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Comparison of the published contact configurations for the determination of electrical resistivity of CFRP composite

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Abstract. Damage detection methods for electrically conductive composite materials based on the electrical potential or electrical resistance measurement have been widely investigated in the literature. Damage growth inside the material has been also studied using finite element simulation. For the numerical simulations, it is necessary to know nominal resistivity of the material. Several contact configurations have been published in literature for determination of the nominal electrical resistivity in the in-plane and through-thickness directions. For in-plane and through-thickness directions electrical resistivity was experimentally investigated using electrical contact configurations published in literature. Measured electrical resistivity was used for finite element analysis of delamination growth in Carbon Fibre-Reinforced Polymer composites (CFRP).

Introduction

Damage detection of electrically conductive composite materials based on the electrical potential or resistance measurement has been widely investigated in the literature. Damage growth inside the material has been also studied using the numerical simulation. It is effective to simulate various damage scenarios in order to get information about influence of different parameters on the measurement configuration, such as size of the specimen, distance of the electrical contacts or damage size and location. In order to obtain relevant information about the real structure, it is necessary to enter correct material characteristics into the FEA model, primarily values of the nominal resistivity of the examined material.

Several contact configurations for determination of the nominal electrical resistivity in the in-plane and through-thickness direction have been used in recently published works [1- 3].

Overview of such electrical contact configurations is given in the presented article. Three contact configurations were tested in case of determination of in-plane resistivity. The resistance in through-thickness direction was determined using two contact configurations. The obtained values were compared and used subsequently for the numerical simulation of delamination specimen test.

Experimental procedure

Material and Specimen Preparation. Hexply AGP 193PW/8552S RC40 composite material was used for specimen preparation. $[45/0]_{4S}$ lay-up scheme was used. The specimens were prepared from the same material, which was used for manufacturing of specimens in [4]. Electrical contacts (made from a conductive epoxy and a thin copper strips) were manufactured after the curing. Surface of the specimens was slightly sanded at first with sandpaper P120 and P600 and then degreased. Electrical contacts were prepared using a CHO-BOND® 584-29 conductive epoxy and a thin copper strips.

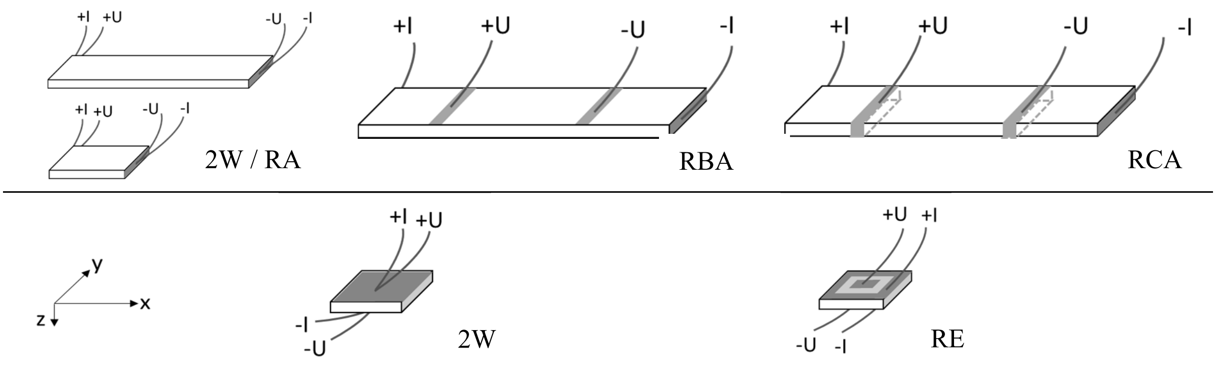

Fig. 1: Configurations of electrical contacts for determination of in-plane and through-thickness resistivity

Measurement procedure. The configurations of the electrical contacts used for electrical resistance measurement are shown in the Fig. 1. When using the RA configuration, measurement has to be performed on specimens with different length. Electrical resistivity of CFRP composite was successfully determined using the RA configuration and electrical contacts prepared by electroplating in [1]. Two-wire (2W) contact configuration is the same as in case of RA, but the contact resistance is neglected. In case when the value of contact resistance is close to the measured values of resistance, it could not be neglected and four probe method must be used. We have performed 2W measurement to demonstrate the influence of using values of electrical resistivity obtained by 2W configuration on the results of finite element analysis. The measurement was performed using the HP E3631A current source and two Agilent 34461A multimeters. The series comparison measurement method was performed.

Table 1: Overview of specimens used for determination of in-plane resistivity and measured electrical resistivity using 2W method

	Length [mm]	Width [mm]	Thickness [mm]	1/Thickness [1/m]	2W - R [Ω]	2W- ρ_x [Ωm]	Temp. t [°C]
L1	88.4	25.2	3.1	0.328	0.293	0.000254	21.4
~~L2~~	~~88.4~~	~~25.2~~	~~3.2~~	~~0.317~~	~~0.792~~	~~0.000711~~	~~21.5~~
L3	87.6	25.2	3.1	0.319	0.316	0.000284	21.8
L4	93.6	25.2	1.6	0.61	0.476	0.000209	21.8
~~L5~~	~~93.1~~	~~25.2~~	~~1.6~~	~~0.63~~	~~1.074~~	~~0.000465~~	~~21.8~~
L6	91.9	25.1	1.6	0.61	0.498	0.000222	21.8
L10	92.5	25.1	1.6	0.63	0.502	0.000218	23.5
L11	92.5	25.1	1.6	0.63	0.412	0.000179	23.7
L12	92.5	25.2	1.6	0.63	0.388	0.000169	23.8
L13	46.3	25.1	1.6	0.63	0.344	0.000298	23.8
L14	46.3	25.1	1.6	0.63	0.270	0.000234	23.7
					Av.	0.000201	
					St.dev.	0.000041	

Experimental Results

In-plane resistivity. Six specimens L1 - L6 were prepared for determination of the in-plane resistivity (ρ_x). Because of the lay-up of the material, we assume that the resistivity in the x and y direction (see Fig. 1) is the same. First 2W and RA method was adopted. Results of 2W measurements are given in Table 1. It was found that measured resistivity of specimen L2 and L4 is outlying from other measured values. For this reason, five more specimens L10 – L14 were prepared and results for specimens L2 and L5 were not considered.

If we assume that it is possible to neglect the contact resistivity, we can determine the electrical resistivity using 2W configuration. Following formula was used for determination of 2W resistivity.

$$R = \rho \cdot \frac{l}{A} = \rho \cdot \frac{l}{w \cdot t} \tag{1}$$

$$\rho = R \cdot \frac{A}{l} \tag{2}$$

Results of 2W measurements are given in Table 1.

Measured electrical resistance of the specimen is dependent on the dimensions of the specimen, see formula (1). When we consider that the contact resistance (R_C) is not negligible, but constant, we can determine the resistivity of the specimen and also the value of the contact resistance. This approach was used successfully for electrical resistivity determination of CFRP specimens with electrical contacts prepared using electroplating, as described in [1]. Here the method is marked as RA. So it is necessary to evaluate 2W measurement on specimens with different dimensions. It is possible to use linear regression for measured data for specimens, which differ in their thickness according to following formula:

$$R = R_C + \rho \cdot \frac{l}{w} \cdot \frac{1}{t} \tag{3}$$

For the linear regression equation of measured data

$$R = 0.6286 \cdot \frac{1}{t} + 0.1012 \tag{4}$$

We can calculate the resistivity for the material as follows

$$\rho \cdot \frac{l}{w} = 0.6286 \rightarrow \rho = 0.6286 \cdot \frac{w}{l} = 0.162\ \Omega mm = 0.000017\ \Omega m \tag{5}$$

First, we evaluated only data for specimens L1, L3, L4, L6 and obtained value of in-plane resistivity $\rho_x = 0.000174\ \Omega m$, see Fig. 2. After preparing specimens L10-L14 we also performed linear regression for measured data of group of specimens L1, L3, L4, L6, L10 - L12, see Fig. 3. According to formula (6), we also proceed linear regression for specimens which differ only in its length (group of results for specimens L10 - L14, see Fig. 3, and group of results for specimens L4, L6, L10 - L14, see Fig. 5.

$$R = R_K + \rho \cdot \frac{1}{w \cdot t} \cdot l \tag{6}$$

Measured electrical resistivity, equation of linear regression and determined values of in-plane resistivity are given in Fig. 2 - 5.The lowest value of in-plane resistivity according to RA configuration was 0.00011 Ωm.

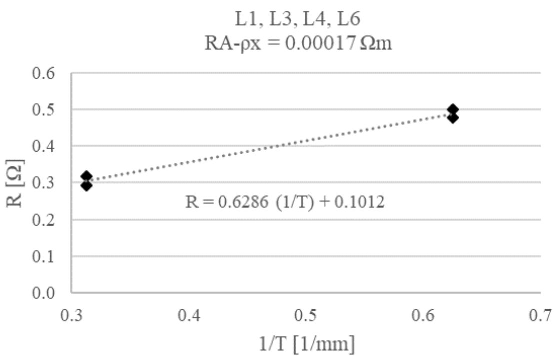

Fig. 2: Evaluation of RA measurement on specimens L1, L3, L4, L6

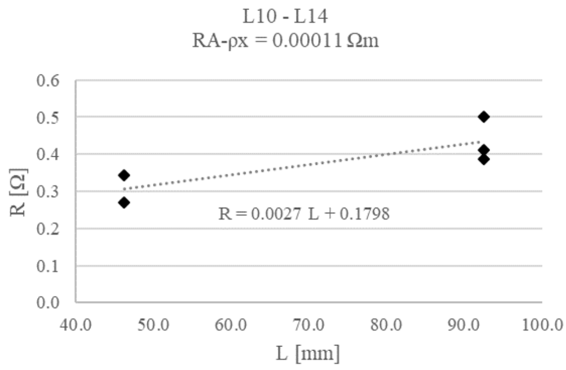

Fig. 3: Evaluation of RA measurement on specimens L10 – L14

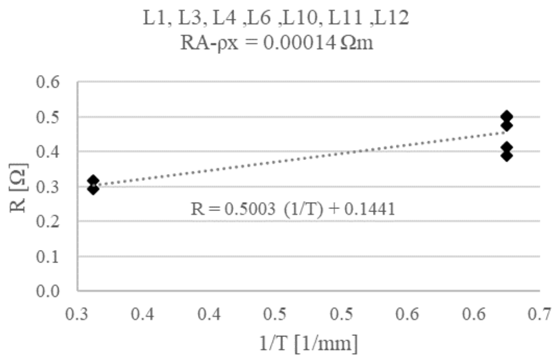

Fig. 4: Evaluation of RA measurement on specimens L1, L3, L4, L6, L10, L11, L12

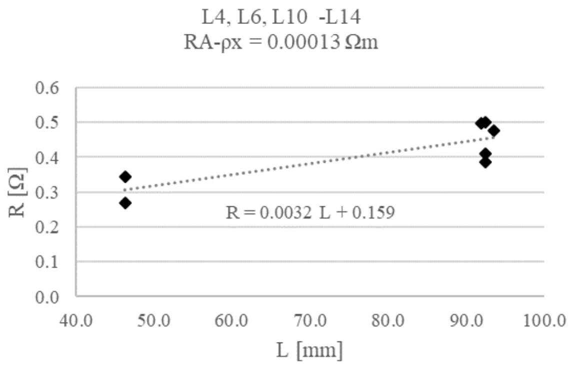

Fig. 5: Evaluation of RA measurement on specimens L4, L6, L10 – L14

The RBA and RCA electrical contact configurations were prepared on specimens L1-L6. The distance between the inner voltage electrodes according to (Fig. 1) was 30 mm for both configurations. For the resistivity determination the same formula as for the 2W configuration (eq. (2)) was used, but the distance between inner electrodes was considered in the formula. Measured data are given in Fig. 6. Although the measurement for the 2W configuration on specimens L2 and L4 were outlying, measurements with RBA and RCA on these two specimens were not outlying.

Through-thickness resistivity. The RA method was not studied for the through-thickness direction. For the 2W and RE measurement configuration four specimens with dimensions (15 x 15 x 1.6 mm) were prepared. For the 2W electrical contact configuration electrical resistivity ρ_z was determined to be 0.12 ± 0.034 Ωm.
The RE electrical configuration was prepared according to Fig.1. The inner voltage electrodes dimensions were 5 x 5 mm. There was distance of 2 mm between the inner voltage and outer

current electrodes. The through-thickness electrical resistivity ρ_z according to RE contact configuration was determined to be 0.06 ± 0.005 Ωm.

Table 2: Overview of results of measured electrical resistivity using RBA and RBC method

Specimens	RBA [Ωm]	RBC [Ωm]
L1	0.000075	0.000075
L2	0.000082	0.000085
L3	0.000086	0.000084
L4	0.000068	0.000080
L5	0.000081	0.000078
L6	0.000067	0.000074
Av.	0.000076	0.000079
St.dev.	0.000007	0.000004

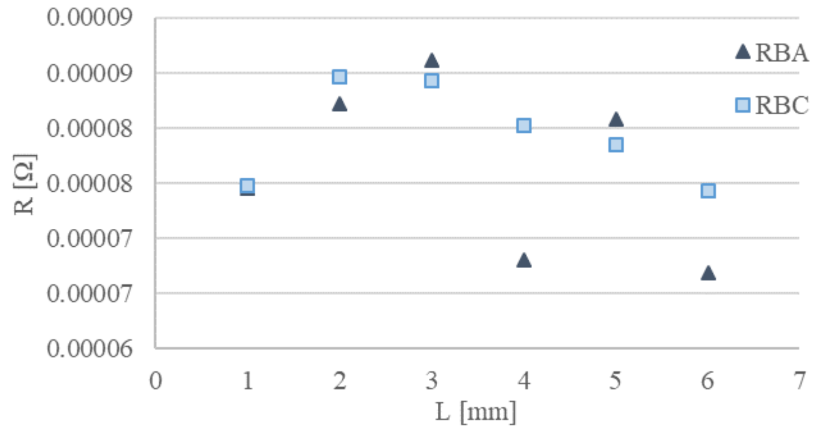

Fig. 6: Results of measured electrical resistance using RBA and RBC method

Numerical Simulation of Delamination Specimen Test

Obtained values of electrical resistivity of the material were used in the finite element analysis of the delamination growth. Simulated data were compared to those obtained during experimental investigations of delamination growth on specimens loaded simultaneously by mode I and mode II loading (Mixed-Mode Bending – MMB Specimens) published in [4]. The dimensions of the specimens were 185 x 25 x 3.3 mm. The numerical analyses were carried out using the commercial code Ansys 17. The MMB specimen was prepared as a 2D model, over 31,000 pane elements were used with element size from 0.008 mm to 0.5 mm. Mechanical loading was not considered during the simulation.

Results of the conducted finite element analysis are given in Fig. 8. and Fig. 9. It can be seen that results obtained with electrical resistivities using 2W method do not correspond to the measured data at all. When using data obtained by RA and RE configuration, the longer the delamination, the bigger the difference between measured and simulated data can be seen.

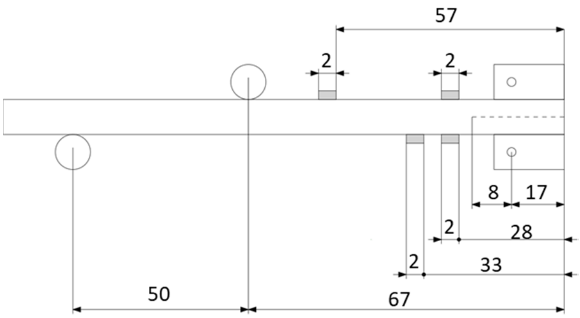

Fig. 7: Dimensions of MMB specimen and electrical contact configuration used for the experimental investigation and numerical simulations

Table 3: Overview of the electrical resistivities used in finite element analysis

	2W – 2W	RBA – 2W	RBA - RE	RA - RE
ρ_x [Ωm]	0.0002	0.000076	0.000076	0.0001
ρ_z [Ωm]	0.12	0.12	0.06	0.06

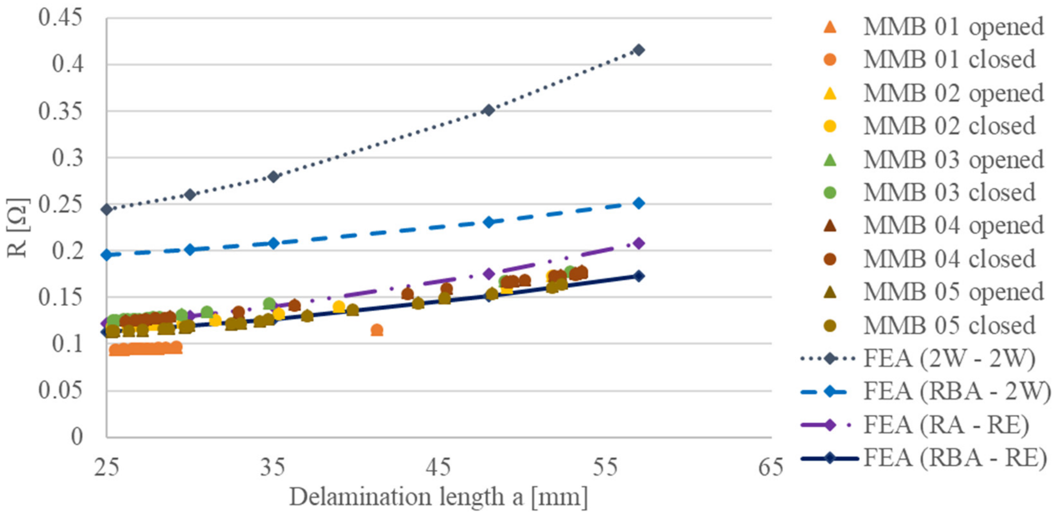

Fig. 8: Results of finite element analysis and measured experimental data

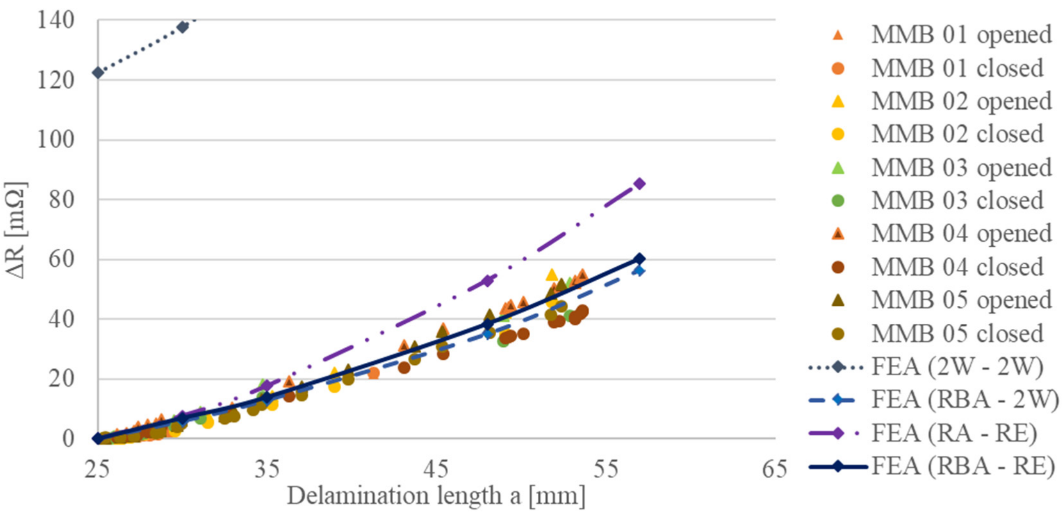

Fig. 9: Results of finite element analysis and measured experimental data

Conclusions

In contrast to the results presented in [1] we prepared electrical contacts for configuration RA using conductive epoxy instead of electroplating. We determined higher electrical resistivity for contact configuration RA than for contact configuration RBA and RCA.

According to obtained values of through-thickness resistivity, it is not possible to neglect the contact resistance and use 2W configuration also when measuring in through-thickness direction, although the through-thickness resistivity is higher by an order than the in-plane resistivity. Negligible difference in measured data for configuration RBA and RCA was found.

According to our investigation it is more convenient to use separated current and voltage electrodes when using conductive epoxy for electrical contact preparation.

The finite element analysis has shown that there is difference in simulated and measured data for electrical resistivities determined according to different contact configurations.

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