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Self-sensing properties of continuous carbon fiber reinforced, 3D-printed beams

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Summary:
This paper investigates self-sensing properties of continuous carbon fiber reinforced, 3D-printed beams as function of the number of reinforced perimeters. Samples containing various numbers of reinforced perimeters are tested for their stiffness and strain-dependent resistance using three-point bending tests. The mechanical properties are modelled using classical beam theory and the resistance can be estimated using the resistance of the fiber additive. Large resistance changes are measured during bending, which results in a high responsivity.

Keywords: 3D-Printing, continuous carbon fiber, self-sensing structures, strain gauge, piezoresistivity

Introduction

A novel method in fused filament fabrication (FFF) called composite fiber co-extrusion (CFC) enables to 3D-print continuous carbon fiber (CCF). Using this method a thermoplastic polymer is extruded around the fiber, embedding it inside the printed part [1]. The fiber provides excellent mechanical properties, crucial for making lightweight and stiff components. Additionally, CCF is electrically conductive and has piezoresistive properties, enabling the use of CCF for self-sensing structures in which fibers provide strength as well as sensing functionality [2, 3]. This offers numerous advantages over traditional separate sensors, such as a simplified manufacturing process and distributed sensing of large-scale structures. Luan et al. showed that such self-sensing structures can function as strain gauge measuring a linear reversible resistance increase for elastic deformation and also to measure structural damage [3]. To investigate the influence of the fiber count on the performance of the strain gauges, this work presents the electrical and mechanical characterization of 3D-printed self-sensing reinforced beams with various numbers of reinforced perimeters.

Methods

The tested samples are beams with a rectangular cross section containing CCF perimeters in top and bottom layers, where they provide maximum stiffness, fig. 1. Beam theory is used to determine the stiffness of the beams from a three-point bending test. The beam model is split into five layers with varying volume fractions to account for different materials. Using the rule of mixtures [3] the effective Young's moduli E_{eff} for each section can be determined and with the transformed section method the area moment of inertia I_{eff}. The center deflection y_{max} during a three-point bending test and the stiffness k of the samples can be calculated using [4]:

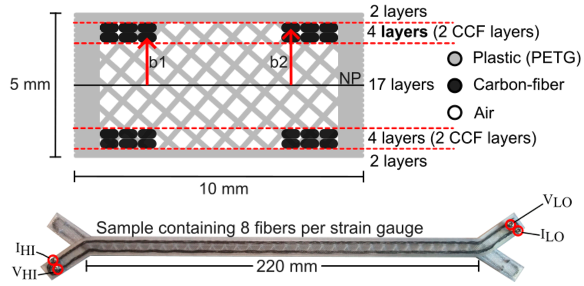

Fig. 1: Cross-section of the 3D-printed beams containing two strain gauges, made up of 2 fiber layers at distance b_1 and b_2 from the neutral plane (NP) and 3 reinforced perimeters (top). The 5 sections for the mechanical model are indicated by red lines. Topview of a beam with two CCF strain gauges (bottom)

$$y_{\text{max}} = \frac{FL^3}{48E_{\text{eff}}I_{\text{eff}}}, \quad k = \frac{F}{y_{\text{max}}} = \frac{48E_{\text{eff}}I_{\text{eff}}}{L^3} \quad (1)$$

where L the distance between supports and F is the applied force at $L/2$. The neutral electrical resistance is calculated from the resistance of a single filament and the number of fibers per beam, the piezoresistive responsivity K is defined as the relative resistance change per applied force:

$$R = \frac{R_{\text{fiber}}}{N_{\text{fiber}}} = \frac{R_{\text{fiber}}}{2N_{\text{layer}}N_{\text{perim.}}}, \; K = \frac{\Delta R/R_0}{F} \quad (2)$$

The test samples are printed on the Anisoprint

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Composer A4 [1], an FFF 3D-Printer with a secondary extruder for CFC with CCF and Polyethylene terephthalate glycol (PETG) as materials. The layer height is set at 0.17 mm for PETG and 0.34 mm for CCF. The fibers are placed as reinforcing perimeter in top and bottom layers with different perimeter counts, either with one fiber layer on each side with 1 to 3 reinforcing perimeters or with two fiber layers with 1 to 4 reinforcing perimeters. Additional samples are printed without fibers and with a maximum number of fibers (120). Each sample has two outer perimeters of PETG, with 20 % triangular infill and the first two and last two layers with 100 % PETG. CCF is placed symmetrically at the top and bottom to ensure a centered neutral plane and to prevent warping caused by the different coefficients of thermal expansion of PETG and CCF. Stainless steel M2 bolts are used as electrical connection to the carbon fibers. A Keithley 2000 multi-meter is used to measure resistance with 4-terminal sensing. The samples are tested on a three-point bending setup with rounded supports ($r = 5$ mm) placed 200 mm apart. A load is applied at the center using a linear actuator in force control mode (SMAC LCA25-050-15F), while also measuring the displacement in compression and tension. A triangular load is applied from 0 N to 12 N with a period of 20 s for ten periods. Equations 1 and 2 are used to predict the stiffness and resistance.

Results

The force deflection curves for tension and compression show a linear trend with hysteresis, fig. 2. The resistance change for the sample with two fiber layers and 1 reinforcing perimeter during compression and tension can be seen in fig. 2. Large changes in resistance of up to 50 % are measured, exceeding previous research with changes of ≈1 % [3]. Like in previous research, the piezoresistive response is non-linear, showing a decreasing sensitivity for larger deflections. The stiffness of the sample with 120 fibers has been used to determine the Young's modulus of the printed CCF: $E_{\text{CCF}} = 57.45$ GPa. The result is 43 % of the advertised CCF composite filament [1]. This result is confirmed by the model which matches the measured sample stiffness, fig. 2. Extrapolating the resistance of the unstrained, unprinted, CCF composite filament gives the expected neutral resistance in fig. 2. While most measured resistances are slightly higher than the expectation, there is a clear correlated trend. The resistance of the sample with two fibers is likely lower than the expected resistance as a result of inconsistent fiber placement. Due to unstable electrode connections under strain for the samples containing one fiber layer, the sensitivity is only determined for the two layered samples, fig. 2 bottom plot. It shows that the sensitivity of the CCF is higher in tension compared to compression. There is a negative correlation between the sensitivity and the fiber count, however, this is partly due to the relation between stiffness and fiber count.

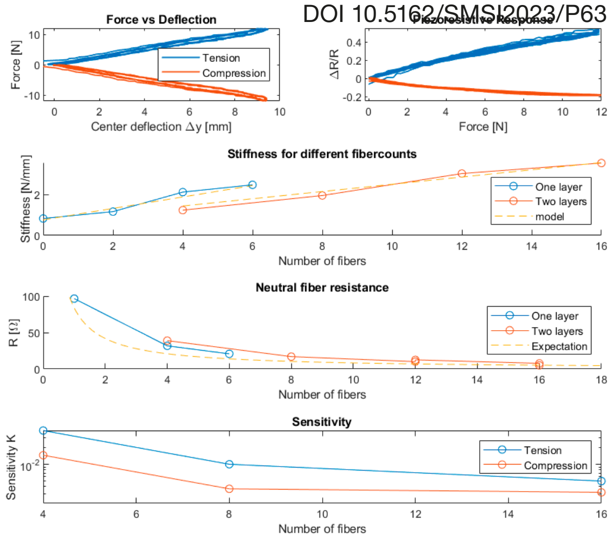

Fig. 2: Force deflection curve showing hysteresis (top left); Resistance response to tensile and compressive strain (top right); Measured stiffness (2nd row); Measured fiber resistance (3rd row) and Sensitivity for the two layered samples (bottom)

Discussion and Conclusion

This work demonstrates that resistance and stiffness of 3D printed continuous carbon fiber beams can be controlled by varying the perimeter count and can be predicted from theory. A high sensitivity of the strain gauges shows potential for sensitive CCF self-sensing structures, where the sensitivity is lower for compression compared to tension. More research is required to determine a correlation between the reinforcing perimeter count and the sensitivity of the self sensing structures. In future research the influence of other slicing settings, such as the fiber extrusion multipliers and plastic infill density, will be explored.

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