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Damage Detection in Carbon Fibre Reinforced Composites Using Electric Resistance Change Method

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Abstract. In the present study, 2-D numerical analyses of strip-type specimens of laminated composites with and without damage are considered and numerical investigation is carried out by using the finite element program ANSYS. Electrical conductivity of the composite laminate in the longitudinal direction is given constant, while electrical conductivity in the through-thickness direction is used as a variable in the parametric study. The resistance changes for each case due to delamination is estimated by comparing the obtained resistance with the corresponding value of the specimen without delamination. The surface and oblique resistances are numerically calculated according to the two-probe 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. 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.

1. Introduction

Advanced composite materials, such as carbon-fibre-reinforced polymers [CFRP], are used extensively in the fabrication of high-performance structures for a variety of engineering application. Composite laminates often show considerable advantages of stiffness and strength over homogeneous materials.

CFRP are widely used in civil engineering as the construction material and for strengthening of civil structures. 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 structural health monitoring of composite structures using fibre optic sensors [1], piezoelectric sensors [2], and electrical resistance change method. The electrical resistance change method has been employed by many researchers for internal delamination in CFRP laminates with electrically conductive carbon fibres. 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.

Todoroki et al. [3-7] used an electrical potential method to measure delamination of crack length by the electric resistance. Damage identification based on electrical resistance change using surrogate modelling based on response surface methods has been presented in his research works. It was concluded that usage of response surfaces is very effective in identifying delamination on CFRP laminates. Wang et al. [8] used drop impact to inflict damage on the composite cylinder. Damage was effectively monitored by electrical resistance method. Finite Element (FE) analyses were carried out by Todoroki et al. [9] to search for the best placement of probes for matrix crack detection using a rectangular plate. Shen et al. [10] numerically investigated two beam-type specimens with and without damage. Various resistances and voltage changes were simulated and compared. Wen et al. [11] presented modelling from microscale to continuum levels for the predictions of resistance change due to mechanical damages. An analytical, numerical and experimental study were carried out on the electrical response of a delaminated conductive laminate in the work of Zappalorto et al. [12]. Theoretical prediction was verified with finite element analysis.

The aim of this study was to investigate electrical resistance changes of the strip-type CFRP laminates composite specimens with and without delamination by using the finite element program ANSYS. The electrical resistance change method for delamination detection based on the electrical resistance measurement of CFRP composites is proposed. The surface and oblique resistances are numerically calculated according to the two-probe and four-probe methods. Applicability and effectiveness of the proposed methods were 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 CFRP laminated composites are two-probe method and four-probe methods. The two-probe method is based on the determination of an electrical resistance when two electrodes are used to measure the electrical voltage and current (Figure 1A). The resistance of the segment between the voltage electrodes can be calculated through Ohm's law:

$$R = V / I \quad (1)$$

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

The four-probe method is an alternative to the two-probe method. Electrical current is passed through the outer probes whereas voltage is measured between the inner probes (Figure 1B). Based on the measured voltage and current, the resistance between the voltage contacts is then measured.

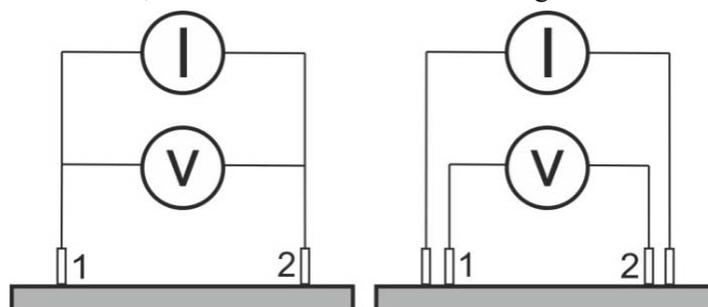


Figure 1. Methods: two (A) and four (B) probes

3. Numerical analysis

A 2-D strip-type laminated composite specimen is modelled for the validation of a range of applicability of the four-probe method for measurement of electrical resistance of CFRP laminates, as shown in Figure 3. The following dimensions of the specimen are used: $l_0 = 170$ mm, $l_1 = 10$ mm, $l_2 = 25$ mm, $l_3 = 2$ mm and $h = 3.2$ mm. The specimen has seven equally spaced electrodes mounted on the top and bottom to measure the surface and oblique resistance by two and four probe methods.

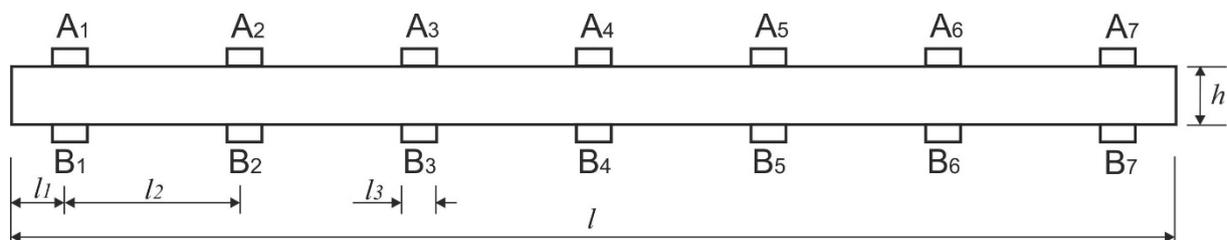


Figure 2. 2D specimen and electrode locations

A 2-D finite element model of the composite strip-type specimen is designed by using the 8-node current-based electric element Plane230 in the finite element software ANSYS. Figure 3 shows a fragment of finite element mesh for a specimen with delamination. Delamination crack is created by cutting of elements from the finite element model.

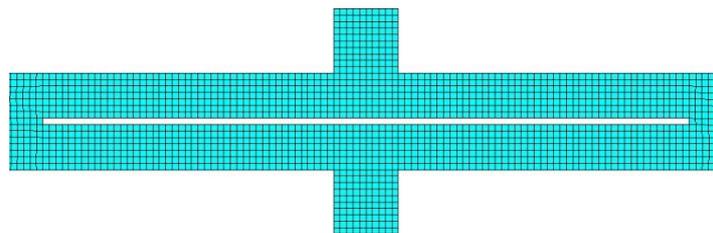


Figure 3. Fragment of the finite element model with electrodes and delamination crack

Electrical resistance measured between the 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 were determined by using the two- and four probe methods. For example, to compute the surface resistance $R_{A_2A_6}$ by two-probe method, a direct electric current of 10 mA is charged from electrode A_2 to electrode A_6 . The electrical voltage of electrode A_6 is set to 0 V. Electrical voltage obtained at the electrode A_2 is divided by the electrical current (10 mA) to calculate the electrical resistance of segment A_2A_6 . To compute the surface resistance $R_{A_2A_6}$ by four-probe method, a direct electric current of 10 mA is charged from electrode A_1 to electrode A_7 and the electrical voltage of the electrode A_6 is set to 0 V. Electrical voltage measured at the electrode A_2 is divided by the electrical current (10 mA) to calculate the electrical resistance of segment A_2A_6 . For the oblique resistance measurements, instead, a unit current I is applied as input to the electrode pair A_2B_6 or A_1B_7 , and the voltage V between the electrode pair A_2-B_6 as output were determined 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 modelled for the validation of a range of applicability of the four-probe method for measurement of electrical resistance of CFRP laminates.

The electrical conductivity in 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 of the parametric study. In

CFRP panel, the through-thickness conductivity σ_t is usually much smaller compared to the longitudinal conductivity σ_l . The conductivity of the electrodes is $10^8 \Omega^{-1} \text{mm}^{-1}$ and their very small electrode resistances can be assumed negligible.

The results of the surface and oblique resistances for various through-thickness conductivities are outlined in Table 1. These results testify that discrepancy between the values of electrical resistances calculated by two- and four-probe methods are significantly increased when through-the-thickness conductivity of CFRP panel is less than $1 \Omega^{-1} \text{mm}^{-1}$. As through-thickness conductivity decreases, the difference of obtained resistances by two- and four-probe methods significantly increases. For commonly used composite panels, the through-thickness conductivity is much smaller than the longitudinal.

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

σ_t ($\Omega^{-1} \text{mm}^{-1}$)	Surface resistance $R_{A_2A_6}$ (Ω)			Oblique resistance $R_{A_2B_6}$ (Ω)		
	Two probe	Four probe	Δ , %	Two probe	Four probe	Δ , %
0.01	11.95	4.07	65.9	12.01	4.17	65.3
0.1	4.24	2.71	36.2	4.24	2.71	36.1
0.5	3.18	2.65	16.8	3.18	2.65	16.7
1	2.97	2.64	10.9	2.97	2.64	11.1
2.5	2.79	2.63	5.8	2.79	2.63	5.7
5	2.71	2.61	3.4	2.70	2.61	3.3
10	2.65	2.60	1.9	2.65	2.60	1.9
15	2.62	2.58	1.3	2.62	2.58	1.5

4.2. The voltage and resistance percentage change due to delamination

In the next stage, the specimens with delamination are investigated and similar computation procedure is used for calculating the electrical resistance at the segment with delamination by 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_d of the delamination is also varied 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 and R_0 are the electrical resistances of a specimen with and without delamination, respectively.

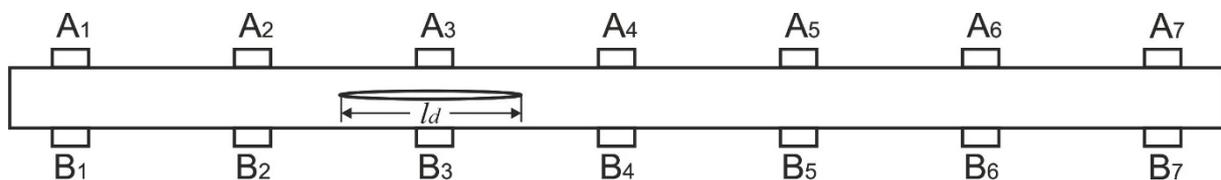


Figure 4. Delamination location between A_3 and B_3 electrodes

Percentage changes of the surface and oblique resistances, obtained by the two-probe method, are presented in Figures 5 – 7. The data of Figure 4 illustrate the location of delamination in the specimen studied. The surface resistances between the pairs of electrodes A_1A_7 , A_2A_6 , A_3A_5 and the oblique resistances between electrode pairs A_1B_7 , A_2B_6 , A_3B_5 are investigated using these methods. The data of Figure 5 demonstrate percentage changes of the surface and oblique resistances in two-probe method when A_1A_7 and A_1B_7 , are the locations of the current electrodes, respectively. The percentage

changes of the resistances begin to grow with increase of delamination length. The smallest values of percentage changes correspond to the lowest through-thickness conductivity.

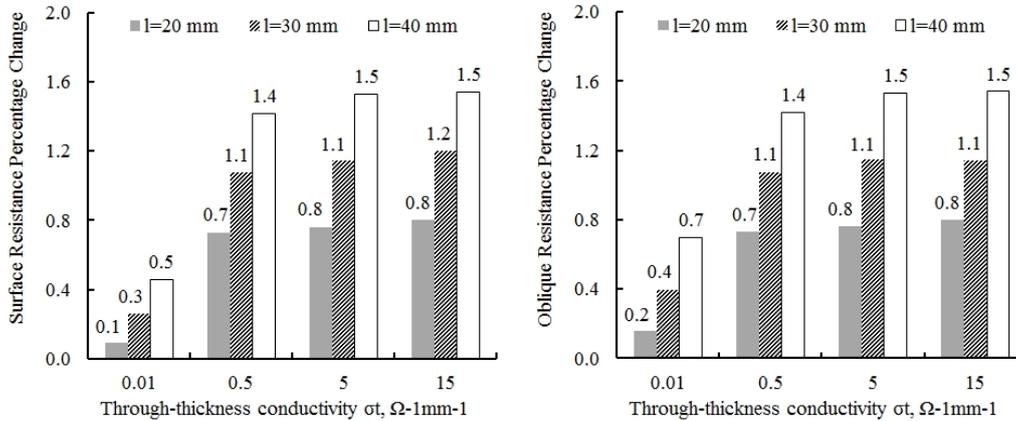


Figure 5. Surface and oblique resistance percentage changes in two-probe method when the location of current electrodes is A_1A_7 and A_1B_7

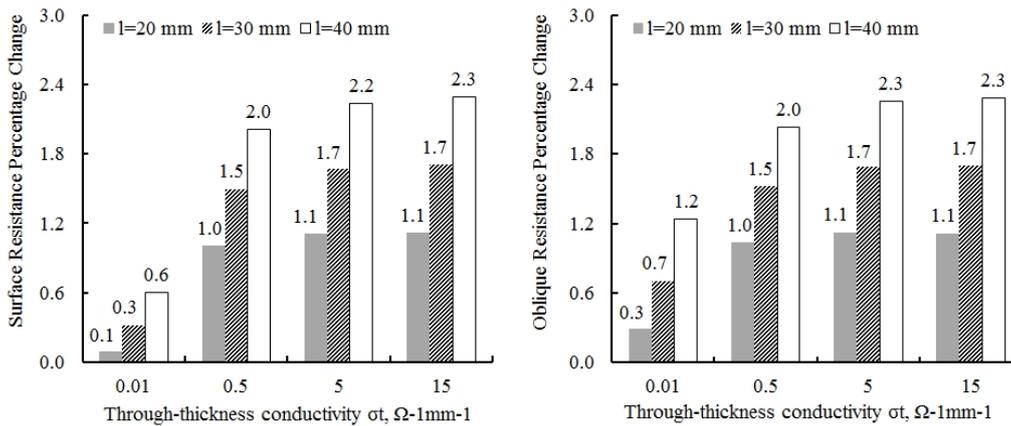


Figure 6. Surface and oblique resistance percentage changes in two-probe method when the location of current electrodes is A_2A_6 and A_2B_6

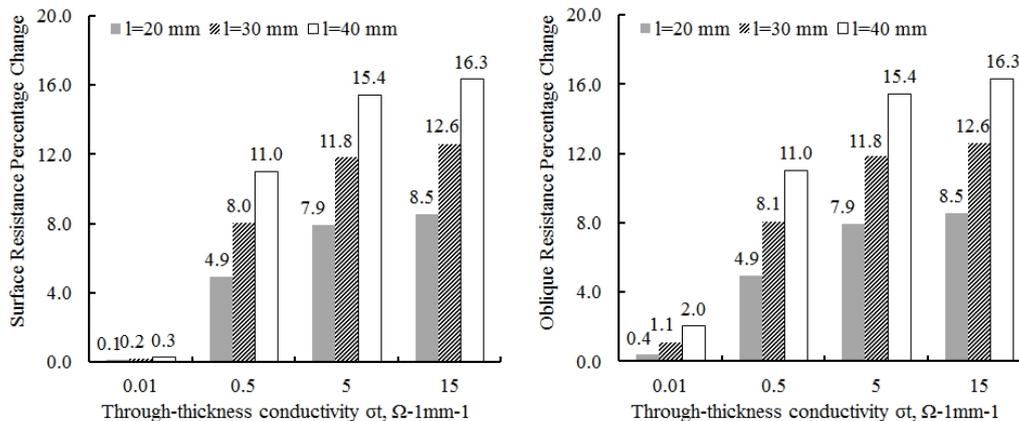


Figure 7. Surface and oblique resistance percentage changes in two-probe method when the location of current electrodes is A_3A_5 and A_3B_5

As shown in Figures 5 and 6, the percentage changes are also increased when distance between electrodes decreases. For example, maximum resistance percentage change between electrodes A_1 and B_7 for the oblique resistance cases does not exceed 1.5% and 2.3% between electrodes A_2 and B_6 .

The resistance percentage change obtained between electrodes A_3A_5 and A_3B_5 for surface and oblique resistance cases gives comparably larger values (Figure 7). This is explained by the fact that previous electrodes lie between the introduced delamination, but electrode A_3 is located above the delamination and thus significantly affects the electrical resistance in this segment of the composite strip-type specimen. One can see that resistance percentage changes differ significantly depending on the current contacts used.

The corresponding resistance percentage changes are also calculated by using the four-probe method and the results are presented in Figures 8–10. The surface resistance is studied between two pairs of current electrodes A_1A_7 and voltage electrodes A_2A_6 or A_3A_5 (Figures 8–9). It can be seen from the Figures 8 and 9 that the resistance percentage change is similar. Distance between the current and voltage electrodes can be assumed as negligible but location of the voltage contact is affected on the percentage changing.

In the next calculations, two pairs of current electrodes A_2A_6 and voltage electrodes A_3A_5 are numerically obtained and compared (Figures 10). For the oblique resistance measurements, a unit current I is applied as input to the electrode pair A_1B_7 or A_2B_6 , and the voltage V between the electrode pair A_2B_6 and A_3B_5 as output is obtained from numerical experiments.

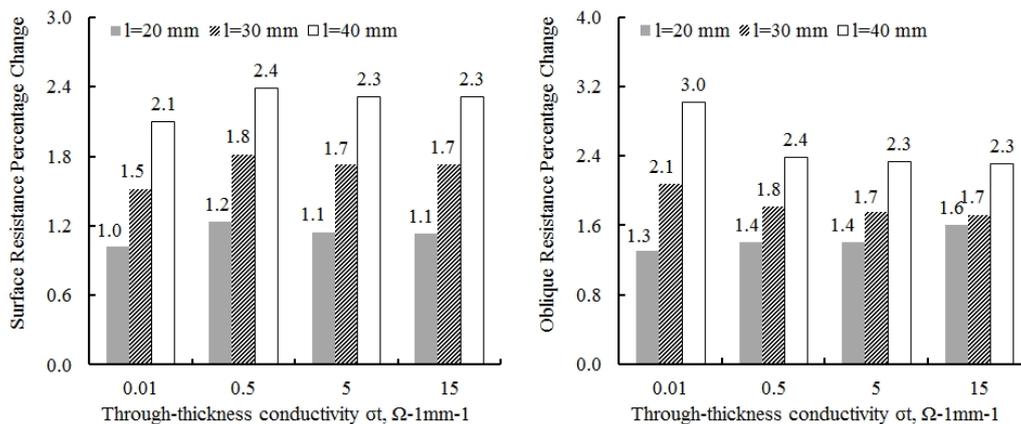


Figure 8. Surface and oblique resistance percentage changes in four-probe method when the location of current electrodes is A_1A_7 (A_1B_7) and the location of voltage electrodes is A_2A_6 (A_2B_6)

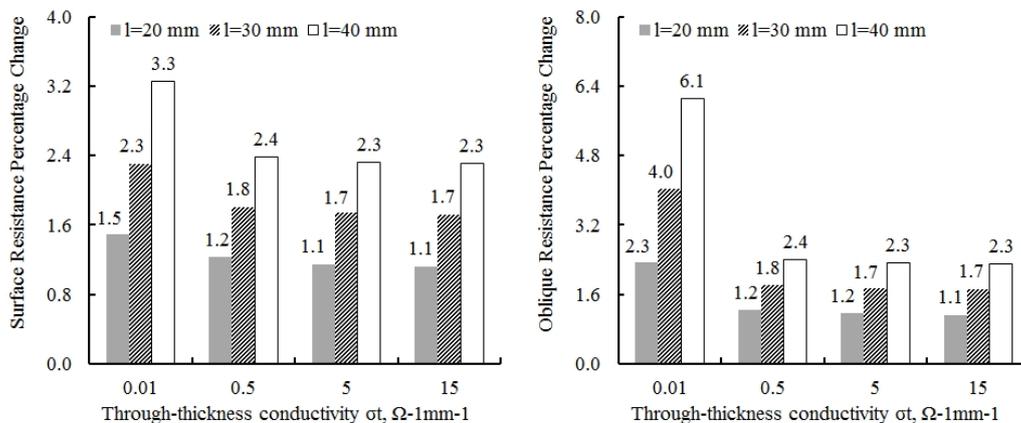


Figure 9. Surface and oblique resistance percentage changes in four-probe method when the location of current electrodes is A_1A_7 (A_1B_7) and the location of voltage electrodes is A_3A_5 (A_3B_5)

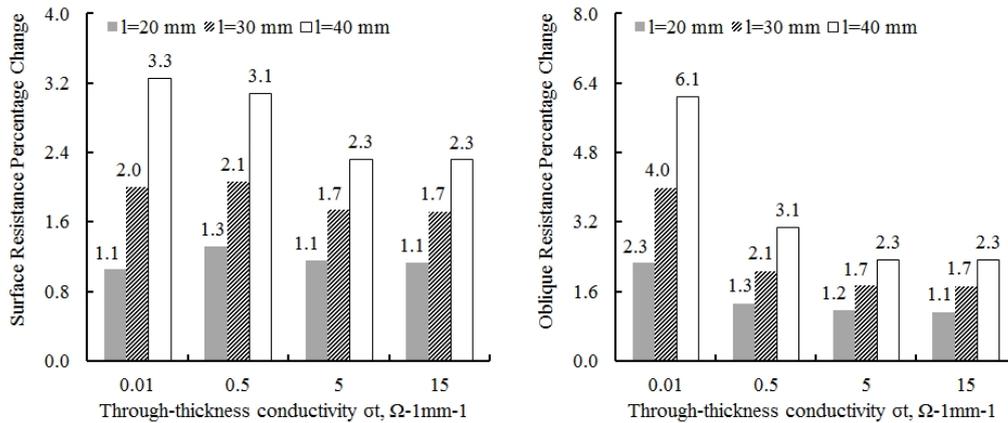


Figure 10. Surface and oblique resistance percentage changes in four-probe method when the location of current electrodes is A_2A_6 (A_2B_6) and the location of voltage electrodes is A_3A_5 (A_3B_5)

As it can be seen from these Figures for the case of the smallest through-thickness conductivity in this study, the resistance percentage changes are the largest ones and decrease as the through-thickness conductivity increases. Difference between the surface and oblique changing for smallest value of the through-thickness conductivity is increased twice: 3.3% and 6.1%, respectively (see Figure 9-10). The resistance percentage changes obtained between voltage electrodes A_3A_5 and A_3B_5 for the surface and oblique resistances are comparatively large.

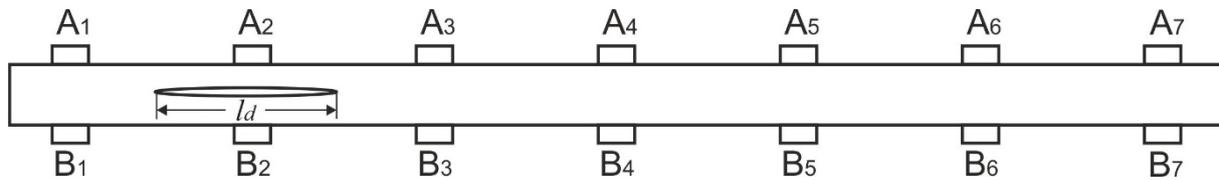


Figure 11. Delamination location between A_2 and B_2 electrodes

For the comparative study, the location of delamination in the specimen is placed under electrode A_2 (Figure 11). The surface and oblique resistance percentage changes obtained by the two-probe method are given in Figures 12 – 13.

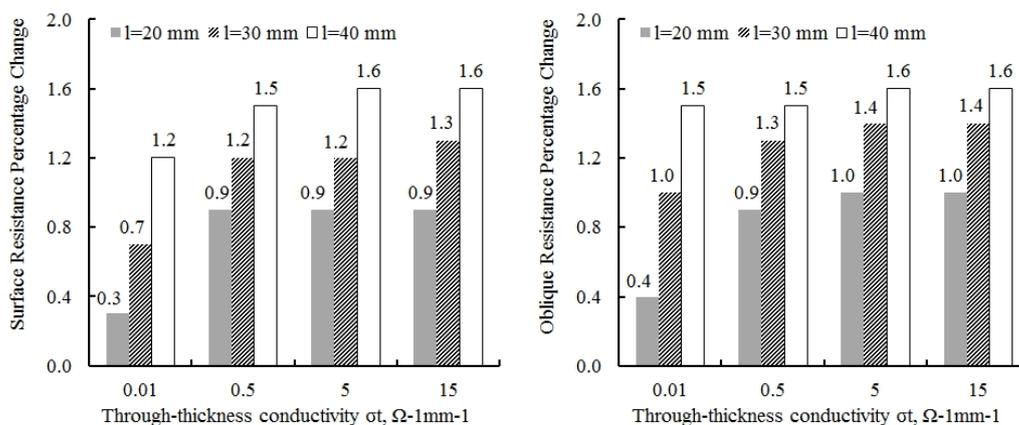


Figure 12. Surface and oblique resistance percentage changes in two-probe method when the location of current electrodes is A_1A_7 and A_1B_7

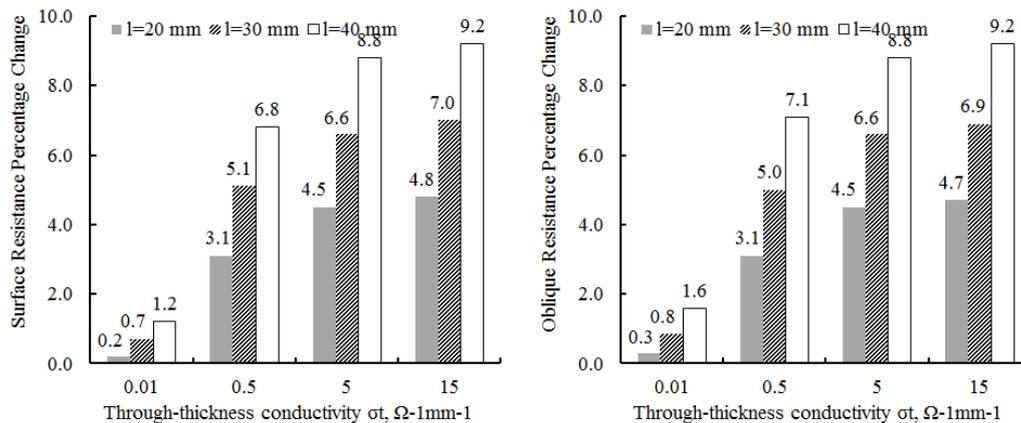


Figure 13. Surface and oblique resistance percentage changes in two-probe method when the location of current electrodes is A_2A_6 and A_2B_6

One can see that resistance percentage changes differ significantly depending on the current contacts used. For example, resistance percentage change between electrodes A_1 and A_7 for both the surface and oblique resistance cases does not exceed 1.6%, while the resistance percentage change obtained between electrodes A_2 and A_6 gives comparably larger value – 9%. In Figure 7, the largest value is 16.3%. In Figure 7 and Figure 13 delamination is situated under voltage contact. This difference can be explained by the fact that small distance between voltage contacts gives largest value of percentage change.

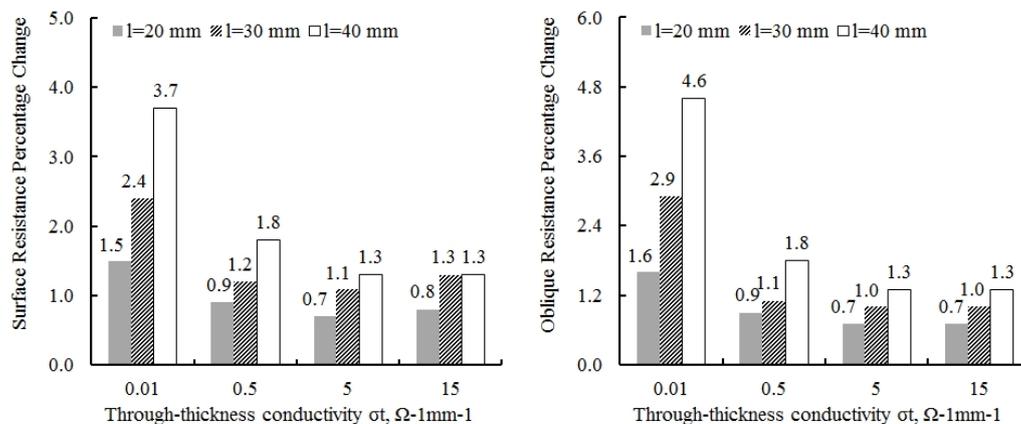


Figure 14. Surface and oblique resistance percentage changes in four-probe method when the location of current electrodes is A_1A_7 (A_1B_7) and A_2A_6 (A_2B_6)

The corresponding resistance percentage changes are also obtained by using the four-probe method where the outside electrode pairs A_1A_7 or A_1B_7 are used as the current contacts and inside electrode pairs A_2A_6 or A_2B_6 as the voltage contacts (Figure 14). As seen in this figure, when delamination is situated under voltage contact the resistance percentage changes has largest value with smallest value of the through-thickness conductivity.

By comparing the two methods used in this study, it must be noted that the two-probe method works better for delamination detection 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 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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