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Measurement of two-dimensional electrical potential fields in CFRP using four-probe resistance scans

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Abstract

The carbon fibers in fiber reinforced plastics could be used sensorially to observe the present stress state of the structural component by measuring its electrical resistance. However, the use of resistivity requires a detailed understanding of the electrical potential distribution in a given specimen. Current experimental techniques measure the electrical potential on a limited amount of relatively large electrodes mounted onto the parts surface. This approach suffers from the limited spacial resolution as well as the retroactivity between attached electrodes and observed specimen. This article discusses an experimental method to scan the electrical potential distribution on the surface of a conductor using a typical 4-probe setup and a gantry style robot to move one of the probes. The method is applied to electrical conduction processes in carbon fiber reinforced plastics (CFRPs) in an effort to visualize the electrical potential distribution near current contacts. This approach allows us to have a much more detailed understanding of electrical conduction processes in CFRP, which can help to better interpret experimental data in the future. A two-dimensional mathematical model based on Laplace equation is derived with appropriate boundary conditions and compared to the measured results. Experimental and numerical results agree well and show the existence of strong current inhomogeneities within the CFRP part. The developed setup is simple to implement, but nevertheless proved to be effective in measuring the explicit electrical conduction paths in both isotropic and anisotropic conductors.

1. Introduction

Carbon fiber reinforced plastics (CFRPs) have been gaining more and more attention from both research and industry in these past years. Due to their high stiffness and strength as well as their low density, CFRPs can be an excellent choice of material in highly demanding applications with harsh restrictions in weight. Over the years, many structural health monitoring techniques have been developed in order to monitor carbon fiber structures. Many of these techniques rely on the application of external sensors such as piezoelectric or fiber optic sensors [1]. Other approaches take advantage of the electrical conductivity of carbon fibers and their polymer composites to build a Self-Sensing material. Using Self-Sensing approaches, researchers developed methods to measure various properties such as fiber damage [2, 3], delamination [4], fatigue damage [5], strain [6] and others [7].

The electrical conduction in unidirectional carbon fiber reinforced plastics is a complex phenomenon due to its inherent structure. The material is build up from highly conductive fibers embedded in an insulating matrix. The electrical conduction process in any direction other than the fiber orientation is therefore created solely by individual fibers touching one another in random locations. This makes CFRP a highly anisotropic electrical conductor with a complex internal current flow. Self-Sensing approaches measure changes to this internal current flow. For example, fiber damage causes a strong irreversible increase of longitudinal resistivity while delamination causes an irreversible increase in through-thickness resistivity. Strain causes a reversible change to the resistivity. Measuring these influences requires precise knowledge of the electrical properties of the structural part.
When the electrical properties of a CFRP specimen are to be analyzed, electrical contacts have to be made to the material. This is generally done by applying highly conductive coatings such as silver paint or silver epoxy at specific positions in the material and attaching a wire to it. This necessary application of a conductive coupling agent limits the achievable spatial resolution because of the size of an electrode and because the attachment of wires is labor-intensive. Furthermore, as will be demonstrated in section 3, the highly conductive coating can significantly influence the voltage distribution in the part under observation because of a retroactivity that in some cases can be too large to be neglected. Thus, typically only few potential differences are measured, and the results are then interpreted based on different simplifications and assumptions.

In some cases, finite element studies or analytical equations are used to interpolate the few measured datapoints and get the full internal voltage distribution [8–12]. In these finite element studies, the model is generally simplified by using smeared parameters that are constant in a given specimen. The model validation process for many of these applications can be improved by significantly increasing the number of measurement points obtained on a given surface. For example, Hart et al [9] measure the electrical potential on two sets of electrodes, one on the top side and one on the bottom side of the specimen. While this allows to get a good estimate of the mean resistivities of the sample, it does not allow to discuss about any localized phenomena. Park et al [10] use a similar setup but attach many more electrodes to the surface. In both cases, the authors implicitly assume that the potential distribution is constant over the width direction of the surface. Deviations from this assumption cannot be observed with current techniques, but would have important consequences for detailed studies of conduction processes. This article therefore explores a simple way to experimentally acquire the electrical potential field on a surface with very fine spatial resolution. We propose to use a spring loaded electrical probe in a typical four-probe resistance measurement and mount it onto a gantry style robot to automatically scan entire surfaces of parts. To our knowledge, this method has not been reported before, even though it can be nowadays easily realized using readily available gantry style robots in the form of 3D printers.

We apply this method using different boundary conditions relevant for the field of Self-Strain-Sensing. In Self-Strain-Sensing applications, a resistance change that occurs due to dimensional change and piezoresistivity is measured and correlated with the strain. Due to the anisotropic nature of CFRP, inhomogeneous current flow has to be taken into consideration in many practical applications [13]. Especially due to the very small resistance changes occurring in this application, a detailed understanding of the current flow has to be generated to be able to interpret measurement results. The experimental setup proposed in this article is therefore applied to make the current inhomogeneity in a CFRP part experimentally accessible. In the past, articles working on Self-Strain-Sensing applications of large CFRP parts found some diverging results for the gauge factor of unidirectional laminates [14]. A more detailed understanding of the conduction processes could help to find explanations for these results and thereby aid in the future development of this technology.

2. Mathematical model for anisotropic conductors based on laplace equation

Before showing the results obtained in the experiments, we would like to present a numerical study that allows to calculate the expected voltage distribution in a conductor. This allows us to assess the plausibility of the results obtained with this newly proposed scanning technique.

We calculate the distribution of electrical potential within the Ohmic region of a specimen by solving the Laplace equation with appropriate boundary conditions [15]. Consider a rectangular block as displayed in figure 1. The two-dimensional voltage distribution in the xz-plane can be determined by the continuity equation \( \text{div}(\mathbf{J}) = 0 \), where \( \mathbf{J} \) is the current density. In this analysis, we assume a homogeneous current introduction throughout the specimen width. We further assume that it is possible to use smeared parameters for the calculation of the potential distribution. We solve the continuity equation with appropriate boundary conditions where current is introduced homogeneously through a set of electrodes with the width \( w_t \) on the top surface. The Laplace equation for the potential in an electrically anisotropic medium can then be given as [16]

\[
\frac{1}{\rho_L} \frac{\partial^2 V}{\partial x^2} + \frac{1}{\rho_T} \frac{\partial^2 V}{\partial z^2} = 0
\]

(1)

In this equation, \( \rho_L \) and \( \rho_T \) are the longitudinal and transverse resistivity of the material. Zimney et al [12] show an interesting way to have a more intuitive way to look at this equation and anisotropic conduction in general. If we perform a variable substitution \( z_{eff} = z \sqrt{\frac{\rho_L}{\rho_T}} = z \sqrt{\xi} \) the equation now describes an isotropic conductor with a thickness of \( t_{eff} = t \sqrt{\xi} \). An anisotropic conductor can therefor be regarded as a much thicker isotropic conductor. A solution of the Laplace equation that satisfies the boundary conditions
can be written as: \[ V(z, x) = \sum_{m=1,3,5,...} V_m \sin \left( \frac{\pi mx}{L} \right) \cosh \left( \frac{\xi \pi mh}{L} \right) \] where \( \xi = \sqrt{\rho_T/\rho_L} \) is a fraction that describes the electrical anisotropy of the material. The coefficients \( V_m \) of this equation are determined by the boundary condition on the upper surface \( z = h \):

\[ \rho_T \frac{\partial V}{\partial z} \bigg|_{z=h} = J_L(x, z = h) \]

Levin [16] derives these coefficients as:

\[ V_m = \frac{-2 \sqrt{\rho_T \rho_L}}{\pi m \sinh (\xi \pi mh/L)} \int_{-L/2}^{L/2} J_L(x, h) \cdot \sin \left( \frac{\pi mx}{L} \right) dx \]

These coefficients are now further developed for finite size contacts. The current injected normally to the top surface can be described using the Heaviside function \( \Theta(x) \).

\[ J_L(x, h) = \frac{J}{w} \left( \Theta \left( x + \frac{L}{2} - c + \frac{w}{2} \right) - \Theta \left( x + \frac{L}{2} - c - \frac{w}{2} \right) - \Theta \left( x - \frac{L}{2} + c + \frac{w}{2} \right) + \Theta \left( x - \frac{L}{2} + c - \frac{w}{2} \right) \right) \]

where \( J = I/b \) is the current density per unit length of the contact. With this current entry condition we can write:

\[ V_m = \frac{-4J \sqrt{\rho_T \rho_L} L}{\pi^2 m^2 \sinh (\xi \pi mh/L) w} \left( \cos \left( \pi m \left( \frac{1}{2} + \frac{c}{L} + \frac{w}{2L} \right) \right) - \cos \left( \pi m \left( -\frac{1}{2} + \frac{c}{L} + \frac{w}{2L} \right) \right) \right) \]

Using these coefficients, we can write an equation for the potential distribution:

\[ V(x, z) = \sum_{k=0}^{\infty} \frac{1}{(2k+1)^2 \sinh (\xi/h(2k+1))} \left( \cos (\pi(2k+1) \left( \frac{1}{2} + \frac{c}{L} + \frac{w}{2L} \right)) - \cos (\pi(2k+1) \left( -\frac{1}{2} + \frac{c}{L} + \frac{w}{2L} \right)) \right) \cdot \sin (\pi(2k+1)x/L) \cosh (\xi \pi(2k+1)z/L) \]

Two solutions to this equations using different parameters are displayed in figures 2 and 3. In figure 2, the transverse resistivity is chosen to be 1000 times larger than in figure 3. The amplitude and direction of the current density in the part is displayed in the form of lines with varying thicknesses. It is calculated using the local gradient of the potential distribution multiplied with the conductivities in each direction. The figures clearly show the strong influence of a change of transverse resistivity. Consider the distribution of current in the cross section at \( x = 0 \). In the figure 3, the current is homogeneously distributed in the whole cross section. In contrast,
the current is concentrated on the top surface in figure 2. This is due to the combined effect of the electrical anisotropy and the physical dimensions of the part. Another noteworthy observation for figure 2 is the fact that a large amount of current does not flow directly from current entry to current exit. Consider the situation at the current entry on the top left corner. A large part of the total current flows towards the left instead of directly flowing towards the current exit on the right. This is because the resistivity in z-direction is very large and the current cannot easily spread into deeper layers of the material.

3. On the retroactivity of electrical contacts on carbon fiber reinforced plastics

One of the potential problems of applying multiple highly conductive electrodes onto a carbon fiber reinforced plastic is their retroactivity to the current flow in the part itself. Due to their high conductivity, electrodes can significantly change the overall current transport in the part that is to be observed. If we want to precisely analyze the conduction process in the CFRP part, this influence is undesired, firstly because it perturbs the potential distribution, and secondly because the extent of this perturbation is dependent on the manual electrode installation process which will differ from one specimen to another. The model developed in section 2 does not account for this influence. To underline this point, we would like to present a simple experiment that shows the extent to which retroactivity can influence a measurement result.

For this experiment, four copper wires are attached to a pultruded CFRP rod (8 × 0.8 × 200) mm³ with a conductive silver paint (RS Pro silver paint). Before electrode application, the surface is thoroughly sanded with a #600 sandpaper. The four electrodes are used for the four wire DC resistance measurement on the Keithley DMM6500. The experimental setup and dimensions are displayed in figure 4 (bottom). The resistance obtained
through 4-wire measurements is continuously monitored during the experiment. Additional electrodes are painted onto the rod in a symmetrical manner at different times throughout the experiment. All silver paint electrodes are placed 5 mm apart and have a length of 2 mm.

The results displayed in figure 4 exemplify how much the application of additional, highly conductive, electrodes can influence the potential distribution within a CFRP. When a new electrode is painted onto the surface, the resistance slowly changes for approximately 10 min. This is due to the evaporation of solvent in the silver paint, which increases the conductivity over time. A maximum potential change of 2.5 % is observed. Depending on the exact location of the added electrode, the observed resistance between the original measurement electrodes can either increase or decrease. This is due to a redistribution of the electrical potential field within the CFRP specimen. For some applications such as damage sensing, this retroactivity could be ignored because resistance changes due to damage are significantly larger than the observed retroactivity. For applications that require a high-precision potential measurement such as strain sensing, this difference can however be quite significant. This is especially true because the amount of retroactivity is likely to change when the contacts are strained, because the contact resistance is sensitive to strain. This means that part of an observed resistance change is influenced by a changing contact resistance of every electrode attached to the specimen. The extend to which this retroactivity is of importance cannot quantitavely be evaluated with the simple experiment presented here. However, the general necessity to discuss the retroactivity of electrodes can be observed.

4. Methods and material

A general purpose 3D printer (Anycubic i3 Mega S) is used as a gantry robot to move the scanning probe. A spring loaded, gold covered, electrical probe (PTR 1015-B-0.7N-AU-0.75) is mounted to the printer instead of the hot-end and extrusion system. According to its data sheet, the probe is pressed onto the surface of the part with approximately 0.7 N when fully engaged. Figure 5 shows a picture of the experimental setup. The printer is controlled by G-Code to move to different positions on the xy plane, engage the spring loaded contact by moving down at this point and move on to the next position. This process is repeated multiple times until a larger area on the specimen is fully scanned.

The potential distribution is measured using a digital multimeter (Keithley DMM6500) in four-probe DC resistance configuration. The digital multimeter combines both a current source and a voltmeter and returns a value with the unit Ohm by internally using Ohms law. Using Ohms law implies a constant current density in the conductor, which is often not the case for anisotropic conductors such as CFRP. We nevertheless decided to report the voltage distribution in terms of measured resistances to be able to use the raw data obtained from the DMM, since the potential distribution is directly proportional to resistance distribution.

Different CFRP material is used in this study. For experiments on pultruded carbon fiber rods, the specimen are made from a T700 fiber and an epoxy based matrix with a fiber volume fraction of approximately 60%. Based on a rule-of-mixture model the longitudinal resistivity of this material can be estimated to be 2.7e-5 Ωm. Based on our experimental research that is currently under review elsewhere the transverse resistivity of this material
varies between 0.6 Ωm and 2.2 Ωm. These values exemplify the large anisotropy of unidirectional CFRP. For experiments on prepreg materials, an 8552/AS4 prepreg is cured in an autoclave with a unidirectional stacking in accordance with the manufacturing conditions found in the materials data sheet (180 °C, 7 bar). In comparison, the parts manufactured from prepreg material have a distinct resin rich surface zone, while the pultruded rods do not have this. In order to measure the surface potential with an electrical probe, carbon fibers have to be sufficiently exposed at the parts surface. For the pultruded rods used in this study, it is found that the fibers are already sufficiently exposed and a very light sanding with a #600 grit sandpaper is sufficient to fully expose the fibers everywhere. For the prepreg material, the surface is wet-grinded more thoroughly with a #600 grit sandpaper. The necessary duration for this grinding process is dependent on the thickness of surface rich resin zone. For this study, we sand the surface for approximately 2 min until the surface looks dull and no more glossy parts are visible. Figure 6(a) shows a typical microscopic image of a sanded CFRP surface.

In most examples, electrical contacts are manufactured using a silver paint (RS Pro Conductive Paint). One of the goals of this article is to determine the influence of surface preparation to the homogeneity of the current introduction in a CFRP part. We hypothesize, that a thorough surface preparation is necessary that uniformly exposes the carbon fibers on the top surface of a part to homogeneously introduce current. This hypothesis is analyzed by wet-grinding the surface with #600 sandpaper with varying intensities.

In one example, electrical contact is generated using the electrodeposition process with nickel (Tifoo Nickel Electrolyte) at a current density of approximately 0.2 A dm⁻². The deposited metal layer itself is then connected to a measurement wire using silver epoxy. In this example, the surface of the pultruded rod is cleaned by putting a drop of concentrated sulfuric acid on the surface for 30 sec.

Figure 5. Experimental setup consisting of a Keithley DMM6500 and an altered 3D printer.

Figure 6. Microscopic images of the experimental setup showing (a) The size of the measurement tip in comparison to the sanded CFRP surface (b) Markings formed on a silver paint surface after the scan showing the accuracy of the setup.
5. Initial experimental investigation of machine parameters

5.1. Stability of potential measurements over time
When the scanning voltage probe is lowered onto the surface of the CFRP part, the acquired voltage signal sometimes is non stationary at the beginning of the measurement. The acquired signal however generally stabilizes much quicker than within 1 sec. In some cases, especially in areas of high potential gradient, it takes up to 3 sec to reach a stable value. One plausible explanation for this phenomenon is a viscoelastic material behavior under the tip of the measurement probe that results in a changing contact to individual fibers and thus slowly alters the measurement. As displayed in figure (6a), the measurement tip is relatively sharp in order to gain a detailed scan. This however inevitably results in a high hertzian stress concentration in the material. The extend to which this non stationary behavior is relevant can be assessed by calculating the span of all measured points in an intervals and normalizing it by its the mean value of each interval:

\[
\text{span}(R) = \frac{\max(R(t)) - \min(R(t))}{\text{mean}(R(t))}
\]

(9)

Thus, a large value means that the measured signal drifts a lot in the measurement window, while a small value means that the value is very stable. To quantify this behaviour, we take the results of a typical measurement where the voltage is measured continuously for 5 sec at each position. Figure 7 shows a histogram of all normalized spans observed in the measurement. The vast majority of measurements observed in this study are stable with a normalized span of less than 0.5 %. We assess this stability to be sufficient for the analysis of surface potentials in many applications and therefore use the mean value obtained in a 5 sec interval for all measurements.

5.2. Overall repeatability of measurements
The repeatability of the positioning can be assessed by repeating a measurement multiple times. As an initial study, a specimen made from prepreg material is mounted into the machine and scanned 15 times at 30 measurement positions. After each scan, the machine is turned off and a new homing step is performed. The experimental setup and results are presented in figure 8. The results show a repeatability of measurements of approximately 0.5 %. This is within the same order of magnitude as the stability of single measurements shown in figure 8. We therefore assess the repeatability of the experimental setup used for moving the probe to be sufficiently accurate. This is also supported by the microscopic picture displayed in figure (6 b) that shows very evenly spaced markings left by the probe on a silver painted surface. Even a small distance between points of 50 µm can be realized with the experimental setup used in this section, even though some µm deviation from a perfect line can be observed. These inaccuracies could lead to erroneous measurements, especially at positions of high potential gradients. For typical CFRP specimen such as the one used here, the differences can be assessed to be very small, especially when compared to the alternative solution of highly conductive electrodes with high retroactivity to the specimen. This demonstrates the potential of this experimental approach to measure the potential distribution with a minimal perturbation.
6. In-plane current homogeneity near electrical contacts

The mathematical model developed in section 2 assumes a 2-dimensional current flow by assuming a constant current density in the width of the specimen. In this section we show, if and when this is a valid assumption.

The repeatability and accuracy of Self Strain Sensing CFRPs are dependent on a reliable electrical connection between measurement equipment and specimen. It has been correctly pointed out in the past that surface polishing damages the fibers \([10, 17]\), which is detrimental to the mechanical properties of the part. On the other hand, we could hypothesize that this step is important for a uniform current introduction. If the contact resistance is distributed nonuniformly over the electrode surface, the current introduction should be equally nonuniform. The extent of this nonuniformity can be expected to have an influence on the Self Strain Sensing properties of the part. In fact, it has been previously reported that insufficient surface preparation has a large influence on the Self-Strain-Sensing properties, not only because of current inhomogeneity, but also because the electrical contact can change under the influence of mechanical strain \([18]\). Therefore, we would like to show experimental results for parts manufactured with different surface preparations in this section and discuss the uniformity of current introduction using the experimental setup proposed in figure 9. In all cases, two electrodes are painted onto a CFRP using silver paint. These electrodes are used as current introduction. One of the voltage contacts of the 4-wire setup is also attached to one of the electrodes, while the other voltage terminal is connected to the scanning probe. The voltage distribution is then measured using a measurement grid that spans a large section of the parts surface.

6.1. Current flow in isotropic conductors

The experimental setup itself can be analyzed by measuring an isotropic material. In this case, a metallic resistance wire with a rectangular cross section of \((4 \times 0.2) \text{ mm}^2\) is used. Two cables are symmetrically soldered onto the wire 100 mm apart. The result of this scan is displayed in figure 10. The obtained resistance is very constant along the \(y\)-direction of the conductor. In \(x\)-direction, the resistance is constant both before and after the current introduction. In between the current wires, the obtained resistance changes linearly with distance from the electrodes. This is a plausible result as the resistance wire is an isotropic conductor, which means that the current flow can be regarded to be 1-dimensional. The result is also consistent with equation (8) analyzed for an isotropic material at \(V(x, z = h)\) and is qualitatively similar to the distribution depicted in figure 3.

This plausible result gives us further confidence for the applicability of the experimental setup proposed in this article. In a next step, we quantify the current homogeneity in anisotropic conductors by repeating the experiment with CFRP.
6.2. Current flow in a pultruded specimen

To begin our experimental analysis on CFRP material we use a unidirectional pultruded rod with the dimensions \((8 \times 0.8 \times 250)\text{mm}^3\) with current electrodes painted symmetrically and 100 mm apart. The potential distribution of a typical example is depicted in figure 11. Some significant differences can be observed when the distribution is compared to isotropic material depicted in figure 10.

Firstly, the gradient in x-direction rapidly rises in the vicinity of both current contacts. This is because the current density near current introduction is very large and only gradually decreases by current spreading into deeper material layers. This observation is consistent with the mathematical model described by equation (8) and is also depicted in figure 2.

Secondly, the potential distribution is less homogeneous in y-direction. The assumption of 2-dimensional current flow used in section 2 is thus violated to a certain extent. One reason for this behavior could be an inhomogeneous introduction throughout the width of the specimen that could be caused by differences in contact resistance in y-direction. Due to the anisotropic nature of CFRP, this inhomogeneity does not even out easily and would require a very large distance from the current introduction to homogenize. Differences in contact resistance could either be caused by an inherent variability of the silver paint used in this study or by different surface conditions on the CFRP material. Another possible explanation for this could be an inhomogeneously distributed through-thickness resistivity, which could also result in regions of larger and smaller current density.

We would like to point out that this happened even though we tried to create a homogeneous current introduction with the silver paint. Other experimental setups using large surface electrodes are not capable of measuring this inhomogeneity. It is therefore very likely that this is a typical example of the true current flow in unidirectional CFRP which has not been observed previously and can only be observed with an experimental setup as proposed in this article.
6.3. Current flow in prepreg material with different surface preparations
The influence of surface condition at the current electrode position can be studied with three prepreg sheets. One of the sheets is thoroughly sanded before electrode application. The second specimen is sparsely sanded for a much shorter duration before electrode application. The third sheet is only cleaned with acetone and is not sanded before electrode application. After electrode application, all remaining surfaces are sanded to allow the specimen to be scanned.

The resulting resistance distribution of the fully sanded specimen is depicted in figure 12. Due to the symmetry of the distribution, only one half of the specimen is scanned. The results look very similar to those obtained for the pultruded rod, with a relatively constant potential distribution in y direction and a monotonously decreasing potential in x direction. In comparison, the resistance distribution appears to homogenize more effectively when compared to the pultruded specimen. A possible explanation for this could be the fact that prepreg materials generally have a higher fiber waviness than pultruded specimen [19]. This larger fiber waviness could be beneficial in the homogenization of current by producing multiple contact points between many different fibers.

The resulting distribution of a sparsely sanded specimen is depicted in figure 13. The results look relatively similar to the scan of a thoroughly sanded specimen. Unlike the thoroughly sanded specimen however, the...
resistance distribution shows a constant gradient along the y-direction of the specimen. This gradient is an indication for current inhomogeneity in the width of the specimen. A plausible explanation for this phenomenon could be nonuniform surface conditions along the width of the specimen.

Figure 14 shows the potential distribution of a prereg sheet without surface sanding before application of the electrodes. The result looks vastly different when compared to the previous sanded specimen. Firstly, the resistance measured on top of the electrode is approximately 9 Ω and thus significantly higher than on the sanded specimen where it is only 1 Ω. This is because the contact resistance is much higher due to the partially insulating resin rich surface zone. The 3D surface plot of figure 14 shows the scanned surface without the electrode area. There is still an expected gradient of potential along the x-direction. However, a large gradient in y-direction is also visible. This gradient in y-direction is much larger than observed for the sparsely sanded specimen. One plausible explanation for this again could be an inhomogenous electrical contact on the electrode, with lower resistance paths available at positions of larger y-values. Another plausible explanation could be an inhomogeneous removal of material with the manual sanding process. We attempted to uniformly sand the surface, but it is still possible that we introduced some nonuniformity to the system that results in this measurement. It is however important to note that this same problem could equally occur in experimental
setups that use highly conductive surface electrodes with sanded surfaces. These experimental setups however do not allow to observe the resulting voltage inhomogeneity. Instead, the influence of this surface preparation step would only be observed through a larger scattering of the measurement.

Independent from the reason of this gradient in y-direction, it is an undesired phenomenon for Self-Strain-Sensing composites. This is because it complicates the electrical conduction process in the CFRP and thereby also complies the measurement of electrical potential change. Furthermore, it is likely that the exact extend of current inhomogeneity in y-direction strongly depends on the surface condition after manufacturing, which is difficult to control reliably. This limits the reproducibility of strain sensors manufactured from CFRP material. Even a sparse surface sanding appears to be effective in minimizing this type of current inhomogeneity. However, more experimental research is necessary to evaluate the statistical reproducibility of the influence of surface preparation. It would also be very interesting to more thoroughly analyze differences between specimen manufactured by different means such as pultrusion, infusion or prepreg. The experimental setup proposed in this article however proved to be effective in providing a quantifiable measurement for the current homogeneity in electrical conductors.

To further develop the proposed method, it would be very beneficial to increase the scanning speed, because a full surface scan with high resolution at the moment takes more than 20 h in some cases. In order to measure large surfaces of many different specimen, it would be very beneficial to significantly reduce this time. There are however several possibilities to significantly increase the speed of measurement. For example, instead of waiting a fixed amount of time at each scanning position, it would be beneficial to only engage the probe until a stable value is measured. Another way to increase the measurement speed is to use a larger array of spring loaded electrodes, that could be attached to a multiplexer circuit in order to more quickly scan a larger part of the surface.

6.4. Current flow in a pultruded specimen with cut-edge electrodes

The final example of current homogeneity is that of a pultruded rod \((7 \times 0.3 \times 250) \text{ mm}^3\) with galvanized electrodes at the cut end of the specimen. The experimental setup is almost identical to figure 9, but the current contacts are located at the cut ends of the specimen. This way, all fibers can be connected with a low resistance path to the current source simultaneously. Figure 15 shows the resulting surface potential distribution of the specimen. In comparison with other carbon fiber specimen, the current is significantly more homogeneous in the y-direction. We would argue, that—from a purely electrical point of view—this experimental setup is therefore more suitable for high precision applications such as Self-Strain-Sensing. Our results obtained in this article demonstrate, that the proposed experimental setup allows novelly to obtain the necessary quantifiable data to discuss the topic. However, more research needs to be carried out that directly compares the different contacting methods and surface preparations to clearly evaluate this point.

7. Out-of-plane current homogeneity in CFRP

The previous section visualized current inhomogeneities in y-direction that occur in anisotropic conductors when using surface electrodes. It is shown that this inhomogeneity can be minimized by sufficiently preparing the surface, for example by mechanical sanding. Using surface electrodes however inherently leads to another type of current inhomogeneity which is in the z-direction of the part. Since current is introduced only through
the parts surface, the current has to spread into deeper material layers through the percolative conduction network of the fibers, which only happens very gradually due to the anisotropy of the material. Hart et al.\cite{Hart2019} recently described this using the term effective conducting thickness, which can be much smaller than the true thickness of the part. This is also the reason for the large potential gradients observed in the last section in the $x$-direction in anisotropic conductors. This through-thickness current spread can readily be calculated using equation (8) and is targeted to be visualized in this section by using the experimental setup shown in figure 16.

The current is introduced into the material using two electrodes located on the edge instead of the surface of the part. We use the edge for this experiment, because it would be much more difficult to reliably scan the small thickness of a part. Since the transverse anisotropy should be very similar to the through thickness anisotropy the results obtained in this case should be very comparable. Figure 17 shows a numerical solution calculated using equation (8). As expected based on the previous measurements on CFRP material, two large peaks can be seen near the points of current introduction. In $x$-direction a distribution similar to that observed in the previous section is observed. In $y$-direction, the electrical potential asymptotically approaches 0, which agrees well with the notion of effective conductive thickness mentioned previously by Hart et al.\cite{Hart2019}. Due to the symmetry of the distribution, the following experimental evaluation only scans one half of the specimen.

Figure 18 shows an experimental result of the potential distribution for a pultruded specimen. The overall qualitative shape of the distribution is similar to the theoretical distribution depicted in figure 17, showing a strong peak at the point of current entry and a decrease in both $x$- and $y$-direction. Overall however, it also is clearly visible, that the measured distribution is much less smooth than the theoretical distribution. This could be due to inaccuracies in the experimental setup. Another plausible explanation however would be inhomogeneities in the material itself. Since the
transverse electrical conduction in CFRP is an inherently random process caused by contact points between fibers, it seems plausible that the voltage distribution equally shows randomness when the surface is scanned with a fine resolution. In this case, the resolution is set to 0.05 mm in y-direction and 0.5 mm in x-direction. The experimental procedure proposed in this article therefore might prove to be helpful in the analysis of the randomness of the electrical conductor network in CFRP.

8. Summary and outlook

The article proposes and discusses a novel experimental setup that allows to quantify the electrical potential distribution on the surface of a conductor. The setup is applied to carbon fiber reinforced plastics and is used to experimentally assess the homogeneity of current flow in Self-Strain-Sensing applications. The experimental setup proved to be effective in visualizing the potential distribution for various materials and electrode manufacturing processes with minimal retroactivity and shows the necessity to more thoroughly discuss the current inhomogeneity in self-strain-sensing CFRP structures. Surface sanding proved to be effective in minimizing current inhomogeneity in the part. Since there are inherent drawbacks of surface sanding, the experimental setup developed here could next be used to assess the applicability of other surface preparation techniques. We believe it could be fruitful to evaluate whether some surface preparation techniques from the field of adhesive joining such as laser based ablation could be adapted for usage in the electrical contacting of CFRP. Furthermore, the developed technique could be used to evaluate the durability of electrical contacts. Microscopic detachments between contact and CFRP surface occurring due to mechanical strain can be studied with this setup by measuring a specimen before and after several load cycles, thereby studying differences in the electrical current paths. It might even be possible to integrate the scanning technique into a tensile test machine, which would allow to scan the surface of a specimen under mechanical strain.

We furthermore believe, that it would be very interesting to use this experimental approach for damage detection in CFRP. While it could be difficult to use this approach as an in-service monitoring system, it should prove to be valuable for the development of resistance and impedance based damage monitoring systems by allowing to measure the surface potential with a very high spatial resolution and thus allow to see changes in the potential field in CFRP that cannot be observed using locally applied electrodes.

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Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5281/zenodo.5075916.

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References

[1] Giurgiutiu V 2015 Structural Health Monitoring of Aerospace Composites (London, UK: Academic Press is an Imprint of Elsevier)
[2] Schulte K and Baron C 1989 Load and failure analyses of CFRP laminates by means of electrical resistivity measurements Compos. Sci. Technol. 36 63–76
[3] Schulte K 1993 Damage monitoring in polymer matrix structures Le Journal de Physique IV 03 C7–1629–C7–1636
[4] Todoroki A, Kobayashi H and Matuura K 1995 Application of electric potential method to smart composite structures for detecting delamination JSME International Journal. Ser. A., Mechanics and Material Engineering 38 524–30
[5] Wang X and Chung D 1998 Self-monitoring of fatigue damage and dynamic strain in carbon fiber polymer-matrix composite Composites Part B: Engineering 29 63–73
[6] Wang X and Chung D D L 1996 Continuous carbon fibre epoxy-matrix composite as a sensor of its own strain Smart Mater. Struct. 5 796
[7] Chung D 2019 A review of multifunctional polymer-matrix structural composites Composites Part B: Engineering 160 644–60
[8] Angelidis N, Wei C Y and Irving P E 2004 The electrical resistance response of continuous carbon fibre composite laminates to mechanical strain Composites Part A: Applied Science and Manufacturing 35 1135–47
[9] Hart R J and Zhupanska O 2020 The role of electrical anisotropy and effective conducting thickness in understanding and interpreting static resistance measurements in CFRP composite laminates J. Compos. Mater. 54 867–82
[10] Park J B, Okabe T and Takeda N 2003 New concept for modeling the electromechanical behavior of unidirectional carbon-fiber-reinforced plastic under tensile loading Smart Mater. Struct. 12 103–14
[11] Park J B, Hwang T K, Kim H G and Doh Y D 2007 Experimental and numerical study of the electrical anisotropy in unidirectional carbon-fiber-reinforced polymer composites Smart Mater. Struct. 16 57–66
[12] Zimney E J, Dommermuth G H B, Ruoff R S and Dikin D A 2007 Correction factors for 4-probe electrical measurements with finite size electrodes and material anisotropy: a finite element study Meas. Sci. Technol. 18 2067–73
[13] Ueda M, Yamaguchi T, Ohno T, Kato Y and Nishimura T 2019 Fem-aided identification of gauge factors of unidirectional CFRP through multi-point potential measurements Adv. Compos. Mater 28 37–55
[14] Scholle P and Sinapius M 2021 A review on the usage of continuous carbon fibers for piezoresistive self strain sensing fiber reinforced plastics Journal of Composites Science 5 96
[15] Feynman R, Leighton R B and Sands M L 2001 Elektromagnetismus und Struktur der Materie Bd. 2 of (Vorlesungen über Physik) ed v R P Feynman, R B Leighton and M Sands (München und Wien: Oldenbourg) 3 durchgesehene auflage edition
[16] Levin G A 1997 On the theory of measurement of anisotropic electrical resistivity by flux transformer method J. Appl. Phys. 81 714–8
[17] Wang S and Chung D D L 2007 Negative piezoresistivity in continuous carbon fiber epoxy-matrix composite J. Mater. Sci. 42 4987–95
[18] Todoroki A and Yoshida J 2005 Apparent negative piezoresistivity of single-ply CFRP due to poor electrical contact of four-probe method Key Eng. Mater. 297–300 610–5
[19] Möller C 2011 Zur Steigerung der faserverliefenden Druckfestigkeit von CFK: Potenzielle präzisierteller Stütze und Konstruktionslösungen für ihren Einsatz in Strukturbauzeiten: Zugl.: Darmstadt, Techn. Univ., Diss., 2011 (Aachen: Schriftenreihe konstruktiver Leichtbau mit Faser-Kunststoff-Verbunden. Shaker)