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New electrical tomographic method to determine dampness in historical buildings

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Abstract: This paper presents a new, nondestructive method of testing brick wall dampness in wall structures. The setup was used to determine the moisture in a specially built laboratory model. Topological methods and the gradient technique are used to optimize the approach. A forward model of a wall was constructed to solve the inverse problem resulting in moisture buildup inside the wall.

Key words: electrical impedance tomography, inverse problem, finite element method, level set method

1. Introduction

The brick wall dampness testing has a major role in the assessment of building structures' technical condition, especially old apartments and historical buildings. The vast majority of European buildings made of ceramic bricks before 1945 and almost 100% of such constructions raised till 1920 have insufficient damp-proof insulation or do not possess it at all [1]. It mostly concerns horizontal damp-proof protection. Modern standard horizontal insulation solutions have been implemented since the 1920's. The lack of effective horizontal and vertical protection of this kind in the present-day brick buildings is the most common cause of the accumulation of moisture in walls (Fig. 1). Long-term dampness combined with a high level of salinity result in wall erosion, especially in subsurface areas. The realization of the efficient protection against the dampness coming from the ground water is significant for walls of already built structures in terms of durability, the restoration of usability and economic reasons. Before performing such tasks or even their planning, it is necessary to conduct specialized research on the level of dampness and its distribution in walls, both in thickness and height. The results of these measurements have substantial influence on the choice of the adequate protection against the moisture and procedure against the excessive salinity [1]. They should also be a reference point for analogous control measurements conducted later to assess protection quality and speed of walls desiccation. The excessive level of dampness decreases strength parameters of bricks and joint mix. It also decreases overall walls durability and safety of operating conditions. Water accumulated in walls creates the adverse microclimate in rooms, deteriorates thermal insulation and acoustic properties of barriers and contributes to gradual wall destruction, loosening of the plaster and paint coatings. A high moisture content inside walls along with high humidity in rooms, partially due to the lack of the proper ventilation, ease the development of the true fungi and mould which both negatively affect human health [1].

Fig. 1. Walls damaged by dampness

2. Electrical impedance tomography

a) b)

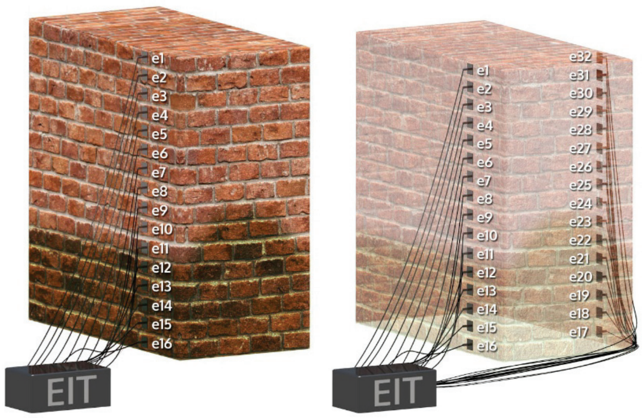


Fig. 2. Measurement EIT system with (a) 16 electrodes on one side and (b) 32 electrodes on two sides of the brick damp wall

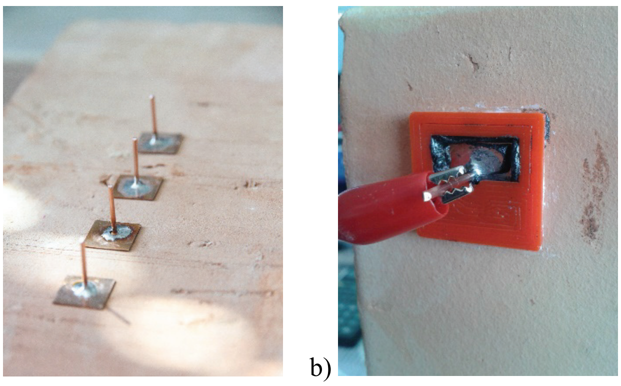
The electrical impedance tomography (EIT) is a technique of imaging distribution of conductivity inside the tested object based on measurements of the distribution of potentials on the object's surface [7]. The object is a brick wall with damp rising from the ground (Fig. 2).

Test results obtained by the nondestructive impedance tomography method are compared with the results obtained by numerical simulations. We prepared prototype measuring systems containing 16 electrodes. It is a low cost EIT tomography system for measuring a damp brick wall on one side. The 32 electrode system for measurements on both sides of the wall is currently being constructed.

3. Models

The use of EIT method does not require sampling from the wall. Among nondestructive methods the most popular are electric and nuclear methods, particularly: electric resistance method, dielectric method, microwave method and neutron method. Also, in case of nondestructive methods, dampness measuring instruments must be calibrated in order to determine the correlation between their indications and the weight moisture content of tested material. In this paper the inverse problem for electric field is investigated. Level set method and the gradient technique are based on shape and topology optimization approach to the electrical impedance tomography. Such task can be considered as an application of the electrical impedance tomography.

The object is a brick wall with damp rising from the ground (Fig. 2). Surface electrodes can be easily attached to a wall (Fig. 3) by special conductive gel.



a) b)

Fig. 3. Surface electrodes (a) on the brick damp wall and (b) on special mounting clamp with conductive gel

Investigated damped wall *NETGEN* model with measure electrodes is presented on Fig. 4. Real brick prepared for experiment wall was 1 m height, 1 m long and 0.5 m thick. It was flooded up to half height with water. The measurements were made a day after the water was drained.

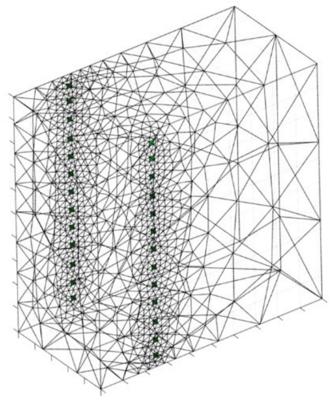


Fig. 4. Geometrical model of the investigated dumped wall with electrodes

4. Optimization algorithm

Numerical methods of the shape and topology optimization were based on the level set representation and the shape differentiation and they made possible topology changes during the optimization process. For the minimization of the problem, iterative coupling of the level set method and topological method has been proposed. Both methods are gradient-type algorithms, and the coupled approach can be cast into the framework of alternate directions descent algorithms.

The forward problem in EIT is described by Laplace's equation:

$$\nabla \cdot (\gamma \nabla u) = 0, \tag{1}$$

where γ denotes conductivity. Symbol u represents electrical potential.

The level set method is based on shape and topology optimization approach to the electrical impedance tomography. The process is described by the Hamilton-Jacobi equation:

$$\frac{\partial \phi}{\partial t} + \vec{v} \cdot \nabla \phi = 0. \tag{2}$$

Here $\vec{v}$ is the desired velocity on the interface and is arbitrary elsewhere. Actually only the normal component of $\vec{v}$ is needed ($v_n \equiv \vec{v} \cdot \vec{n} \equiv \vec{v} \cdot \nabla \phi / |\nabla \phi|$), so (2) becomes:

$$\frac{\partial \phi}{\partial t} + v_n \, |\nabla \phi| = 0. \tag{3}$$

We can update the level set function φ by solving discretized version of the Hamilton-Jacobi equation:

$$\frac{\phi^{k+1} - \phi^k}{\Delta t} + v_n^k \, \left|\nabla \phi^k\right| = 0. \tag{4}$$

Transforming above equation we get:

$$\phi^{k+1} = \phi^k - v_n^k \left|\nabla \phi^k\right| \Delta t. \tag{5}$$

The gradient of the level set function in the k-th time step ($\left|\nabla \phi^k\right|$) has been calculated by the essentially non-oscillatory (ENO) polynomial interpolation scheme. The stability of received solution is achieved by Courant-Friedreichs-Lewy condition (CFL condition):

$$\Delta t < \frac{\min(\Delta x, \Delta y)}{\max(|\vec{v}|)}. \tag{6}$$

Inequality (6) is satisfied by choosing the CFL number α:

$$\Delta t \frac{\max(|\vec{v}|)}{\min(\Delta x, \Delta y)} = \alpha, \tag{7}$$

where $0 < \alpha < 1$. The optimum value equals 0.9.

The calculated velocity must be extended off the interface to the whole domain. This process is called the extension of velocity and is based on the solution of the additional partial differential equation. The reference [2] suggests:

$$\frac{\partial v_n}{\partial t} + S(\phi) \frac{\nabla \phi}{|\nabla \phi|} \cdot \nabla v_n = 0, \tag{8}$$

where $S(\phi)$ is defined as following [1]:

$$S(\phi) = \frac{\phi}{\sqrt{\phi^2 + \varepsilon^2}}. \tag{9}$$

In (9) $|\varepsilon| \ll 1$. Additionally, we need extend velocity to neighbourhood of the interface, by defining velocity along normal direction. Reinitialization is necessary when flat or steep regions complicate the determination of the zero contour. The level set function ϕ is signed distance function if at given time for every point (x, y):

$$|\nabla \phi| = 1. \tag{10}$$

Reinitialization is based on replacing ϕ by another function that has the same zero level set, but satisfies condition. This process is described by following Equation [3]:

$$\frac{\partial \phi}{\partial t} + S(\phi)\,(|\nabla \phi| - 1) = 0. \tag{11}$$

Differential Equation (11) is solved until a steady state is achieved. Similar to the velocity extension a first order upwind scheme for the spatial dimension and forward Euler time discretization is used. The topological method is based on the so-called conical differentiability of solutions to variational inequalities with respect to the coefficients of the governing differential operator. Such a property is sufficient to obtain the directional differentiability of solutions to the variational inequality, with respect to the boundary variations and changes in the topology, by the creation of a small object. A useful concept for calculating derivatives for cost functional is the so-called material and shape derivative of states u. In the application of inverse problems, these states typically are the solutions of partial differential equations which model the probing fields and which depend one way or another on the shape. Let λ be the adjoint function satisfying [4]:

$$-\Delta\lambda = u - u_m. \tag{12}$$

The material derivative $\dot{u}(x)$ is given by [5]:

$$\dot{u}(\vec{r}) \equiv \lim_{t\to 0}\frac{u_t(\vec{r}+t\vec{v}(\vec{r}))-u(\vec{r})}{t}, \tag{13}$$

where $(x,y)\in\Omega_t$. The shape derivative is following [8]:

$$\dot{u}(\vec{r}) \equiv \lim_{t\to 0}\frac{u_t(\vec{r})-u(\vec{r})}{t} = \dot{u}(\vec{r}) - \vec{v}(\vec{r})\cdot\nabla u(\vec{r}). \tag{14}$$

The steepest descent direction $\vec{v}$ is given by [8]:

$$\vec{v} = -(\nabla u\cdot\nabla\lambda)\,\vec{n}. \tag{15}$$

The normal velocity is evaluated by using weighted least squares interpolation to get [8]:

$$v_n^k = \nabla u^k\cdot\nabla\lambda^k + \varepsilon\kappa^k. \tag{16}$$

In next step the level set function is updated:

$$\phi^{k+1} = \phi^k - \left(\nabla u^k\cdot\nabla\lambda^k + \varepsilon\kappa^k\right)\left|\nabla\phi^k\right|\Delta t, \tag{17}$$

where Δt is obtained from CFL condition (7).

5. EIT measurement system design

The purpose of the prototype device is to verify the repeatability of test results by eliminating laboratory equipment, and to validate the use of simple and cheap electronics in EIT (Fig. 5).

The characteristic of such a device is a generator and multiplexer put on a single small circuit board, which allows mobility and enhances work comfort. Another advantage of this device is that the power supply voltage is 12 V, and the maximum current is 60 mA and that it greatly reduces energy consumption. The prototype device is controlled with a program written in the *LabView*. The device allows for fairly smooth measurement of voltage drops in all angles of projection and saving them to file. The measuring device includes a program written in the *LabView* environment, microcontroller evaluation board *STM32 F4 Discovery*, a proprietary circuit board with a generator and multiplexer.

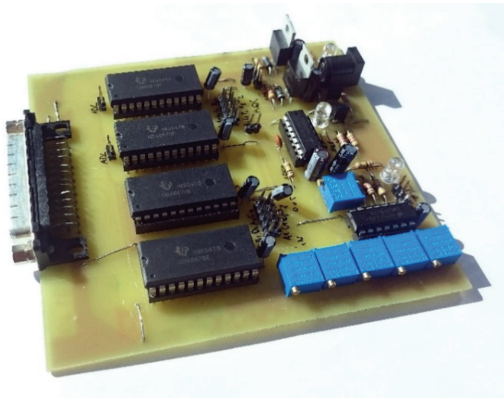


Fig. 5. The prototype of measuring device

The general scheme of cooperation between all the components of the measurement system is shown in Fig. 6.

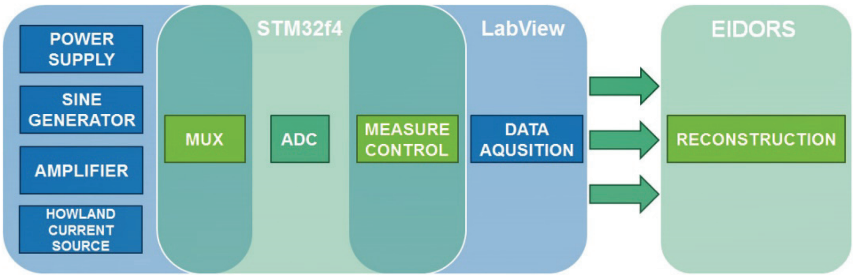


Fig. 6. Scheme of the block diagram operation of the measuring device

The device is controlled with the user panel *LabView* program. The measurement conditions are set, such as the number of connected electrodes, the number of measurement samples, microcontroller serial communication port, the output file path, the method of electrodes switching and the number of full series of measurements. After setting the operating parameters, the program starts to calculate sequences of particular electrodes becoming variably power sources and voltage meters and then transmits this information to the *STM32* microcontroller Waiting for the feedback information comprising the measured voltage drop on the following electrodes it saves the results to a file. A microcontroller interpreting the information from *LabView* sets the corresponding states on pins connected to the logic control multiplexers, and then performs voltage measurement in the ones attached to 12 -bit ADC pins. The measured value is sent via the serial port to the program. The authorial circuit board contains a proprietary stabilization system supply to ±5 V, function generator, a chip with four operational amplifiers, four 16-channels multiplexers and connectors which are coupled with multiplexers' logic. What is worth to point out is that the signal power test object is generated with a Howland current source with amplitude of 1 mA_{pp} and its frequency is adjustable. Fig. 7 shows a laboratory test model.

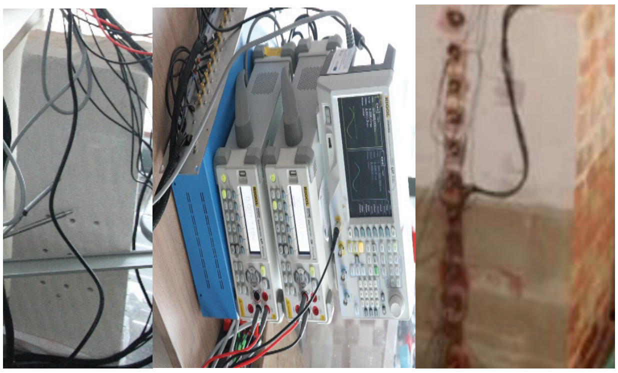


Fig.7. Laboratory setup to test the methods and measured objects

6. Results

There were two prototype measuring systems prepared. The first of them is the EIT tomography system containing 16 electrodes for measuring a damp brick wall on the one side. The second one is a full EIT system for testing on both sides of the wall. Fig. 8 shows the exemplary numerical reconstruction of moisture in a damped wall achieved with the Gauss Newton one step method. Fig. 9 presents the image reconstruction realized with the level set method.

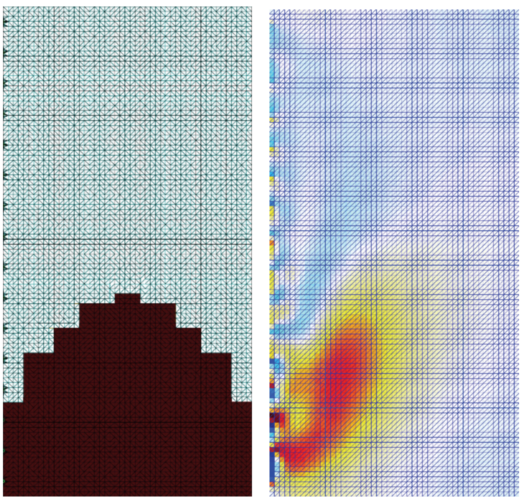


Fig. 8. Model and numerical reconstruction of moisture in a damped wall

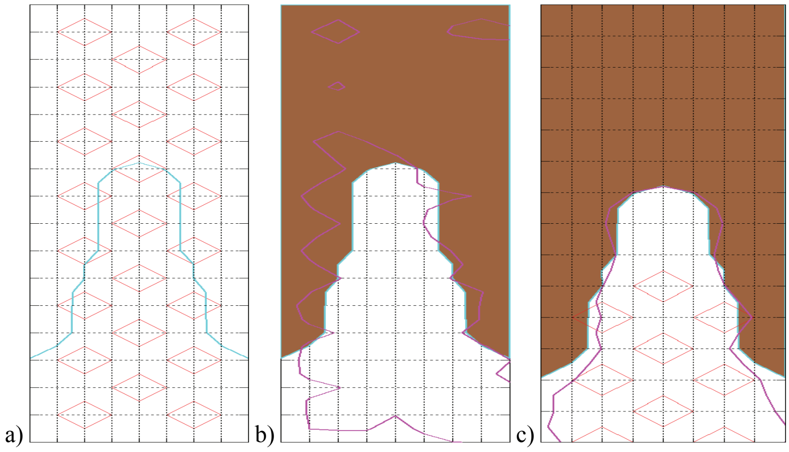


Fig. 9. The image reconstruction achieved with the level set method: (a) original objects and the zero contour, (b) reconstructed object with electrodes on one side of the wall, (c) reconstructed object with electrodes on both sides of the wall

Surface potential measurements are performed at different angles of projection (Fig. 10) whereby the information needed to determine an approximate distribution of conductivity inside For the minimization is obtained. The forward problem was solved with the finite element method.

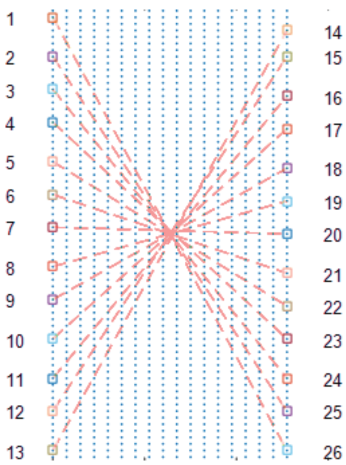


Fig. 10. Angles of projection in object with electrodes mounted on both sides

Fig. 11 shows image reconstruction obtained with the Gauss Newton one step method from the original measurement object.

Figure 12 shows image reconstruction obtained with optimization: Nelder-Mead Simplex Method from the original measurement object. Different values of the moisture are presented by separated lines.

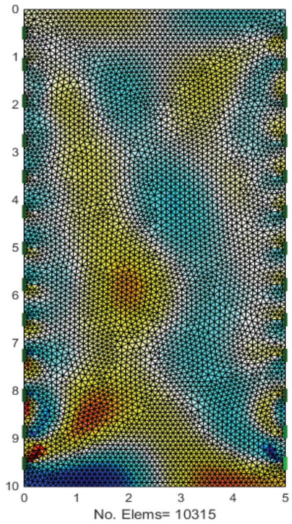


Fig. 11. Image reconstruction obtained with the Gauss Newton one step method

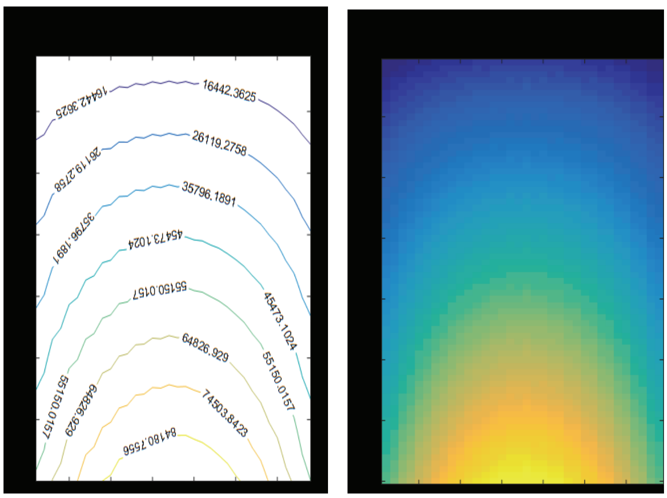


Fig. 12. The reconstruction image obtained with optimization: Nelder-Mead Simplex Method

7. Conclusions

The new nondestructive method of brick wall dampness assessment was tested with EIT. The setup was used to determine the moisture level in a wall structure being a part of a specially built testing model. Numerical methods of shape and topology optimization were based on gradient and level set representation. Presented methods have been applied very successfully in many areas of scientific modelling (the Gauss Newton one step method is the fastest, level set function is the most precision, while the Nelder-Mead Simple shows the process of change in the distribution of conductivity). An efficient algorithm for solving the forward and inverse problems would also improve a lot the numerical performance of proposed methods.

References

[1] Hoła J., Matkowski Z., Schabowicz K., Sikora J., Nita K., Wójtowicz S., *Identification of Moisture Content in Brick Walls by means of Impedance Tomography*, COMPEL 31: 1774-1792 (2012).
[2] Osher S., Santosa F., *Level set methods for optimization problems involving geometry and constraints. Frequencies of a two-density inhomogeneous drum*, Journal of Computational Physics 71: 272-288 (2001).
[3] Allaire G., Gournay F., Jouve F., Toader A., *Structural optimization using topological and shape sensitivity via a level set method*, Control and Cybernetics 34: 59-80 (2005).
[4] Osher S., Sethian J.A., *Fronts Propagating with Curvature Dependent Speed: Algorithms Based on Hamilton-Jacobi Formulations*, Journal of Computational Physics 79: 12-49 (1988).
[5] Rymarczyk T., *Using electrical impedance tomography to monitoring flood banks*, International Journal of Applied Electromagnetics and Mechanics 45: 489-494 (2014).
[6] Sokolowski J., Zochowski A., *On the topological derivative in shape optimization*, SIAM Journal on Control and Optimization 37: 1251-1272 (1999).
[7] Adler A., Lionheart W.R.B., *Uses and abuses of EIDORS: an extensible software base for EIT*, Physiological Measurement 27/5: 25-42 (2006).
[8] Rymarczyk T., Tchórzewski P., Sikora J., *Topological Approach to Image Reconstruction in Electrical Impedance Tomography*, ADVCOMP 2014, Rome, Italy, 42-45 (2014).