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Examination of Delamination in Carbon-Epoxy Laminate by the Method of Resistance Change Measurement*

Karbon-epoxi kompozitok nyúlásainak vizsgálata ellenállás változás mérésével

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Kulcsszavak: karbon-epoxi kompozitok, ellenállás változás mérése, húzófeszültség mérése

Keywords: carbon-epoxy composite, resistance change measurement, determination of tensile stress

Összefoglalás

Karbon erősítésű epoxi bázisú kompozitok jeltősége a szerkezetépítésben egyre nagyobb, napjainkban már teherviselő elemekként is egyre nagyobb a jelentőségük, elsősorban az autóipar, de egyéb más, pl. repülés, hajózás területein is. A teherviselő elemek többségében a jellemző igénybevétel a húzás, valamint a nyírás (megfelelő szálelrendezés megléte esetén). A dolgozat egy új eljárás, az ellenállás változás mérésének lehetőségét mutatja be, különböző rétegrendű kompozitok esetén, azok húzó igénybevételeikor keletkező feszültségek meghatározására.

1. INTRODUCTION

Carbon-epoxy laminates have still-growing application in various branches of industry, especially in aviation and shipbuilding. They are applied not only in elements subjected to moderate load, but – to a growing extent – in the crucial elements of high-strength structures. One of the most frequent defects in the composites is delamination occurring between individual layers of multi-layer structures made of fabrics. For this reason, it is purposeful to develop a quick and effective method that would allow for detecting delamination, and for evaluating its size and location.

In this paper, the authors describe the research on forced delamination of six-layer synthetic fabric of various kinds of fiber lay. The present research are preliminary studies aimed at confirming usefulness of resistance change measurement method for examining the delamination process, and finding the best placement of electric contacts.

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2. METHOD OF RESISTANCE CHANGE MEASUREMENT

For measuring properties of composite materials, as well as for examining defects of their internal structure – such as delamination – one can use standard experimental methods, similar to those applied for other materials, especially measurements of rigidity changes and ultrasonic detection. One of such methods, applied in the reported research, is the method based on measurement of electrical properties – specifically the changes of electrical resistance. It allows for measuring the quantities we are interested in by using very simple sensors and instrumentation. The measurements can be taken on-line without the need of having a permanent access to the measured object, and this is one of the advantages of this method over the most popular ultrasonic method.

2.1. Method description

Carbon-epoxy composites are made of two materials – carbon fabric and epoxy resin – whose electrical properties significantly differ. Carbon fibers, being the main component responsible for material strength, are a relatively good conductor, while the resin, constituting the matrix that supports the fibers, exhibits the characteristics of a good insulator. In an ideal composite, the carbon fibers should be unbroken, straight and separated one from another by a layer of the matrix. Such a composite would conduct electric current only along the fibers. In reality, arrangement of fibers depends on the method of composite production. Usually, the fibers do not lay along straight lines, and there are contacts between the fibers both within the fabric (in the case of a composite made of a fabric), and between the layers. Consequently, the whole structure has the features of a poor conductor, and the directivity of specific resistance is consistent with that of mechanical properties, although it is closer to an isotropic distribution than the latter one. Because electrical resistance of a composite depends on the existence of contacts between the fibers, one observes an increase of resistance in the cases when the fiber fractures and delamination or micro-delamination takes place.

Resistance of an arbitrary conductor can be calculated from the following formula

$$R = \int_0^L \frac{\rho}{A} dl$$

where ρ – characteristic resistance, A – section area, and l – length of current flow path.

In the case of large-scale delamination (like that in the reported investigations), there are significant changes first of all in the shape and length of the current flow path L, and in the section area of the specimen' conducting part, A. In the cases of micro-delamination and fractures of fibers, there are also changes in characteristic resistance ρ.

The usefulness of resistance measuring method in examining destruction processes in carbon-epoxy composites has been widely confirmed by many investigations, examples of which are reported in the works [1÷7].

3. EXPERIMENTAL INVESTIGATIONS

The experimental investigations were carried out on simple specimens, for which one could easily determine the influence of defects on the change of resistance. After constructing adequate mathematical models, one will also be able to perform such tests on elements of actual structures. At this stage of investigations, however, only simple, quasi-static tests were performed.

3.1. Specimen characteristics

Investigations on composite delamination were carried out on two sets of specimens, consisting of 5 or 6 specimens each, so that it was possible to perform simple statistical analyses. The specimens of each set were cut out of one, bigger piece of the laminate. This gave us a guarantee that the technological process was identical for all specimens. The possible differences of test results could only be caused by parameter variability – normal for the composites. All the specimens were six-layer ones, made of synthetic carbon fabric 452T of basic weight 200 g/m2, with matrix of epoxy resin EP6011. The volumetric reinforcement factor was approx. 60%. The dimensions of specimen surface were 160 x 10 mm, and the thickness was 1.25 mm. In the first set, one assumed the lay of layers 45º/0º/45º//-//45º/0º/45º, and that in the second set it was 0º/45º/0º//-//0º/45º/0º (the symbol //-// between the layers denotes the section of delamination under test). The angle of 0° was the direction consistent with the longer side of the specimen. An initial delamination of 35 mm length was introduced at the stage of making the specimens. The general view of the specimen after completion of delamination is shown in Fig. 1.

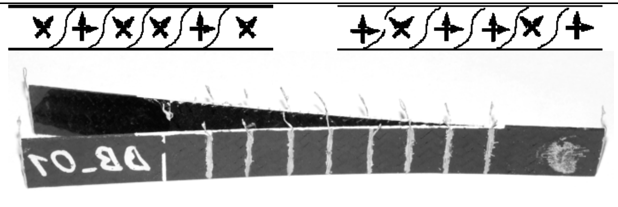

Fig. 1. General view of specimen for delamination investigation (after the end of experiment)
1 ábra A réteg szétválási vizsgálathoz használt próbatest (a kísérlet befejezése után)

3.2. Making contacts and resistance measurements

The key issue when applying the resistance measurement method is ensuring that there are adequate electrical contacts between the investigated specimen made of composite, and the measuring system. The important problem is to properly allocate the measuring points and make the contacts in the way that ensures low, stable in time, and insensible to external influences electrical resistances between the leads and the fibers. Different methods can be used for this purpose. In the reported tests, we made the contacts with the use of conducting glue. This method was chosen taking into account the possibility of making the contacts in specimens prepared in advance. However, it required that a direct access to the carbon fibers would be available.

Short, thin conductors were glued to mechanically-cleaned contact surface by using a conducting glue on silver base. Then, measuring leads were soldered to these wires using low-melting Wood's alloy. In this way, we managed to obtain resistance between the measuring points not greater than 100 Ω (including the composite resistance) for any possible combination of the leads. For resistance measurement, we used a precise 6½-digit multimeter type Agilent 34401A. In the measuring range of 1.2 kΩ, with measurement current of 1 mA, the instrument ensured measurement uncertainty lower than ±0.03 Ω.

Nineteen measurement points were made on each specimen, three of them on external borders (denoted as 0÷2), and eight on each side of the specimen in delamination zone (denoted as 3÷18). Due to such a placement of contacts, the connection between the composite and the ohmmeter extended over the whole width of specimen, which ensured greater sensitivity of measurement. The dimensions of contacts (approx. 0.5÷0.8 x 10 mm), used in these experiments, did not influence the

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accuracy of measurement, because the longer side of contact was parallel to the front of the developing delamination (perpendicular to the longer side of specimen). Allocation of measuring points and the applied denotations are shown in Fig. 2. The contacts 1 and 2 were placed on each of the borders separated by the initial delamination. These contacts provided electrical connection to three layers of the fabric, while contact 0 extended the whole thickness of specimen, i.e. over six layers of the fabric. The contacts 3÷18 were located on the surface of specimen.

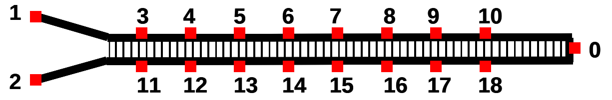

Fig. 2. Placement and enumeration of contacts
2. ábra Az érintkezések elhelyezkedése és számozása

The delamination test was performed on a specially designed experimental stand (Fig. 3) by means of a movable wedge made of non-conducting material. During the tests, one registered the length of delamination and the changes of electrical resistance, according to the test protocol shown in Table 1. In order to increase measurement accuracy, one measured actual delamination length in the specimen instead of displacement of the wedge. Due to the fact that delamination was a stepwise process (each 0.5÷1.5 mm, depending on the step), these two values were not identical. The resistance was measured each time the delamination length increased by approx. 2 mm.

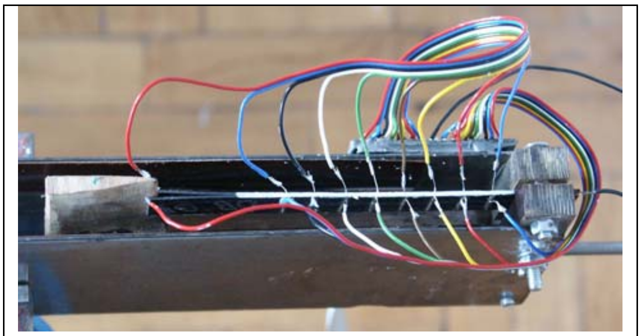

Fig. 3. Test stand for delamination examination
3. ábra A szétválási vizsgálat elrendezése

3.3. Test results

The results are shown below in Fig. 5 as graphs of changes of resistance between measurement points 0 and 1 (measurement A), and between points 0 and 2 (measurement B) for the first and second set of samples (in Figs. 5a and 5b, respectively). In each configuration of contacts, the current flowed along the length of specimen. Therefore, one could primarily detect the defects that produce discontinuities in the perpendicular plane, i.e. across the specimen. In order to facilitate comparison of results, identical scales were applied in both graphs. The results of the two measurements, A and B, can be treated jointly, because of full symmetry of the system.

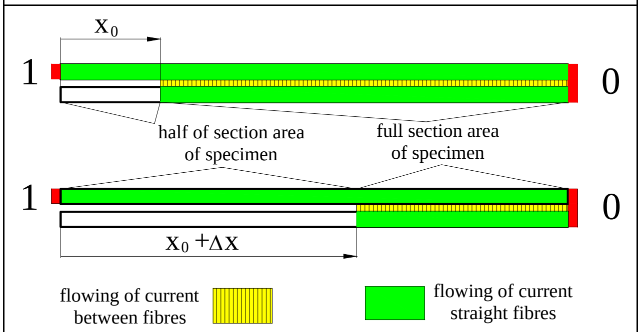

Fig. 4 Effect of delamination on resistance change measured between contacts 0 and 1, or 0 and 2.
4. ábra A 0 és 1 illetve 0 és 2 pontok között mért a szétválás hatására bekövetkezett ellenállás-változás

Table 1 Protocol of resistance change measurement

Measurement denotation	Measurement of resistance between contacts No.	
	First	Second
A	0	1
B	0	2
C	1	2
D	3	11
E	4	12
F	5	13
G	6	14
H	7	15
I	8	16
J	9	17
K	10	18
L	3	10
M	4	9
N	5	8
O	6	7
P	11	12
Q	13	14
R	15	16
S	17	18

The results showed that the changes of resistance between points 0 and 1, and between 0 and 2, were small in all examined specimens, and remained approximately proportional to the increase of delamination length. The reason, as it seems, was that the defects caused by micro-delamination and fiber fractures did not appear in the composite. Small changes of resistance could be the result of reduction (due to large-scale delamination) of specimen's section area through which flows the current, as it is explained in Fig. 4.

The graphs in Fig. 6 show the changes of resistances between measurement points 1 and 2 (measurement C) in the first and the second set of specimens (Figs. 6a and 6b, respectively). Also in these graphs, the scales are identical for both sets of specimens.

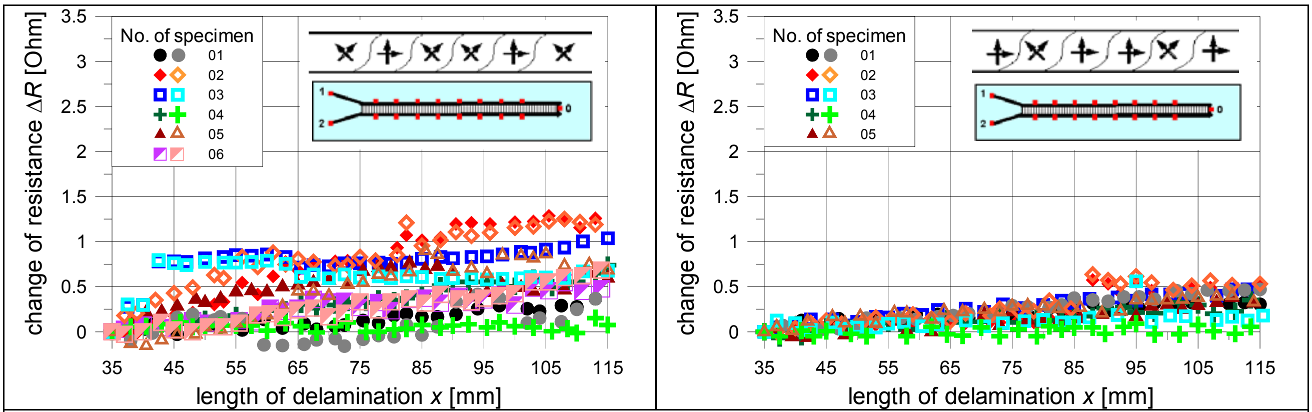

Fig. 5. Change of resistance measured in delamination tests between points 0 - 1, and 0 - 2
5. ábra A 0 és 1 valamint a 0 és 2 pontok között mért a szétválás hatására bekövetkezett ellenállás-változás

a) in the first set of specimens
a) a próbatestek első sorozata esetében

b) in the second set of specimens
a) a próbatestek második sorozata esetében

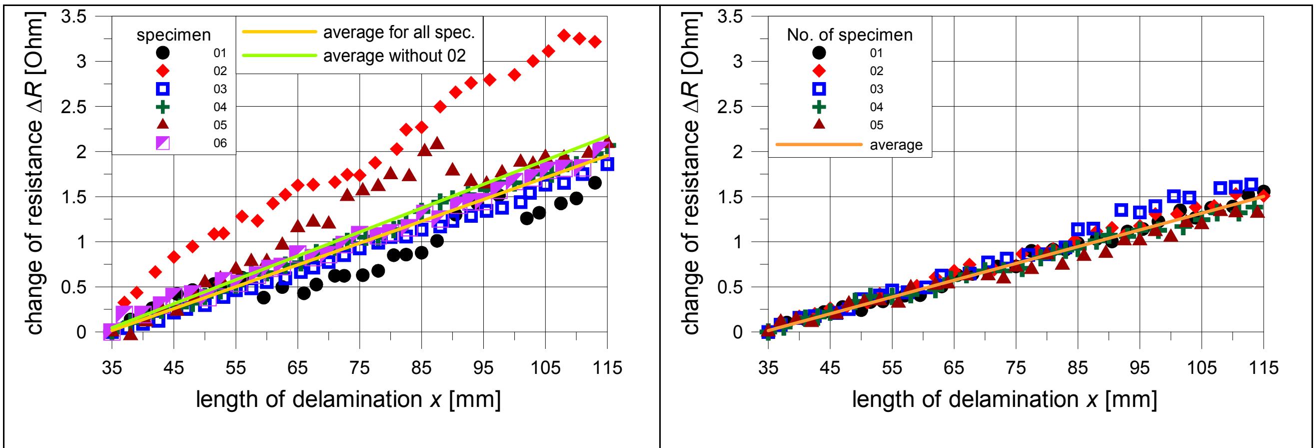

Fig. 6. Change of resistance between measurement points 1 and 2 in delamination test
6. ábra Ellenállás változás az 1 és 2 pontok között a réteg szétválási vizsgálat során

a) for the first set of specimens,
a) a próbatestek első sorozata esetében

b) for the second set of specimens
a) a próbatestek második sorozata esetében

The changes of resistances between points 1 and 2 (on both sides of the developing delamination) were significant in all specimens. In the part of specimen where delamination already took place the current flowed only along the specimen, i.e. between contacts 0 and 1 or 0 and 2, similarly as in the previous case. In the remaining part of the specimen, not yet delaminated, the necessary flow of current between the layers was possible only through the contacts between the fibers (let alone the short-circuit between layers caused by contact 0). This flow can be disturbed in the result of micro-delamination between the fibers in a single layer of the fabric, or by a large-scale delamination between the layers. Because the measurements in configurations A and B showed that the influence of delamination was insignificant, the observed changes could only result from the controlled delamination between the layers 5 and 6 of the composite. The course of resistance change is a linear function in both examined sets of specimens, because the area of the current-carrying section changes linearly. In the first set of specimens, Fig. 5a, one observed a greater dispersion of results, and the inclination coefficient of the line $\Delta R(\Delta x)$ was equal to approx. $a = \Delta R/\Delta x = 26.5\ \Omega/\text{m}$, if one took into account all the specimens. If one neglected specimen No. 02, the results for which were apparently outlying – which could result from a deviation of technological parameters – this coefficient dropped to the value of $a = \Delta R/\Delta x = 24.2\ \Omega/\text{m}$. On average, this coefficient was assumed as $a = \Delta R/\Delta x = 25\pm2\ \Omega/\text{m}$. In the second set of specimens, variability of results was much lower, and the analogous coefficient was $a = \Delta R/\Delta x = 18.5\pm1\ \Omega/\text{m}$. The difference might result from a lower resistance of delaminated part of specimens in the second set (⅓ of directly-conducting fibers in the first set, versus 2/3 of the fibers in the second set), or a slightly different course of delamination process. A definite answer to this question could be found in further investigations.

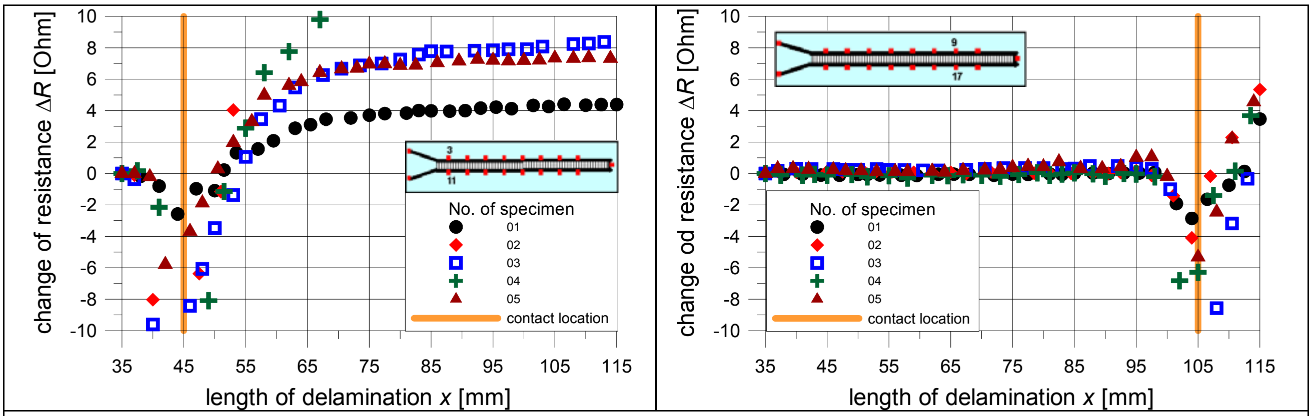

Fig. 7. Change of resistance between measurement points in delamination test in the second set of specimens

7. ábra Ellenállás változás a vizsgált pontok között a réteg szétválási vizsgálat során a második sorozatba tartozó próbatestek esetén

a) between points 3 and 11
a) 3 és 11 pontok között

b) between points 9 and 17
b) 9 és 17 pontok között

Besides of resistance measurements taken along the specimen, we also performed a series of such measurements across the specimen, perpendicularly to the developing delamination (measurements D÷K), and for the contacts glued to the surface of specimen (measurements L÷S). In both sets of specimens, in which similar configurations of contacts were assumed, these measurements gave similar dependencies. For this reason, only a couple of example results pertaining to the second set are presented below.

Fig. 7 shows the graphs illustrating changes of resistance in transverse measurements between contact points 3 and 11 (measurement D in Fig. 7a), and between contacts 9 and 17 (measurement J, in Fig. 7b). Fig 8 depicts similar results of resistance measurements between surface contacts – measurement points 5 and 8 (Fig. 8a), and points 7 and 8 (Fig. 8b). Here again we assumed identical scales in the graphs to facilitate comparison of results.

Both kinds of measurements, across the specimen and between surface contacts, gave very interesting results. The drop of resistance, reaching the value of approx. 10 Ω, begins when delamination front is about 5 millimeters before the contact. The drop continues until the front occurs right under the contact, and then the resistance starts increasing, exceeding its initial value by several ohms. The drop of resistance is probably caused by the decrease of section area of the conducting part of the sample, similarly as it was in measurements of resistance between contacts 1 and 2 (Fig. 6). The tests on an analogous composite specimen, where the applied load was similar to that acting in this specimen, but no delamination was evoked, gave very similar result of resistance decrease at the place where specimen's curvature increases in the result of bending. Therefore, this effect is most probably the result of permanent changes in composite structure. The drop of resistance could be caused by a reversible effect of contact improvement between fibers inside the composite, or the effect of change in interaction between the contact itself and the specimen. A more precise explanation of this effect would need further investigations.

4. SUMMARY

The results presented in this paper confirm the usefulness of the resistance change measurement method in investigations on delamination of carbon-epoxy composites. The measurement of resistance between contacts placed in unloaded part of the specimen indicated an evident growth of this resistance with the increase of delamination magnitude. The function of resistance growth versus delamination magnitude is linear, and its departure from linearity is very small. The measurement of resistance between contacts placed within the loaded zone did not allow, at that time, for delamination measurement, because of sensitivity of the resistance to the specimen's curvature.

Further investigation should make it possible to define the placement of contacts on the basis of knowledge of the element's shape, the load and the expected situation of delamination. It is also necessary to create a mathematical model allowing for calculation of the influence of delamination on the change of the measured resistances, and, what is even more important from practical point of view, for calculating the magnitude and determining situation of delamination on the basis of the measured changes of resistances between contacts.

The ultimate goal of the research should be prognostication of safe exploitation period for elements and structures made of the composites.

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