International Journal of Fatigue 32 (2010) 197–207

Contents lists available at ScienceDirect

International Journal of Fatigue

journal homepage: www.elsevier.com/locate/ijfatigue

Electrical resistance measurement for in situ monitoring of fatigue of carbon fabric composites

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ARTICLE INFO

Article history:
Available online 16 March 2009

Keywords:
Carbon fabric
Polyphenylene sulphide
Damage monitoring
Electrical resistance
Four probe method

ABSTRACT

This study investigates whether fatigue damage can be monitored using the electrical resistance of the carbon fabric-reinforced thermoplastic. A four-probe method, using rivets for the current injection and conductive tape for the voltage measurement is presented. Quasi-static and hysteresis tests are presented to assess the method, with promising results. Then, fatigue tests at both 2 and 5 Hz are discussed. For the material under study, neither stiffness reduction nor permanent elongation occurred and therefore, fibre fracture is not the dominant mode of damage. As a result, the electrical resistance measurement was not capable of monitoring damage growth inside the specimen, since it is sensitive to fibre failure.

1. Introduction and principle

An ideal solution for monitoring damage in a material is to use the material itself as a sensor. This is possible in the case of carbon fibre-reinforced polymers, since carbon fibres are electrical conductors embedded in an insulating matrix [1].

The principle of electrical resistance measurement is illustrated in Fig. 1. Since carbon fibres conduct electricity, they can be represented by resistors and for a carbon fabric, one can imagine the following symbolic lay-out (Fig. 1a). 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 Fig. 1b.

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 [1–11].

While doing the literature study, it was noticed that most authors concentrated their work on polymers with unidirectional fibre reinforcement [4–13]. Occasionally, cross-ply laminates are studied [3–5,11,12], 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 used carbon fabric-reinforced PPS. 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 will be even more so for a fabric-reinforcement.

There have already been a few studies on the use of this technique for monitoring fatigue [4,5,11–14], but as previously mentioned, the focus lies mostly on unidirectional [4,5,11,13,14] or cross-ply reinforcement [5,12]. In [4], a very promising correlation between stiffness degradation and relative resistance change was found, but for a unidirectional carbon fibre-reinforced epoxy.

The order of change tends to vary with the used material. In [4], the resistance increased about 30% for the UD carbon epoxy, whereas in [12], an increase of 5% was reached at failure for a cross-ply material.

In some industries, for instance in the aeronautical industry, composites are attached using rivets. In [15], the authors have examined whether these rivets can be used for the purpose of electrical resistance measurement for static tests, with good results. This study investigates whether the same principle can be used to monitor a fatigue experiment.

In the next paragraph, the used materials and experimental setups are discussed. This is followed by the discussion of the conducted experiments, both under quasi-static and fatigue loading conditions. Finally, some conclusions are drawn.

2. Materials

2.1. Composite material

The material under study was a carbon fabric-reinforced polyphenylene sulphide (PPS), called CETEX. This material is supplied

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doi:10.1016/j.ijfatigue.2009.02.044

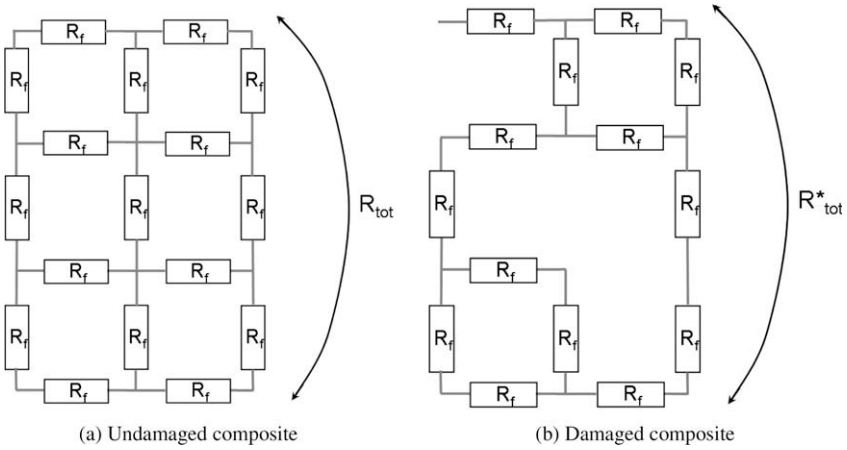

Fig. 1. Electric network of resistors, representing a fabric of carbon fibres in an insulating matrix.

to us by Ten Cate. The fibre type is the carbon fibre T300J 3K 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 $[(0°,90°)]_{4s}$ were $(0°,90°)$ represents one layer of fabric and therefore eight layers in total were laid up.

The in-plane elastic properties of the individual carbon PPS lamina were determined by the dynamic modulus identification method as described in [16] 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 are shown in Fig. 2. Electrically isolating end tabs of glass fibre-reinforced polyethylene imide (PEI) are bonded to the end of the specimen, but a small zone is left uncovered to mount the electrodes, as described in [15].

2.2. Equipment

All tensile tests were performed on a servo-hydraulic INSTRON 8801 tensile testing machine with a FastTrack 8800 digital controller and a load cell of ±100 kN. The used power source for the resistance measurement was a PL330-32V-3A PSU from Thurlby Thander instruments (TTi). For the registration of the tensile data, a combination of a National Instruments DAQpad 6052E for fireWire, IEEE 1394 and the SCB-68 pin shielded connecter were used.

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	717.0	MPa
ε_{11}^{ult}	0.011	–
Y_T	754.0	MPa
ε_{22}^{ult}	0.013	–
S_T	110.0	MPa

The load, displacement and strain, given by the FastTrack controller, as well as the extra signals from the resistance measurement were sampled on the same time basis.

3. Method

The resistance of the specimen is measured by injecting a known current through two electrical contacts on the specimen and measuring the voltage between two electrodes. In [15], a two-probe technique was used, which means that the voltage is measured on the same electrodes where the current is introduced. For these electrodes, rivets were used, as illustrated in Fig. 3, which are mounted in the stress free zone of the specimen.

An example of a specimen can be seen in Fig. 4, a detail of the riveting is depicted in Fig. 5.

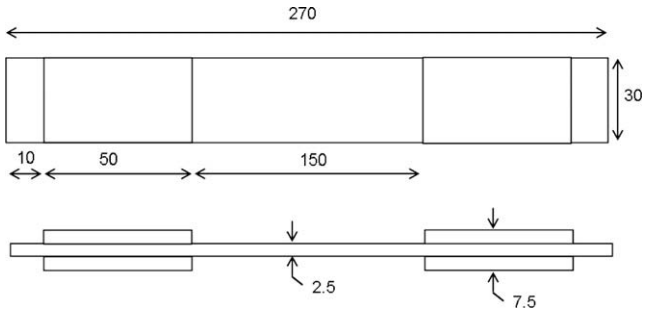

Fig. 2. Dimensions of the used tensile coupon, equipped with isolating tabs of $[\pm45°]_{5s}$ glass fibre PEI.

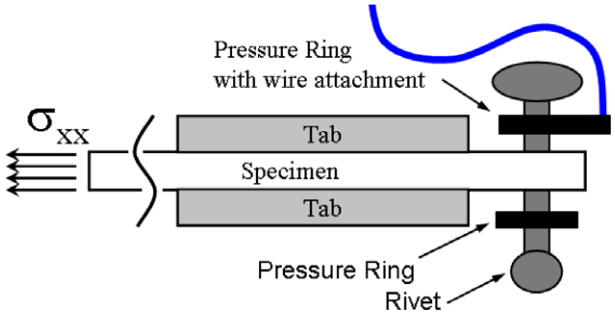

Fig. 3. Illustration of how the rivet is mounted in the stress free zone of the specimen.

Fig. 4. Specimen prepared with rivets for electrical resistance measurement.

This principle worked excellent for the quasi-static tests, but an extra parameter is introduced when conducting fatigue experiments: time. Therefore, the time-stability of this setup was first tested by measuring the resistance of an unloaded specimen for an extended period of time, corresponding with an average fatigue test. Several of these tests have been performed in order to have reproducible results; they are shown in Fig. 6. For specimen I7, a current of 1000 mA was injected and three successive tests (I7-1 till I7-3) were done. After a certain period of time, the current was removed and the specimen was left untouched for a few hours. Afterwards, the current was injected again and the measurement was redone to see if the increase in resistance was reversible. It can clearly be noticed that the resistance change is irreversible, since the initial resistance of I7-2 differs from the starting resistance of I7-1. Also, should this be a reversible phenomenon, one would expect coincident curves for all three tests and this is definitely not the case. The same experiment was done on specimen I8 (I8-1 and I8-2), but with a current of 100 mA, to assess whether the high current may cause the increase. Again, there is an irreversible increase in resistance, since the initial value of I8-2 is higher than the initial value of I8-1. To assess whether this effect is due to the data-acquisition unit, a reference resistor was also measured using the same setup. It can be noted that the measured value is constant, which rules out the data-acquisition unit.

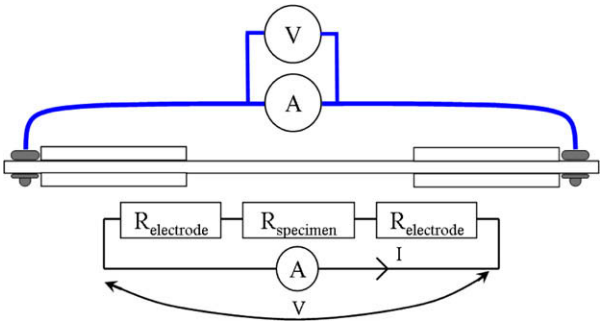

Fig. 7. The two-probe system for resistance measurement.

It must be remarked that during the experiments described above, the temperature was monitored. There was no significant increase or decrease of the temperature (measured difference, both increase and decrease was less than 2 °C), which rules out the temperature as possible influence.

For the quasi-static tests, this increase did not have any influence on the measurement, since the total time needed for the experiment was too short for any significant increase to occur. For the fatigue experiments, however, this could be a major

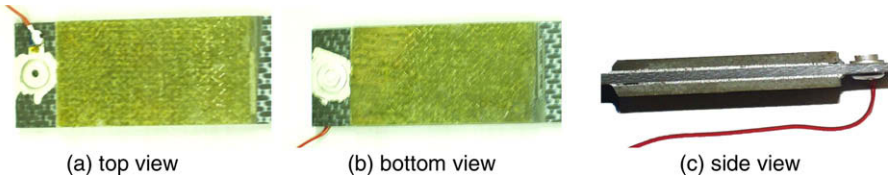

Fig. 5. Detailed pictures of the rivet.

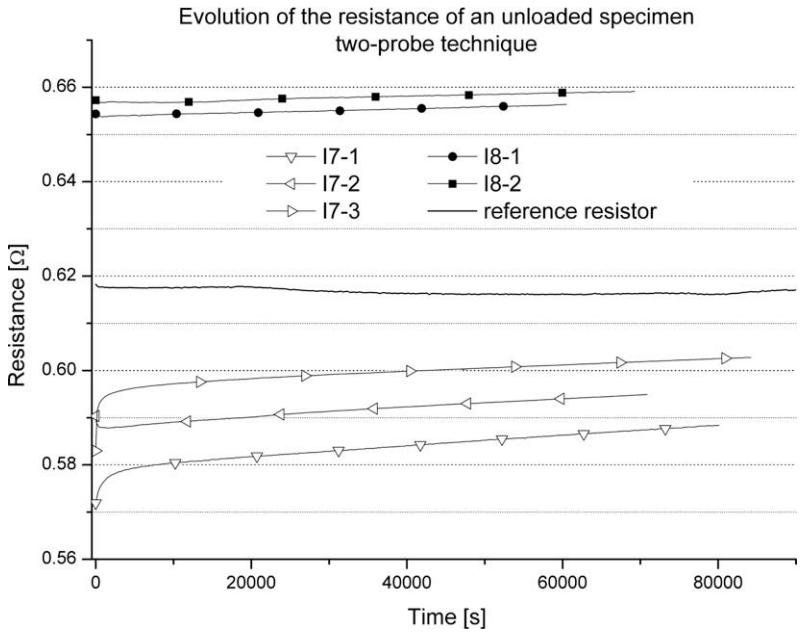

Fig. 6. Evolution of the resistance of an unloaded specimen, measured with the two-probe technique.

problem, since the value of the increase due to fatigue damage may be of the same order as the increase measured above.

The main reason for this increase is that in the two-probe method, the contact resistance of the electrodes is also measured. The principle of the two-probe method is illustrated in Fig. 7.

The voltage measured by the system is given by

$$V = R_{tot} \cdot I = (2R_{\text{electrode}} + R_{\text{specimen}}) \cdot I \quad (1)$$

Therefore, if the resistance of the contact electrodes varies in time, this variation is also measured by the system and this is the reason why the measurements depicted in Fig. 6 are not stable. The variation of the contact resistance may have various reasons, such as creep of the composite around the rivets, electrochemical reactions in the soldered connection between rivet and wire ... It is impossible to model all these effects on the total resistance, so the best solution is to avoid measuring the contact resistance.

Therefore, a four-probe method is considered. This setup is also used in [2,5,7,10,12,13,17,18]. This technique is said to be more accurate [7,10] than the two-probe technique, but is more complicated as experimental setup. Furthermore, it may not represent subsurface behaviour if all probes are mounted on the same surface [5]. The used setup for this research is illustrated in Fig. 8. The two electrodes for current injection are the same as for the two-probe method, but for the voltage electrodes, rivets are no option since this would require drilling holes in the loaded part of the specimen. Therefore, a special conductive copper tape is wound around the specimen and the wires for the voltage measurement are then attached to this tape. By winding the electrode around the specimen, subsurface behaviour is represented. The area underneath the tape is degreased with acetone, but it is not polished, since this would damage the surface and induce premature fatigue failure.

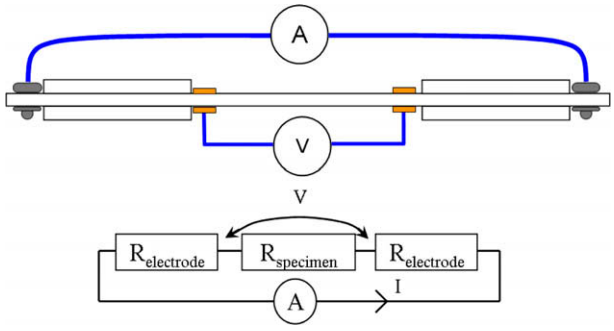

Fig. 8. The four-probe system for resistance measurement.

As for the two-probe method, the current still travels through the contact electrodes $R_{\text{electrode}}$, but the measured voltage is now given by

$$V = R_{\text{specimen}} \cdot I \quad (2)$$

Normally, the voltage measurement unit has a very high input impedance, so no current travels through the wires from the specimen to the unit and therefore, the contact resistance of the copper conductive tape has no influence. However, some say the quality of the electrodes tends to have a small influence [19].

Of course, the time-stability of this method should still be tested. Again, a current of 1000 mA was injected through the specimen and the resistance was measured for an extended period of time. The result was also depicted in Fig. 9 and as can be seen, no increase occurs. In fact, the signal is even more stable than the reference resistor measurement, which proves that the four-probe method is definitely an improvement.

Furthermore, the low value of the resistance should be noted. The voltage, given by the current source, was about 0.7 V, while the actual resistance of the specimen is only 0.1518 Ω, meaning that the contact resistance of each of the rivets is about 0.275 Ω. As a result, the sensitivity of the setup should have increased.

The choice of 1000 mA was made to further increase the signal to noise ratio. Of course, this current could cause heating of the specimen due to Joules heating, but temperature was monitored for all of the experiments and no significant increase in temperature was noted. The increase in current however did have a significant effect on the noise on the signal, as is illustrated in Fig. 10. It must be noted that the measured noise is white noise, the average value of both signals is 0 and this noise can be easily filtered away by using a low band pass filter.

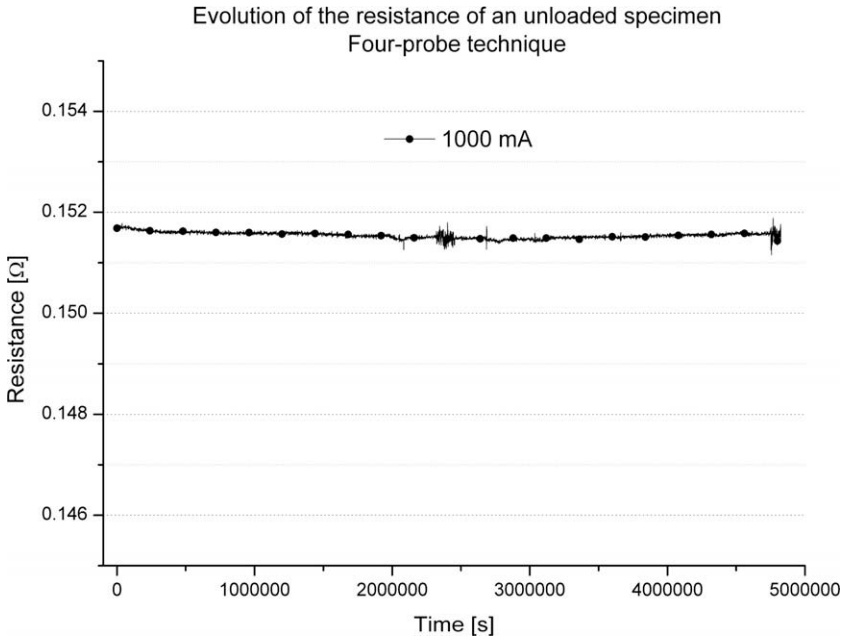

Fig. 9. Evolution of the resistance of an unloaded specimen, measured with the four-probe technique.

4. Experiments and discussion

4.1. Quasi-static tests

In the previous paragraph, the four-probe method was introduced. Before conducting any fatigue experiments, first the conclusion made in [15] should be verified. Therefore, a few static tests have been performed, of which the results are shown in Fig. 11; both the measurement and the filtered signal are presented. The tests were displacement controlled at a speed of 2 mm/min. The relative resistance change ρ, plotted in the graph is calculated as

$$\rho = \frac{\Delta R}{R_0} = \frac{R_t - R_0}{R_0} \tag{3}$$

where R_0 is the resistance of the unloaded specimen and R_t is the resistance of the loaded specimen.

When comparing these static results to the ones in [15], it should be noted that the value of ρ at failure is more than double. Here, values of 0.0304 for K10 and 0.028 for K11 are found, compared to values of 0.011 and 0.013 found in [15]. This illustrates the increase in sensitivity of the four-probe over the two-probe method. On the other hand, the higher sensitivity might be the rea-

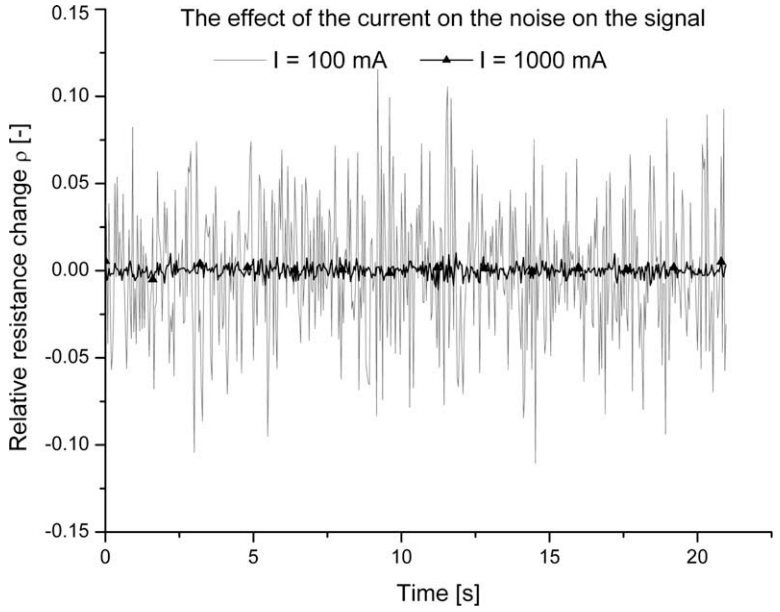

Fig. 10. Increasing the current from 100 mA to 1000 mA drastically reduces the noise on the signal.

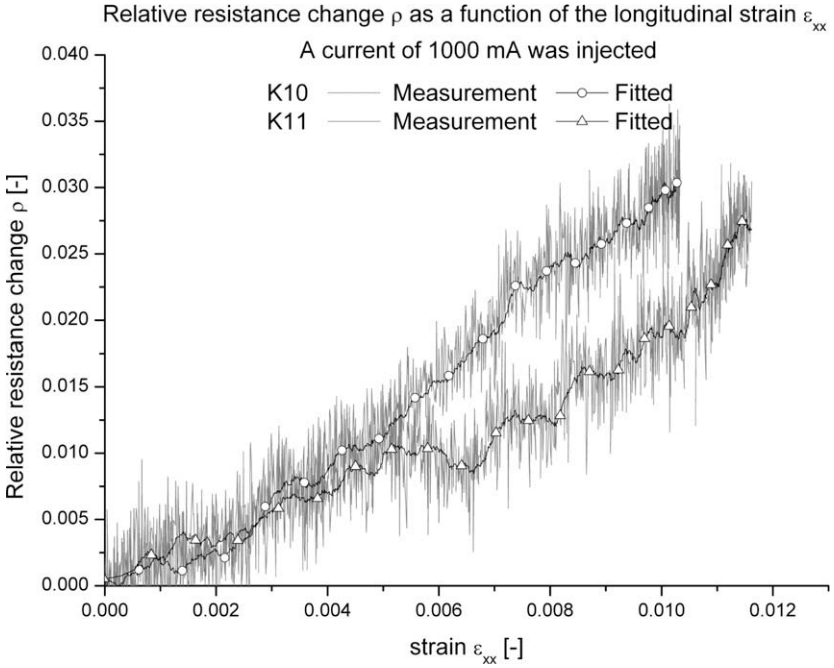

Fig. 11. Quasi-static tests of the four-probe method for resistance measurement.

son why the reproducibility is not as high as in the previous study. The increase of both signals is very similar, apart from the small dip in the curve of K11.

4.2. Hysteresis tests

Because of the promising results from the previous paragraph, the next step towards fatigue loading is now taken. A number of hysteresis tests are performed to assess whether the resistance has an irreversible growth. As was shown in [5,10] the resistance should increase if the specimen elongates, but as long as no damage occurs, the resistance should decrease to its original value if the load is removed. Therefore, a number of successive loading cycles were imposed on the specimen, starting from 100 MPa and then increasing with 50 MPa per cycle until fracture occurred. The tests were done in displacement controlled mode using a speed of 2 mm/min. The corresponding stress–strain curves are shown in Fig. 12. The different tests are given an offset of 0.0015 along the strain-axis for a clear picture. It must be noticed that no stiffness degradation occurs and that there is only very limited permanent deformation. Premature failure in the tabs occurred for specimens L1 at 600 MPa (=11 cycles) and for L5 and L6 at 500 MPa (=9 cycles). The latter is due to bad bonding quality on PPS and the occurring stress combinations underneath the tabs, as explained by the authors in [20]; H14 failed outside the tabs at 753 MPa (=14 cycles).

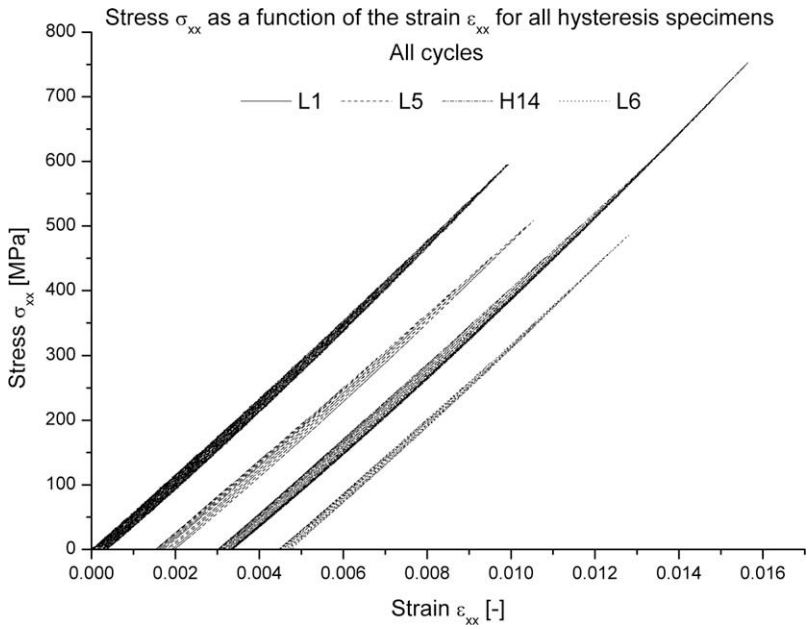

Fig. 12. Stress as function of the strain for the hysteresis tests.

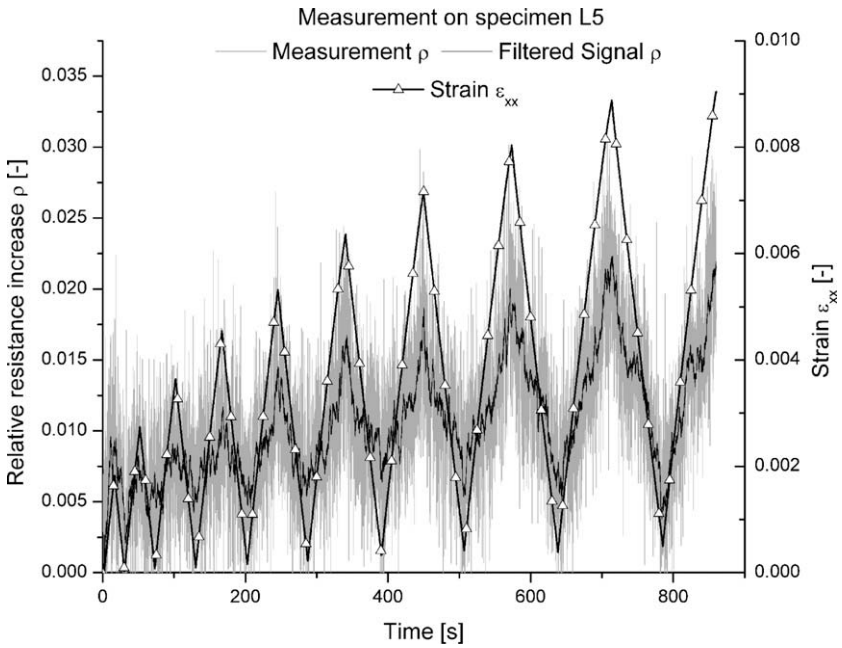

Fig. 13. Relative resistance and strain as a function of time for specimen L5.

The evolution of the relative resistance, as well as the corresponding strain is given in Figs. 13 and 14 for specimen L5 and H14, respectively. The tests on specimens L1 and L6 gave a similar image as L5.

It must be noted that there is a lot more (white) noise present on the signal L5 than on the static tests. Investigation yielded that a power converter, which generates large electromagnetic fields was working close by. This system was shut down before conducting the test on H14, resulting in a lot less noise.

It was noticed from all the tests that the relative resistance change follows the evolution of the strain as it is supposed to, meaning the rivets and copper conductive tape establish a good constant contact [5,10]. During the higher loading cycles, it can be seen that the relative resistance no longer returns to zero, which means that this method is sensitive to the occurring damage.

4.3. Fatigue tests

Because of the good results from the hysteresis tests, considering the fact that the material under study is a fabric-reinforced instead of a unidirectional reinforced, the method is now used for monitoring fatigue tests. Two types of tests were performed; the first has a loading frequency of 2 Hz and the second of 5 Hz. Two frequencies were chosen to assess whether the frequency has an influence on the evolution of elastic and fatigue parameters and to see whether the resistance measurement still follows the load-

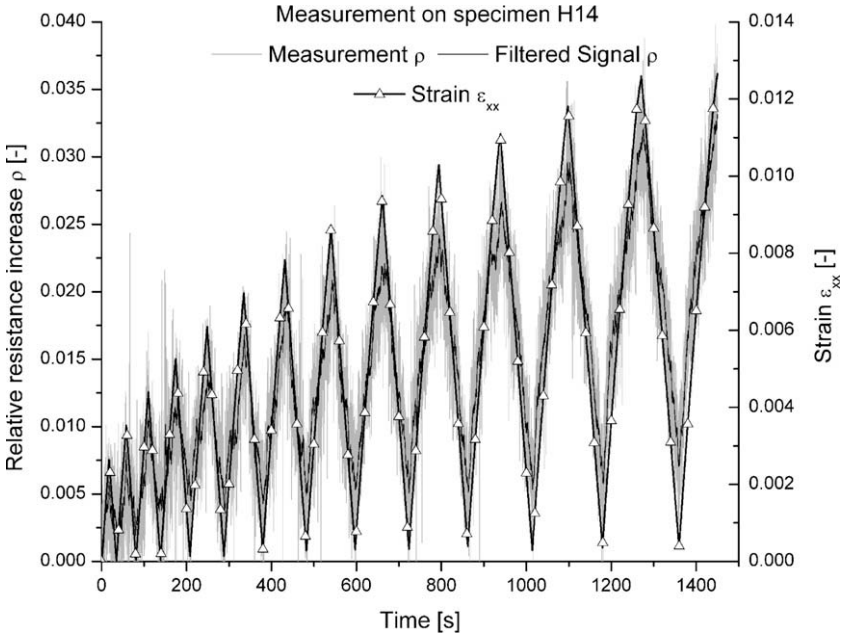

Fig. 14. Relative resistance and strain as a function of time for specimen H14.

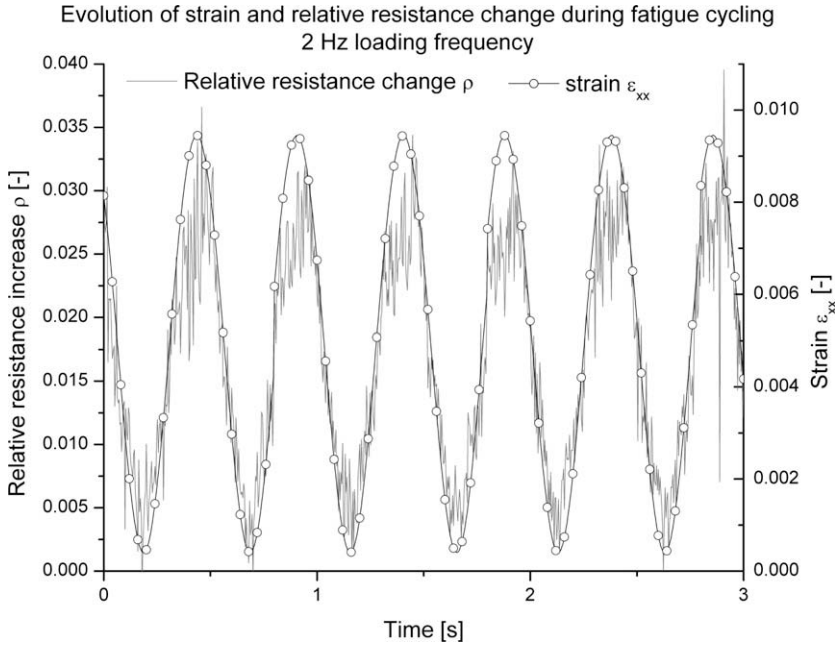

Fig. 15. Strain and resistance change during fatigue cycling at 2 Hz, specimen K4.

ing at higher frequencies. Both tests were done between $\sigma_{min} = 0$ and $\sigma_{max} = 550$ MPa ($R = 0$). The latter is about 75% of the ultimate stress (Table 2) which should be high enough for damage to occur. Preliminary tests yielded infinite lifetime at stresses below 450 MPa and for stresses higher than 600 MPa, failure occurred after no more than a few hundred cycles.

Figs. 15 and 16 show the evolution of the relative resistance change as a function of time for a few fatigue cycles, as well as the corresponding strain for the test at, respectively, 2 and 5 Hz. It can be noted that ρ clearly follows the loading and unloading of the specimen in both cases.

During the fatigue test, every 5 min five cycles are registered by the data-acquisition system and the maximum, minimum and mean value of these measurements (load, displacement, strain and resistance) are calculated. Fig. 17 shows the evolution of these values for the longitudinal strain for both a 2 Hz and a 5 Hz test until failure of the specimen. It can be seen that for the two tests, the strain behaviour is much alike. Furthermore, only a very limited increase is registered of about 1E−10 per cycle.

One can also notice that the amplitude of the strain (=difference between the maximum and minimum value) does not significantly increase. Since the tests were done in load-controlled manner, the stress amplitude is constant, meaning that no real stiffness degradation occurs. As a result, the damage growth cannot be monitored by stiffness degradation or by permanent elongation. The latter is typical for the material under study, there are no off-axis plies,

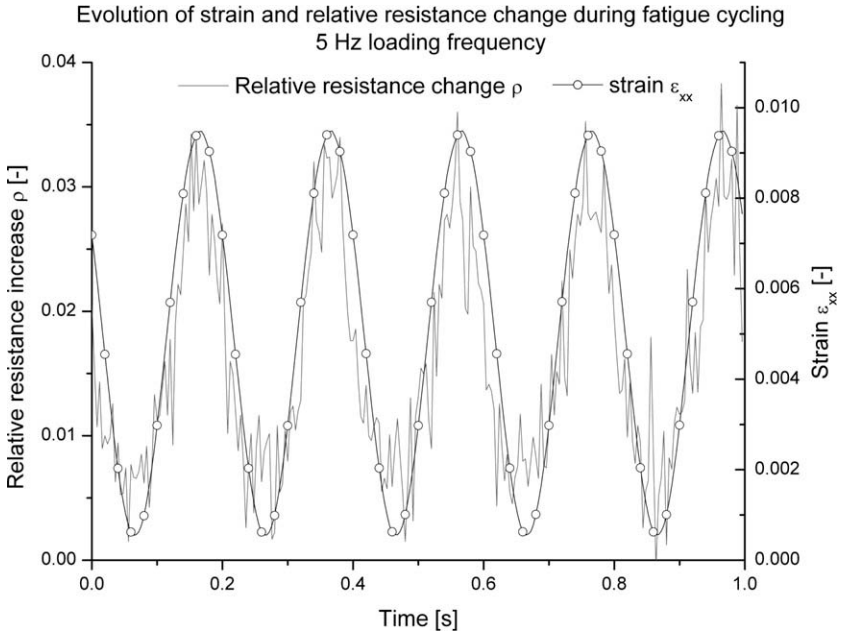

Fig. 16. Strain and resistance change during fatigue cycling at 5 Hz, specimen M1.

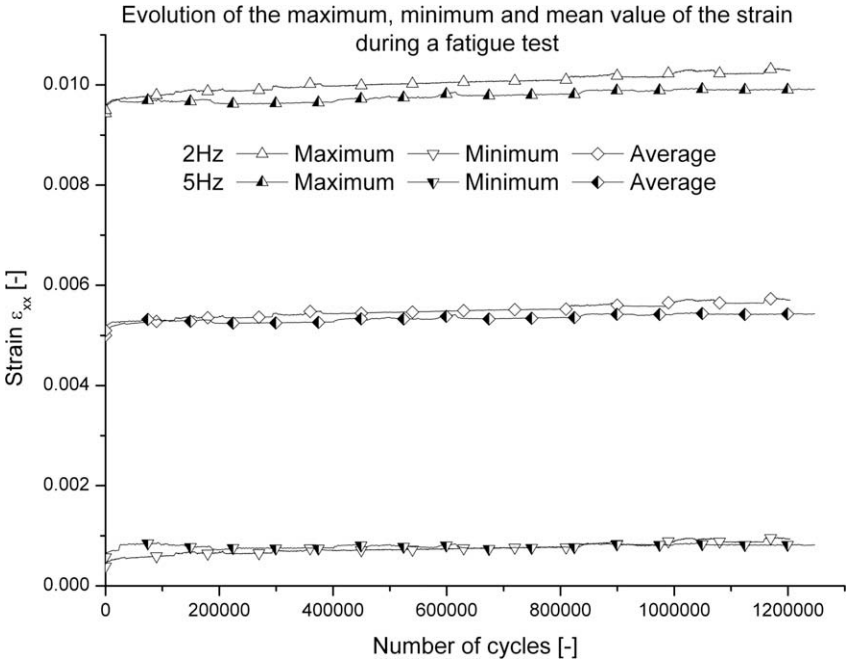

Fig. 17. Illustration of the evolution of the maximum, minimum and mean value of the strain as a function of the number of fatigue cycles for both a 2 Hz and a 5 Hz test.

only the warp and weft direction is used for the stacking sequence $[(0°,90°)]_{4s}$ Furthermore, this material exhibits very brittle fracture behaviour; failure occurs quite sudden, without any preliminary (visible or audible) cracks.

To assess whether damage can be visualised by the relative resistance change, the evolution of its average value during cycling is plotted in Fig. 18 for the 2 Hz test. The corresponding temperature is also added, to evaluate whether there is a temperature increase due to the used 1000 mA and whether the temperature increases near the end of life of the specimen. It should be noted that the temperature remains constant throughout the test.

One would expect that the resistance curves for both tests would be coincident, since the relative resistance is plotted instead of the absolute value, but this is not the case. The two specimens were sawn from different plates and maybe this causes the difference in measurements. However, it can be noted that both curves have a similar increase of 6.989E−09 per cycle for K4 and 5.185E−09 per cycle for I12 (the given values are the slopes of fitted linear trend lines). These values, however, are not much higher than the increase in strain, which is of the order 1E−10 per cycle. As such, the evolution of the resistance is no great improvement for monitoring damage. This could be explained by the fact that the

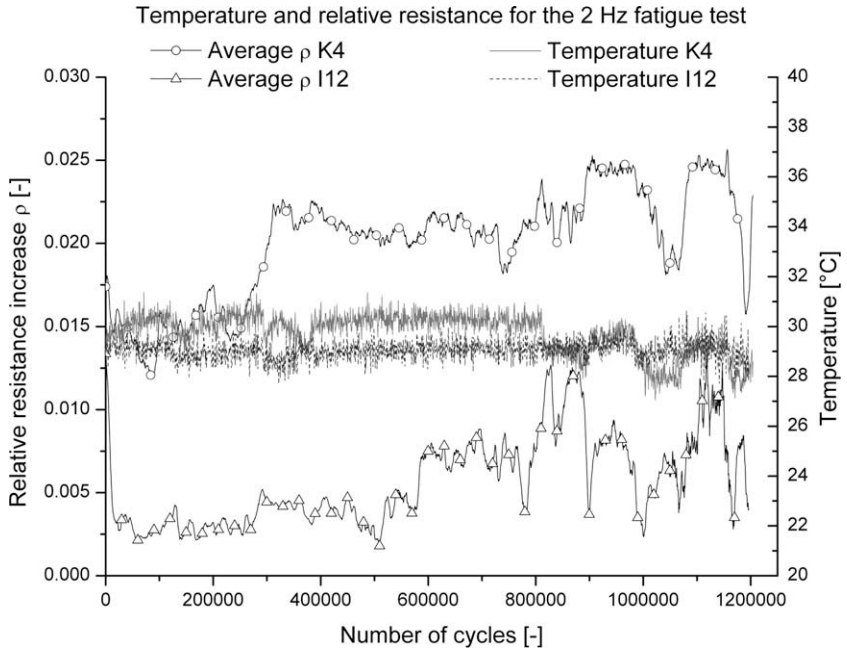

Fig. 18. Evolution of the relative resistance change and the temperature throughout the 2 Hz fatigue test.

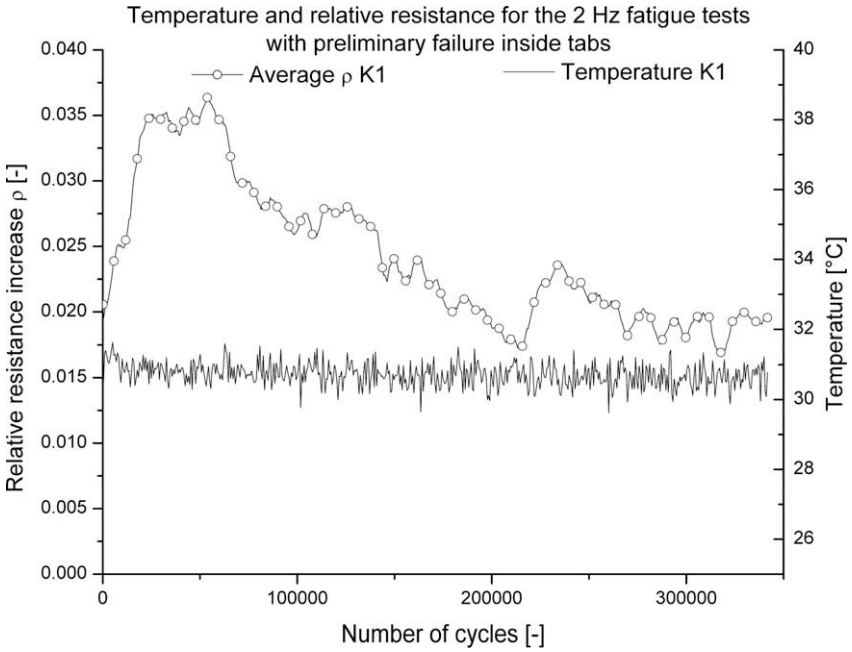

Fig. 19. Evolution of the relative resistance change and the temperature throughout a 2 Hz fatigue test with a decreasing resistance.

longitudinal resistance that is being measured is highly influenced by failure of the carbon fibres. Since there is neither real stiffness degradation nor permanent elongation that suggests fibre damage and a very sudden brittle failure, the expected increase of resistance of the specimen is limited. This could also be concluded from the damage model in [4] where a correlation was found between stiffness degradation and the reverse of the relative resistance increase. Since the material used in [4] exhibited a large decrease in stiffness, a large increase (up to 0.3) in relative resistance was measured.

In some cases however, a decrease in resistance is noticed instead of an increase. An example of such a test is shown in Fig. 19, where the average value of the relative resistance change is depicted. First, there is a significant increase in relative resistance, but than it gradually decreases. Failure occurred after 347,757 cycles. This phenomenon of a decreasing resistance has already been reported in literature [12,13] and is due to an increase in the degree of fibre alignment and due to a reduction of residual stress [13]. However, this usually only happens during the first few hundred cycles of the fatigue test. In this case, the decrease may be explained by an increasing number of adjacent fibres that make contact, due to matrix damage.

For the 5 Hz test, the problem of tab failure occurred more often. A lot of test samples failed during the first 50,000 cycles due

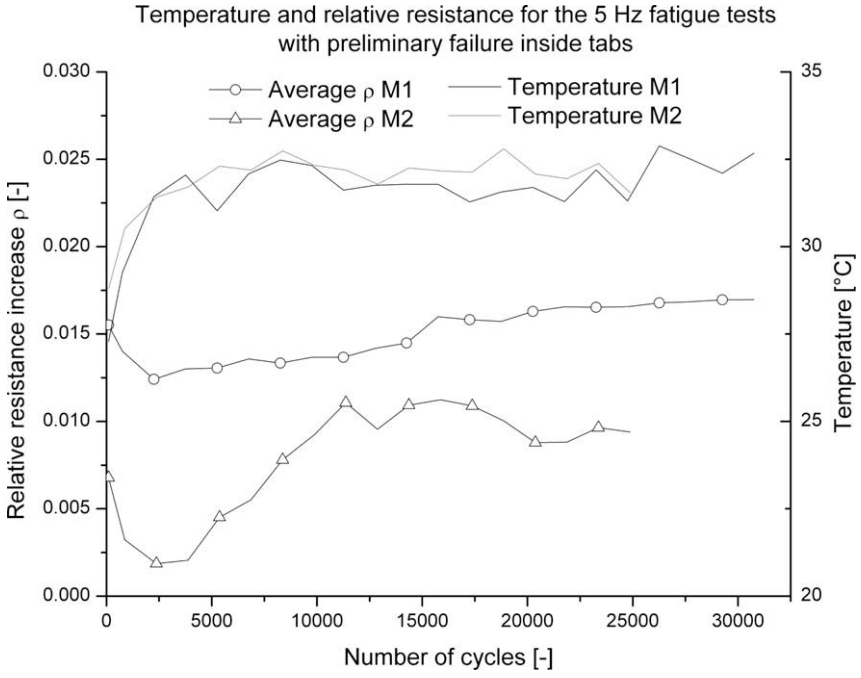

Fig. 20. Evolution of the relative resistance change and the temperature throughout the 5 Hz fatigue test for the specimens with preliminary failure.

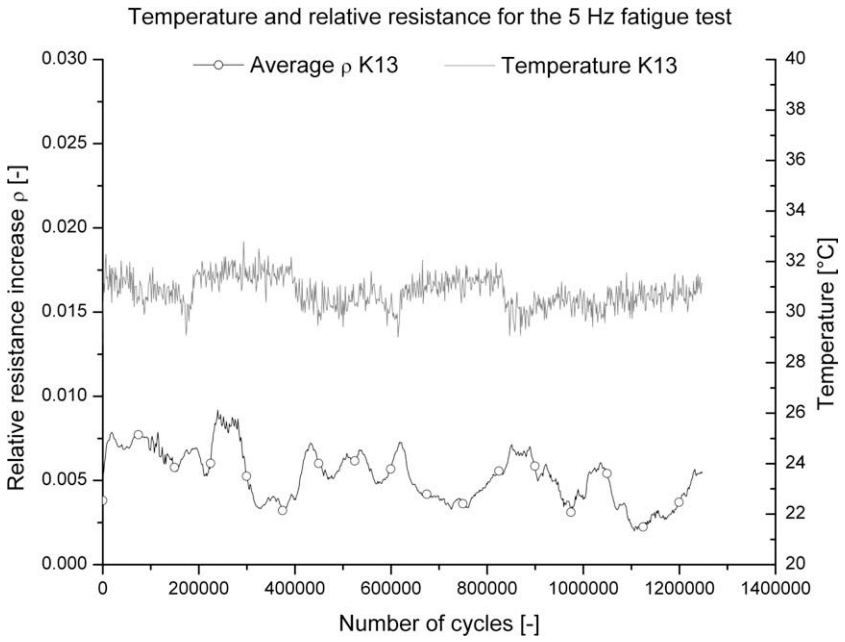

Fig. 21. Evolution of the relative resistance change and the temperature throughout the 5 Hz fatigue test.

to stress concentration in the tabs [20] or gradual decay of the adhesive resulting in heating due to friction between tabs and specimen with failure as result. Since the purpose of the resistance measurement is to predict damage and failure, two of these experiments are shown in Fig. 20. It can be noted that there is no significant increase in temperature. The relative resistance increases about 1.378E−07 per cycle, which still is not suited for damage monitoring, although it is almost 100 times higher than for the 2 Hz samples. Furthermore, there is no significant change in evolution right before failure, so failure predictability does not seem possible.

It should be noted that there is a small decrease for M1 and a large decrease for M2 in resistance for the first 2000 cycles, which may be due to the increase in the degree of fibre alignment and due to a reduction of residual stress [13], as previously mentioned.

An example of a successful test at 5 Hz is shown in Fig. 21. Again, the temperature remains constant until failure of the specimen at 1,296,769 cycles. It must be noted that in this case, again, the relative resistance tends to decrease, as was the case with the 2 Hz test in Fig. 19, so this phenomenon does not depend on the used frequency. Again, this evolution of the relative resistance cannot be used to monitor damage or predict failure.

5. Conclusions

This study investigates the use of electrical resistance measurement on carbon fabric-reinforced polyphenylene sulphide (PPS) for monitoring fatigue damage. Two rivets, placed in a strain free zone outside the tabbed section, were used to inject the current in the specimen, but a two-probe method was not stable for an extended period of time and therefore, a four-probe method was presented. The sensitivity of this four-probe method for the material under study is more than twice as high when compared to the two-probe method, as was proven by quasi-static tests. Then, several hysteresis tests were performed, which provided proof that the resistance follows the load and a small increase resulting from damage is present.

Finally, several fatigue tests were done to assess the performance of the resistance measurement in damage detection. Two frequencies, 2 and 5 Hz, were chosen to assess the influence of the frequency on the fatigue lifetime and damage growth. It could be concluded that the frequency does not have any demonstrable influence; in both cases, no stiffness degradation occurred and only a limited amount of permanent deformation was present. Furthermore, this material exhibits very brittle fracture behaviour; failure occurs quite sudden, without any preliminary (visible or audible) cracks.

As a result, the electrical resistance measurement could not monitor damage growth, since no measurable damage was present. The longitudinal resistance is very sensitive to fibre failure and since neither stiffness reduction nor permanent elongation occurred, the dominant damage mode is not a gradual increase in the number of fibres that break under fatigue loading conditions.

Acknowledgements

The authors are highly indebted to the university research fund BOF (Bijzonder Onderzoeksfonds UGent) for sponsoring this research and to Ten Cate Advanced Composites for supplying the material.

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