11th Canadian Masonry Symposium, Toronto, Ontario, May 31- June 3, 2009

# NON-DESTRUCTIVE EVALUATION OF UNGROUTED CELLS IN CONCRETE BLOCK WALLS

**A. A. Nassr[1], W.W. El-Dakhakhni[2], and M.T. Shedid[3]**

[1]Graduate student, Center for Effective Design of Structures, Department of Civil Engineering, McMaster University, Hamilton, ON, L8S 4L7, Canada, nassraa@mcmaster.ca

[2] Martini, Mascarin and George Chair in Masonry Design, Center for Effective Design of Structures, Department of Civil Engineering, McMaster University, Hamilton, ON, L8S 4L7, Canada, eldak@mcmaster.ca

[3]PhD candidate, Center for Effective Design of Structures, Department of Civil Engineering, McMaster University, Hamilton, ON, L8S 4L7, Canada, shedidmm@mcmaster.ca

## ABSTRACT

In this study, a new technique for detecting ungrouted cells in concrete block constructions was developed. The concept, based on detecting the local dielectric permittivity variations, was employed to design coplanar capacitance sensors with high sensitivities to detect such construction defects. An analytical model and finite element simulations were used to assess the influence of the sensor geometrical parameters on the sensor signals and to optimize the sensor design. To experimentally verify the model, dielectric properties of various materials involved in concrete masonry walls were measured. In addition, a masonry wall containing predetermined grouted and ungrouted cells was constructed, and inspected using the developed sensors in a laboratory setting. The proposed sensor design, coupled with a commercially available portable capacitance meter would facilitate employing this technique in the field for rapid inspection of masonry structures without the need for sophisticated data analyses usually required by other more expensive and time consuming methods.

**KEYWORDS**: concrete blockgrout; measurement; non-destructive tests; sensors.

## INTRODUCTION

When reinforcement is introduced in masonry constructions, grouting of the block cells is necessary for bond development between the steel reinforcement and masonry blocks. Problems associated with incomplete grouting, unfilled cells, and unbonded reinforcement can significantly alter the response of masonry walls and may result in an unsatisfactory response, or lower strength, and may require demolition and reconstruction of a significant portion or complete walls. The engineering inspection and detection of unfilled walls cells is essential especially in shear walls designed to resist seismic forces. In developing a proper technique to detect poorly grouted and ungrouted cells, it was kept in mind that the technique should be quick to apply, inexpensive, and more importantly, easy to use and interpret, especially, in real-life applications. Although repair techniques are available for such construction problems, the associated cost and detection limitations typically result in partial or complete demolition of the walls with such defects.

Various nondestructive evaluation (NDE) techniques have been used to evaluate damages and to detect voids and ungrouted zones in masonry walls. Ultrasonic techniques proved to be promising for their application in damage detection in concrete and masonry constructions. Williams et al. [1] used impact-echo ultrasonic for detecting voids in grouted cells of concrete block walls, and in a mortar-filled collar joint. The same technique was used by Sadri [2] to locate voids, and to evaluate the bonding quality in stone masonry structures. Ultrasonic techniques have several shortcomings such as the requirements of a coupling medium, and the need for highly experienced operators to properly acquire and interpret collected data. More recent research projects have demonstrated the possibility of detecting voids and internal cavities in masonry walls using infrared thermography [3]. Although infrared thermography facilitates inspection of large areas, the main disadvantage is its limited defect detecting depth, as it is only effective for detecting near-surface damage. Other NDE techniques such as microwave [4], and ground penetrating radar [5] were also associated with difficulties in their results interpretation and limited penetration depth.

The objective of this study is to present a new in-situ NDE technique for detection of accidentally ungrouted zones in masonry constructions based on detecting the local variation of material dielectric signatures using practical and cost-effective capacitance sensors. The developed coplanar sensors have the benefit that the sensor electrodes are in the same plane and, thus, can be applied to the masonry wall from one side, instead of having to sandwich the wall between the electrodes. In the following sections, the theoretical background employed in developing the proposed capacitance technique is highlighted. An analytical and finite element models are also used for the proposed capacitance sensor. This is followed by the sensor design and optimization procedures, and experimental verification of the developed technique.

## COPLANAR CAPACITANCE SENSOR THEORY

The proposed technique relies on detecting the variations of the dielectric signatures in material compositions of concrete block walls. The change in dielectric permittivity within different parts of the masonry walls, as a result of defects, produces change in the measured capacitance. The proposed coplanar capacitance sensor can be modeled as two adjacent electrodes of width, *s*, with spacing, *2g*, over a layered media as shown Figure 1-(a). For grouted cells, two layers of grout and masonry face shell with heights $h_1$ and $h_2$ from the outer surface of the face shell and dielectric permitvities of $\varepsilon_1$ and $\varepsilon_2$ respectively, are considered. The same model is used for unfilled cells, where $\varepsilon_1$ is taken as the dielectric permittivity of air which is equal to 1.0.

The total capacitance per unit length for the two layers substrate, [6]can be computed as:

$$C = \varepsilon_o \varepsilon_{eff} \frac{K(k_o^{'})}{K(k_o)} \tag{1}$$

where $\varepsilon_o$ (the permittivity of free space) is equal to 8.8541x10$^{-12}$ F/m, and $\varepsilon_{eff}$ is the effective of dielectric permttivity of the two substrate layers. *K(k)* is the complete elliptic integral of the first kind, *k* is the modulus of the elliptic integral function as described in [7].

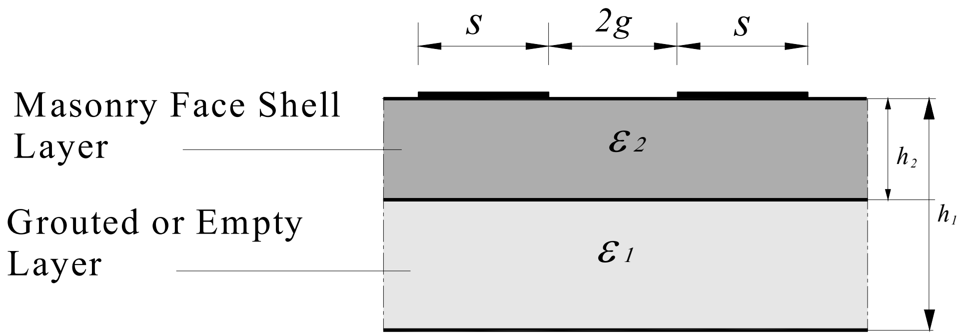



**Figure 1: Coplanar capacitance sensor model over a layered media**

## CAPACITANCE SENSOR FINITE ELEMENT MODELLING

Due to the general uniformity of the electric field along one direction compared to the other dimensions of the proposed coplanar sensor, and in order to be consistent with the analytical model, where ($l > s$), a 2D finite element simulation was selected for modelling the sensing system. Unlike 3D modelling, 2D simulations neglect the fringe-field effects at the outer edges of the electrodes. However, these effects resulted in minor differences between the predicted and measured capacitance results as will be shown later.

The 2D models considered in this study were constructed using a commercially available finite element modelling (FEM) package, [8]. Figure 2 shows the results of the FEM analysis with the electric field distribution and equipotential lines for the developed coplanar capacitance sensor over a grouted cell. The electric field is represented by a set of curves (field lines) aligned along the local field direction with spacing inversely proportional to the field strength.

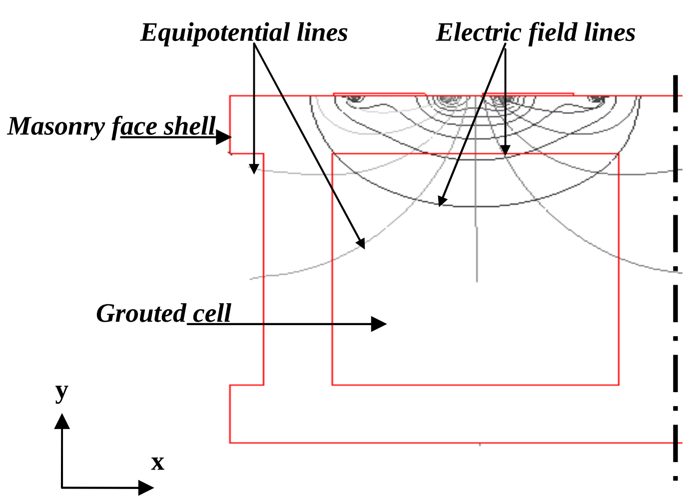



**Figure 2: The electric field and equipotential lines obtained from FEM for a grouted cell of concrete block**

## SENSOR DESIGN AND OPTIMIZATION

For an accurate detection of ungrouted cells in masonry walls, the sensor parameters must be optimized. The capacitance across the sensors depends on the dielectric values of the material compositions, material thicknesses and the sensor's geometrical parameters. With proper sensor design, differences in material dielectric properties between grouted and ungrouted cells should result in a significant change of the sensor output signals. The influence of geometrical parameters of the capacitance sensors on the capability of detecting ungrouted cells was identified as the governing factor as will be discussed in the following sections.

## SIGNAL STRENGTH

The signal strength is an important aspect to be considered in any sensor designs; as a high signal strength leads to a high Signal-to-Noise Ratio (SNR) which, in turn, leads to more stable and robust results. Figure 3 shows the change of the predicted capacitance using Eq. (1) with the electrode width, *s*, and electrode spacing, *g*. It is convenient to express the capacitance, C, in terms of a dimensionless parameter, C* as:

$$C^* = C / \varepsilon_{eff} \varepsilon_o l \qquad (2)$$

where C is the actual capacitance in (F), $l$ is the length of the electrode in (m), $\varepsilon_{eff}$ is the effective dielectric permittivity for the substrate layers, and $\varepsilon_o$ is the permittivity of free space in (F/m). From Figure 3, it can be seen that the electrode spacing has a strong influence on the capacitance signals, as the sensor with a narrow gap spacing yields higher signals than the sensor with a wider gap spacing. The capacitance also increases with the electrode width, *s*.

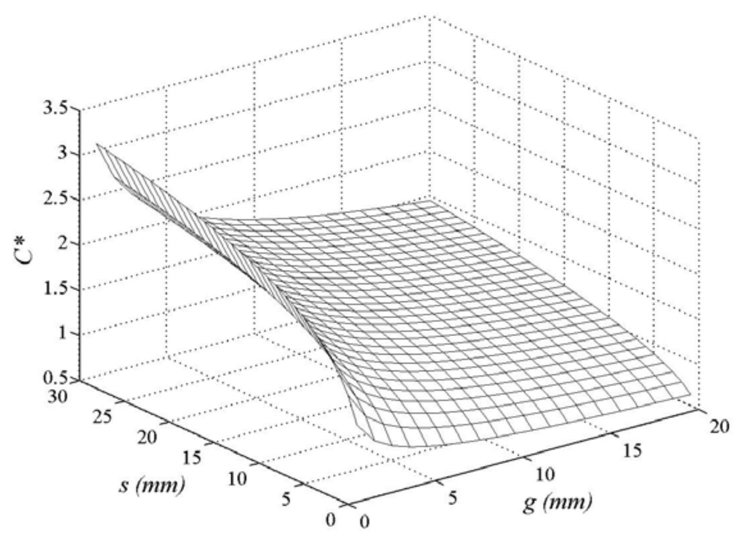



**Figure 3: Normalized capacitance versus *s* and *g***

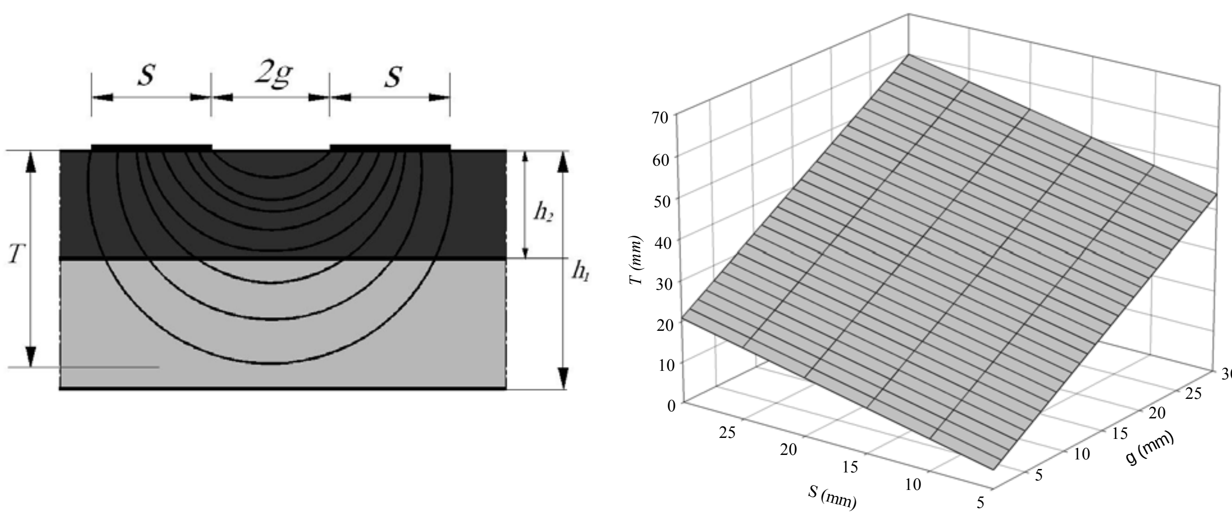
**SENSOR PENETRATION DEPTH**

Another important factor in sensor design is the sensor penetration depth, *T*, which indicates how deep the electric field effectively penetrates into a test specimen or the material thickness, as shown in Figure 4-(a). It should be noted that the electric field strength decays exponentially through the material thickness. Therefore, the dielectric permittivities of materials nearest to the electrodes have greater influence on the sensor signals compared to dielectric permittivities of materials deep in the test specimen. It was expected that, similar to fringing electric field sensors [9], the penetration depth, *T*, of the developed coplanar capacitance sensor would depend on the sensor geometry and be proportional to the distance between the centrelines of the two coplanar electrodes. It was demonstrated that the effective sensor penetration depth depends on the selection sensor geometrical parameters, [7], and can be given by:

$$T=1.35g+0.65s \tag{3}$$

Figure 4-(b) shows that sensors with wide electrodes and widely spaced are capable of penetrating deeper in the materials further away from their surfaces than the sensor with narrow and closely spaced electrodes.

The optimal design of the coplanar capacitance sensors is achieved by the proper selection of the sensor geometrical parameters in order to get a sufficient penetration depth, *T*, with the highest signal strength. This, in turn, depends on the specific application and desired detection depths for a certain block geometry.




(a) (b)

**Figure 4: (a) The penetration of the electric field through the material layers, (b) Penetration depth as a function of the sensor geometry**

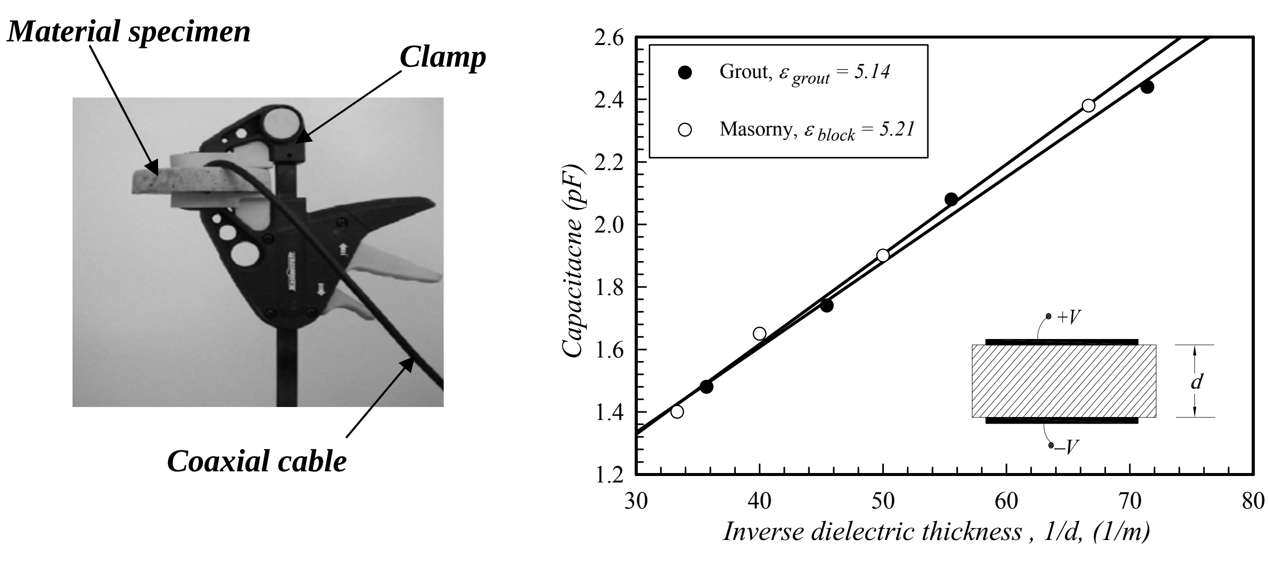
## EXPERIMENTAL VERIFICATION

## MEASUREMENT OF DIELECTRIC PROPERTIES OF MATERIALS

The accurate measurement of the dielectric properties of different materials of grouted concrete masonry composition is of prime importance in order to facilitate correlation of the experimental data to the predicated analytical and FEM simulation results. A simple technique to determine the dielectric permittivity of a material is to sandwich a disk of the material of a known thickness, *d*, between two parallel conductors. Two 25 mm square copper plates, ($A$ = 625 mm$^2$), were used as a parallel plate capacitor electrodes. In order to ensure full contact between the material and copper plates, the material specimens were placed between the two grips of a non-conductive clamp as shown in Figure 5-(a). Dielectric permittivities cannot be determined experimentally by a single capacitance measurement. This is because the capacitance produced by the measuring leads, $C_{lead}$ , will lead to be isolated and subtracted from the total measured capacitance. Therefore, four samples with different thicknesses were tested to obtain different data points to establish a relationship between the thickness, *d*, and the measured capacitance, *C*, as follows:

$$C = C_{lead} + A\,\varepsilon_o \varepsilon_r \frac{1}{d} \tag{4}$$

Figure 5-(b) shows the capacitance plotted as a function of the reciprocal of the dielectric thickness, *1/d*, for the concrete block and grout materials used in the wall test discussed in the following section. For each material, a linear relationship was plotted with a slope equal to the material's dielectric permittivity. The dielectric permittivity of the concrete block and grout were found to be 5.21 and 5.14, respectively.




**(a)** **(b)**

**Figure 5: Evaluating the dielectric properties of materials, (a) the dielectric permittivity determination setup, and (b) the capacitance as a function of the inverse of dielectric thickness**

## TEST SPECIMEN

A half-scale square masonry wallet, 4 block wide by 8 block high, was constructed with two fully grouted columns, C-1, and C-7 (see Figure 6). Another two columns were grouted expect for one cell in column C-5, and two cells in column C-3, which were filled with Styrofoam during the grouting process to simulate air (the Styrofoam's dielectric permittivity is equal to that of air). The rest of the cells were kept ungrouted, as shown in Figure 6.

A coplanar capacitance sensor with an electrode width $s$ = 25 mm, a gap spacing, $2g$ = 8 mm, and an electrode length, $l$ = 50 mm was fabricated. The sensor electrodes were made of a copper tape and mounted together on a thin plastic sheet to maintain the constant separation gap between the copper electrodes. The penetration depth, $T$, of the sensor, from Eq. (3), was estimated to be 25 mm.

Using the coplanar sensor, the 29 grouted and the 35 ungrouted cells were scanned along the surface of the wall. Measurements were collected using an INSTEK 816 LCR meter with 0.10% accuracy. The LCR meter was provided with a test fixture that facilitated the connection to the sensor by coaxial wires.

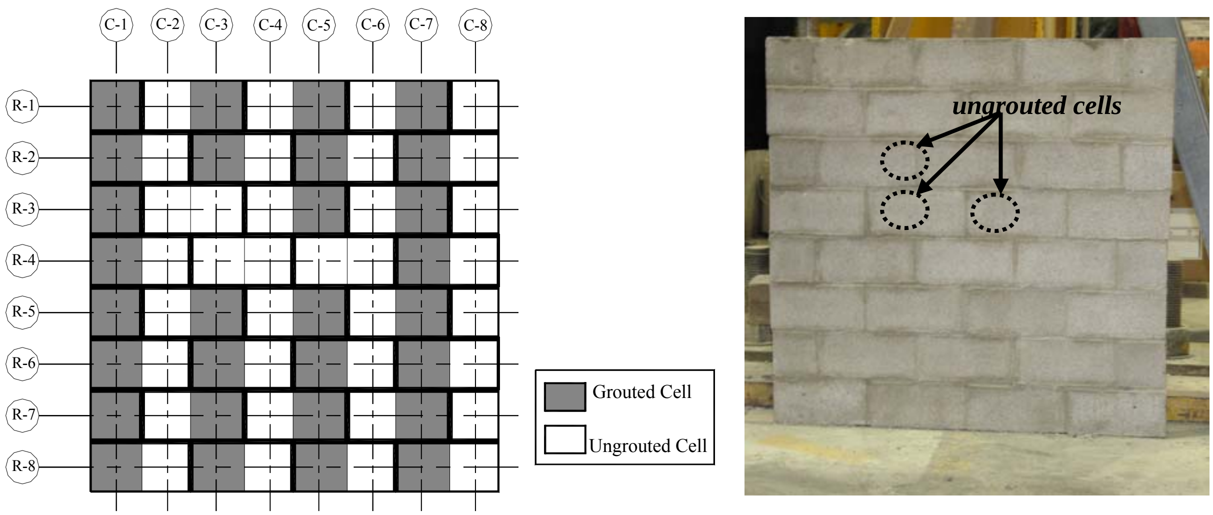
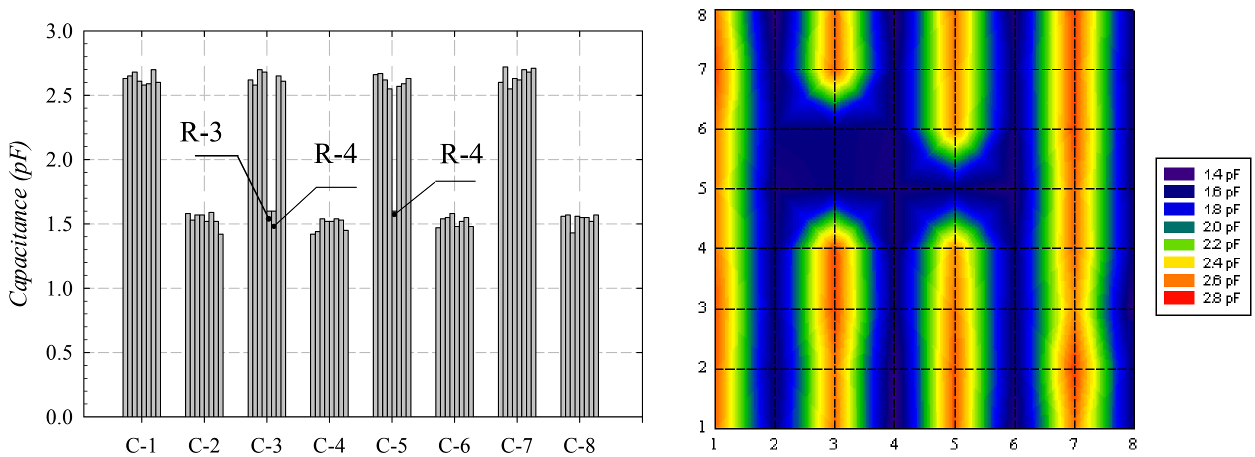



**Figure 6: Masonry wallet specimen**

## TEST RESULTS

Figure 7-(a) gives the capacitance measurements for different cells of the inspected wall. The measured capacitances were affected by the presence of voids and unfilled cells as the capacitance decreased in these regions. The decrease of the output signals is attributed to the low value of the dielectric permittivity of air, $\varepsilon_{air}$ =1, compared to that of the grout, $\varepsilon_{grout}$ = 5.14. The mean values for the measurements of grouted and ungrouted cells were 2.61 pF and 1.52 pF respectively with average coefficient of variation (COV) for both grouted and ungrouted cells of 2.56 %. The capacitance profiles from the measurements were extrapolated from the measured capacitance obtained from the three sensor configurations and presented in Figure 7-(b). The voids and ungrouted zones can be identified by the dark regions while the grouted cells appear as light regions. The analytical and FEM simulations results were also obtained to verify the

experimental results. A comparison between the results obtained from the experimental data, analytical model, and FEM simulations is shown in Table 1. The theoretical results over-predicted the experimental values by 9 % on average. The deviation between experimental data and the theoretical results may be attributed to the fact that the *2D* FEM does not account for the fringing end effect as electrodes were assumed to be of infinite length. In addition, disturbance factors such as the stray capacitance of the test lead wires and sensor/wall contact quality had other contribute to these deviations.




**(a)** **(b)**

**Figure 7: (a) Capacitance measurements for different cells of the wall, (b) Capacitance profile for inspected wall**

**Table 1.** Comparison between the experimental and theoretical results

| | *Experimental data* | *Analytical Model* | *FEM* |
|---|---|---|---|
| *Grouted cells* | *2.63 pF* | *2.84 pF* | *2.70 pF* |
| *Ungrouted cells* | *1.50 pF* | *1.72 pF* | *1.63 pF* |

Sensor sensitivity is an important factor used to investigate the sensor performance. Sensor sensitivity is an indication of how much sensor signals change for ungrouted cells compared with grouted cells. The sensor sensitivity is defined as:

$$\% \text{ Sensor Sensitivity} = \frac{C_{grouted} - C_{ungrouted}}{C_{grouted}} \times 100 \qquad (5)$$

where $C_{grouted}$ and $C_{ungrouted}$ are the average capacitance measurements for grouted and ungrouted cells. The sensitivity of the coplanar sensor in the study conducted herein was found to be approximately 40%.

The Signal-to-Noise Ratio (SNR) is another important factor and can be estimated as follows, [3]:

$$SNR = \frac{C_{grouted} - C_{ungrouted}}{\sigma_g} \tag{7}$$

where $\sigma_g$ is the standard deviation of sensor measurements for the grouted cells. The SNR was found to be approximately 22.

## CONCLUSION

The design of a coplanar capacitance sensor for detecting ungrouted zones in concrete block walls was presented. The development of the sensor was based on detecting the variation of dielectric signatures on different points along the wall surface and correlating these variations to presence or absence of the grout. Both analytical model and finite element simulations were performed to examine the influence of different sensor geometrical parameters on the sensor responses. The developed models were verified using measurements performed on a block wall containing grouted and ungrouted cells. The coplanar capacitance sensor was capable of identifying the ungrouted cells. There was excellent agreement between the experimental results and theoretical prediction data with errors attributed to fringing end effects, and stray capacitance. The results of the study clearly demonstrated that dielectric signatures of different materials can be used to detect unfilled cells in grouted masonry constructions.


## ACKNOWLEDGEMENTS

This study forms a part of an ongoing research program in McMaster University, Centre for Effective Design of structures (CEDS), funded through the Ontario Research and Development Challenge (ORDC) Fund, a program of Ministry of Research and Innovation (MRI). This research falls under CEDS Focus Area I: Masonry Design and Construction, and CEDS Focus Area III: Investigation and Remediation of Structures. The financial support of the Centre is greatly appreciated.


## REFERENCES


1. T. J. Williams, M. Sansalone, W. B. Streett, R. W. Poston, and A. R. Whitlock, "Nondestructive evaluation of masonry structures using the impact-echo method," *TMS Journal,* vol. 15, pp. 45-57, June 1997.

2. A. Sadri, "Application of impact-echo technique in diagnoses and repair of stone masonry structures," *NDT & E International,* vol. 36, pp. 195-202, 2003.

3. C. Meola, "Infrared thermography of masonry structures," *Infrared Physics & Technology,* vol. 49, pp. 228-233, 2007.

4. J. Bois, H. Campbell, A. Benally, S. Nowak, and R. Zoughi, "Microwave noninvasive detection of grout in masonry," *TMS Journal,* vol. 16, pp. 49-54, 1998.

5. M. Pieraccini, M. Pisaneschi, L. Noferini, and C. Atzeni, "Polarimetric radar signature of masonry walls," *NDT & E International,* vol. 40, pp. 271-274, 2007.
6. S. Gevorgian, H. Berg, H. Jacobsson, and T. Lewin, "Basic parameters of coplanar-strip waveguides on multilayer dielectric/semiconductor substrates. Part 2: Low permittivity superstrates," *Microwave Magazine, IEEE,* vol. 4, pp. 59-78, 2003.

7. A. A. Nassr, W. H. Ahmed, and W. W. El-Dakhakhni, "Coplanar capacitance sensors for detecting water intrusion in composite structures," *Meas. Sci. and Technol.,* vol. 19, 2008, 075702.

8. *Maxwell 2D*, V.10, Pittsburgh, PA: Ansoft Corporation 2003.

9. X. B. Li, S. D. Larson, A. S. Zyuzin, and A. V. Mamishev, "Design of multichannel fringing electric field sensors for imaging. Part I. General design principles," in *IEEE International Symposium on Electrical Insulation, 2004*, 2004, pp. 406-409.