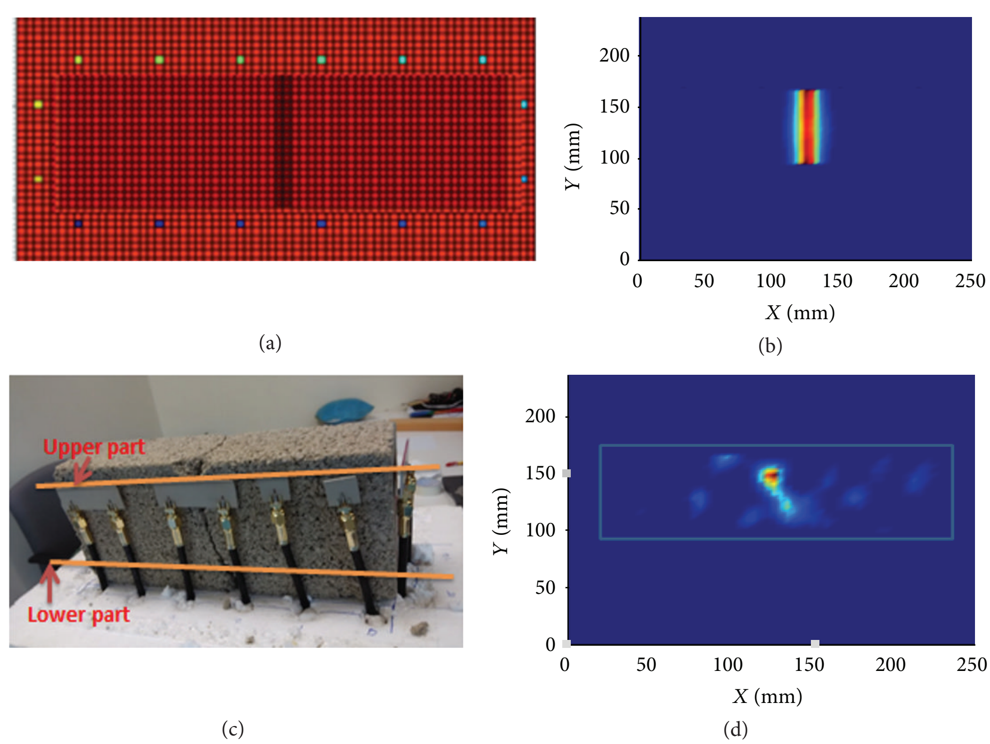
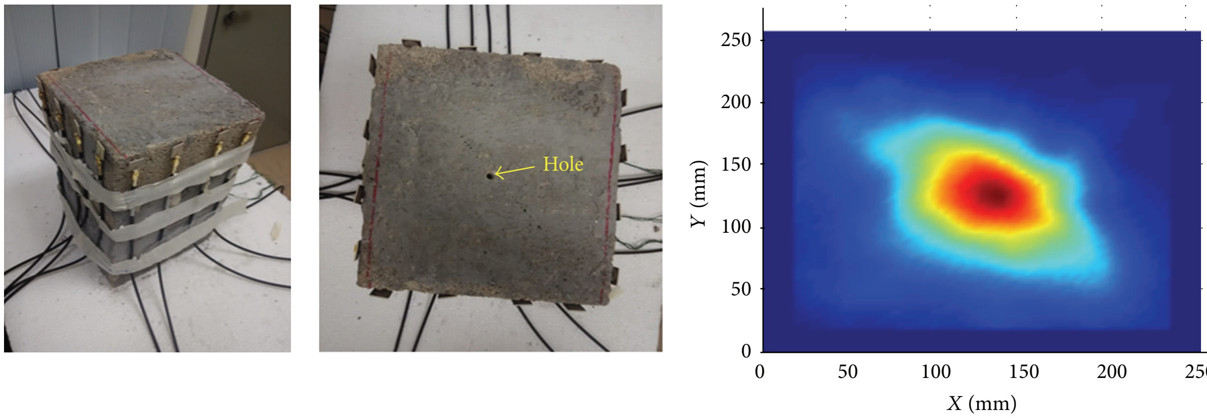



FIGURE 5: (a) The FDTD model with a 5 mm line crack. (b) The simulation result. (c) The broken and reassembled brick. (d) The experimental result.




(a) (b) (c)

Figure 6: (a) Experiment with a constructed brick structure. (b) Top view of the brick structure. (c) Reconstructed image for the structure with hole.

The effectiveness of this technique can be very much appreciated when compared with other forms of nondestructive measurements techniques. Firstly, according to [10], one of the techniques that have been used for crack detection is to draw up details sketch of the distribution of cracks and measure the corresponding data for each crack in order to acquire the knowledge about the condition of the concrete determined by the required standard. The major drawbacks of the visual inspection include the following: it lacks objectivity for quantitative analysis, it requires many efforts, and it is also time-consuming. In addition, [11] stated that human inspectors need too many professionals for just a single task, which is financially restrictive. Another downside is that two inspectors could give different results of distress information even when studying the same problem or defects. Secondly, semiempirical model, X-band (8.2–12.4 GHz) frequency model, was used with a probe. This method involves computing the reflection coefficient for both the starting point and the middle point. The downside of this technique is that, to evaluate the reflection coefficient for these points, especially the central point, an electromagnetic model needs to be developed which may be difficult to design. Though another technique was used to measure the magnetic field around the device under test, the result shows that the calculated positions in the absence of crack were found to be correct, but in the presence of crack, the calculated position and the actual position do not agree which give rise to broader distribution. This led to the introduction of a new parameter in order to be able to resolve these differences [12]. Thirdly, the technique is cost-effective, avoids the use of ionizing radiation, and gives a high definition image compared to ultrasonic technique. It provides clearer images of the object under detection and can be easily applied to the peripheral areas of the material under test [13].

## 5. Conclusion and Future Work

From the simulation and experimental results of various anomaly scenarios, it could be concluded that microwave imaging technique has a high potential to be applied to defect detection of cement based materials. The achieved resolution of $\lambda/14$ enables detection of cracks as small as 5 mm in size. Such a resolution enables detection of crack at the early stage of development.

## Competing Interests

The authors declare that they have no competing interests.

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