

Delamination Detection in Carbon Fibre Reinforced Composites Using Electrical Resistance Measurement

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Abstract. In the present study 2-D numerical analysis of strip-type laminated composite specimens with and without damage is considered and numerical investigation is carried out by using a finite element method. The surface and oblique resistances are numerically calculated according to the two-probe and four-probe methods. The electrical conductivity of the composite laminate in the longitudinal direction is constant, while the electrical conductivity in the through-thickness direction is used as a variable in the parametric study. The resistance change due to delamination for each case is estimated by comparing the obtained resistance with the corresponding resistance of the specimen without delamination. Applicability and effectiveness of the proposed method are investigated by using various lengths of a delaminated crack in the specimen.

1. Introduction

Composite materials, such as carbon-fibre-reinforced polymers, are extensively used in the fabrication of high-performance structures for a variety of engineering applications such as aircraft, automobiles, sporting goods and electronics. Composite laminates often show considerable advantages of stiffness and strength over homogeneous materials. However, these advantages are counterbalanced by lower damage tolerance level. External mechanical loads, repeated cyclic stresses, and impact lead to damage in laminated composites due to their low delamination resistance. Damage in a structure may cause failure leading to tragic consequences and therefore structural health monitoring and damage detection in civil, mechanical and aerospace engineering structures has become one of the most important keys in maintaining the integrity and safety of a structure.

Several methods have been developed for the structural health monitoring of composite structures using fibre optic sensors [1], piezoelectric sensors [2], and electrical resistance change method [3-10]. The electrical resistance change method has been employed by many researchers for detection of internal delamination. This method does not require expensive instruments, and it is applicable to existing structures. The basic idea of this method is that damage such as fibre fracture or delamination between plies will cause a decrease of the electrical conductivity in the damaged region leading to a resistance or voltage change. For the measurement of electrical properties of laminated composites the two-probe and four-probe methods are employed.

The aim of this study is to investigate electrical resistance changes of strip-type laminated composite specimens with and without delamination by using the finite element method (FEM). The electrical resistance change method for delamination detection based on the electrical resistance



measurement of laminated composites is proposed. The surface and oblique resistances are numerically calculated by using the two-probe and four-probe methods. Applicability and effectiveness of the proposed methods are investigated by using various lengths of a delaminated crack in the specimen.

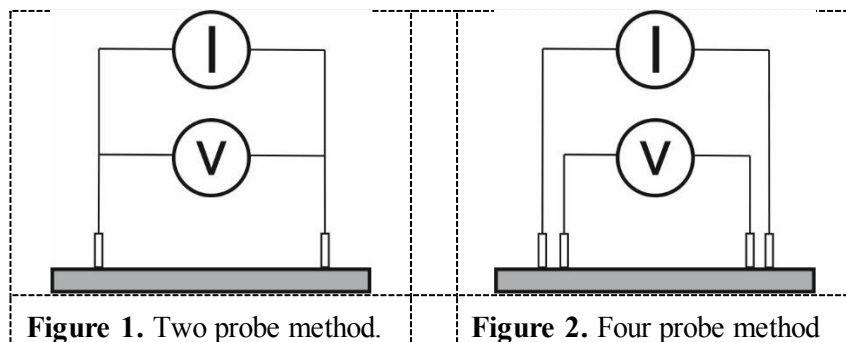
2. The two-probe and four-probe methods

The techniques for the measurement of the electrical behaviour of laminated composites are the two-probe method and four probe methods. The two-probe method is based on the definition of resistance when two electrodes are used to measure the electrical resistance. Figure 1 schematically shows a specimen, on which a pair of contacts (probe 1 and probe 2) with conductive wires is attached. Two probes are used for the electrical current input, as well as for the voltage measure. The resistance of the segment between the voltage contacts can be calculated through Ohm's law:

$$R = \frac{V}{I} \quad (1)$$

where, V and I are the voltage and current from the voltage and current contacts, respectively.

The four-probe method is an alternative to the two-probe method. Electrical current is passed through the outer probes and induces voltage in the inner probes. Based on the measured voltage and current, the resistance between the voltage contacts is then calculated. The four-probe method is schematically shown in Figure 2.



3. Numerical analysis

A 2-D strip-type laminated composite specimen is designed for FEM analysis of the delamination monitoring, as shown in Figure 3. The dimensions are similar to the specimen used by Wang et al. [4, 5], i.e., $L_0 = 200\text{mm}$, $L_1 = 10\text{mm}$, $L_2 = 30\text{mm}$, $L_3 = 2\text{mm}$ and $H = 3.2\text{mm}$. Figure 4 shows the location of delamination. The specimen has seven equally spaced electrodes mounted on the top and bottom to measure the surface and oblique resistance by the two- and four-probe methods.

The electrical conductivity in the longitudinal direction is taken as $\sigma_l = 15\Omega^{-1}\text{mm}^{-1}$ and the electrical conductivity in the through-thickness direction σ_t is used as a parameter to carry out a parametric study. For a composite panel the through-thickness conductivity σ_t is usually much smaller compared to the longitudinal conductivity σ_l . The conductivity of the electrodes is taken as $10^8\Omega^{-1}\text{mm}^{-1}$ and in this case the electrode resistances can be assumed negligible.

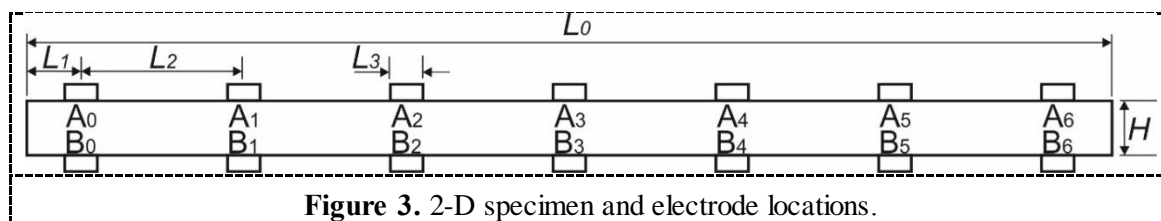


Figure 3. 2-D specimen and electrode locations.

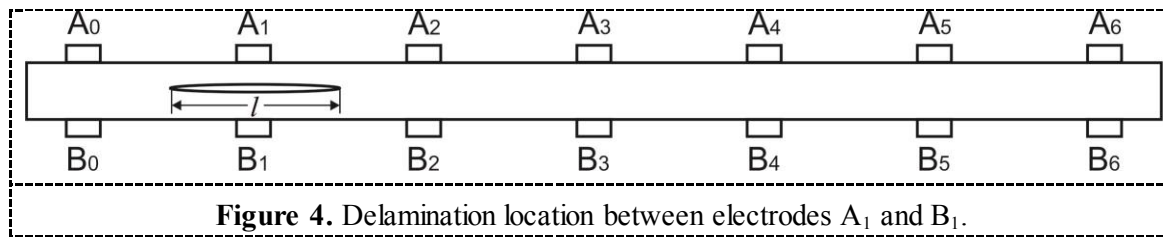


Figure 4. Delamination location between electrodes A₁ and B₁.

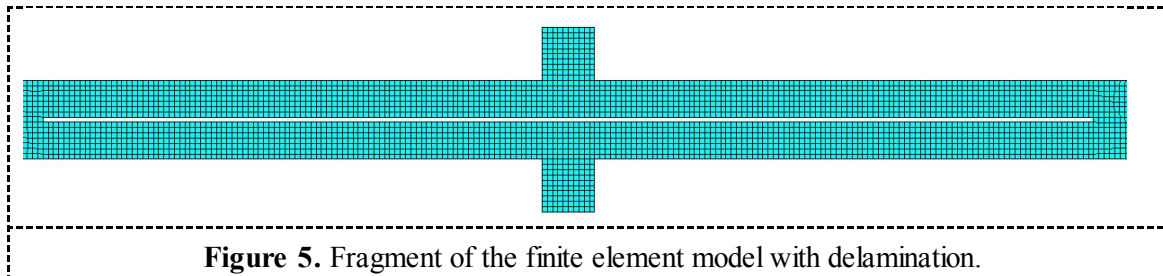


Figure 5. Fragment of the finite element model with delamination.

A 2-D finite element model of the composite strip-type specimen is designed by using the finite element method code ANSYS. Figure 5 shows the fragment of the finite element mesh for a specimen with delamination. A delamination crack is created by cutting off elements from the finite element model.

The electrical resistances between electrodes located on the same side of the specimen and electrodes located on different sides of the specimen are named as the surface and the oblique resistance, respectively. The resistances are obtained by using the two- and four probe methods. To compute the surface resistance $R_{A_1A_5}$ by the two-probe method, a direct electric current of 10 mA is charged from electrode A₁ to electrode A₅. The electrical voltage of electrode A₅ is set to 0 V. Electrical voltage obtained at the electrode A₁ is divided by the electrical current (10 mA) to calculate the electrical resistance of the segment A₁-A₅. To compute the surface resistance $R_{A_1A_5}$ by the four-probe method, a direct electric current of 10 mA is charged from electrode A₀ to electrode A₆ and the electrical voltage of the electrode A₅ is set to 0 V. Electrical voltage obtained at the electrode A₁ is divided by the electrical current (10 mA) to calculate the electrical resistance of segment A₁-A₅. For the oblique resistance measurements, instead, a unit current I is applied as input to the electrode pair A₁-B₅ or A₀-B₆, and the voltage V between the electrode pair A₁-B₅ as output is obtained from numerical experiments.

4. Results and discussion

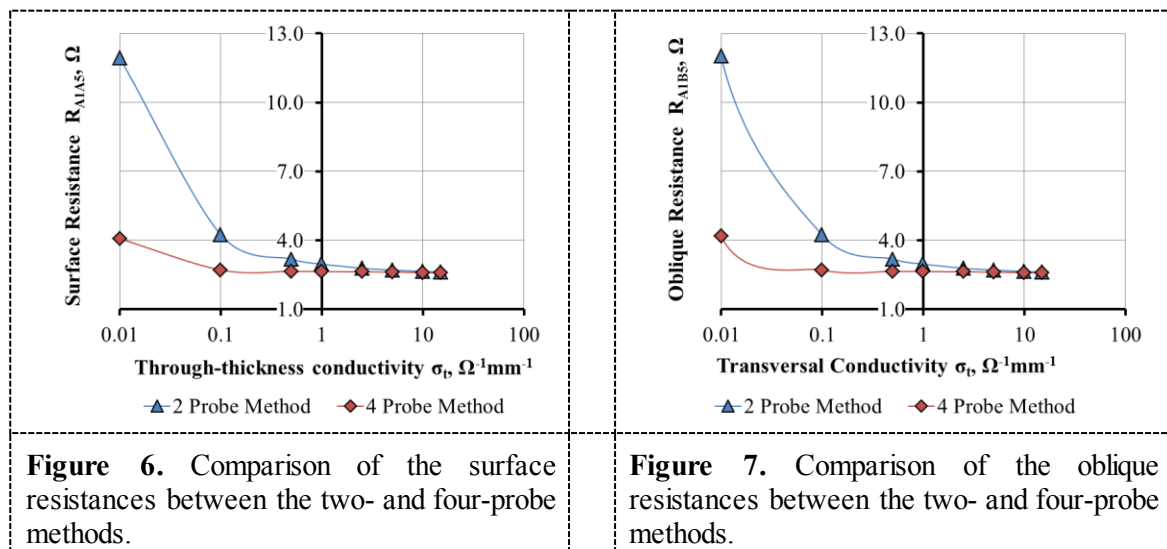
4.1. Comparative study of the two and four probe methods

In the first stage, a specimen without delamination is designed to check the validity of the four-probe method. The purpose of this study is to determine the validity range of the four probe method for the measurement of resistance in laminated composites.

The results of the surface and oblique resistances for various through-thickness conductivities are listed in Table 1 and plotted in Figures 6 and 7. In the Figures 6 and 7 the through-thickness conductivity is presented in the logarithmic scale. It is seen that the four-probe method is applicable for the measurement of resistance when the through-thickness conductivity does not exceed $2.5 \Omega^{-1}\text{mm}^{-1}$. As the through-thickness conductivity decreases, the difference of obtained resistances by two- and four-probe methods significantly increases. For commonly used composite materials, the through-thickness conductivity is much smaller than the longitudinal conductivity. Thus, the four-probe method cannot be effectively used to measure the surface and oblique resistances for real composite materials. This result confirms the research of Todoroki [8] based on measurements of voltage in the through-thickness direction for plate type specimens.

Table 1. Comparison of electrical resistances between the two- and four-probe methods.

σ_t ($\Omega^{-1}\text{mm}^{-1}$)	Surface resistance R_{A1A5} , Ω		Oblique resistance R_{A1B5} , Ω	
	Two probe	Four probe	Two probe	Four probe
0.01	11.95	4.07	12.01	4.17
0.1	4.24	2.71	4.24	2.71
0.5	3.18	2.65	3.18	2.65
1	2.97	2.64	2.97	2.64
2.5	2.79	2.63	2.79	2.63
5	2.71	2.61	2.70	2.61
10	2.65	2.60	2.65	2.60
15	2.62	2.58	2.62	2.58



4.2. The voltage and resistance percentage change due to delamination

In the next stage, the specimens with delamination are introduced and the similar computation procedure is used to obtain the electrical resistance at the segment with delamination by the two- and four-probe methods. The through-thickness conductivity σ_t of the composite specimens is varied from $0.01 \Omega^{-1} \text{mm}^{-1}$ to $15 \Omega^{-1} \text{mm}^{-1}$. The length l of delamination is varied also starting with 20 mm up to 40 mm. The resistance percentage change is calculated using the ratio of the corresponding resistances for specimens with and without delamination as follow:

$$R_{\%} = \left(1 - \frac{R_0}{R_d} \right) \times 100\% \quad (2)$$

where R_d is the electrical resistance of a specimen with delamination and R_0 is the electrical resistance of a specimen without delamination.

Surface and oblique resistance percentage changes obtained by the two-probe method are given in Figures 8 – 11. One can see that the resistance percentage changes differ significantly depending on the current contacts used. For example, the resistance percentage change between electrodes A_0 and A_6 for both the surface and oblique resistance cases does not exceed 1.5%, while the resistance percentage change obtained between electrodes A_1 and A_5 gives a comparably larger value – 9%. This is explained by the fact the electrode A_1 lies right above the introduced delamination, and thus significantly affecting the electrical resistance in this segment of the composite panel.

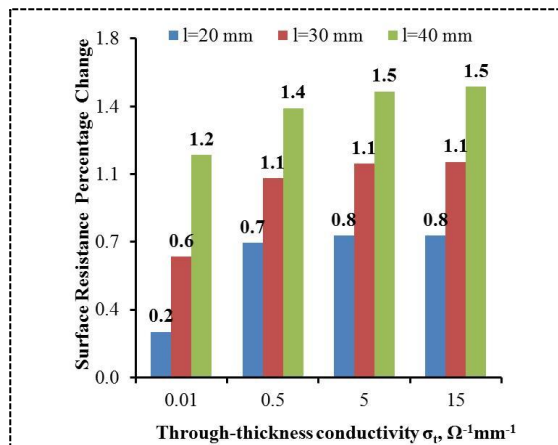


Figure 8. Surface resistance percentage changes in the two-probe method when location of current electrodes is A_0A_6 .

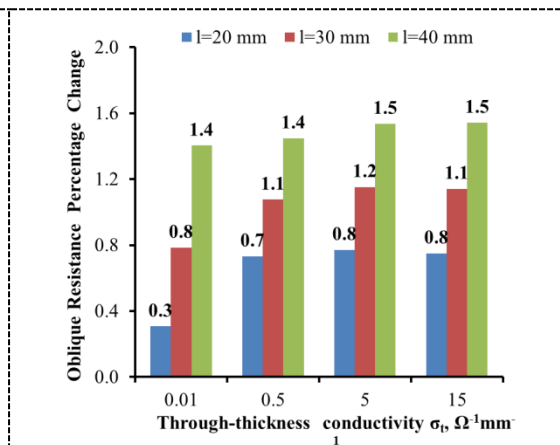


Figure 9. Oblique resistance percentage changes in the two-probe method when location of current electrodes is A_0B_6 .

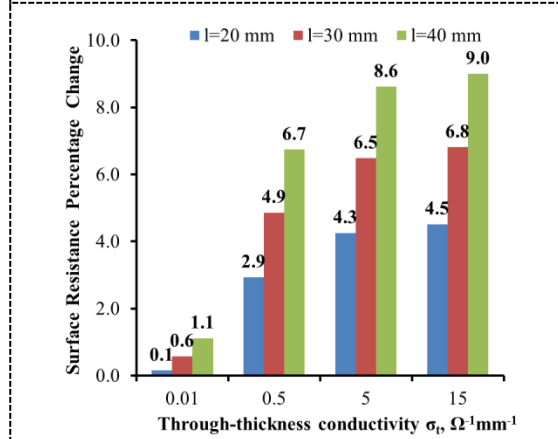


Figure 10. Surface resistance percentage changes in the two-probe method when location of current electrodes is A_1A_5 .

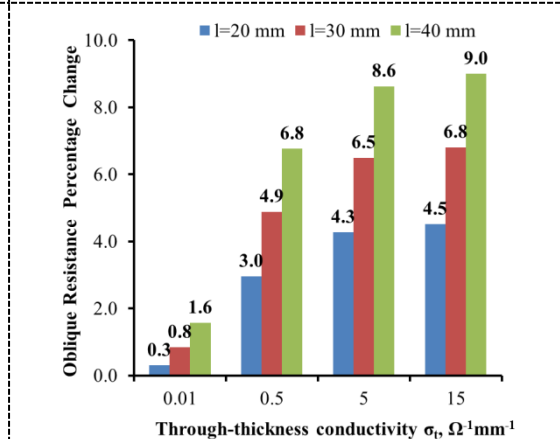


Figure 11. Oblique resistance percentage changes in the two-probe method when location of current electrodes is A_1B_5 .

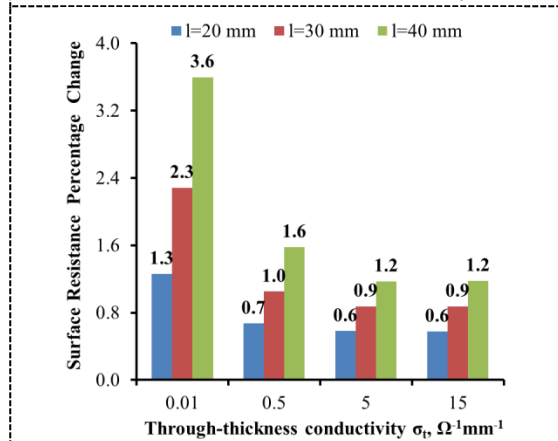


Figure 12. Surface resistance percentage changes in the four-probe method when location of current electrodes is A_0A_6 and location of voltage electrodes is A_1A_5 .

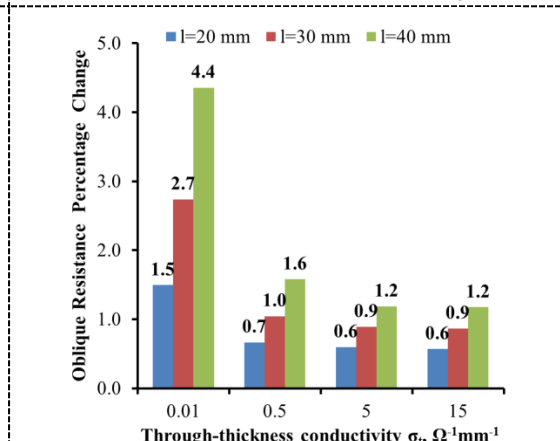


Figure 13. Oblique resistance percentage changes in the four-probe method when location of current electrodes is A_0B_6 and location of voltage electrodes is A_1B_5 .

The corresponding resistance percentage changes are also obtained by using the four-probe method where the outside electrode pairs A_0A_6 or A_0B_6 are used as the current contacts and inside electrode pairs A_1A_5 or A_1B_5 as the voltage contacts (Figures 12-13). As it can be seen from these figures for the case when the through-thickness conductivity is the smallest one used in this study, the resistance percentage changes are the largest ones and they decrease as through-thickness conductivity increases. By comparing the two methods used in this study it must be noted that the two probe method works better for detection of delamination in case when material tends to be homogenous while the four-probe method is very effective when the through-thickness conductivity of a material is significantly smaller as it is for commonly used composite materials.

5. Conclusion

A 2-D numerical analysis of the electrical resistance for strip-type laminated composite specimens with and without delamination is carried out. The surface and oblique resistances are numerically calculated according to the two- and four-probe methods. The results obtained show that the four-probe method for the resistance measurements is valid only when the through thickness conductivity is comparable to the longitudinal conductivity. However, for the delamination detection in commonly used composite materials the four-probe method is more effective. The present study shows that the resistance percentage change is dependent on the location of electrode pairs used for the resistance measurement with the respect to the location of delamination. Thus, the resistance percentage changes could be used not only for the detection of the presence of delamination but also for the localization of delamination.

Acknowledgments

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