NON DESTRUCTIVE TESTING OF BONDED COMPOSITE REPAIRS USING EMBEDDED METALLIC GRIDS – NUMERICAL ANALYSIS

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ABSTRACT

The development of fibers and adhesive systems with high durability has recently led to the creation of a new repair method of metallic structures, by the use of reinforcing patches made of composite materials. This technique is generally reported as "Composite patch repair" and provides very important advantages compared to the conventional methods of repairs. On the other hand, the technology of induction heating constitutes an innovative approach to achieve the supply of energy for the curing of resins or for the manufacturing of composite materials. Induction heating takes place in the ferromagnetic materials, when these are submitted in periodically varying magnetic field. As a result, eddy currents are induced in the material, producing heat through the Joule phenomenon. In the case of resins, a ferromagnetic material must be imported into the resin, to produce the required heat. This may be achieved by importing a metallic grid in the resin. Moreover, this metallic grid, which remains inside the resin after the curing, may serve as sensor by analyzing its electrostatic properties, thus providing useful information about the structural integrity of the area (e.g. potential increase of the crack below a bonded composite repair). In this paper, it is examined whether the total resistance of the grid's branches can be translated to deformation. As it has been shown by means of numerical simulation, these measurements can be associated with good accuracy to the size of the crack, using appropriate neural networks.

INTRODUCTION

Current economic world conditions are forcing to the operation of both military and civil aircraft well beyond their original design life, resulting in innovative repair techniques. The recent development of high strength fibres and adhesives has led to the invention of a new methodology for the repair of metallic structures, by the adhesive bonding of patches manufactured by composite materials. Bonded repairs are mechanically efficient, cost effective and can be applied rapidly to produce an inspectable damage tolerant repair. With this technique, the patch is usually manufactured using carbon/epoxy or boron/epoxy composite materials, while it's bonding on the structure is achieved using high strength adhesives. Even though the technique presents great advantages from a life cycle cost point of view for the aeronautical structures, the rules of certification of the method for operational usage are not yet adequately established. Various problems, such as the long term stability of

the adhesive bonding, preclude the method from a widespread acceptance in the field of repair techniques.
An important drawback of the conduction heating process generally used for bonded composite repairs, is the unavoidable simultaneous heating of the metallic substrate together with the composite. This has negative consequences on the durability of the repair, because of the stresses induced by the different coefficients of thermal expansion of the metal and the composite patch. Ideally, when bonding composite on metal, one should avoid heating the aluminium substrate, while the composite is itself raised to its curing temperature of 120 °C or 180 °C. This means that the metallic areas around the patch should be maintained at a temperature of approximately seventy degrees and that the aluminium base in contact with adhesive should be heated in a depth of some millimeters only (skin heating).
On the other hand, the induction heating technology is a rather new approach in the repair technology area. Induction heating occurs in ferromagnetic materials, when they are submitted to a varying magnetic field, as the result of the development in the material of eddy currents. The magnetic field is itself generated by a time varying current, running through the induction coil. The material to be bonded (patch) and the susceptor are in a fixed position with regard to the coil. Heat generation is mainly the result of the Joule effect. To generate the eddy currents, a ferro-magnetic material called susceptor must be added, in order to create the heat into the resin. By nature the susceptor is metallic and with a high magnetic coefficient. The susceptor should be in the form of a grid, so that the resin can migrate through its holes while heat is transmitted from the susceptor to the adhesive by conduction [1],[2].
Induction heating constitutes an ideal candidate for supplying the energy needed for curing adhesives and resins, which are used for the fabrication of reinforcing patches, either on flat or over geometrically complex surfaces. The induction process cancels the need for the design and manufacturing of conformable patching element to complexed geometrical profiles, requiring only the use of an induction coil, which is installed at a certain distance from the reference area, as presented in Figure 1. Moreover, induction heating techniques allow to control the distribution of heat, which is applied only to the composite patch and to a small depth into the metallic base.
Finally, various methodologies have been lately developed for the examination of the integrity of the repair and the structural health monitoring of the concerned area, including the embedding of optical fiber sensors [3],[4] or wires from magnetic materials [5], in order to determine the strain field in the region of the patch. The metallic grid, which remains in the patch after the repair by means of induction heating, could be used as a sensor, by measuring changes of its electrical resistance caused by deformation. To achieve that, the grid is considered as an electrical circuit, in which a constant difference of potential between any two nodes (voltage V) is imposed. Consequently, potential deformation in the grid will cause changes in the intensity of the electric current. The aim of the present work is to connect these changes in the intensity of electric current with the length of the crack under the patch.

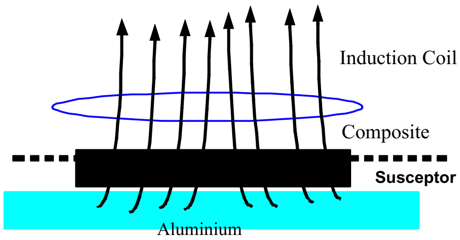


Figure 1: Main elements involved in the induction heating process

MECHANICAL ANALYSIS

In order to simulate a potential increase of the crack length, orthogonal plates of aluminium, with various crack lengths (0,8,12,16 and 20 mm) in their centre, were considered, as presented in Figure 2. The plates were supposed to be repaired with boron / epoxy composite patches and subjected to standard tensile load. Consequently, each grid embedded inside the repair would also be deformed and the difference in the crack length will be calculated onto the grids.

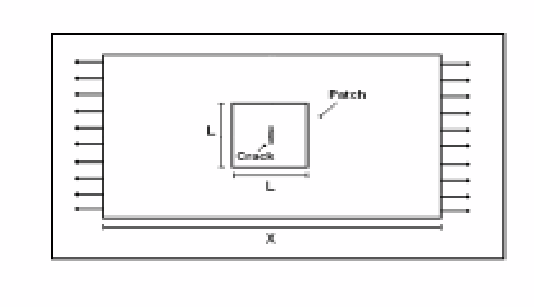


Figure 2: Considered geometry of the structure

All the results have been calculated by means of Finite Element Analysis. Due to the double symmetry of the problem, only one quarter of the configuration was modeled, as presented in Figure 3. The rigidity of the metallic grid was omitted from modeling, due to its trivial effect on the total patch stiffness. For simplification purposes, it was considered that the nodes of the square grid were identical with the nodes of finite element mesh (the whole grid is considered to be constituted of 25x25 nodes). Using this technique, the nodal transposition of the grid after the application of the load was calculated and the geometry of the deformed grid was determined. All calculations were performed for the middle thickness of the adhesive layer.

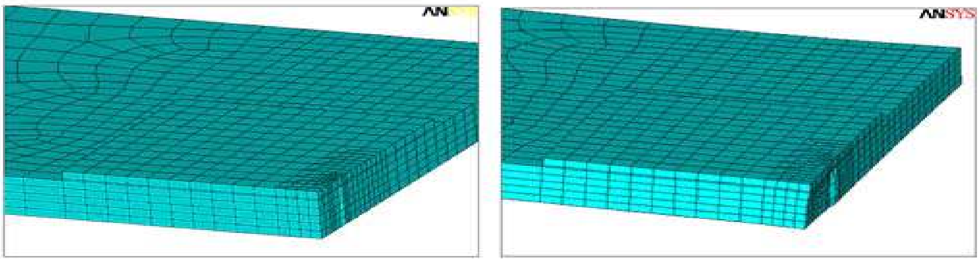


Figure 3: Undeformed and deformed presentation of the finite element model in the crack region (only 1/4 of the assumed structure was modeled due to symmetry).

ELECTROSTATIC ANALYSIS

To determine the geometry of the grid after deformation, it is required to calculate the distance between each node and between the nodes in close proximity (horizontal and vertical). The coordinates of two horizontal neighboring nodes (in their local system) is initially $\mathbf{K_i(0,0,0)}$ and $\mathbf{K_{i+1}(L_0,0,0)}$, while after the tension they become $\mathbf{K_i(\upsilon x_i,\upsilon y_i,\upsilon z_i)}$ and $\mathbf{K_{i+1}(\upsilon x_{i+1}+L_0,\upsilon y_{i+1},\upsilon z_{i+1})}$, respectively. Using this definition, the distance of two successive displaced nodes in the horizontal direction is given by the form:

$$L=\sqrt{\left(\upsilon x_i-\left(\upsilon x_{i+1}+L_0\right)\right)^2+\left(\upsilon y_i-\upsilon y_{i+1}\right)^2+\left(\upsilon z_i-\upsilon z_{i+1}\right)^2}$$

and respectively in the vertical direction:

$$L=\sqrt{\left(\upsilon x_i-\upsilon x_{i+1}\right)^2+\left(\upsilon y_i-\left(\upsilon y_{i+1}-L_0\right)\right)^2+\left(\upsilon z_i-\upsilon z_{i+1}\right)^2}$$

where υx,υy,υz are the displacements at the corresponding axis, which are calculated from the finite element models. The electric resistance of a conductor with a circular intersection $A=\pi\cdot r^2$, length L and specific resistance ρ_0, is given by:

$$R=\rho_0\frac{L}{A}$$

Thus, the calculation of resistance between two nodes is possible before and after the deformation of the grid, if we consider that they are connected with a wire of constant circular intersection and known resistivity. Consequently, the wire's cross section, which will be modified after the application of the load, must be initially calculated. The cross-sections that correspond to horizontal branches will suffer tension (i.e. reduction of initial cross section), while those who correspond in vertical branches will suffer compression (i.e. increase of cross section). Each cross-section change is calculated separately, using the Poisson ratio:

$$v=-\frac{\left(\Delta r/r\right)}{\left(\Delta l/l\right)}$$

The Ohm law for a single element (resistor) is given by:

$$\boldsymbol{G\cdot V=I}$$

or by nodal analysis :

$$\begin{pmatrix} \boldsymbol{G} & \boldsymbol{-G} \\ \boldsymbol{-G} & \boldsymbol{G} \end{pmatrix}\begin{pmatrix} \boldsymbol{V_1} \\ \boldsymbol{V_2} \end{pmatrix} = \begin{pmatrix} \boldsymbol{I_1} \\ \boldsymbol{I_2} \end{pmatrix}$$

where $\boldsymbol{G = 1/R}$ is the conductivity. For an electric circuit the conductivity matrix can be obtained from the algorithm:

$$G^{n+1}_{global}(I, I) = G^{n}_{global}(I, I) + G^{n}_{local}(1, 1)$$
$$G^{n+1}_{global}(I, J) = G^{n}_{global}(I, J) + G^{n}_{local}(1, 2)$$
$$G^{n+1}_{global}(J, I) = G^{n}_{global}(J, I) + G^{n}_{local}(2, 1)$$
$$G^{n+1}_{global}(J, J) = G^{n}_{global}(J, J) + G^{n}_{local}(2, 2)$$

where n is the branch number. Accordingly, the elements of the intensity matrix can be calculated by the formula:

$$CU^{n+1}(I) = CU^{n}(I) - G^{n}_{global}(I, J)gV(J)$$

where ***V(J)*** is the source voltage matrix. The node numbering used for this analysis is presented in Figure 4. Only the nodes which are linked to the source will have a non zero value, following Kirchoff's law that the algebraic sum of the currents entering any node is zero. Consequently, applying Gaussian Elimination, the Node voltage vector can be obtained.
A numerical simulation software was used to calculate initially the connectivity of the nodes and the corresponding values of the electrical resistance. To perform this calculation, the voltage magnitude between some pair of nodes needs to be input. This corresponds theoretically to a source of constant current, which is linked to the grid with a conductor of negligible resistance. In this particular case, a relatively low voltage was considered, in order not to cause any negative effects to the patch. Finally, measurements were only performed around the grid, as it is supposed that the grid is covered by the patch. The purpose of this analysis is to measure the changes in the source's intensity I, between the initial and the deformed grid.

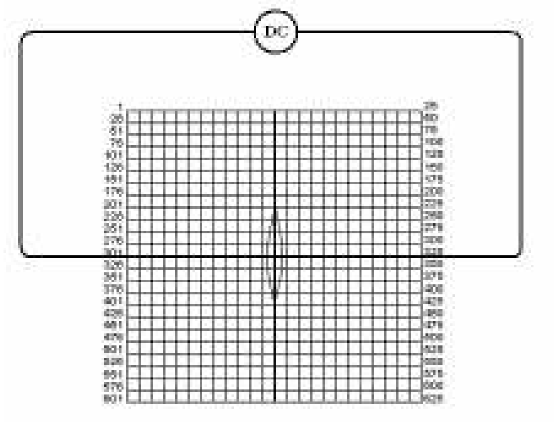


Figure 4: Node numbering used for the analysis

It is expected that the branches which belong to plates with different crack length will not deform in the same way. This variation causes corresponding differences to the values of electrical resistances of the branches, due to the changes in their cross-section and length, which can be traced by measuring the change of intensity I, when electrical current is applied. This way a potential elongation of a crack can be diagnosed, as presented in Table I.

QUANTITATIVE ESTIMATION OF THE CRACK

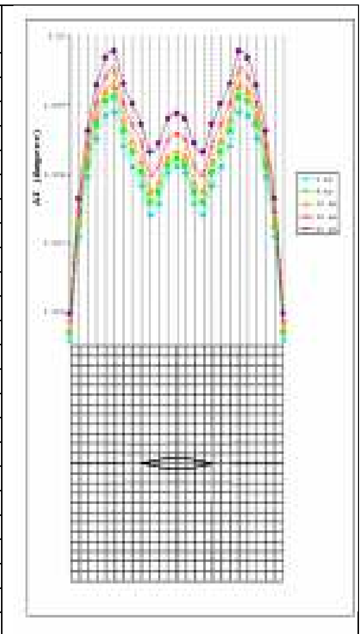
Due to the complexity of the problem, it is rather difficult to export direct quantitative results concerning the length of the crack. The measurements of intensity I, provide only an indicative measure of the deformation of the patch, globally. If measurements were derived from straight wires and not from a square grid, it would be possible with simple equations of linear elasticity to calculate the deformation of the plate and approach the length of crack. However, the existence of the grid makes it difficult to derive direct quantitative results, since current does not flow through one direction only, but through the entire network. Although there is no obvious law that would link the measurements of electric current I with the length of crack, it is certain that cross-correlation between these two magnitudes exists.
To derive quantitative results, an Artificial Neural Network (ANN) was developed. Generally an ANN is an adaptable system, to recognize the cross-correlation between certain sizes, via a

repetitive treatment process of data (input data). After training, this system can calculate this cross-correlation for new data entries. The training process of a neural network is based on the input data that the user provides. This data should cover an important part of the behavior of the phenomenon that is examined. For this purpose, sufficient indicative cases are employed which are derived from theoretical or experimental results.

In this particular problem these cases should belong to all sizes of cracks and correspond to a satisfactory range of load. Results concerning the static analysis of the grid as well as the electrostatic analysis were derived, using numerical simulation. The ANN model was a Multilayer Perceptron (MLP) which uses the momentum learning algorithm. For each plate, a tension load of 100,120,140 and 160 MPa is applied, in order to achieve results independent from the magnitude of the load. The final measurements are derived only from the region of crack, as it appears in Figure 5, and they correspond to the alteration of intensity of the electric current I, of the deformed grids, as presented in Table II.

Table I: CALCULATED CHANGES OF INTENSITY BETWEEN THE INITIAL AND THE DEFORMED GRID

Node Pair	crack 0mm	crack 8mm	crack 12mm	crack 16mm	crack 20mm
	ΔI (A)	ΔI (A)	ΔI (A)	ΔI (A)	ΔI (A)
1-25	0.00558	0.00569	0.00574	0.00584	0.00597
26-50	0.00709	0.00723	0.00731	0.00745	0.00764
51-75	0.00795	0.00812	0.00823	0.00840	0.00862
76-100	0.00852	0.00871	0.00883	0.00903	0.00928
101-125	0.00884	0.00905	0.00920	0.00941	0.00968
126-150	0.00890	0.00912	0.00928	0.00951	0.00978
151-175	0.00840	0.00862	0.00879	0.00902	0.00930
176-200	0.00811	0.00832	0.00849	0.00873	0.00901
201-225	0.00783	0.00802	0.00819	0.00844	0.00873
226-250	0.00740	0.00759	0.00776	0.00800	0.00832
251-275	0.00758	0.00773	0.00788	0.00813	0.00844
275-300	0.00801	0.00813	0.00826	0.00850	0.00880
301-325	0.00811	0.00821	0.00833	0.00858	0.00888
326-350	0.00801	0.00813	0.00826	0.00850	0.00880
351-375	0.00758	0.00773	0.00788	0.00813	0.00844
376-400	0.00740	0.00759	0.00776	0.00800	0.00832
401-425	0.00783	0.00802	0.00819	0.00844	0.00873
426-450	0.00811	0.00832	0.00849	0.00873	0.00901
451-475	0.00840	0.00862	0.00879	0.00902	0.00930
476-500	0.00890	0.00912	0.00928	0.00951	0.00978
501-525	0.00884	0.00905	0.00920	0.00941	0.00968
526-550	0.00852	0.00871	0.00883	0.00903	0.00928
551-575	0.00795	0.00812	0.00823	0.00840	0.00862



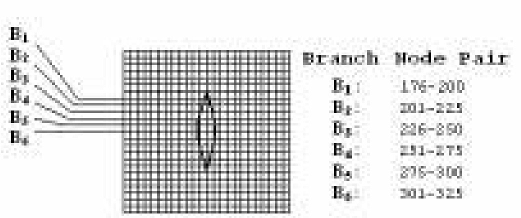


Figure 6: Representative results calculated for the region of the crack.

The magnitude of the load applied has been selected so that the deformation of the plate would be strictly elastic. The total grid's electric resistance is proportional to the deformation, while the intensity of the current is reverse proportional to it. Consequently, the phenomenon is characterized by a relatively linear behavior.
To increase the input data, used for the training of the neural network, the interpolation method was applied to every branch. In this manner, the values of ΔI for each branch B_i can be calculated from the intermediate values of the crack. As interpolation functions, 4^{th} degree polynomials were used and an example of exported data is presented in Figure 6. These data sets are used to train three neural networks with different characteristics. Finally a part of this data is used as a test file for the already trained neural networks.

Table II: CALCULATED CHANGES OF INTENSITY OF ELECTRIC CURRENT BETWEEN THE INITIAL AND THE DEFORMED BRANCHES

B_1 ΔI (A)	B_2 ΔI (A)	B_3 ΔI (A)	B_4 ΔI (A)	B_5 ΔI (A)	B_6 ΔI (A)	Crack (mm)	Load (MPa)
0.008111	0.007831	0.007402	0.00758	0.008017	0.008114	0	100
0.008323	0.008028	0.00759	0.007739	0.008133	0.008214	8	100
0.008495	0.008198	0.007763	0.007888	0.008263	0.008334	12	100
0.008735	0.00844	0.008004	0.008132	0.008504	0.00858	16	100
0.009018	0.008733	0.00832	0.008444	0.008803	0.008885	20	100
0.01301	0.012563	0.011887	0.012169	0.012854	0.013009	0	160
0.013341	0.012873	0.01218	0.012405	0.013038	0.013177	8	160
0.013609	0.013142	0.012441	0.012652	0.013266	0.013389	12	160
0.014016	0.013552	0.012868	0.013063	0.013657	0.013774	16	160
0.014467	0.014021	0.013356	0.013554	0.014139	0.014255	20	160

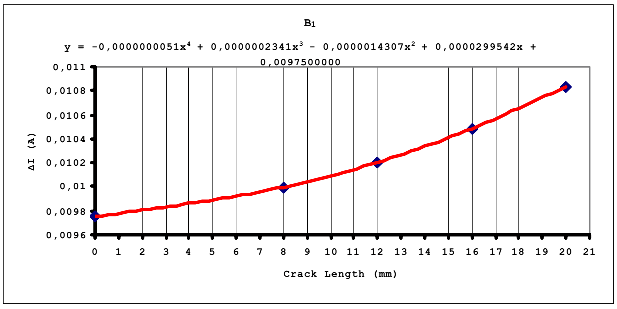


Figure 6: Example of exported data by the use of 4^{th} degree polynomials.

RESULTS
In Table III some representative results calculated by ANN are presented. ANN **NURO_6** uses data from all six branches $\mathbf{B_i}$**,** and calculates the corresponding length of the crack. **NURO_4** uses data only from the branches $\mathbf{B_1,B_3,B_5,B_6}$ to calculate the corresponding length of the crack. Finally, **NURO_LOAD** uses data only from the branches $\mathbf{B_1,B_3,B_5,B_6}$ to calculate the corresponding load value.

Table III: REPRESENTATIVE RESULTS CALCULATED BY ARTIFICIAL NEURAL NETWORKS

Preset value	NURO_6	│ΔL/L│* 100%	NURO_4	│ΔL/L│* 100%	Preset value	NURO_ LOAD	│ΔL/L│* 100%
4.5	*4.344988*	*3.444 %*	*4.348926*	*3.357 %*	*100*	*100.3283*	*0.328 %*
12.5	*12.40493*	*0.760 %*	*12.47183*	*0.225 %*	*100*	*99.56422*	*0.435 %*
17	*16.98643*	*0.079 %*	*17.03494*	*0.205 %*	*100*	*100.2272*	*0.227 %*
7	*7.031327*	*0.447 %*	*7.038251*	*0.546 %*	*120*	*119.9115*	*0.073 %*
18.5	*18.53029*	*0.163 %*	*18.51103*	*0.059 %*	*120*	*119.7499*	*0.208 %*
12.5	*12.52523*	*0.201 %*	*12.53392*	*0.271 %*	*140*	*139.9776*	*0.016 %*
17	*17.04982*	*0.293 %*	*16.93094*	*0.406 %*	*140*	*139.9897*	*0.007 %*
4.5	*4.53348*	*0.744 %*	*4.530768*	*0.683 %*	*160*	*159.9057*	*0.058 %*
14.2	*14.17017*	*0.210 %*	*14.14103*	*0.415 %*	*160*	*160.0372*	*0.023 %*
18.5	*18.64933*	*0.807 %*	*18.59484*	*0.512 %*	*160*	*159.9514*	*0.030 %*

CONCLUSIONS

As shown from the above described results, through the application of neural networks it is possible to calculate the length of the crack and the size of the load, with satisfactory precision, taking only a few measurements of intensity of electric current I, in predetermined points of the patch. However, it should be noted that for every different geometry and layout of materials, a new neural network must be trained. On the other hand, it is possible to create a neural network which would include all the typical parameters of a repair. An experimental confirmation of the theoretical results described in this paper is currently under process, in order to verify the practical applicability and accuracy of this methodology in actual repairs.

REFERENCES

[1] COMPRES–GMI. "Thermal transfer when bonding- constraints for process control". Paris, June 2001–Version III

[2] M. Ramulu, P.B. Stickler, N.S. McDevitt, I.P. Datar, D. Kim, M.G. Jenkins. "Influence of processing methods on the tensile and flexure properties of high temperature composites". SCIENCE DIRECT. December 2003.

[3] G.J. Tsamasphyros, N.K. Furnarakis, G.N. Kanderakis, Z.P. Marioli-Riga, "Three-Dimensional Finite Element Analysis of Composite Patches with Embedded Optical Fibres – Through Thickness Optimization", ICCES 01, P. Vallarta, Mexico, 19-24 August 2001.

[4] G.J. Tsamasphyros, N.K. Furnarakis, G.N. Kanderakis, Z.P. Marioli-Riga, "Detection of patch debonding in composite repaired cracked metallic specimens, using optical fibers and sensors", SPIE Optical Metrology Conference, 23-26 June 2003, Munich, Germany.

[5] William J.Biter, Stephen M.Hess, Sung Oh. "Magnetic Wire for Monitoring Strain in Composites". SENSORS. June 2001.

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