Numerical Analysis of Electrodes Position for Delamination Detection by Using Electric Resistance Change Method

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Abstract. The electric resistance method for detection of the internal delamination in laminated carbon-fiber-reinforced polymers composite material has been explored in the paper. The effect of spacing between electrodes on the crack detection efficiency has been investigated. The problem has been solved by the method of planning of the experiment and response surface method by using 2-D finite element model. The distance between the electrodes and the crack length have been selected as the parameters of the study. The results of the numerical solution have been obtained by using the four probe method of measurement of the surface and oblique electrical resistance. The optimal distance between the inner and outer probes for the effective detection of the crack and delamination has been determined. The influence of the distance between the internal and external probes has been identified to have greater effect on the detection of the crack than the distance between the internal probes.

1. Introduction
Advanced composite materials, such as carbon-fiber-reinforced polymers (CFRP) are widely used in civil engineering as the construction material and for strengthening of civil structures. They have unique physical and mechanical properties. Their lightness, high strength, durability, reliability, longevity, and different other characteristics ensure extensive engineering applications not only in civil structures but also in various industries. However, composite materials also have a number of disadvantages. External mechanical loads, repetitive cyclic stresses and impulsive loads lead to the appearance of various defects, such as rupture of fibers or delamination in the material. These damages are invisible on the surface of composite elements, which can lead to a serious weakening of the structure and tragic consequences. Therefore, the structural health monitoring and damage detection for the identification of the cracks and delamination of composite elements is required.

Currently, there are various methods of non-destructive inspection, which make it possible to monitor the technical condition of composite elements. These methods include optical methods (thermography, shearography), acoustic emission, computer tomography, traditional ultrasonic testing, ultrasonic examination and the electrical resistance method [1].

The electric resistance method is used by various researchers to detect the internal delamination in CFRP composite material, since this method does not require expensive tools, and is applicable to various structures. The main idea of this method implies that the damage, for example, fiber breakage or delamination between layers in a CFRP composite material, leads to a decrease in electrical conductivity in the damaged area, and results in a change in electrical voltage. Many publications that
demonstrate the use and applicability of this method for the assessment of the damage in laminated fiber composites have appeared over the past decades. A brief review of the literature can be found in the paper.

Baron and Schulte were among the first to study the use of electrical conductivity in order to detect damage in a composite material [2]. Since that time, many scientific groups have continued research in this direction [3-17]. Most of the papers in this area were created by Todoroki and his co-authors (Todoroki et al.) [7-14]. Todoroki used the method of electrical resistance to determine the sizes and location of the delamination in CFRP laminated plate by using multiband electrodes located on the specimen surface. By using the finite-element modeling, the distribution of the electric field and the current inside the specimen was investigated. These calculations were made to understand the orthotropic electrical properties of the unidirectional CFRP [8] and were further expanded to a multi-layer composite with different laminating [9]. The delamination in the specimens was created on laboratory equipment by using the three-point bending scheme. The size of the damage and the location were checked by ultrascanning. Electrical resistance was measured before and after the experiment. The two-probe and four-probe methods were used for the study [12]. In parallel, the numerical studies were performed to assess the damage and its location. By using the method of finite-element modeling, the results of damage identification by means of surface response method were presented in the research papers [9, 14]. It was concluded that the use of surface response is very effective for identification of the delamination in CFRP.

The study of the electrical resistance continues to our days. In the papers [15-17], the authors conduct experiments to determine the electrical resistance of a multilayer composite. The results of the experiment are numerically and analytically compared. Thus, a review of the literature of past years has clearly demonstrated that the measurement of electrical resistance in carbon fiber-reinforced polymer materials can be considered a sensitive indicator of internal damage.

The aim of this study is to investigate the relationship between the change in the electrical potential of the unidirectional CFRP specimen and the distance between the electrodes in order effectively to detect the crack. The problem is solved by the method of experiment planning and response surface method (RSM) with the use of 2-D finite element model. Electric resistance percentage change between a damaged and undamaged composite specimen is the considered as an approximation function.

2. Design and Methods

2.1. Electric Resistance Method

Carbon fiber-reinforced composite materials are electrically conductive due to the high conductivity along the carbon fiber. Despite the fact that the polymer matrix in the composite material acts as an insulator, the contact between the fibers creates electrical conductivity, which allows the current to flow both in the transverse direction and through-the-thickness. In this case, the electrical conductivity in cross direction and through-the-thickness is much lower than along the fibers. The electrical resistance of a composite specimen depends on the fiber volume fraction of CFRP composite material, the fiber size and the laminate sequence [6].

The method of measurement of electrical resistance is based on transmission of a direct current through the specimen and determination of the drop in voltage between the contacts. The electrical resistance R is calculated according to Ohm’s law: \( R = \frac{V}{I} \), where, V and I are the voltage and current, respectively.
Two-probe and four-probe methods are used to measure the electric resistance of a composite specimen and detection of the delamination in the composite material (Figure 1). Two-probe method is based on the determination of electrical resistance, when two electrodes are used both for current supply and voltage measurement (1, 2). The four-probe method is an alternative to the two-probe method. When using the four-probe method, the electric current is passed through external probes (3, 4), and the voltage is measured between the internal probes (1, 2). Based on the measured voltage and current, the resistance between the voltage contacts is measured.

In the paper [18], the authors showed that the direct current differences for two and four probe methods are associated with the contact resistance of the two probe method. In addition, the measured voltage values can strongly depend on the state of the specimen surface in case of a two-probe method with a DC effect [19]. The four probe method was recommended as the best for the assessment of the internal damage to CFRP. In the present study four-probe methods are used to measure the electric resistance of a CFRP composite specimen and detection of the delamination in the composite material.

2.2. Statement of the Problem

For the numerical calculation of the spacing effect between probes on the electrical resistance, we will explore the unidirectional CFRP composite in plane in Figure 2. The specimen length is 200 mm and thickness is 2 mm. The height of the probe is 0.5 mm and the width is 2 mm. 4 probes (A0 - A3) are placed on the surface of the specimen when measuring the surface resistance and 2 probes are placed at opposite ends of the specimen, on the upper (A0- A1) and lower surfaces (B2- B3), when measuring the oblique resistance (Figure 2).

![Figure 1. Methods: Two (A) and Four (B) Probes](image)

The electrical conductivity along the fibre is taken up as $\sigma_0 = 5500$ S/m. The electrical conductivity in thickness is taken up as $\sigma_0 = 20.9$ S/m. The data correspond to fiber volume fractions of 62% [8]. The material of the probes are silver, the conductivity of which is equal to 62.9 S/m.

The calculation was performed by using the commercial finite-element software ANSYS 16.0. The two-dimensional finite-element model of the composite specimen was developed for the study, which was constructed with the use of the 8-node current-based electric element Plane230. The size of the element was chosen based on the study of the mesh convergence. The crack in the specimen is created...
by cutting of elements from the finite-element model. The crack thickness is 0.1 mm and is located at the same distance between the upper and lower surfaces of the specimen.

To calculate the surface resistance R by the four-probe method, the electric current of 30 mA is transmitted from the external probe A0 to the probe A3. The electric voltage at the probe A1 is assumed to be 0 V. The resulting difference of electric potentials at the probe A2 is divided by the transmitted electric current of 30 mA for the calculation of the surface resistance between the internal probes A1A2. The calculation is made for the specimens with the damage and without damage.

For the oblique resistance measurements, instead, a unit current I is applied as input to the probe pair A0B3 and the voltage V between the probe pair A1B2 as output were determined from numerical experiments.

By using the ratio of the obtained results, the Electric Resistance Percentage Change \( R_{\%} \) is calculated as:

\[
R_{\%} = \left(1 - \frac{R_0}{R_d}\right) \times 100\% \tag{1}
\]

where \( R_d \) and \( R_0 \) are the electrical resistance of a specimen with and without delamination, respectively.

2.3. Response Surface Technique and Plan of the Experiment

The purpose of this study is the identification of the functional relationship between the distance of the probes and the percentage change in electrical resistance. The solution of the problem is divided into several stages: the choice of design parameters and the interval of variation of each parameter, the construction of the experiment plan for the selected parameters, the execution of the numerical experiment and the determination of the general form of the regression equation according to the results of numerical experiments.

The numerical experiments are designed according to Full Factorial design (FFD). FFD of experiment is the most popular designs owing to their simplicity and relatively low cost. It is very useful for preliminary studies or in initial optimization steps.

The objective of the present study is to establish the functional relationships between design variables and electrical resistance percentage change. \( 3^k \) Full Factorial Design is selected for the solution of the problem, where \( k \) is the number of parameters and 3 is the number of levels for each reviewed parameter.

The plan of the experiment is formulated for 3 design variables: the distance between the internal probes that are measuring the specimen resistance (\( l_1 \)), the distance between the internal and external probes (\( l_2 \)) and crack length (\( l_{\text{crack}} \)). The design variable of the CFRP composite and probes are shown in Figure 3 for surface resistance and in Figure 4 for oblique resistance, respectively. Thus 27 numerical experiments were obtained that should be calculated to construct the approximating function. The minimum and maximum bounds for design variables are listed in Table 2.

Figure 3. Design Variables: Surface resistance
Figure 4. Design Variables: Oblique resistance

Table 1. Design variables and bounds

| Title                                              | Bounds |
|----------------------------------------------------|--------|
| Spacing between voltage probes \( l_1 \), mm       | 20     | 30    | 40 |
| Spacing between voltage and current probes, \( l_2 \), mm | 20     | 30    | 40 |
| Crack length, \( l_{crack} \), mm                 | 20     | 30    | 40 |

Using the points of the experiment plan, the finite-element solutions were obtained, the numerical results of which were used to determine the Electric Resistance Percentage Change and to construct the approximating function. The functional relationship between the design variables and response was modeled through a non polynomial regression function (20).

In the present approach the form of the regression equation is unknown in advance. There are two requirements for the regression equation: accuracy and reliability. Accuracy is characterised as a minimum of standard deviation of the table data from the values given by the regression equation. Increasing the number of the terms in the regression equation, it is possible to obtain a complete agreement between the table data and values given by the regression equation.

3. Results and Discussion

3.1. Parametric Study by Response Surface Method of Surface Resistance

The numerical data obtained by the finite element calculations in the points of plan of experiments has been used to build the approximating functions by using the program RESINT [20]. A polynomial equation is given as follow:

\[
Y = -0.33 + 0.15 \cdot \frac{l_{crack}}{l_1} + 1.66 \cdot 10^{-2} \cdot l_2 - 3.17 \cdot 10^{-3} \cdot l_2 \cdot \frac{l_{crack}}{l_1} - 1.19 \cdot 10^{-3} \cdot \frac{l_1 \cdot l_{crack}}{l_1} - 3.08 \cdot 10^{-5} \cdot \frac{l_1 \cdot l_{crack}}{l_2} + 2.65 \cdot 10^{-7} \cdot \frac{l_2^3 \cdot l_{crack}}{l_1} \tag{2}
\]

Response surface is verified by the finite element solutions in the points different from the points taken in the plan of experiments. Examples of finite element verification with the response surfaces of unidirectional CFRP composites are presented in Figure 4, where a very good correlation is observed for the approximations and finite element solutions.

Upon selection of equation of regression, the parametric studies are carried out to study the influence of the design variables on the change in electrical resistance percentage. Figure 5 shows the dependency of the change in electrical resistance percentage on the distance between the internal probes that are measuring the specimen resistance \( l_1 \) and the distance between the internal and external probes \( l_2 \). The length of crack is 20 mm and 40 mm, respectively.

It can be seen that when the distance between the internal and external probes \( l_2 \) is minimal, resistance percentage value grows significantly (Figure 5a). In opposite, when the distance the internal and external probes \( l_2 \) is maximum, and distances between internal probes \( l_1 \) decrease, the resistance percentage value slightly decreases. With change of distance between the internal probes \( l_1 \) the value
of the resistance percentage significantly increase with decreases of the distance between the internal and external probes ($l_2$). Maximal value of resistance percentage achieves 1.63%, when distance between probes ($l_1, l_2$) is minimal and is equal to 20 mm.

![Figure 4](image)

**Figure 4.** Accordance between approximations function and control points

The dependence of the distances between probes on the resistance percentage value, when length of crack is 40 mm, is illustrated in Figure 5b. In this case, the resistance percentage begins to grow significantly with a decrease of distances between all probes ($l_1, l_2$). Only when the distance between the internal and external probes ($l_2$) is maximal the resistance percentage value increases slightly. The maximum resistance percentage reaches 3.26% for minimal distances between probes, respectively.

![Figure 5](image)

**Figure 5.** Dependency on the electrical resistance percentage change: $l_{crack} = 20$ mm; $l_{crack} = 40$ mm

The Figure 5b shows that the reduction of the distance between the internal and external probes ($l_2$) makes it possible more effectively to detect the crack while growing. When the distance between the internal and external probes ($l_2$) has minimal distance, resistance percentage increases from 2.80% to 3.26%. Values are changing by 1.17 times. In case of the maximum value between the internal and external probes ($l_2$), resistance percentage increases slightly. On the other hand, if the distance between the internal probes ($l_1$) is maximum, the resistance percentage value increases from 2.18% to 2.80%. Values are changing by 1.28 times. In case of a minimum distance between the internal probes ($l_1$), resistance percentage increases from 2.15% to 3.26%. Values are changing by 1.52 times. Thus, it can
be seen that in case of the crack growth, a decrease in the distance between the internal and external probes ($l_2$) has a greater effect on the detection of the crack than the change in the distance between the internal probes.

3.2. Parametric Study by Response Surface Method of Oblique Resistance

In the next step, the numerical data obtained by the finite element calculations using oblique resistance has been used to build the approximating functions. A polynomial equation is given as follow:

$$
Y = 2.46 - 6.34 \cdot 10^{-3} \cdot l_2\cdot \frac{l_{\text{crack}}}{l_2} - 6.89 \cdot 10^{-3} \cdot l_1\cdot \frac{l_{\text{crack}}}{l_1} + 1.23 \cdot 10^{-2} \cdot \frac{l_{\text{crack}}^2}{l_1}\cdot \frac{l_{\text{crack}}}{l_2} + 2.95 \cdot 10^{-4} \cdot \frac{l_1\cdot l_{\text{crack}}}{l_2} + 1.44 \cdot 10^{-5} \cdot \frac{l_{\text{crack}}^3}{l_2^2} + 1.41 \cdot 10^{-4} \cdot \frac{l_{\text{crack}}^2}{l_1} - 2.39 \cdot 10^{-4} \cdot \frac{l_1\cdot l_{\text{crack}}^2}{l_2},
$$

(3)

Examples of finite element verification of the response surfaces are presented in Figure 6, where a very good correlation is observed for the approximations and finite element solutions.

![Figure 6. Accordance between approximations function and control points](image)

Figure 7 shows the electrical resistance percentage change dependency on the distances between probes when the length of crack is 20 mm and 40 mm, respectively. Resistance percentage achieves maximal value, when the distance between probes ($l_1$, $l_2$) is minimal and is equal to 20 mm. The maximum resistance percentage reaches 6.66% for unidirectional CFRP composite when length of crack is 40 mm.

It can be observed (Figure 7b) that when the distance between the internal and external probes ($l_2$) has minimal distance, resistance percentage increases from 3.17% to 6.66%. Values are changing by 2.10 times. In case of the maximum distance between the internal and external probes ($l_2$), resistance percentage increases from 2.18% to 2.73%. Values are changing by 1.25 times. On the other hand, if the distance between the internal probes ($l_1$) is maximum, the resistance percentage value increases from 2.18% to 3.17% with decrease the distance between the internal and external probes ($l_2$). Values are changing by 1.45 times. In case of a minimum distance between the internal probes ($l_1$), resistance percentage increases from 2.73% to 6.66%. Values are changing by 2.44 times. Thus, it can be seen that in case of the crack growth, a decrease in the distance between the internal and external probes ($l_2$) has a greater effect on the detection of the crack only for minimal distance between the internal probes ($l_1$). In other hand, when the distance between the internal and external probes ($l_2$) is minimal greater effect on the detection of the crack has distance between the internal probes ($l_1$).
4. Conclusion
A 2-D numerical analysis of the electrical resistance for strip-type composite specimens with and without delamination is carried out. The surface and oblique resistances are numerically calculated using the four-probe method. The planning of experiments and the response surface technique was used to obtain optimal distance between probes to achieve maximal Electric Resistance Percentage Change. The surface and oblique resistances are numerically calculated according to the four-probe method. 

The present study shows that the electric resistance percentage change is dependent on the location of probe pairs used for the resistance measurement. Maximal value of electrical resistance percentage changes achieves when distance between all probes is minimal - 20 mm and the length of crack is maximal 40 mm.

The results of surface resistance shows that in case of the crack growth, a decrease in the distance between the internal and external probes has a greater effect on the detection of the crack than the change in the distance between the internal probes. In case of oblique resistance, the influence of the distance between the internal and external probes ($l_2$) has not so significant effect on the detection of the crack as on surface resistance.

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