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Modern experimental method for assessment of metallic structures joined by rivets from architectural heritage elements

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Abstract: *Nondestructive testing techniques in the cultural heritage field has advantages in the analysis of monumental objects (i.e., undisturbed, non-contact and fast inspection of large surfaces). Architectural heritage, i.e., antique buildings and small architecture are affected by many degradation processes of varied course, dependent on characteristics of used materials as well as the object's age, working conditions and random natural or anthropic events. Structures containing metallic parts from architectural heritage shall receive structural health monitoring analysis for preservation. Thus, general engineering problems can be addressed by electromagnetic nondestructive testing of metallic structures jointed by rivets, using a new type of sensor array, in order to emphasize the eventually discontinuities which favors the corrosion acceleration.*

Keywords: *cultural heritage structures, non-destructive testing, sensors array.*

1. INTRODUCTION

The cultural assets that belong to the cultural heritage constitute the indicators of the technical, cultural and socio-economic evolution and represent a testimony and an expression of the national values. The action of preserving the assets belonging to the cultural heritage is first of all a problem of scientific research and then of technical execution. Conservation and restoration interventions and techniques are carried out only after an approval of the materials and the expertise of the causes that produced the degradation. In order to protect the assets, it is necessary to know the masterpiece's materials. Knowing the origins, characteristics, different ways to behave in time, we can understand and prolongs the life durability of cultural heritage assets and avoids agents or factors that cause damage as environmental factors (humidity, temperature, air pollution, etc.), biodegradation (bacteria, fungi, algae, etc.) and also human actions due to ignorance.

When constitutive material is inorganic (granite, metal, basalt, etc.), the most important condition is to remedy any existing danger by the correct approach of the conservation and restoration methods. Visual examination is a first step and the fastest method in recognizing damage, when it is visible [1]. Usually, structures from cultural heritages are evaluated by classical nondestructive testing/evaluation (NDT/E) procedures as ultrasound [2], eddy current [3] or ground penetrating radar [4]. Iron objects are subjected to corrosive degradation under environmental factors, becoming coated with a large amount of iron sulfide. This sulfide produces strong corrosion of both iron and cast iron [5].

From cultural heritages of Iasi, part of a work after Eiffel's plans, the former Central Hall (1883) was studied. The building, made on a metal structure and with a tin roof was intended for the sale of perishable foods with storage spaces in the basement and refrigeration installations, an innovative concept for those times. The metallic elements of the structure, made from latticed wrought iron were made in France.

The roof of the Central Hall partially collapsed in the 1960s, due to heavy snow and, later, the decision was to completely demolish the entire structure. A fragment of this metal structure is displayed in front of Faculty of Architecture "G.M. Cantacuzino" (Figure 1).

Figure 1. Fragment extract of Great Market House - Central Hall;

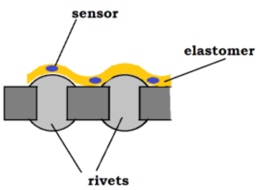
Nowadays cultural heritage structures must be high documented before performing structural health monitoring analysis for further preservation, NDE playing an important role. Non-invasive investigation of historic structures can be used for architectural archaeology, structural stability analysis, or materials characterization. Corrosion on metal constructions is usually located around areas difficult to paint, where moisture is stored over time. This fact is specific to the areas joined by rivets. Flat surfaces are usually in better condition under a paint coating. Corrosion of open-air exposed surfaces is usually in areas facing moisture accumulation. In order to make an assessment of these structures, NDT has been employed using an electromagnetic (EM) adaptive sensors array. The methods involve both numerical approach and experimental investigation.

This paper presents the results obtained at the NDT by EM method of metallic structures jointed by rivets in order to emphasize the possible discontinuities which favors the corrosion acceleration. It is known that the corrosion is accelerated in joined structures where nuts, bolts and rivets are. The rust detected around the heads can accelerate the corrosion along their stem length, causing a reduced integrity. These can become traps for humidity retaining.

2. Experimental method

The eddy current technique ~~is~~ applicable to conductive materials it is a non-contact method, characterized by repeatability and high sensitivity to the presence of defects upon and below the surface. From the point of view of the calculation of the EM field, the researches in the NDT domain follows the detection of the defects and the reconstruction of the defect's shape. The method is not influenced by thin material coatings, however the sensitivity is influenced by lift-off, the position of the sensor surface relative to the surface to be inspected and may be insensitive to volumetric discontinuities placed inside the materials when the ultrasound method can be used as a complementary method [6]. Consider a conducting material containing a long sub-surface discontinuity, very thin, the magnetic field created by the emission part of eddy current sensor will be scattered by discontinuity. The scattered field can be considered as a diffracted field and computed in terms of geometric theory of diffraction if the modes are satisfied [7]. In order to measure the diffracted field, the linear displacement of a sensor [8] or of an adaptive sensor array can be used. In this case the digitized signals from each element on the sensors are summed up, "the detection of the arrival finding" method being used [9].

The NDT method using EM sensors has been permanently developed in relation to nowadays applications. The characteristics of the sensors as the spatial resolution, the penetration depth and the conductivity of the material to be evaluated led to the development of new types of sensors. The surfaces and locations of architectural assets that require NDT have determined the design of a new sensor. Having as a model a 2D architecture [10], the concept of the sensor was remodeled to improve the ability to focus the diffracted EM field response at the time of testing. The matrix calculation required for the simulations to evaluate the amplitude and phase response of the EM sensor in the presence of rivets with and without defects is adapted to the relationships in [11]. A structure similar to the fragment that made up the structure of the Central Hall was replicated and tested to study the response of the sensor array. The sensor array was superimposed over the designed model, Figure 2.



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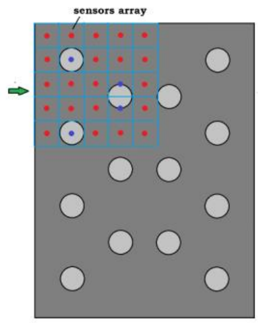

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Figure 2. Experimental set-up: a) the concept of sensors array for testing rivets; b) the design of simulation

Considering 5x5 reception coils (10mm high and 20 turns) placed over the surface to be inspected containing 14 rivets, placing 2 rivets under 2 reception coils as well as for the situation where 2 coils lay-down tangential to one rivet's circumference. By means of electro discharge machine, 0.2mm discontinuities with edge at depth of 0.5 and 1 mm have been machined in the plate made from wrought iron (with less than 1% carbon, density 7.7g/cm^3) near the rivet with conductivity of 10^7S/m. Emission is assured by a rectangular coil with 100x100mm, with 50 turns fed by 0.1A current at 25KHz frequency. The uniform field produced by the emission coil calculated using dyadic Green's function is given in [12]. The dependence of electromotive force (emf) induced in the array's coils, due to the distribution of the field created by the emission coil, do not have signals with equal amplitudes. The signal-to-noise ratio (SNR) can be improved. SNR is defined as the ratio between the mean square value of the signal and noise components, more precisely the ratio between the signal strength and that of the noise. The gain of the matrix G = 0.7*N*M is obtained, which will lead to an improvement of the SNR compared to that of an array of individual sensors, where M and N the number of rows, respectively columns of the uniform arrangement of the receiving coils that form the array (in our case N = M = 5).

3. Results and discussions

The architecture is designed to be reconfigurable, the coil support being an elastomer that fits to the test surface, Figure 3, the interrogation of the receiving coils is carried up by programming the data acquisition board.

The field created by the emission coil and scattered by discontinuities is received by the array, the signal being analyzed in amplitude and phase. Simulation of array operation was performed using XFDTD software. The FDTD algorithm provides the solution for EM excitation of the frequency function sensor and is used in evaluating the approximate solutions of Maxwell's equations in differential forms, the working procedure was described in [13]. The field decreases exponentially inside the material and in the presence of a discontinuity it will be scattered, appearing a gradient in the Oz direction that will allow the identification of the position of the electric/magnetic field of the peaks, corresponding to the position of the discontinuities, Figure 3.

The coils that are represented higher than the other laydown on the rivets, their position being modified towards the surface of the emission coil.

FDTD algorithm for array aspect analysis, allows testing of design data from a geometric point of view. The discretization of the computational problem is given by Δx, Δy, Δz and corresponding, the permittivity, the permeability and the conductivity defined in the center of the Yee cell [14], a basic element of the FDTD method. The surface scan was designed in a "leap-frog" style, the step being equal to the width of the array. The amplitude of the electric and magnetic fields for the considered array placed on the surface of the conductive material in the presence of the rivets is presented in figure 4.

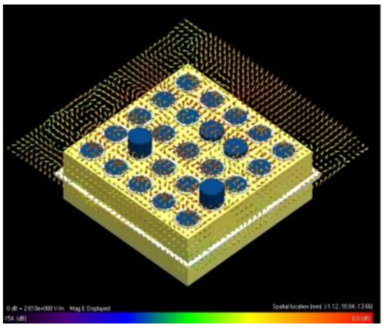
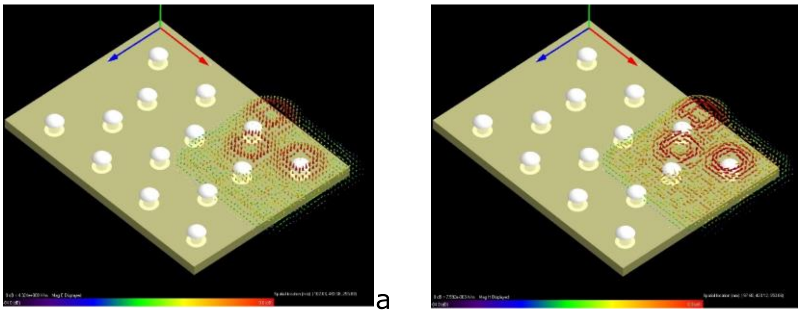


Figure 3. The EM field for the reception coils fitted to surface under test



a b

Figure 4. Amplitude of EM field: a) electric field; b) magnetic field

The amplitude of the field is dependent on the location of the coils in the array, Figure 5 shows the amplitude and phase of the emf in the array for 25 coils placed on the surface of the conductive material with rivets.

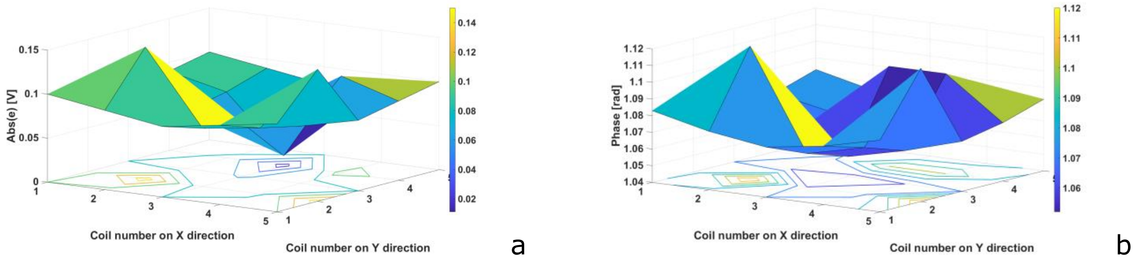


Figure 5. Amplitude and phase of the emf induced in the array of 25 coils placed on the surface with rivets

The appearance and development of a crack near the rivet are specific to the fatigue phenomenon, which leads to the modification of the conductivity and implicitly of the impedance of the coils. Placing the array on a plate of the same material that has cracks near rivets with a depth of 1 mm, placed under the centers of the receiving coils (2, 2) and (4, 2) (the number in parentheses represents the position of the sensor in the array) get the different response signal, Figure 6.

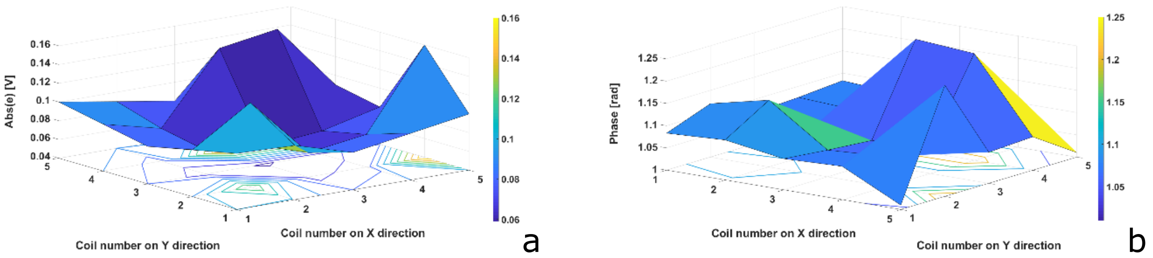


Figure 6. Amplitude and phase of the emf induced in the array of 25 coils placed on the surface with rivets and flaws under coils (2,2) and (4,2)

The results obtained in the laboratory show the possibility to apply this procedure on historical sites, to be further recommended as a method of NDE if the tests are approved by institution on charge.

4. Conclusions

Metallic structures, without regular maintenance, mainly by painting, as a measure of protection against corrosion caused by pollution, suffer a process of degradation. Most of historical assets are structures made of wrought iron or mild steel, specific to the construction period. It is important for the protection and conservation of the heritage that each object shall be evaluated and conserved in an adequate way. Estimation of the location of the cracks was carried out using a 5x5 sensor array, a super resolution algorithm was used which was applied to the response signal of the sensor matrix. The promising results of the application of this method suggest that the location of cracks in metallic structures from heritage assets by non-invasive methods can be applied without destroying their quality. The decisions regarding the interventions on them are always based on complex evaluations, adequate to the legislation regarding the protection of the national cultural patrimony and to the criteria for granting the norms of conservation and restoration of each state. Historical constructions behave relatively well over time, but a process of non-invasive investigation (regular maintenance) by different methods depending on the type of material (concrete, metallurgical structure, wood) seems to be useful for recognizing the presence of relevant discontinuities. Deterioration of the material occurs gradually at unpredictable rates and therefore adequate maintenance for the preservation process is recommended.

Further works implies the increasing the number of reception coils to increase the spatial resolution.

Acknowledgements

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