MECHANICAL CHARACTERIZATION OF GLASS FIBER-REINFORCED COMPOSITES

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Summary: *The mechanical properties of fiber-reinforced composites are essential for the design of new lightweight structures. Therefore, digital image correlation and strain gages are utilized to measure the Young's modulus and Poisson's ratio of unidirectional and biaxial reinforced glass fiber-reinforced composites in parallel. While the Young's modulus of unidirectional reinforced samples obtained by the different measurements methods is in the same range, larger deviations occur for the Poisson's ratio. Furthermore, the influence of embroidered sensors on the stiffness is characterized for biaxial reinforced samples.*

Keywords: *material properties of GFRP, Young's modulus, Poisson's ratio, digital image correlation, strain gauges*

1 Introduction

During the last three decades, fiber-reinforced composites became more and more important and are now used in a wide range of applications. Being first introduced in aeronautics, they are also applied in shipbuilding, mechanical and automotive engineering as well as electronics, sports and consumer products. Fiber-reinforced composites enable a reduction of the weight and thereby increase the energy efficiency of new components and systems. The growing importance of glass and carbon fiber- reinforced composites can be exemplified with the content of material used in the construction of airplanes manufactured by Airbus [1]. Between 1987 and 2006, the percentage by weight of fiber- reinforced composites of an Airbus A310 increased from $10\,\%$ to about $25\,\%$ for the new Airbus A380.

The design of new lightweight structures based on fiber-reinforced composites requires the knowledge of the mechanical properties depending on the fiber volume fraction and manufacturing process. While different approximations lead to the same properties in fiber direction, these estimations show differences for the properties perpendicular to the fiber orientation [1, 2]. To provide reliable material properties for the FE-analysis during the design phase of new fiber-reinforced components, these approaches have to be compared with the behavior of the real structure, considering not only the fiber content but manufacturing process as well. Especially the stiffness of the material in terms of Young's modulus parallel and perpendicular to the fiber orientation are crucial for functionalized components.

The mechanical properties of unidirectional and biaxial reinforced glass fiber-reinforced composites (GFRP) are analyzed by utilizing both digital image correlation (DIC) and strain gages in parallel. In comparison to strain gages, the DIC provides information about the deformation depending on the coordinate in

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a field. It enables the detection of strain concentrations as well as inhomogeneity of the fiber-reinforced composites and thereby the identification of stress concentrations, weak points and even defects in the laminate structure.

2 Experimental Setup

The experimental setup (Figure 1) combines a universal testing machine Zwick Z005/TN2A (Zwick GmbH & Co. KG Ulm) with an ARAMISV6.0.2-6 based digital image correlation system (GOM mbH Braunschweig) and a MGC amplifier (HBM GmbH Darmstadt) for the strain analysis with strain gages KFG-5-120-D17-23 (Kyowa Electronic Instruments CO., LTD Tokyo).

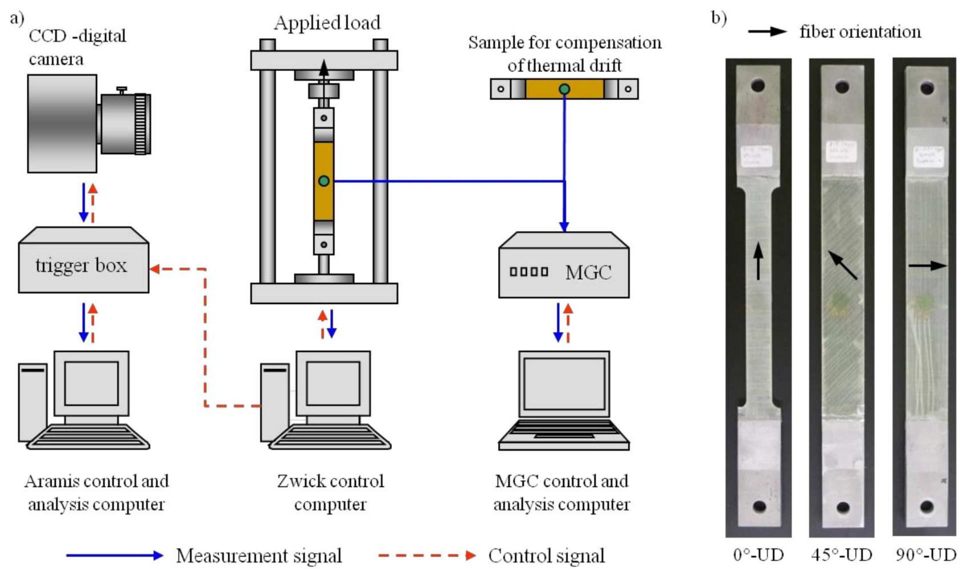

Figure 1: a) Scheme of experimental setup, b) Sample design for different fiber orientations

The fiber volume fraction of the analyzed samples is in the range of $38\,\%$ to $42\,\%$ varies between $1.15\,\mathrm{mm}$ and $1.28\,\mathrm{mm}$. These deviations are caused by the manual manufacturing process of the samples. The unidirectional reinforced samples with a fiber orientation of $45\,^\circ$ and $90\,^\circ$ to the load direction as well as the biaxial reinforced samples are bar shaped. Due to their much higher stiffness, a bone shaped design is used for the GFRP samples with fiber orientation parallel to load direction. The fiber-reinforced samples are loaded displacement controlled. While analyzing the deformation of the samples with DIC and strain gages, the applied tensile load is measured with a $5\,\mathrm{kN}$ load cell (A.S.T GmbH Dresden). The elastic material properties like Young's modulus and Poisson's ratio can be determined for small tensile loads in the strain region of $0.1\,\%$ to $0.3\,\%$ in load direction [3]. This approach enables the measurement of the applied load with a smaller load cell and thereby with a higher accuracy in the force range of interest. Based on the measurement of the strain depending on the applied load, the Young's modulus can be calculated by Hooke's law, while the Poisson's ratio is directly derived from the strain in longitudinal direction and lateral extension.

3 Results

The combined analysis with strain gages and DIC has been carried out for unidirectional reinforced samples, while the biaxial reinforced samples are analyzed by DIC only. Focusing on a small area and considering the deformation of the samples, the Young's modulus and Poisson's ration obtained by strain gages are sufficiently constant (Figure 2 and 3). They only depend on the fiber orientation, leading to the highest stiffness of approx. $35\,\mathrm{GPa}$ for reinforcement in load direction. The Youngs modulus for $45\,^\circ$ and $90\,^\circ$ reinforced sample with $9\,\mathrm{GPa}$ is in the same range, while their Poisson's ratios differ significantly.

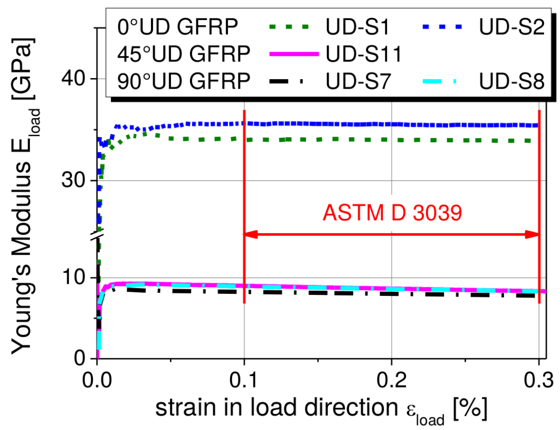

Figure 2: Influence of fiber orientation on Young's modulus measured by strain gage

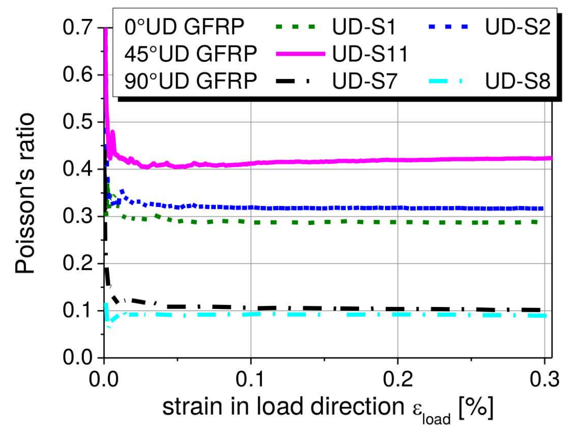

Figure 3: Influence of fiber orientation on Poisson's ratio measured by strain gage

The Young's modulus measured by digital image correlation shows a different behaviour compared to the measurements with strain gages. When reaching a strain of $0.05\,\%$, the Young's modulus obtained by strain gages is almost constant. In comparison, the Young's modulus analyzed by DIC shows slight to medium changes depending on the applied load. While there is almost no difference for reinforcement perpendicular and in $45\,^\circ$ to the applied load, the Young's modulus measured by DIC increases with strain, reaching the values obtained by strain gages at $0.3\,\%$ extension (Figure 4). A similar behaviour can be observed for the Poisson's ratio. Furthermore, the DIC is limited in its resolution of the lateral extension caused by the small deformations, leading to large differences in the Poisson's ratio (Figure 5).

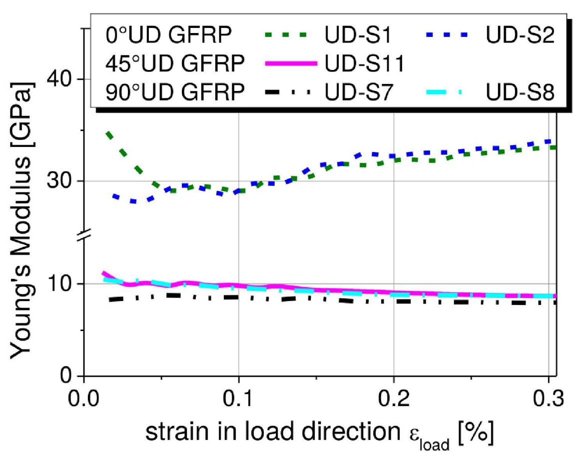

Figure 4: Young's modulus of unidirectional reinforced samples analyzed by DIC

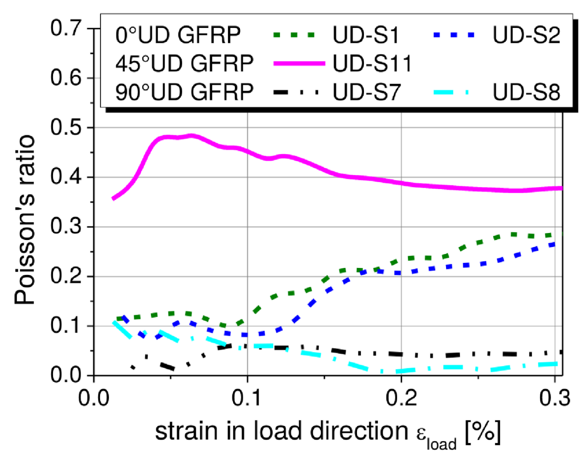

Figure 5: Poissons ratio of unidirectional reinforced samples analyzed by DIC

The Young's modulus of biaxial reinfocred samples with and without embroidered sensors are close to the average of $0\,^\circ$ and $90\,^\circ$ unidirectional reinforcement. The strain fields perpendicular and in load direction are relatively homogenous (Figure 6). They are analyzed in an approx. 500 point containing optical gage area A^{DIC} .

The change in the Young's modulus is smaller than for $0\,^\circ$ unidirectional reinforced samples (Figure 7). For samples without embroidered sensors GFRP_bns it varies between 20 and $22\,\mathrm{GPa}$. The embroidered sensors GFRP_bns also cause a slight reduction of the stiffness, leading to a Young's modulus in the range of 20 to $21\,\mathrm{GPa}$.

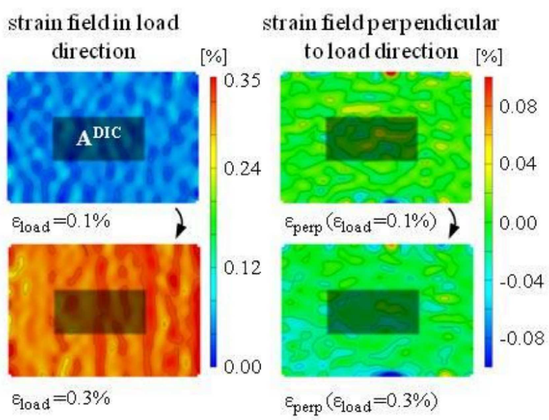

Figure 6: Strain fields for biaxial reinforced sample GFRP_bws-2 with embroidered sensor

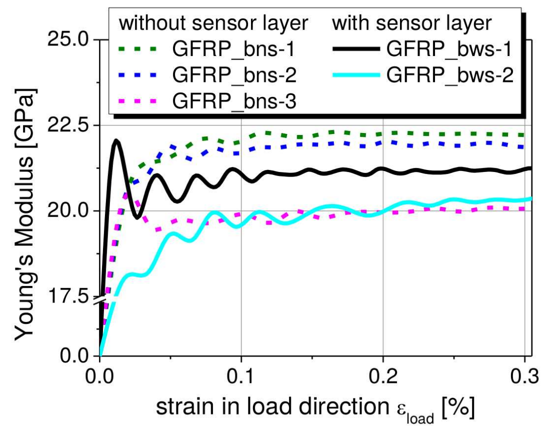

Figure 7: Influence of embroidered sensor on stiffness of biaxial reinforced composite samples

4 Discussion

Due to its medium accuracy in small strain regions, the determination of the Poisson's ratio by DIC is limited to larger deformations or requires an adjusted test setup. Out of the analyzed estimations for the material properties depending on the fiber volume fraction, the adjusted approach according to [2] provides the best approximation for the manual manufacturing process (Table 1).

Table 1: Theoretical Young's modulus for unidirectional GFRP compared to experimental results

Fiber orientation	Mallick	Schuermann	DIC	Strain gage
Parallel	32.2 GPa	32.2 GPa	31.5 GPa	34.5 GPa
Perpendicular	4.9 GPa	7.3 GPa	8.8 GPa	8.4 GPa

Based on the analysis of biaxial reinforced samples with and without embroidered sensors, the influence of the embroidered sensor on the stiffness can be considered as negligible. The Young's modulus in load direction decreased by less $5\,\%$ and is in the range of 20 to $22\,\mathrm{GPa}$.

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