Full-field calibration from DIC: a way to analyze fibre orientation deviations in composites?

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1 Introduction and problem statement

This paper deals with continuous fibre-reinforced plastics, in particular carbon-fibre reinforced plastics (CFRP). A material that is used in many different applications, ranging from transport, automotive and aircraft design to the design of static load-bearing structure. Laminates with numerous, differently orientated layers and possibly even local reinforcements (patches) are used here. The manufacturing processes used for CFRP range from manual lamination in the production of individual items to highly automated processes such as tape laying in series production. What all procedures have in common, however, is that deviations and errors can and will occur. These can affect the external shape of the component on the one hand, but also the internal structure of the fibre-matrix composite, which may have an impact on the mechanical properties.

However, it is not easy to determine the actual fibre orientation in the component. This can either be done in a destructive manner, whereby local samples are taken and micrographs are created. Alternatively, CT scans can be created, which provide a view of the inside of the part. However, this is usually only possible for parts that are limited in size and the technology is rarely available, and its acquisition and use is associated with high costs. This leaves a residual uncertainty, which is compensated for in the component de-sign by applying higher safety margins. Yet the most precise knowledge and calculability of mechanical properties is one of the most important pillars of lightweight design.

2 Materials and Methods

A CFRP manufactured using the prepreg process is used for all the following experimental investigations. Information on the tensile rods, the test methods used and the determination of parameters is provided below.

2.1 Specimen material

The specimens have been manufactured from epoxy resin prepreg material called UNIPREG150 from the manufacturer UNICARBON. The prepreg contains a Zoltek Panex 35 (50k) fiber tow with an aerial weight of 150 g/m^2. The matrix weight fraction is 36 % resulting in a total aerial weight of the prepreg of 234 g/m^2 and a thickness of 0.15 mm. The plates for characterization of the tensile properties in fiber direction and perpendicular to the fiber direction use laminates according to ISO 527-5 with (0°)5 respectively (90°)12. Shear characterization was performed according to ISO 14129 using a (45°/-45°)6S laminate. For validation purposes a fourth plate with a (10°/90°/10°/90°/10°) laminate, including artificial variations (0° layers deviate 10°) which is expected to produce an asymmetric strain field.

2.2 Experimental setup and measurement

A servo-hydraulic HCT 25 testing machine from ZwickRoell in Ulm/Germany is used to carry out the necessary tests under quasi-static conditions. The testing machine allows the application of static loads of up to 25kN and is operated with displacement control. This allows a constant tensile speed of 2 mm/min (1 mm/min for transversal orientation) to be set for the tests on the tensile specimens.

For optical strain evaluation, the ARAMIS 4M camera system from GOM in Braunschweig/Germany is used. The ARAMIS optical measuring system works according to the principle of grey value correlation (also known as digital image correlation, DIC) to measure the deformations and strains visible on the surface.

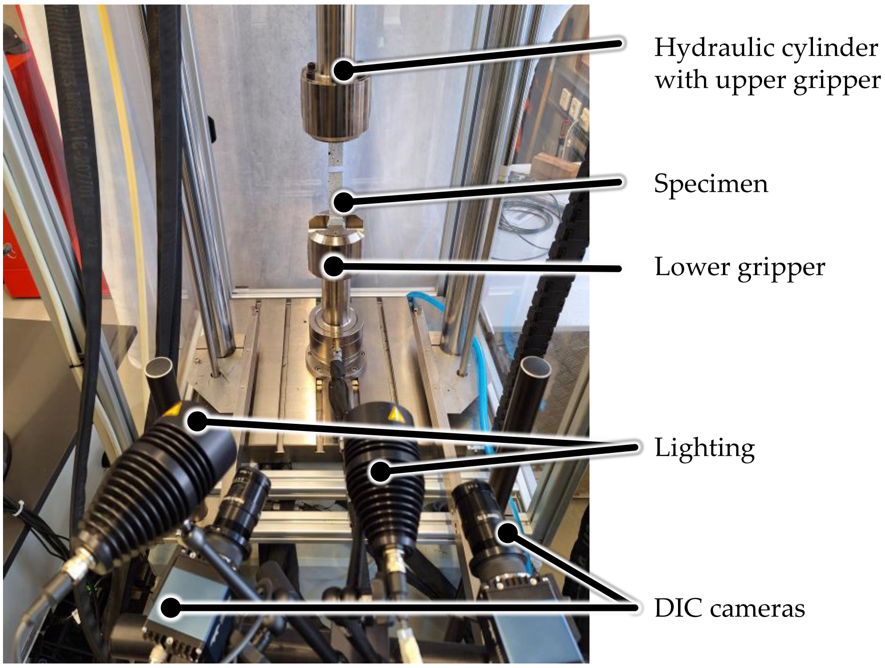

Fig.1: Servohydraulic test rig with specimen and optical measuring system

2.3 Setup of simulation and material model

Simulations were carried out using LS-DYNA and prepared with LS-PrePost. The orientation of the tension rod in the coordinate system corresponds to that of the optical strain evaluation, with the tensile axis running in the y-direction. The material model used is the MAT_58: Laminated_Composite_Fabric. This is suitable for modelling composite materials with unidirectional layers, complete laminates and woven fabrics. In addition to orthotropic elasticity, the material model can also describe non-linear behaviour under shear stress, as can be observed in laminates with di-agonal reinforcement.

2.4 The methods of material parameter identification with Full-Field Calibration

Since not all material parameters can be derived directly from experimental data, so-called inverse methods are used. These deal with the determination of model parameters based on a comparison of experimental and simulated data, with the aim of achieving the best possible quantitative agreement [1]. *Rieger* distinguishes between direct and indirect problems, as shown in Fig. 2. The direct problem corresponds to the usual simulation methods: the material model, load, initial conditions and material parameters are known, and the system response, for example the displacement of a specific point, is sought. In the inverse case, on the other hand, the system response is known, but the material parameters are unknown.

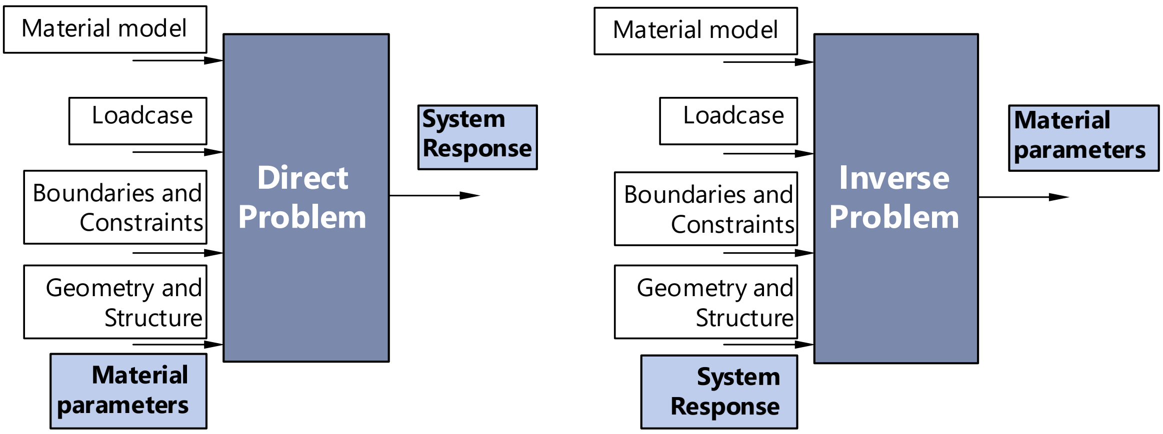

Fig.2: Direct and inverse problems of simulation

The so-called full-field calibration in LS-Opt incorporates the optical strain measurement even more directly for parameter optimisation [2, 3]. Instead of creating an average value curve over the entire strain range, the strain occurring locally per facet or finite element is considered [4]. This means that not just one curve is compared per test, but a large number of them, which also makes it possible to resolve local differences in strain. It is also clear that this intensifies the calculation. An overview as displayed by Ilg et al. in [5] is shown in Fig. 3

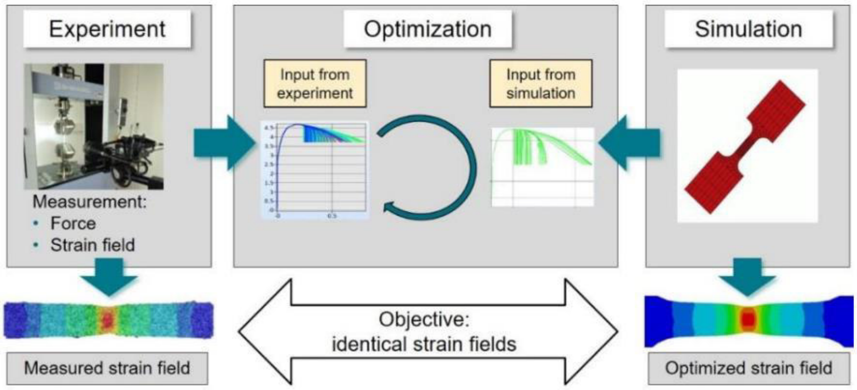

Fig.3: The method of full-field calibration according to Ilg et al. [5]

In the literature, full-field calibration has so far mainly been used for the identification of yield parameters of metallic materials, mostly steel. These offer the clear advantage that very large strain values and localised necking occur. In the case of brittle laminate materials, none of this is to be expected; instead, spontaneous material failure must be reckoned with even if the strain is small.

3 Analysis of deviation parameters by FFC

Full-field calibration is normally used to solve the following problem: The error between the experimentally determined and simulatively calculated curve should be minimised, using material parameters such as the Young's modulus as changeable variables. In the case of the FFC, this is not carried out globally, on a single curve for the entire tension rod, but on one curve per facet of the optical strain measurement.

In order to be able to determine an angular deviation in the laminate of the CFRP, the above procedure is reversed: The optimisation objective of minimising the error between the measured and simulated curve is still maintained, but the layer orientations of the laminate structure are assumed as variable parameters rather than material parameters. Of course, this assumes that the results of the material parameters are already known with sufficient accuracy. To test the method, a laminate structure was falsified from [0°/90°/0°/90°/0°] to [10°/90°/10°/90°/10°].

Firstly, it should be noted that when observing the strain field measured by DIC, a clearly visible change occurs when the sample has a different orientation. This can be seen in Fig. 4. Such a measurement is the input for the study carried out below.

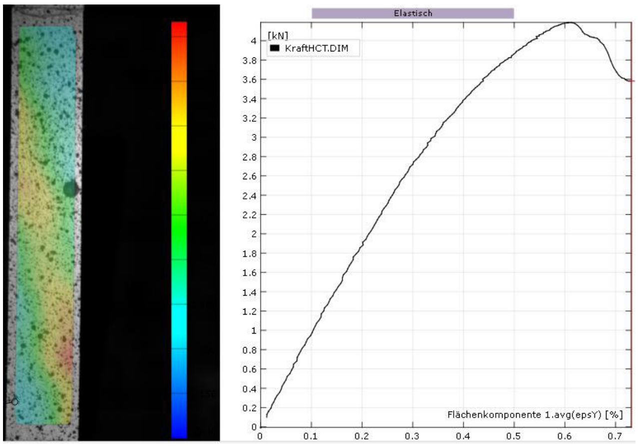

Fig.4: Strain field for a specimen with a 10° deviated fibre orientation

An ideal simulation (which could be called a digital twin) is created from the CFRP sample, in which all layers and fibre orientations correspond to the target values. This simulation is parametric in structure and forms part of an LS-Opt optimisation routine, as shown in Fig. 5.

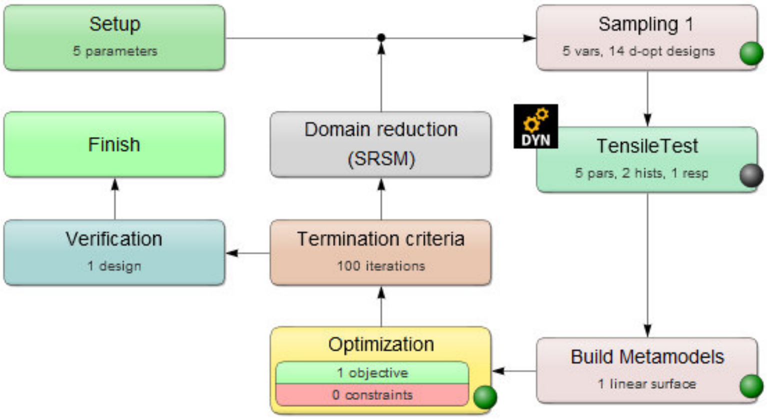

Fig.5: LS-Opt setup for optimisation

The method outlined here was used to find the layer angles; the convergence of the values can be seen in Fig. 6. It should be noted that an angular deviation was recognised for all deviating layers, given around the 10 degrees of error, depending on the specimens used.

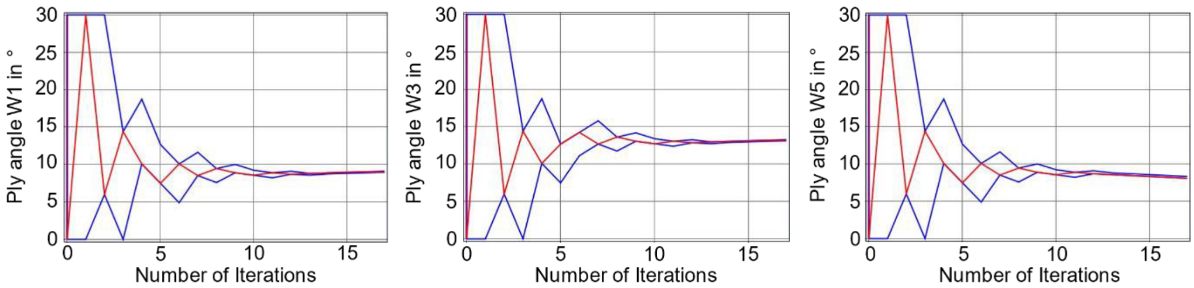

Fig.6: Convergence of deviation angles in the laminate. The deliberately introduced deviation was 10°.

However, it must be noted here that performing these optimisation runs until convergence requires a fairly large number of iterations and simulations. Furthermore, the number of simulations per iteration increases significantly with the number of parameters. So let's first take a look at the development of the error measure, shown here in Fig. 7: Iteration 0, highlighted in red, compares the ideal simulation with the actual measurement, which is subject to deviations. It is therefore already apparent here that there is a very high margin of error, even though only a single simulation was performed and compared with the measured strain field. Even if it is not possible to state precisely how large the angular deviation is, the information obtained in this way may be sufficient to determine whether a part is good or bad.

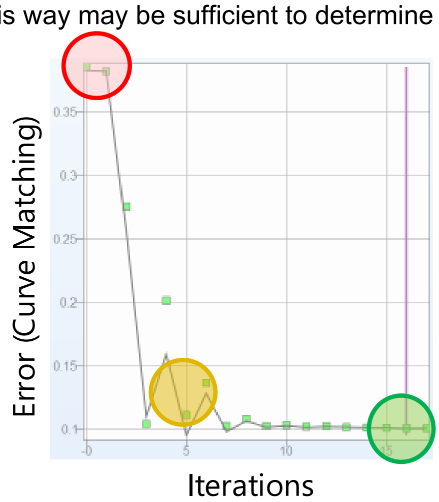

Fig.7: Convergence of error in the optimization.

The study outlined here nevertheless gives cause for hope: on the one hand, it was possible to establish that there are deviations in the laminate at all. The magnitude of the errors found is also acceptable. And it is equally positive to note that this was also possible for those layers that were not directly illuminated on the surface by the cameras.
This study may provide an idea for using full-field calibration to control the production quality of composite laminates. We will continue our research on this and will initially carry out further studies on deviations of the complete layers in the next steps. In the more distant future, it will continue to be interesting to see whether the deviations can be detected not only for an entire layer, but also locally resolved.

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