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The use of rivets for electrical resistance measurement on carbon fibre-reinforced thermoplastics

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Abstract
The use of fibre-reinforced thermoplastics, for example in the aeronautical industry, is increasing rapidly. Therefore, there is an increasing need for *in situ* monitoring tools, which preferably have limited influence on the behaviour of the material and which are easy to use. Furthermore, in the aeronautical industry composites are very often attached with rivets.

In this study, the possibility of the use of rivets as contact electrodes for electrical resistance measurement is explored. The material used is a carbon fibre-reinforced polyphenylene sulphide. First, the set-up used is discussed. Then, static tensile tests on the laminate are performed. The possible influence of an extensometer on the measurements is examined. Furthermore, failure predictability is assessed. It may be concluded that the proposed set-up with the rivets can be used for electrical resistance measurement, with the ability to predict failure, and that the extensometer has a negative influence on the resistance measurement.

(Some figures in this article are in colour only in the electronic version)

1. Introduction and principle

The classical methods for periodical maintenance of composite structures, for example airplanes, use many NDE techniques (e.g. ultrasound, radiography and thermography). However, these techniques require extensive human involvement and expensive procedures. Moreover, this kind of periodical inspection cannot give any information concerning accidents or failures occurring between two successive overhauls. In order to overcome such shortcomings it is now possible to use 'sensitive' materials, which means the material includes sensors providing real-time information about the material itself, e.g. embedded optical fibres [1, 2].

Continuous health monitoring of materials would result in improved durability and safety of structures. On-line health monitoring sensors must meet three requirements: (i) they must be small in size (with no damage to the structure); (ii) they must offer the possibility of being located in remote and inaccessible areas of the structure; (iii) they must be able to transmit information to a central processor. This information must be in direct relation with the physical process being monitored and the properties and performances that have to be maintained. Evidently they must compete in sensitivity with conventional NDE techniques and be able to monitor a sufficient area of the structure.

The most natural way to obtain a 'sensitive' material is to use the material itself (or a part of it) as sensor. Of course, this is possible in the case of carbon fibre-reinforced polymers, since carbon fibres are electrical conductors embedded in an insulating matrix [3].

Furthermore, in some industries, for instance in the aeronautical industry, composites are attached using rivets. Therefore, this study investigates whether these rivets can be used for the purpose of electrical resistance measurement.

The principle of electrical resistance measurement is illustrated in the following pictures. Since carbon fibres conduct electricity, they can be represented by resistors. For

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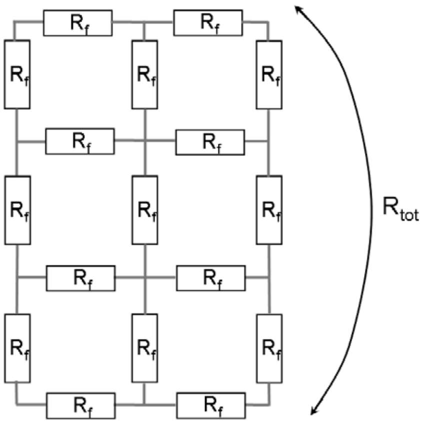

Figure 1. Electric network of resistors, representing a fabric of carbon fibres in an insulating matrix.

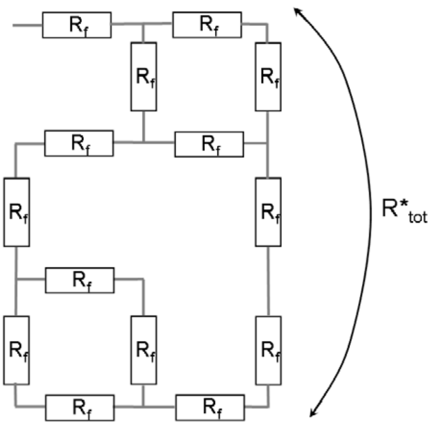

Figure 2. Representation of the result of damage in carbon fibre resistor network.

a fabric, one can imagine the following symbolic layout (figure 1). The total resistance of the composite is R_{tot}.

If a fibre breaks, then the current can no longer travel through that fibre and needs to find another path. This means that the corresponding resistor disappears, leading to a situation as depicted in figure 2.

The more carbon fibres are broken, the fewer paths are available for the electric current, so the higher the total resistance R^*_{tot} becomes. This ends with fracture of the specimen, giving infinite resistance. This conclusion may also be found in various articles about this subject [3–11].

While doing the literature study, it was noticed that most authors concentrated their work on polymers with unidirectional fibre-reinforcement [4–8, 13, 12, 9–11]. Occasionally, cross-ply laminates are studied [4, 3, 5, 12, 11], but materials reinforced with fabrics were never closely observed using this technique. A possible reason may be that the sensitivity of resistance measurement tends to decrease if there are more transverse fibre contacts, which is already the case with cross-ply laminates, but will be even more apparent in fabrics. The latter has been proven theoretically by Xia *et al* [8]. Nevertheless, we have tried this method to observe damage in the carbon fibre-reinforced PPS used. An advantage of cross-ply laminates is that the potential distribution on the surface of the laminate is much more uniform than with unidirectional samples even when point surface introduction of the current is used, because the transverse current is carried by the off-axis plies [5]. This is an important effect for establishing contact.

In the next section, the materials and experimental set-ups used are discussed. This is followed by the discussion of the conducted experiments. Finally, some conclusions are drawn and some remarks for future work are made.

Table 1. In-plane elastic properties of the individual carbon/PPS lamina (dynamic modulus identification method).

E_{11}	56.0	GPa
E_{22}	57.0	GPa
ν_{12}	0.033	—
G_{12}	4.175	GPa

Table 2. Tensile strength properties of the individual carbon/PPS lamina (mechanical testing at TUDelft).

X_T	617.0	MPa
$\varepsilon_{11}^{\mathrm{ult}}$	0.011	—
Y_T	754.0	MPa
$\varepsilon_{22}^{\mathrm{ult}}$	0.013	—
S_T	110.0	MPa

2. Material and equipment

2.1. Material

The material under study was a carbon fibre-reinforced polyphenylene sulphide (PPS), called CETEX. This material is supplied to us by Ten Cate. The fibre type is the carbon fibre T300J 3 K and the weaving pattern is a 5-harness satin weave with a mass per surface unit of 286 g m^{-2}. The 5-harness satin weave is a fabric with high strength in both directions and excellent bending properties.

The carbon PPS plates were hot pressed, only one stacking sequence was used for this study, namely a $[(0°, 90°)]_{4s}$ where $(0°, 90°)$ represents one layer of fabric.

The in-plane elastic properties of the individual carbon PPS lamina were determined by the dynamic modulus identification method described by Sol *et al* [14, 15] and are listed in table 1.

The tensile strength properties were determined at the Technical University of Delft and are listed in table 2.

The test coupons were sawn with a water-cooled diamond saw. The dimensions of the coupons used for the electrical resistance measurement are shown in figure 3.

2.2. Equipment

All tensile tests were performed on a servo hydraulic INSTRON 1342 tensile testing machine with a FastTrack 8800 digital controller and a load cell of ±100 kN. The tests were displacement controlled with a speed of 2 mm min^{-1}.

Since the influence of the extensometer on the resistance measurement needed to be assessed, some specimens were instrumented with both extensometer and strain gauge and others were only equipped with the extensometer. The

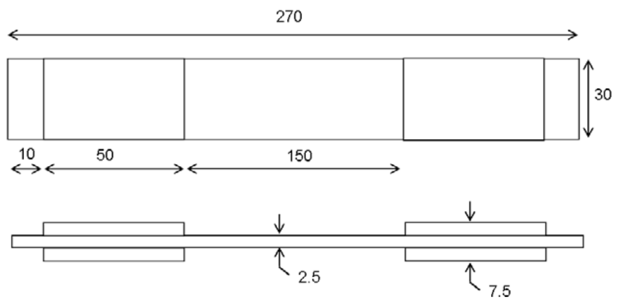

Figure 3. Dimensions of the tensile coupon used, equipped with isolating tabs of [$\pm 45°$]$_{2s}$ glass fibre epoxy.

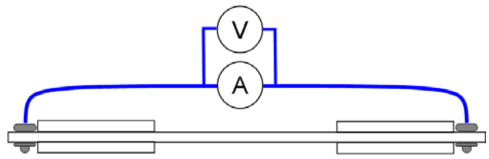

Figure 4. Symbolic representation of the two-probe method used for electrical resistance measurement.

strain gauges were mounted in the 0° direction to measure longitudinal strain.

The current needed for the electrical resistance measurement was given by an ILX lightwave LDX-3412 precision current source. The current used was 100 mA to increase the signal–noise ratio.

For the registration of the data, a combination of a National Instruments DAQpad 6052E for fireWire, IEEE 1394 and the SCB-68 pin shielded connecter were used. The load, displacement and strain, given by the FastTrack controller, as well as the extra signals from strain gauges and resistance measurement were sampled on the same time basis.

3. Method

3.1. Introduction

In order to measure the resistance, a current is introduced in the specimen and the voltage is measured. There are various ways to do this [3–11], but in general, there are two types of configurations: (i) the two-probe technique, which means that the voltage is measured on the same electrodes where the current is introduced and (ii) the four-probe technique, where the first two contacts are needed for the current injection and the voltage is measured with the remaining two.

Both set-ups have advantages and disadvantages. The four-electrode technique is said to be more accurate [7, 10], but is a more complicated experimental set-up. Furthermore, it may not represent subsurface behaviour if all probes are mounted on the same surface [5]. The two-probe technique is easier but the measurement unit needs a high input impedance, to assure that the injected current goes through the specimen and not through the voltmeter. The latter is the case with the SCB-68 used. It is said that the surface conditions have a greater influence in the two-probe method [7]. Sanding or polishing the specimen surface enhances the electrode–fibre contact, but it may induce small surface cracks, influencing fatigue life or tensile strength and therefore corrupting the data.

For the current, both AC and DC can be used. The difference between the two is that the DC technique is mainly sensitive to fibre failures and the measurement is longitudinal, whereas the AC measurements provide information essentially on the development of matrix cracks but the measurement is done perpendicular to the fibres [3]. The latter can be explained since an AC measurement not only measures the resistance, but also the capacitance of the specimen. Most authors use DC measurements [4–7, 9, 10, 12] which also have the advantage of an easier measurement, since there is no need to divide the measured impedance into a resistance and a capacitance, as is the case with AC. Values of the DC current tend to vary between 5 and 50 mA, but most authors use 10 mA.

The measured resistance between the two clamps of the tensile testing machine is approximately 0 Ω, which means a short circuit.

If a current is injected using the two electrodes, it will choose the path of least resistance, meaning through the testing machine. In order to prevent this, the test specimen needs to be insulated from the machine. This can easily be achieved by using end tabs which do not conduct electricity. This means that the fibre reinforcement has to be glass or aramid.

Todoroki *et al* [10] has proven that a poor electrical contact of the electrodes leads to inadequate results. This has also been reported by Angelidis *et al* [5]. However, due to the effect, mentioned above, that in a cross-ply laminate, the transverse current is carried by the off-axis plies, even a point current injection will lead to a uniform potential distribution. The reinforcement fibres for the material being used for this study are a fabric, so the conduction of the transverse current will not be a problem since longitudinal and transverse fibres contact one another in each ply. Therefore, establishing good electric contact should not pose any difficulties.

3.2. Set-up used

In order to mount the rivets, holes must be drilled through the specimen. This damages and therefore weakens the material locally. To avoid these holes influencing the mechanical behaviour of the material, the rivets need to be mounted in a zone that is not loaded. Therefore, the tabs are not attached at the end of the specimen, but a small zone is left uncovered (figure 3). The holes are drilled in this area and the rivets are mounted. Since no stresses occur beyond the tabs, the electrodes are in strain-free zones which should prevent contact loss of the probe.

Figure 4 represents the set-up used for this study. A two-probe technique is used and a DC current of 100 mA is injected through the rivets. The same rivets are used to measure the voltage. In order to isolate the specimen from the tensile machine, a unidirectional glass fibre-reinforced epoxy with a [$\pm 45°$]$_{2s}$ stacking sequence is used.

Figure 5 shows in more detail how a rivet is mounted. A small hole is drilled on each side of the specimen and a rivet with a wire attached to it, is inserted and riveted. The surfaces under the rivets are sanded for better contact with the fibres.

An example of a specimen can be seen in figure 6, a detail of the riveting is depicted in figure 7.

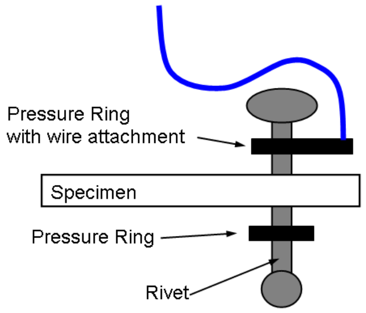

Figure 5. Mounting a rivet through the specimen.

Figure 6. Specimen prepared with rivets for electrical resistance measurement.

The rivets must not exceed the thickness of the tabs, because they would make contact with the clamps of the tensile machine.

4. Experiments and discussion

4.1. Introduction

To assess the proposed method, a first test on specimen F1 was done. For this test, rivets of 10 mm length and 3 mm in diameter were mounted. The longitudinal strain was not measured.

In figure 8, the evolution of the relative resistance is plotted against a pseudo-time, where 0 corresponds with the start of the experiment and 1 corresponds with fracture of the specimen. The relative resistance change ρ is calculated as:

$$\rho = \frac{\Delta R}{R_0} = \frac{R_t - R_0}{R_0} \tag{1}$$

where R_0 is the resistance of the unloaded specimen and R_t is the resistance of the loaded specimen. Because of the large amount of noise on the signal, a polynomial curve was fitted on the original signal, to show the trend of the measurement.

For specimen F1, the starting resistance R_0 was 1.24 Ω and the failure stress of the specimen was 694.5 MPa. The value of the relative resistance change at failure, ρ^{ult} was 0.006 99.

The relative resistance increases, which means that a good contact is achieved [5, 10]. The evolutions can be divided in two separate phases; a 'steady state phase', where the increase

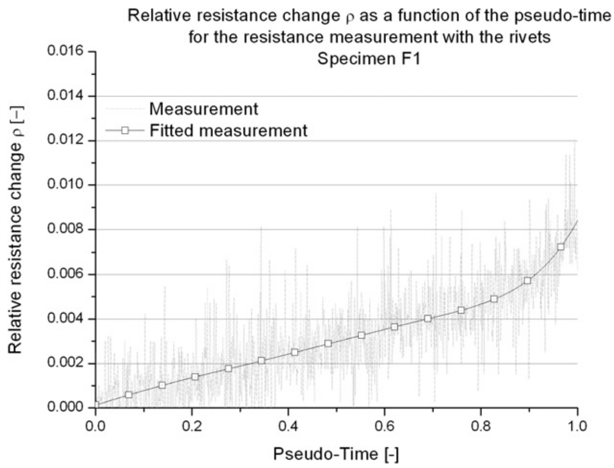

Figure 8. The evolution of ρ as a function of the pseudo-time for the specimen F1.

of ρ is constant, and an 'end of life' phase, where the growth suddenly increases (from $t = 0.8$ and onward).

This suggests that this method can be used for predicting the end of life of carbon-reinforced composites.

Because of the excellent results of the previous test, two more specimens, G1 and G2, were tested to see if the results are reproducible. To further increase the contact conditions, new rivets were used which are 4 mm in diameter and 10 mm in length. The increase in diameter gives a larger contact surface of the rivet. Furthermore, silver paint (RS components) was added around the mounted rivet (see figure 7).

The strain was measured with an extensometer, in order to have an evolution of the relative resistance change as a function of the longitudinal strain. An extensometer was chosen rather than strain gauges, because the authors would like to use this technique for fatigue testing. Under these loading conditions, strain gauges only survive a few thousand cycles and then the adhesive fails.

However, the question is whether the extensometer influences the electrical resistance measurement. To investigate this possible influence, two more specimens, G4 and G7, were tested. Both specimens were instrumented with strain gauges. These strain gauges are isolated from the specimen, because otherwise, they would not function properly. Therefore, they will not have any influence on the measured resistance.

All four specimens were subjected to two loading cycles.

- For the first experiment, the extensometer was mounted and the specimens were loaded until about half the ultimate stress (see table 2). These experiments were

(a) top view (b) bottom view (c) side view

Figure 7. Detailed pictures of the rivet.

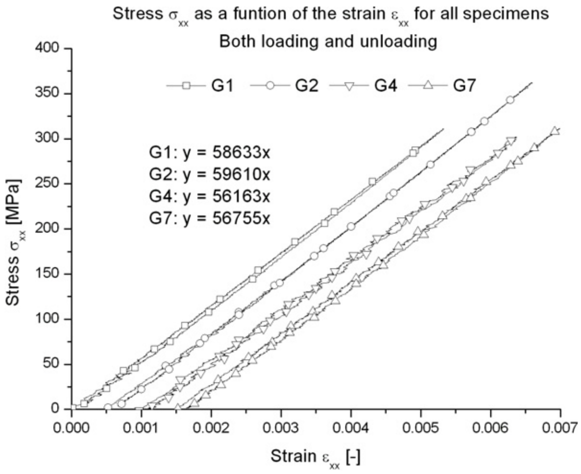

Figure 9. Stress as function of the strain for all specimens.

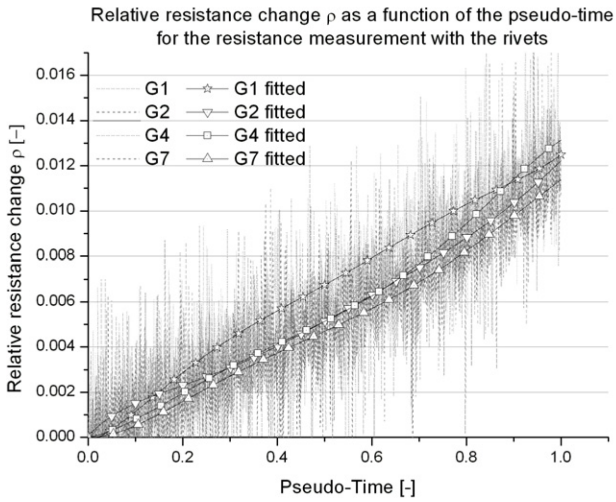

Figure 10. The evolution of ρ as a function of the pseudo-time for specimens G1, G2, G4 and G7.

Table 3. Stiffness moduli derived from the static testing on the specimens.

G1	58.6	GPa
G2	59.6	GPa
G4	56.2	GPa
G7	56.8	GPa

Table 4. Overview of the measured values for the four experiments.

Specimen	R_0 (Ω)	ρ^{ult} (—)	σ_{xx}^{ult} (MPa)
G1	0.705	0.0125	655.2
G2	0.569	0.0122	632.9
G4	0.560	0.0131	643.5
G7	0.563	0.0114	594.3

used to determine any influence of the extensometer on the electrical resistance measurement. This is discussed in section 4.3.

- For the second experiment, the extensometer was removed to avoid any interference of the extensometer on the resistance measurement. The specimen was loaded till fracture to assess the possibility of failure predictability. This is discussed in section 4.4.

In figure 9, the evolution of the stress as a function of the longitudinal strain is shown for all four specimens. Both loading and unloading curves are given. Each curve is given a certain strain offset to have a clear image. The strain used for this picture is from the extensometer, since all four specimens were instrumented with the extensometer.

Table 3 gives an overview of the stiffness moduli of all four specimens. These values show good agreement with the values determined with the dynamic modulus identification method (table 1).

It may be noted from the stress–strain curves above that the reached load level (350 MPa for G2, 300 MPa for the others) does not cause any stiffness degradation or permanent strain. Furthermore, no hysteresis loops are observed. Therefore, it is assumed that these load levels do not induce damage in the specimen and that the secondary loading of the specimen is representative for the loading of an undamaged specimen.

4.2. Assessment of the method

Figure 10 shows the evolution of the relative resistance change ρ as a function of the pseudo-time for all four experiments. Table 4 gives an overview of the initial resistance, failure stress and relative resistance change at failure.

If these initial resistances are compared with the starting value of F1 (1.24 Ω), the effect of the larger rivets and the silver paint cannot be missed. The failure stresses show good agreement with the values obtained from TUDelft (table 2). Finally, the values of the ultimate resistance change are higher than the one obtained for F1 (0.006 99). This is probably due to the better contact established with the larger rivets and the silver paint.

It must be noted that the 'end of life' and 'steady growth' phases, that were clearly distinctive for F1, are no longer visible for any of the specimens. On the other hand, ρ^{ult} is a lot higher. Furthermore, the curves for G2, G4 and G7 are almost identical. G1 deviates slightly. The origin probably lies in a lesser contact of the rivets in comparison with G2, G4 and G7. The initial resistance is also a little higher.

It must be remarked that there is still noise on the measurement. This noise is present because no form of filtering (through software or hardware) was applied, the original raw data is shown. One reason for this noise on the relative resistance is the fact that the absolute increase in resistance is very low, about 7 mΩ which corresponds with an increase of only 0.7 mV, but this is within the range of the data acquisition system used.

This noise will always be present, but most authors present only the filtered signals. The signal to noise ratio may greatly be improved by increasing the current, as is illustrated in figure 11. For this measurement, the specimen was kept unloaded and first a current of 100 mA was injected for a small period of time. Then, a current of 1000 mA was injected. For both cases, first, the average resistance was calculated and then ρ was determined. Should the rivets lie at the origin

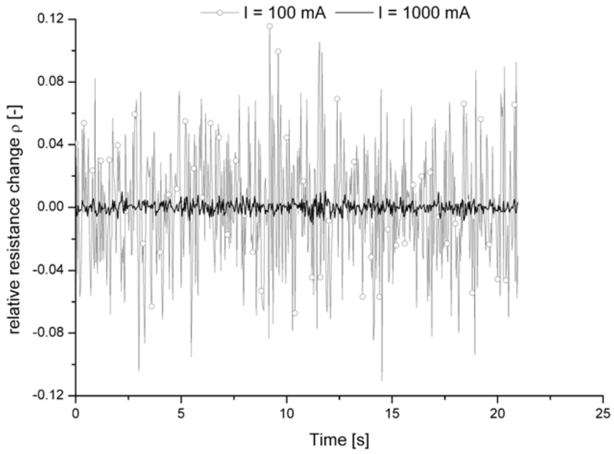

Figure 11. Illustration of the effect of higher current on the signal to noise ratio.

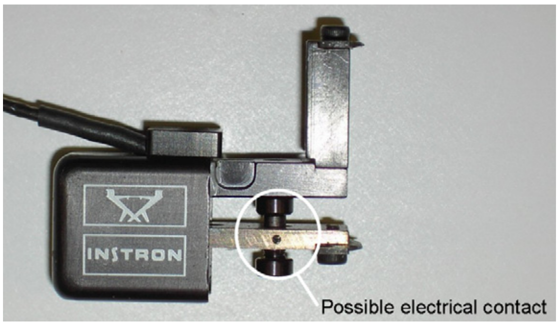

Figure 12. Illustration of the extensometer used. The possibility of electrical contact is highlighted.

of this noise, because of bad contact or alternating contact resistance, then the noise should increase similarly with the signal when the current is increased, since voltage is equal to resistance times current and the contact resistance is also measured, because of the two-probe set-up.

Of course, higher currents may introduce heating of the specimen and therefore, this solution is not considered for this paper. It is also common knowledge that any resistor generates white noise and that carbon film resistors generate more noise than metal film resistors. Therefore, this noise does not pose a problem, since it is most likely to be inherent to the carbon fibres and it can easily be filtered away.

4.3. *Influence of the extensometer*

It is unclear how large the influence of the extensometer is on the electrical resistance measurement. If the current is able to flow through the device, it creates a conductive bridge over the stressed and possibly damaged zone and therefore corrupts the data.

Figure 12 shows the extensometer used for the strain measurements. The movable blade runs over a small cylinder (indicated by the white circle) that is connected with the rigid blade. If contact occurs at the cylinder, the two blades form a short circuit over the specimen, excluding a large area with possible damage from the resistance measurement.

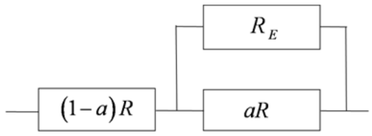

Figure 13. Theoretical illustration of the effect of the extensometer on the resistance measurement.

When measuring the resistance between the fixed and the movable blade, a value of 20.3 Ω is registered. This is certainly not high enough to be considered infinite with respect to the resistance of the specimens. Therefore, the extensometer will influence the resistance measurements on the specimen.

Consider the theoretical resistor model in figure 13 where the specimen is divided in two parts, one which represents the part of the specimen with the extensometer as a parallel resistor, illustrated by R_E, and another part which represents the rest of the specimen. The total resistance of the sample is R and $a < 1$.

If no extensometer is mounted, then the total resistance becomes R and the relative resistance change becomes:

$$\rho = \frac{R_t - R_0}{R_0}. \tag{2}$$

With R_t the resistance of the loaded and R_0 the resistance of the unloaded specimen, as previously mentioned. If the extensometer is mounted, then the relative resistance change at time t, using the same initial resistance, becomes:

$$\rho_E = \frac{\left((1-a)R_t + \frac{aR_tR_E}{aR_t+R_E}\right) - R_0}{R_0}. \tag{3}$$

This can be rewritten as

$$\rho_E = \rho - \frac{a^2R_t^2}{R_0}. \tag{4}$$

This means that the relative resistance change will be higher without the extensometer than when it is mounted. However, when the extensometer is mounted, the initial resistance will not be R_0 but:

$$R_0^E = (1-a)R_0 + \frac{aR_0R_E}{aR_0 + R_E}. \tag{5}$$

If this initial value is used, the following is derived for ρ_E.

$$\rho_E^* = \frac{aR_0 + R_E}{(1-a)aR_0 + R_E}\rho - \frac{a^2R_t^2(aR_0 + R_E)}{R_0[a(1-a)R_0 + R_E)]}. \tag{6}$$

It is now very difficult to estimate the exact influence, because the multiplier of ρ is slightly higher than one, but from this product, a small value is subtracted. The main conclusion, however, is that the extensometer will have an influence.

To investigate the influence of the extensometer on the resistance measurement experimentally, the extensometer was mounted and the specimens were loaded until about half the ultimate stress (see table 2) and then unloaded. Next, the extensometer is removed and the specimen was loaded again. Figure 14 shows the evolution of ρ as a function of the strain ε_{xx} for both these loadings. Only the fitted curves are plotted

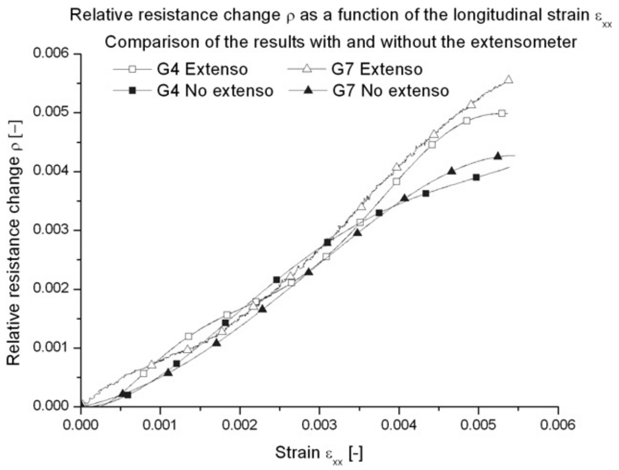

Figure 14. The evolution of ρ as a function of the longitudinal strain ε_{xx} for the specimens G4 and G7. Only the filtered curves are plotted for a clean image.

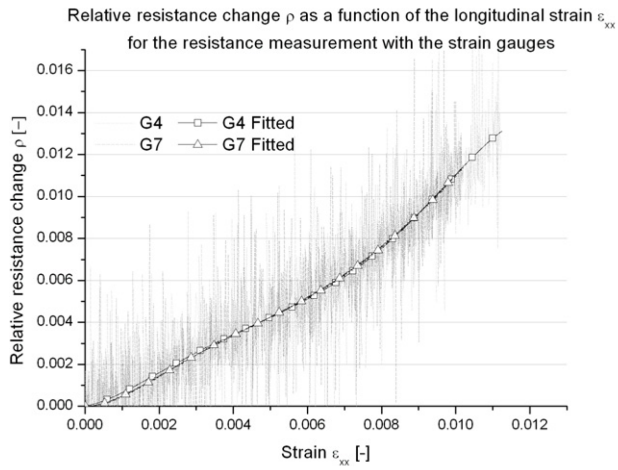

Figure 15. The evolution of the relative resistance change as a function of the longitudinal strain, measured by the strain gauges until fracture for specimens G4 and G7.

for a clear overview. The strain in the abscissa is the one from the strain gauge, to exclude any influence of the difference between the extensometer and the strain gauge.

It can be seen that at larger strains (>0.0035) the relative resistance change increases more when the extensometer is mounted than otherwise. So it may be concluded, both from experimental as theoretical point of view, that the extensometer has an influence on the electrical resistance measurement.

Finally, figure 15 illustrates the evolution of the relative resistance change as a function of the longitudinal strain for G4 and G7, measured by the strain gauges until fracture.

It must be noted that both measurements are almost identical, which illustrates the reproducibility of the results.

4.4. Failure predictability

From the previous paragraphs, it has become clear that the resistance increases with increasing strains (or loads). The question remains whether this increase can be used for damage modelling or to predict failure.

Figures 8 and 10 show the evolution of ρ for all the experiments. Only for F1 can the 'end of life' phase be seen. However, all other experiments tend to have an ultimate relative resistance change of about 0.0012, regardless of the initial resistance. This can also be seen in table 4. When comparing the experiments with the 4 × 10 rivets, it must be noted that the curves for G2, G4 and G7 are very much alike. Only G1 has a slightly different form. Since the R_0 of G1 is slightly higher than the others, this is probably due to an inferior contact.

The authors propose a failure criterion in the form of a maximum allowable value of ρ. Future work will be on the evolution of the relative resistance change as a function of damage, which is needed for damage modelling. For this, more static and cyclic tests are needed.

5. Conclusions

Based on the results of this research, the following conclusions can be drawn.

- Rivets can be used as contact electrodes for electrical resistance measurement with reproducible results. The measured resistance increases with increasing strain, which indicates that good contact is achieved by using rivets. The contact can be improved by using rivets with a larger diameter and by adding silver paint on the contact zone.
- The extensometer certainly has a negative influence on the resistance measurement. The evolution of ρ is wavier and the values are higher than when the extensometer is not mounted.
- A threshold value for the relative resistance change ρ has been determined.
- The evolution of the relative resistance as a function of the damage remains unclear. Further static testing and tests with repeated loading and unloading are necessary to be able to model damage as a function of the relative resistance change ρ.

Acknowledgment

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