PROGRESSIVE FAILURE STRAIN MEASURMENT OF A COMPRESSION LOADED CARBON FIBER LAMINATE

Jonas J. A. D'haen[1], Sebastian Kilchert[2], Octavian Knoll[1], Michael May[2], Stefan Hiermaier[2]

[1] BMW AG, Hufelandstraße 5, 80788 Munich, Germany, Jonas.Dhaen@bmw.de
[2] Fraunhofer Institute for High-Speed Dynamics, EMI, Eckerstraße 4, 79104 Freiburg, Germany

Keywords: Progressive failure, Digital image correlation, Material characterization

ABSTRACT

A new approach to measure the strain in compressive loaded laminates is discussed in this paper. Current state of the art testing standard like the DIN EN ISO 14126 is not able to measure the strain of the laminate after first ply failure. From tests it is known that strain gauge data is not valid after initial failure due to the fact that local strain of the delaminated layers is measured or because of strain gauge delamination. It is observed that multidirectional laminates can have a significant amount of residual strength after initial failure. In order to improve the knowledge of the material and understand the failure mechanisms it is necessary to be able to obtain reliable strain data after initial failure. This paper describes how digital image correlation (dic) can be used to obtain global and local strain data of laminates loaded in compression. The specimen geometry that is used for the dic test is similar to the one of the test standards in order to allow easy comparability. The test results that are obtained using dic measurements show good agreement with the one that are based on standard test methods.

1 INTRODUCTION

The usage of carbon fiber composites is not limited anymore to space crafts and motorsport because the experience on various production processes has gained significantly in the last decade. This can be observed from the fact that parts are produced at a higher speed and lower cost. This is one of the reasons that carbon fiber composites has found its way to the automotive industry. Recently, the material has widely been implemented in automotive series production. In order to promote carbon fiber material even more in automotive structures, it should be analyzed for the advantages that carbon fiber material offers and implement the material accordingly. From literature it is known that it has a very high specific energy absorption making it an interesting candidate material for crash absorbing structures [1]–[3]. Currently used crash structures are often made of steel or aluminum but according to recently presented papers, carbon fiber composites could reduce the weight of energy absorbing structures. However, it is known that carbon fiber composites have a complex failure behavior [4]. This means that the material behavior should be investigated properly before it can be implemented in a crash structure.

In order to design a structure properly the material behavior should be characterized specifically. Characterization is usually done according to the appropriate test standard. Parameters such as measurement type and accuracy, specimen geometry and preparation, clamp type and post processing of the results are defined in these testing standards. Furthermore, these test standards ensure the comparability between different materials and various test labs around the world. Current state of the art measuring techniques for compression behavior of carbon fibre composite laminates is based on the testing standard DIN EN ISO 14126 [5]. This standard proposes to use strain gauges or a extensometer.

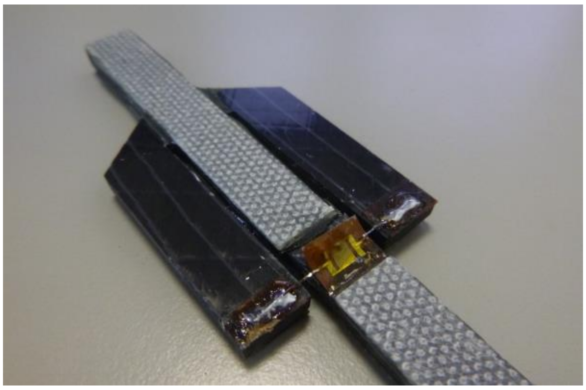

Figure 1: Shown a delaminated Strain gauge on a specimen tested according to DIN EN ISO 14126.

From testing, it is found that the strain after first ply failure is not measurable with currently proposed measurement techniques. Strain gauges often delaminate after initial failure, seen in Figure 1. Furthermore, It is possible that they track the strain of the local delaminated layer instead of the overall laminate, this effect can be seen in Figure 8. The outer layer is completely separate from the specimen and therefore not representable for the overall laminate. Measuring such a small specimen is a challenging task with extensometers because the non clamped height is only 10mm. Furthermore, it is found that extensometers regularly slide at initial failure resulting in non-reliable measurement data. It can be concluded that current proposed measuring techniques are not able to adequately track the strain after initial failure.

2 GOAL

In order to get more insight on the behavior of composite better, measuring techniques should be available. As described in previous section: current used measuring techniques are not able to capture reliable test data after first ply failure. The goal is to be able to gather more accurate strain measurement data of the laminate loaded in compression after first ply failure. The new technique should result in a better accuracy after and a similar accuracy before failure compared to conventional techniques.

This goal is particularly interesting for laminates that are capable of absorbing energy after initial failure. Typically, multidirectional show interesting behavior after first ply failure, usually the laminate is able to absorb more energy after initial failure. On the other hand, this goal would not bring anything for unidirectional laminates that are loaded in tension because, for this specific laminate the initial failure equals complete failure. This is the reason that the tests that are presented in following section are conducted with a $[\pm 45,0]_s$ non-crimped fabric laminate. The laminate is produced using a resin transfer molding production process.

3 METHODOLOGY

Various strain measurements are available in literature, which can be divided in three different classes. There are point, line and surface measurements available. The typical point measurement tool is a strain gauge [6, p. 98]. Line measurements can be obtained with laser, video or (clip on) extensometers [6, p. 335]. Full surface strain measurements devices can be divided in two main groups. The first one is non interferometric measurements such as digital image correlation (dic), Speckle-tracking [6, p. 655] and Grid Method [7], [8]. The second group contains interferometric measurement techniques such as laser Doppler vibrometer [6, p. 834], Moiré Interferometry and speckle interferometry [8].

From the limitations that are listed in the introduction section, it can be concluded that an new type of measurement technique should be selected. With the available hardware it is found out that digital image correlation has the most potential. Furthermore, the system is compact and the specimens require little preparation. Application of the speckle pattern is done using conventional black and white spray cans; the white layer is used as the primer, whereas the black paint creates the random distributed speckle points. The dic system works on the basis of tracking a speckle pattern on the specimen throughout the test using sequential image series. The first image is used as reference image in order to calculate the local deformations [9]. This calculation process is preformed using the commercially available software from the GOM GmbH.

The dic measuring system is setup with two cameras. The first one is pointed towards the front, whereas the second points towards the side of the specimen. This ensures, that both the front and side view of the specimen are tracked. This setup enables to validate the measurement data that is obtained from the strain gaiges. Figure 2 shows a schematic top view of how the measuring has been performed.

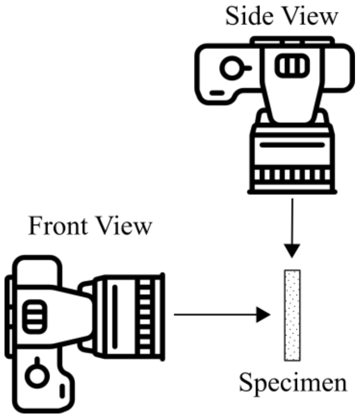

Figure 2: Schematical top view of the camera positions during.

According to the DIN EN ISO 14126 testing standard [5], the strain should be measured from both sides in order to observe buckling of the laminate. However, for the optical measurements it is intentionally decided against the recommendations from the testing standard. This decision is based on the fact that buckling allows better observation from the side view. Another advantage from this setup is that more information from the laminate can be obtained. For example, the side view allows better delamination judgement.

However, it should be noted that dic strain measurements from the side view should be analysed properly. In some cases, when the outer layer delaminates strain data is measured from the outer layer and thus not representable for the overall laminate. This effect can be seen in figure 8 where the delaminated layer blocks the side view to gather overall laminate data. Depending on the type of dic system that is used, the out of plane movement can be detected and thus warn for potential failures. Typically used 2D dic systems cannot measure out of plane movement. 3D systems have the advantage that they are able to track out of plane movement, however they are significantly bulkier and require extensive calibration steps [10, p. 325]. The tests that are shown in this paper are performed with a 2D dic system but the out of plane movement is closely investigated to ensure proper measurements.

The presented methodology yields to the fact that more insight on failure modes after initial failure and more data on the global and local strain of the material can be gathered. The results that have been obtained are shown in following section.

4 RESULTS

The cameras are setup to trigger at a speed of 25 Hz, this results in a picture series throughout the test. A small selection of this picture series is shown in figure 3. The figure shows previously mentioned laminate tested in the 0° direction. From the series it can be seen that a sudden failure is present in the laminate. The first three images look similar without visible damage present whereas the last three images show a similar failure state.

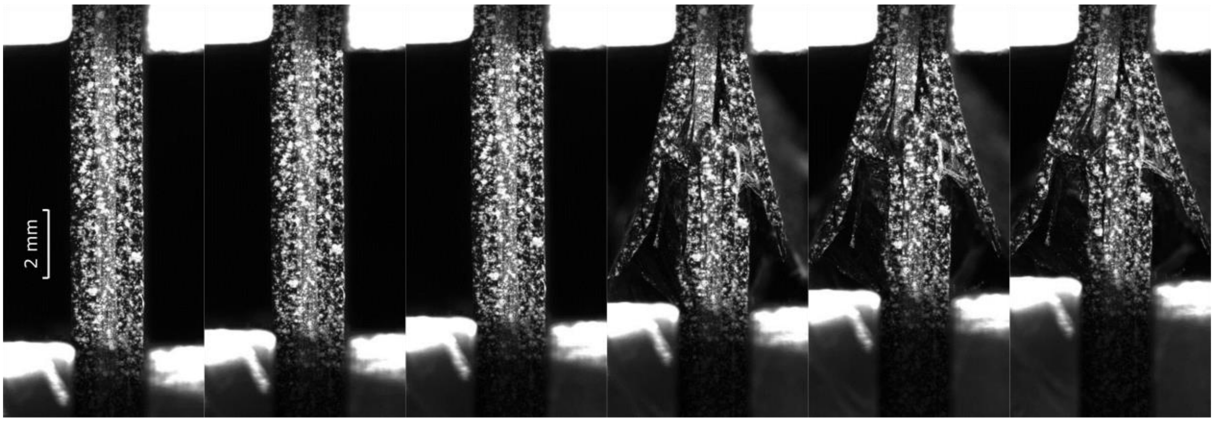

Figure 3: Non-processed images of the side view during compression test in 0° loading direction.

Importing this image series in the GOM software allows the calculation of the strain in the material. In order to be able to accept this measurement data, it should be compared with the data obtained from strain gauges. Figure 4 shows the comparison between the dic and strain gauge measurements in an engineering stress - strain plot. The light grey area spans between the minimum and maximum measuring data, the grey line shows the average of all the test data.

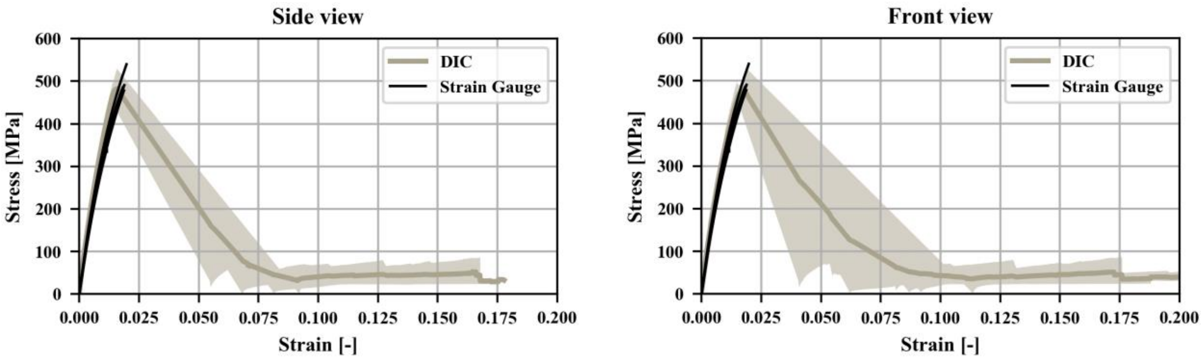

Figure 4: Stress strain plots for the front and side view in 0° loading direction.

From this figures it is clear that the strain gauge data is not present after initial failure. In contrast, the dic measurements produce data with a small variance. It is observed that the side view results in better data because of the smaller scattering in the test data. It should be noted that few measuring points are obtained during the failure, this follows from the fact that the specimen loaded in 0° fail swiftly. Performing the same measurements in the 90° direction results in the picture series shown in figure 5.

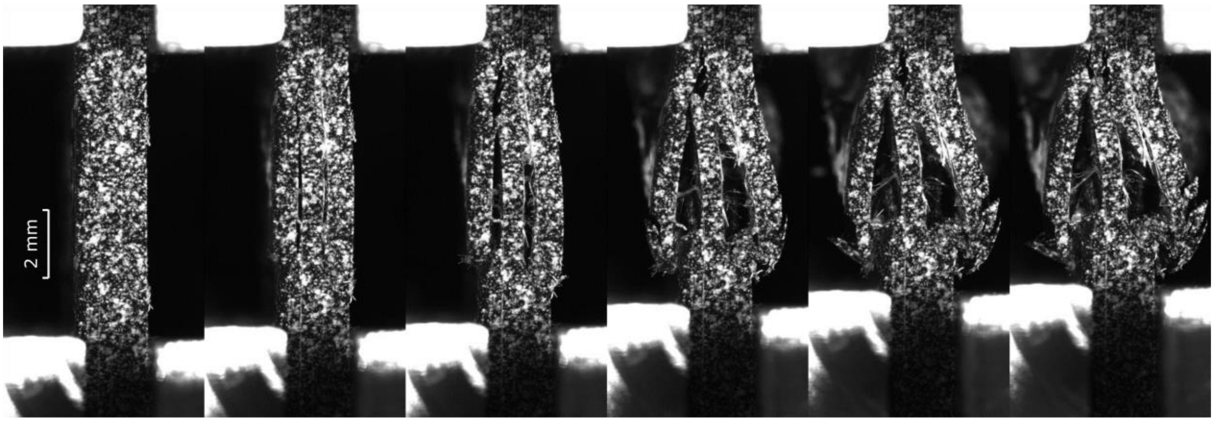

Figure 5: Non-processed images of the side view during compression test in 90° loading direction.

In the comparison between figure 5 and figure 3, it can be seen that the failure in the 90° does not happen instantaneously like the laminate loaded in 0°. From the second image, it can be seen that delamination started to grow between layer 2-3 and 4-5. Afterwards shear failure is observed in layer 1-2. Layer 3-4 oriented in 90° fails on the top under shear failure. The stress strain plot that is obtained from this image series and strain measurement data is shown in figure 6.

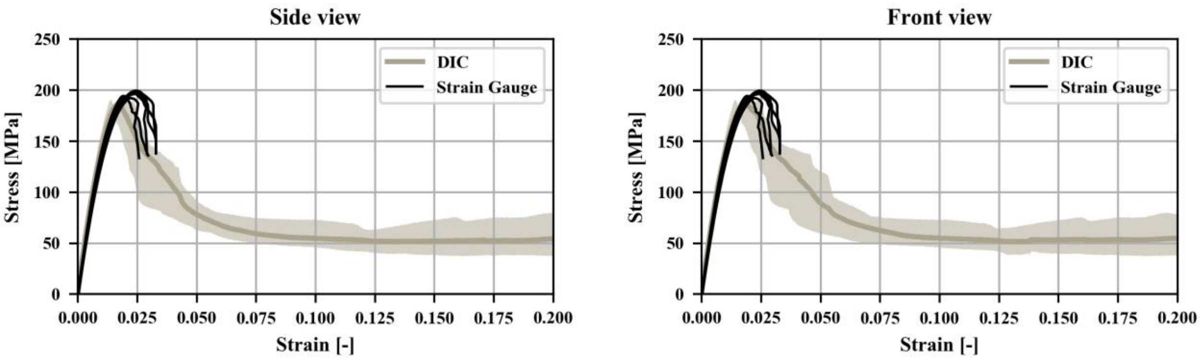

Figure 6: Stress strain plots for the front and side view in 90° loading direction.

When processing the image series from the 90° specimens, it can be concluded that the stiffness obtained from the strain gauge data matches the data obtained from the dic measurements. It is seen that both deviate a bit at initial failure but this could also have to do with artefacts in the strain gauge.

5 CONCLUSION

From previous sections, it can be concluded that optical strain measurements can be used to measure strain of a compression loaded specimen. The accuracy remains similar to the one of strain gauges before initial failure. Furthermore, the newly proposed strain measurement technique improves the measurement data after first ply failure because dic measurements show consistent strain data after first ply failure. It should be noted that the dic strain that is plotted in the figures against the strain gauge data is obtained from global dic measurements, which is schematically shown on the left side in figure 7. The flexibility that comes with strain measurements on surface level is that strain measurements can be analyzed locally and globally, with both options presented in figure 7.

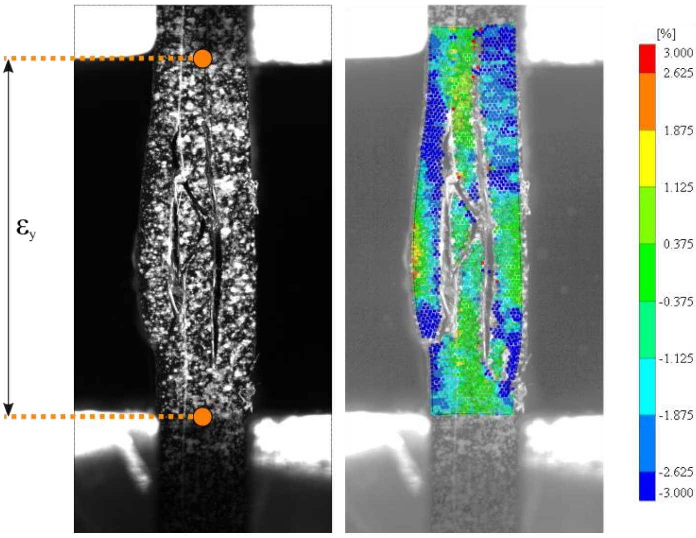

Figure 7: Global and local results that are obtained after post processing.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to the BMW Group, Fraunhofer Institute for High-Speed Dynamics and the University of Freiburg to make this work possible.

REFERENCES

[1] G. L. Farley, "Energy Absorption of Composite Materials," *J. Compos. Mater.*, vol. 17, no. 3, pp. 267–279, 1983.
[2] J.J. Carruthers, A. P. Kettle, and A. M. Robinson, "Energy absorption capability and crashworthiness of composite material structures : A review," *Appl. Mech. Rev.*, vol. 51, no. 10, pp. 635–649, 2015.
[3] J. Peter, "Experimentelle und numerische Untersuchungen zum Crashverhalten von Strukturbauteilen aus kohlefaserverstärkten Kunststoffen," 2004.
[4] M. May, M. Nossek, N. Petrinic, S. Hiermaier, and K. Thoma, "Composites : Part A Adaptive multi-scale modeling of high velocity impact on composite panels," *Compos. Part A Appl. Sci. Manuf.*, vol. 58, pp. 56–64, 2014.
[5] DIN Deutsches Institut für Normung e. V., "DIN EN ISO 14126: Bestimmung der Druckeigenschaften in der Laminatebene," vol. 2000. 2000.
[6] W. N. Sharpe, *Handbook of Experimental Solid Mechanics*, vol. 1. 2015.
[7] M. Grédiac, F. Sur, and B. Blaysat, "The Grid Method for In-plane Displacement and Strain Measurement : A Review and Analysis," *Strain*, vol. 52, no. 3, pp. 205–243, 2016.
[8] M. Grédiac, "The use of full-field measurement methods in composite material characterization: Interest and limitations," *Compos. Part A Appl. Sci. Manuf.*, vol. 35, no. 7–8, pp. 751–761, 2004.
[9] GOM GmbH, *Digital Image Correlation and Strain Computation Basics*, no. 0. 2016.
[10] H. Jin and C. Sciammarella, *Advancement of Optical Methods in Experimental Mechanics, Volume 3*, vol. 3. 2017.

6 APPENDIX

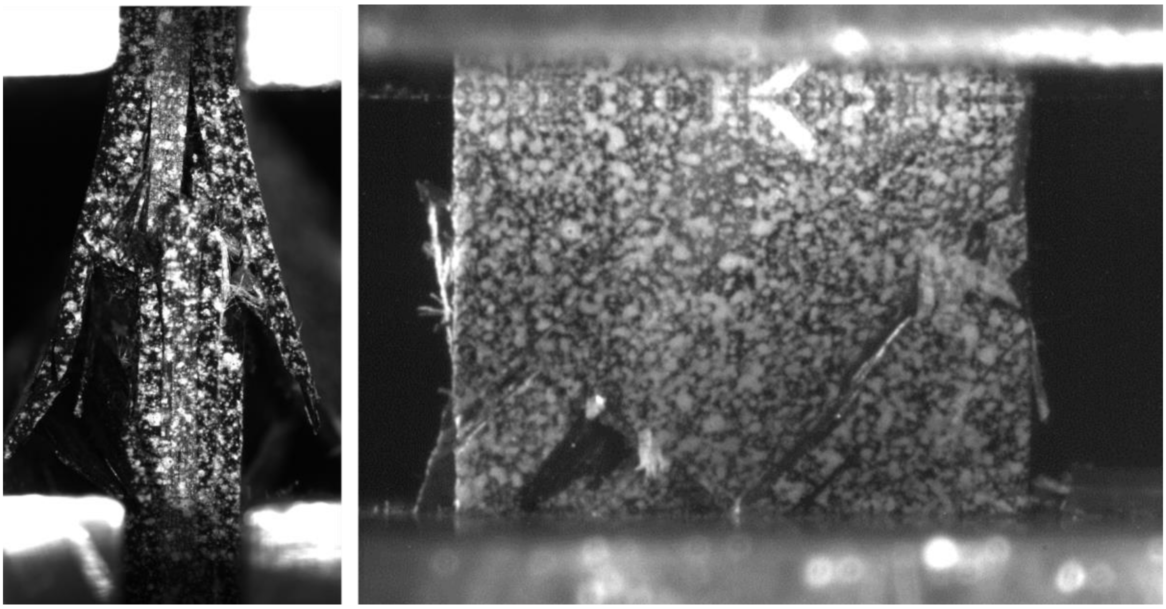

Figure 8: Front and side view of a failed laminate.