THE ARCHIVE OF MECHANICAL ENGINEERING

VOL. LV 2008 Number 2

DOI: 10.24425/ame.2008.131618

Key words: composites; experimental methods; resistance change measurement method

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APPLICATION OF RESISTANCE CHANGE MEASUREMENT METHOD TO EVALUATION OF THE DEGREE OF DESTRUCTION IN CARBON COMPOSITE

A simple resistance-based method was used to study the epoxy-carbon composite material. Measurement of changes of the resistance between contacts, located on the composite specimens, allows detecting the damage process in quasi-static and fatigue tests. The method can be useful to determine the margin of safety of composite elements.

1. Introduction

Composite materials are more and more widely applied in industry, especially in modern industrial branches such as transportation. They are used not only to produce elements subjected to moderate load, but also in the whole high-strength structures. The best example could be aviation industry, in which application of composites (participation of composite mass in total mass of a plane) have increased from approx. 2% (in nineteen eighties, airplanes like MD-80, Boeing 757) up to 47% in Boeing 787 *Dreamliner* (in the year 2007) [7]. The participation of composites is even greater in lighter airships and sailplanes, and in the so-called light airplanes.

One of the most willingly used composites is combination of carbon fibres with epoxy composite. This material has several beneficial characteristics, such as high rigidity and strength and high strength-to-density ratio.

However, the important problem is that load is transmitted practically only through the fibres, and the polymer matrix only protects the fibres from the loss of shape. Due to this fact, any fracture of fibres, defect of the matrix or separation of a fibre from the matrix (delamination) significantly

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affect strength of the element. Even more dangerous situation exists if there appear discontinuities of the structure. Such discontinuities can result from the necessity of giving the structure an adequate shape, introducing loads (especially concentrated forces), and from the requirements of maintenance. In all such places of discontinuity, one can expect concentration of stresses and increased probability of defect.

The problem of the utmost importance is then developing a method of diagnosing the condition of composite, and detecting possible defects that might lead to a catastrophe. Such a method must be, obviously, a non-destructive one, and should allow – if possible – for an automated and continuous monitoring of parameters. Presently, the most popular methods of diagnosing the condition of composites are measurement of rigidity and ultrasonic detection. The first of them is, first of all, very rough. It allows for evaluating the condition of a whole structure (i.e. airplane wing), but does not provide any information about a selected, small part of this structure. It is not suitable for continuous monitoring of the structure, for example during the flight. The ultrasonic method is free of these disadvantages, but it allows for investigating only a very small fragment of the structure, limited by the range of ultrasonic wave propagation. Possible defects, which are located even at a slightly greater distance, will not be detected. The method is also more expensive, especially when one applies a greater number of detectors; besides, access is required to the investigated fragments of the structure.

The method based on measurement of electrical properties of the composite, which is the subject of this paper, is free of theses disadvantages.

2. Method of resistance change measurement

2.1. Method description

Owing to the use of low-resistance carbon fibres, carbon-epoxy composites are characterized by a relatively high electric conductivity. At the same time, the epoxy matrix has the features of a good insulator. In an ideal composite, all carbon fibres should be straight, fully surrounded by the matrix, and should have no contacts between one another (Fig. 1).

In practical conditions, the fibres do not lay ideally straight, and there are numerous contacts between them, which allows for the flow of current. Taking into account the fact that the number of fibres in a composite is very great (their diameters range from several to a dozen or so m), and so is the number of contacts between fibres, average electrical properties are approximately the same in the whole volume of the composite, and the material behaves like a poor conductor. Obviously, electrical properties may, to some degree, exhibit the same directionality like the mechanical ones (i.e. orthotropy).

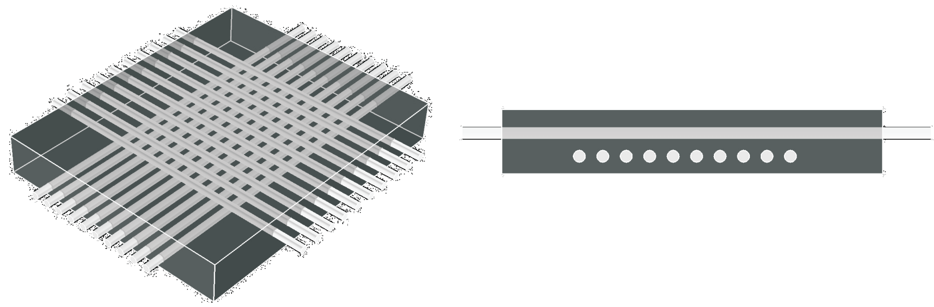

Fig. 1. Simplified diagram of a fragment of a perfect composite

Because of such a kind of internal structure of the composite, and because its electric resistance depends on the existence of contacts between fibres, the composite increases its resistance when a number of fibres are broken in an arising process of destruction, or when it comes to delamination [1,6,10]. Todoroki and Tanaka [8] shown that electric resistance very depend on the direction of the current flow and proper localization of electrodes is required, especially for detection of delamination [9]. Resistance changes in composite beams, both for static and fatigue test, was measured by Irving and Thiagarajan [3], and compared with the mechanical stiffness changes.

Resistance of a conductor can be described by the formula

$$R = \int_0^L \frac{\rho}{A} dl \tag{1}$$

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

When a defect arises in the composite, the values of all three quantities can change.

In practice, two methods are used for examining changes of electric properties of a composite caused by structural defects: measurement of potential change, and resistance change measurement (Fig. 2).

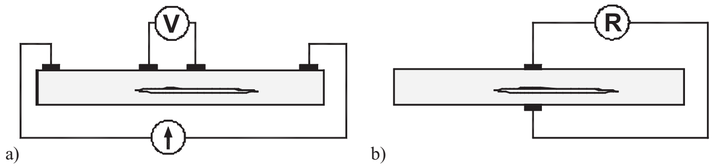

Fig. 2. Methods of examining electrical properties of composite: a) measurement of potential change, b) measurement of resistance change

In the method of potential change measurement, one uses four electrodes. The current source is connected to one pair of electrodes, and the other one is used to measure the potential difference. This voltage depends on the composite resistance, and the latter increases with the decrease of the section area through which flows the current – the decrease being the result of propagating defect. This method is convenient for the use in connection with typical multi-channel data acquisition cards of A/D converters, which provide the possibility of differential voltage measurement. A disadvantage of the method is that the current must flow through the whole volume of the composite between the terminals of the current source, and it is difficult to predict the path of this flow. Besides, it is not always possible to predict to which points the source should be connected.

In the method of resistance change measurement it is enough to have two measurement points between which the resistance is measured. The resistance depends on the length of the path of current flow, which elongates when a defect appears. The disadvantage of the method is that the measurement points must be placed on both sides of the specimen. It is also difficult to apply this method for simultaneous, multi-point measurements when one uses typical data acquisition cards.

In all investigations described in this paper, the author used the method of resistance change measurement.

2.2. Practical realization

A very important matter is to ensure an adequate electric contact between the examined composite and the measurement system. It is usually done by drowning thin wires in the composite during lamination, or by attaching contact electrodes with conducting glue. In the described research, the second method was used. Its advantage was the possibility of attaching electrodes to ready elements. A disadvantage was, however, the necessity to destroy the outer layer of the composite to glue the contacts. In the examined specimens, the outer layer of resin was removed my means of abrasive paper of fine grit. To the surface cleaned in this way, thin, short wires were glued by means of a conducting glue on silver base. Longer measuring terminals were then soldered with a low-melting Wood's alloy. Low temperature of melting of the alloy (approx. 76°C) and short time of soldering (approx. 2s) protected the composite from thermal damage. The contacts made in this way allowed for obtaining the resistance between measuring points not greater than 100 (including composite resistance). Because the changes of measured resistance were relatively high (up to a dozen or so ohms), the two-wire method was considered to be an adequate one. In the measurements, one used a precise 6 $^1/_2$ digit multimeter type Agilent 34401A. In the range of 1.2 kΩ, with measurement current of 1 mA, the instrument's uncertainty of measurement was not greater than ±0.03 Ω.

3. Examples of experimental investigations

The presented method of resistance change measurement was applied, in a couple of cases, to evaluating the degree of damage in a composite. The described research should then be treated as preliminary, aimed at getting familiar with a novel investigation method rather then obtaining concrete results. However, the obtained results already allow us to draw some interesting conclusions.

3.1. Examination of tensioned laminate

Composite structures carrying tensional force are usually made of roving bands or the so-called pre-impregnants. In such a structure, there are practically no transverse fibres.

The laminates made of layers of fabric, although basically intended for carrying shear loads, usually carry some tensional load as well. In such cases, it is interesting to know the composite capability of carrying these kind of loads, and the mechanism of its destruction. In the preliminary investigations, we used a three-layer structure made of synthetic carbon fabric 452T of basic weight 200 g/m^2, with matrix of epoxy resin EP6011. The volume fraction of a carbon was approx. 60%. The dimensions of specimen surface were 160 × 10 mm, and the thickness was 0.6 mm. The layout of layers was 0°/45°/0°, while the reference direction of 0° was consistent with the longer side of the specimen and with the applied load. The sketch of the specimen is shown in Fig. 3. The bosses at the end of the specimen play the role of the so-called lock that allows for applying a force to the specimen. The lock was made of a composite consisting of layers of non-conducting glass fibre fabric. The contacts were glued at the ends of layers, which excludes the possibility of tearing them off when the load was applied.

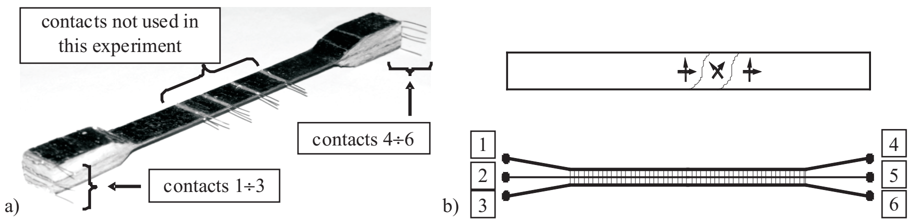

Fig. 3. View of specimen for tension examination: a) general view and position of contacts, b) enumeration of contacts

Tensional tests were carried out in the conditions of controlled displacement, in which one measured tension force, strain (by means of a strain gauge) and resistance changes. The results are shown in Fig. 4 as graphs of resistance change between measurement points 1-4 and 3 6 (Fig. 4a), and 2-5 (Fig. 4b). Identical scales were assumed in order to facilitate comparison of results.

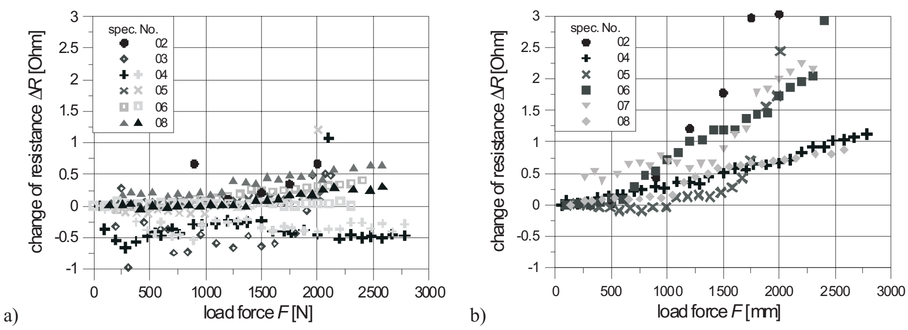

Fig. 4. Changes of resistance between measurement points in tension test: a) between points 1-4 and 3-6, b) between points 2-5

As it can be seen in Fig. 4, resistance changes in the inner layer are much greater than in outer layers. It can be explained by the fact that the work done by the fibres in each of these layers is different. The outer layers are loaded along the fibres (also in transverse direction, but these fibres work under a much lower load), and exhibit significantly greater rigidity than the inner layer. The latter is loaded at the angle of 45° with respect to fibre direction, and behaves like a mechanism of very low rigidity. In effect, much more extensive defects appear in the inner layer, where movements of fibres cause micro-delamination. The experiment also showed that the layers work, to a great extent, independently one of another.

The investigations were described in detail in [4].

3.2. Examination of delamination

The second of the presented investigations concentrated on examination of delamination by the method of resistance change measurement. Delamination, which causes separation of laminate layers, is the kind of defect very often met in practice. So that, it seems purposeful to develop a simple method of delamination detection. In order to examine delamination in a macro-scale, we prepared special specimens of 6-layer fabric. Both the fabric and the resin were the same as in the previous investigation (452T/EP6011), and so was the volume fraction of a carbon (60%). The specimens had dimensions of 160×10 mm, and thickness of 1.25 mm. The lay of the fibres was 45°/0°/45°//-//45°/0°/45°, and one assumed the zero angle parallel to the longer side of the specimen. The symbol //–// means that controlled delamination takes place between these layers. The specimen is shown in Fig. 5. Fig 5a illustrates the state of specimen after the end of test, i.e. when delamination of approx. 80 mm length was produced there.

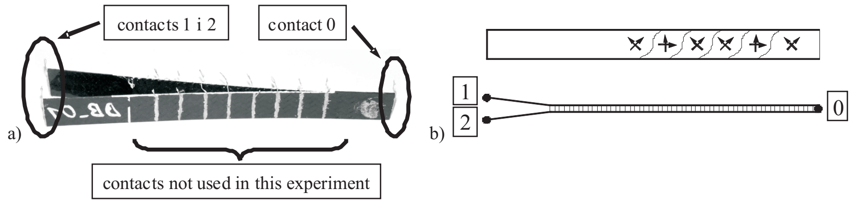

Fig. 5. View of specimen for delamination examination: a) general view and position of contacts, b) enumeration of contacts

Delamination in the specimen was made in a special test stand by using a movable wedge of non-conducting material. The initial delamination, made during lamination of the specimens, had length of x = 35 mm.

The results presented in Fig. 6 illustrate the change of resistance between contacts 0 – 1 and 0 – 2 (Fig. 6a), and between 1 – 2 (Fig. 6b).

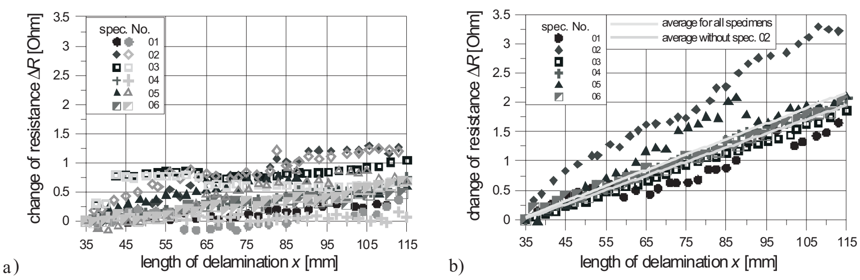

Fig. 6. Changes of resistance between measurement points in delamination test: a) points 0 – 1 and 0 – 2, b) points 1 – 2

The changes of resistance between points 0 – 1 and 0 – 2 are small in all specimens, and are approximately proportional to the length of delamination. It can be explained by relatively small changes of resistance caused by diminishing (in the result of delamination) of the specimen's current-conducting section area. However, the dominating influence has the flow of current along the fibres, on which delamination has only a small effect. An opposite situation can be observed in the resistance measured between points 1 and 2, i.e. on both sides of the developing delamination. In this case, the dominating effect on resistance has the current flowing through the contacts between fibres in adjacent layers, so that delamination leads to a significant increase of resistance. The change of resistance is almost linear, as one can expect, and its course exhibits good repeatability in all examined specimens. The exceptions are specimen No. 02, in which the course of resistance change is linear, but of a different slope, and specimen 05, where abrupt change of resistance was observed when delamination reached the length of $x \approx 87 \div 92$ mm.

The investigations were described in detail in [5].

3.3. Destruction test of bolt joint

The next examination performed by the author was a destruction test, to which a bolt joint made of a composite was subjected. Two experiments were done: a quasi-static test, and a fatigue test. In both experiments we used the same specimen and the same bolt, only the character and magnitude of loads were different.

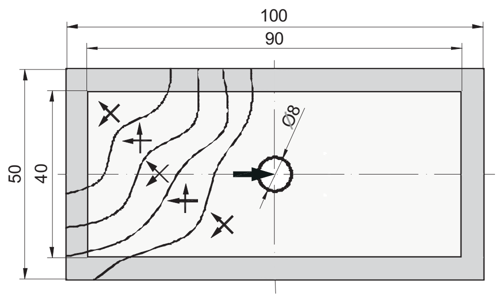

Fig. 7. View of specimen for destruction test of bolt joint

The examined object was a plane plate, shown in Fig. 7, of dimensions 100×50 mm and thickness 4.2 mm. The plate was made of carbon-epoxy composite consisting of five layers of CX600 fabric and EP52 resin. The volume fraction of a carbon was 60%. The layers were arranged so that to make the angles of 45°/0°/45°/0°/45°, thus creating a specimen of quasi-isotropic properties. Along all the borders, at a width of approx. 5 mm, the specimen was glued to the loading frame. A hole of diameter ∅8 mm was drilled at the centre of the plate, and the steel bolt of the same diameter was inserted (tightly) into the hole.

Quasi-static test was the basis for the fatigue tests performed later. In order to facilitate selection of adequate configuration of contact points, one made 40 points on one side of the specimen, and measured resistances between each of these points and the conducting surface on the other side of the specimen. Initially, a part of these points was discarded, because these were probably improperly made. Initial resistance of these points was excessively high (over 100 Ω) and/or instable. Based on measurement results, we selected 3 locations of points, in which we expected to obtain most interesting results. Fig. 8 illustrates positions and denotations of measurement points in both tests. It is worth mentioning that the measurement points in the fatigue test had the same allocation as the respective points in quasi-static test, i.e. point p+1 refers to point 1, p-1 refers to 33, and p0 refers to point 2.

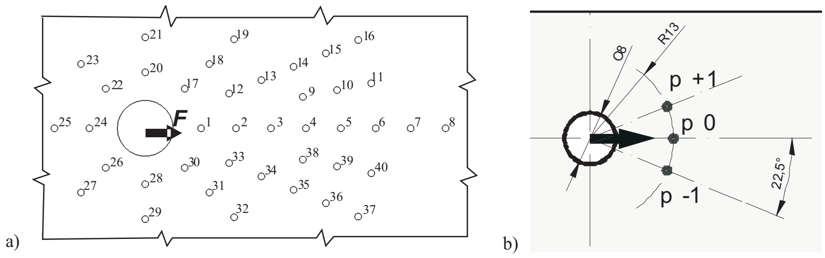

Fig. 8. Allocation of measurement points in destruction test of bolt joint: a) quasi-static test, b) fatigue test

3.4. Examination of quasi-static destruction of bolt joint

In quasi-static examinations, one performed a test in which the composite was destroyed by pulling the bolt. During the experiment, one registered displacement of the bolt in reference to the specimen (specifically, with respect to the frame to which the specimen was fixed), value of the force, and resistances between both sides of the specimen for all measurement points (only 29 points were analyzed, the remaining 11 were badly made).

At the first stage of experiment (until the displacement reached $\Delta x \approx 1.1$ mm), a controlled force was applied, and the function of displacement versus force was approximately linear. The attempt to increase the force beyond some limit led to a fast increase of displacement, so that one changed force control into displacement control. The registered force exhibited only insignificant fluctuations in this range, remaining at the level of approx. $F = 4650$ N, which referred to average contact pressure of $p = 145$ MPa. After the displacement reached $\Delta x \approx 9$ mm, the test was stopped. Fig. 9 illustrates the registered changes of resistance for some selected measurement points.

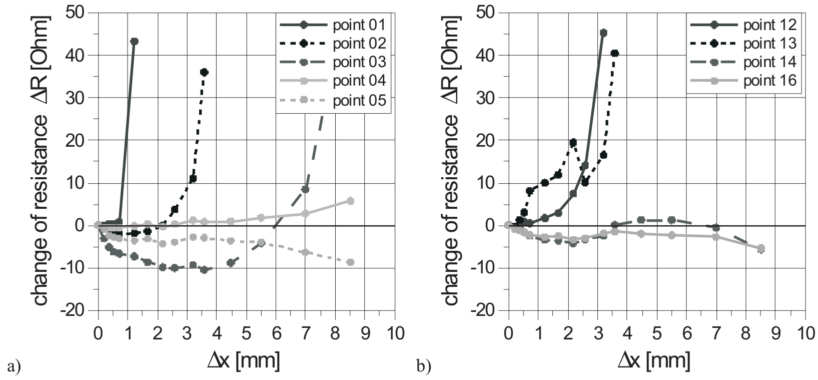

Fig. 9. Resistance changes for selected points in static test

As it can be seen, the method of resistance change measurement very clearly shows the development of large defects in the composite structure. With the progressing defects, the resistance between measurement points placed on opposite sides of the specimen significantly increases. For the moment, this effect has only been confirmed, for example, in impact tests of composite ply carried out by Hou and Hayes [2], Angelidis, Khemiri and Irving [1], and in fatigue tests for smooth specimens. The investigations carried out by the author confirmed this phenomenon also by examining the nodes where concentrated forces were introduced.

A new phenomenon is, however, the observed small decrease of resistance preceding its later growth. The drop of resistance could be the effect of flow of current through the metal bolt rather than of an increase of conductance of the composite. To explain this phenomenon, one should repeat the experiments using the bolt made of a non-conducting material. A detailed description of the investigation results can be found in work [6].

3.5. Examination of fatigue destruction of bolt joint

The fatigue tests were carried out with the use of a cyclic sinusoidal excitation force, of minimal value equal to zero, of amplitude F_1 = 2200 N (which referred to pressure amplitude of p_{1A} = 65.5 MPa) – maximal load 4400 N (p_{1max} = 131 MPa) during first 333 thousand of cycles. The load was consequently increased to F_2 = 2600 N (p_{2A} = 77.5 MPa) – maximal load 5200 N (p_{1max} = 155 MPa). The limit value of $333 \cdot 10^3$ cycles was assumed as $^1/_3$ of a typical number of loading cycles used in fatigue tests of composites. One expected that during the first loading period mechanical parameters of the specimen would stabilize, such as the change of bolt displacement in the function of number of cycles. The excitation frequency was equal to 3 Hz. The obtained results, graphed in the function of number of cycles, are presented in Fig. 10 (displacements), and Fig. 11 (change of resistance).

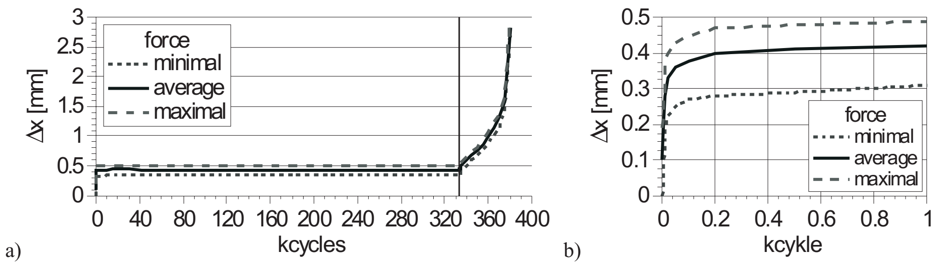

Fig. 10. Displacement of bolt in cyclic load test (description in this Section)

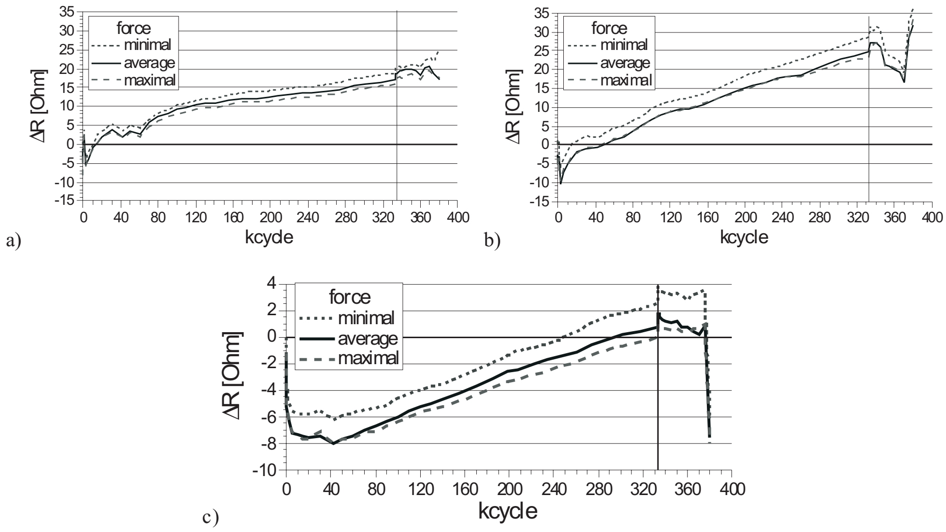

Fig. 11. Change of resistance between measurement points in cyclic load test for: a) point p–1; b) point p+1; c) point p0 (description in this Section)

The fatigue tests showed that, with the applied load, the bolt displacement stabilized already after approx. one thousand cycles. At the same time, a pronounced decrease of resistance between measurement points took place, which was the result of stabilization of composite properties, especially stabilization of fibres broken during drilling the hole for the bolt. After approx. one thousand of cycles, the resistance measured between points placed on specimen's sides started significantly increasing, and the same effect was observed after 40 thousand of cycles for measurement points placed on specimen's axis. It proves that there were slow changes in the composite, and destruction of its structure was progressing, although there were not any changes, like displacement of the bolt, measurable by mechanical methods.

The increase of load after 333 thousand of cycles evoked a rapid mechanical effect – destruction of the joint, seen as dramatic increase of bolt displacement. Similarly, resistance measurement revealed progressing changes, although their character was not quite evident, and which did not allow for unequivocal interpretation of the results. Most probably, it happened that fibres were broken and new contacts between fibres were created in a chaotic way.

The investigations were described in detail in [6].

4. Summary

The results presented in this paper confirm usefulness of the method of resistance change measurement in examining strength properties of carbon-epoxy composite and in assessing the state of its degradation. The investigations also showed high sensitivity of the method. After performing further experiments on different kinds of specimens and in different configurations of boundary conditions, and after developing adequate models, one can expect that the method might become a very useful tool for prognostication of safe exploitation period of composite elements and structures.

Manuscript received by Editorial Board, February 06, 2008;
final version, July 04, 2008.

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Wykorzystanie metody pomiaru zmiany rezystancji do określania stopnia zniszczenia kompozytu węglowego

S t r e s z c z e n i e

W artykule przedstawiono wyniki badań kompozytów węglowo-epoksydowych z wykorzystaniem metody pomiaru zmiany rezystancji. Opisano badania rozciągania i wymuszonej delaminacji laminatu oraz połączenia sworzniowego (próby quasi-statyczne i zmęczeniowe). Zaobserwowano wyraźne zwiększenie rezystancji pomiędzy punktami pomiarowymi umieszczonymi na powierzchni próbek wywołane uszkodzeniem kompozytu. Otrzymane wyniki potwierdzają skuteczność metody w badaniu stopnia degradacji kompozytów węglowo-epoksydowych. Zastosowana metoda może znaleźć zastosowanie w prognozowaniu okresu bezpiecznej eksploatacji elementów i konstrukcji kompozytowych.