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Effect of orientation on the bending properties of a carbon fibre reinforced thermoplastic

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Abstract. Additive manufacturing is becoming a very rapidly developing production technology. It provides a wide range of combinations of material processing and used techniques, including the possibility of using different types of 3D printing machines. In order to know the properties of the part and take them into account in the design of the product, it is necessary to know the behaviour of the sample after loading, which was produced under the given specific conditions. The manuscript aims to study the bending characteristics of samples made of plastic reinforced with carbon fibres using additive technology. The samples of the same type were fabricated by FDM (Fused Deposition Modelling) using a MakerBot Method X printer. The experimental investigation was carried out using a Zwick 1456 testing machine. The experimentally tested samples were oriented in two different ways regarding the layers building. The measured data were evaluated and compared with the numerically obtained values. The results showed a strong effect of the sample orientation on the bending properties.

Introduction

Currently, thanks to the development of technologies, a large number of new materials are created, the properties of which need to be known before their application, especially when it comes to stressed components, the safety and reliability of which is critical for the operation of equipment. Knowing the properties of the component is all the more important if it is made of plastic using an additive approach since the heterogeneity of the properties affects its behaviour in operation. [1,2]

A specific category of materials creates the reinforced materials to which also Nylon 12 CF belong. Nylon 12 Carbon Fiber (Nylon 12CF) material consists of Nylon 12 reinforced with small pieces of cut carbon fibre for better bending strength, making this material one of the best of all materials in terms of stiffness-to-weight ratio. used in the manufacture of FDM (Fused Deposition Modelling) components. [3] Relatively good strength and stiffness allow this material to replace metals in some possible applications, for example replacing heavy metal tools with lighter and more ergonomic tools made of carbon fibre-reinforced plastics. [4] Its unique properties make it ideal for use in many applications across a wide range of industries, including automotive, consumer goods, recreational manufacturing and aerospace. [5]

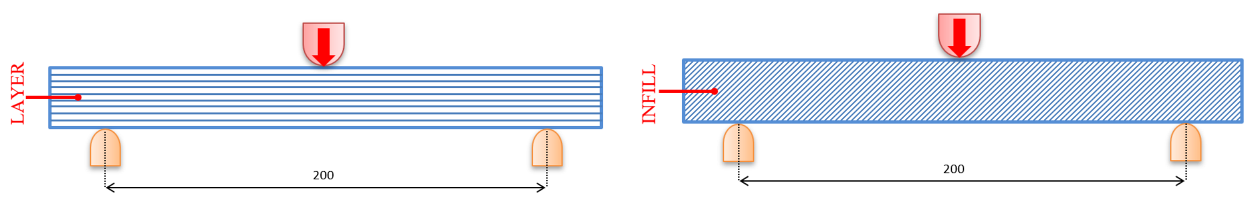
Only a very limited number of studies have dealt with the characteristics of this material. A comprehensive study regarding the effect of printing conditions on the quality of produced samples was provided by Korol et al. [6], however, an investigation of the effect of orientation on the bending properties was not presented in the paper, so the authors decided to deal with the topic.

Production and testing conditions

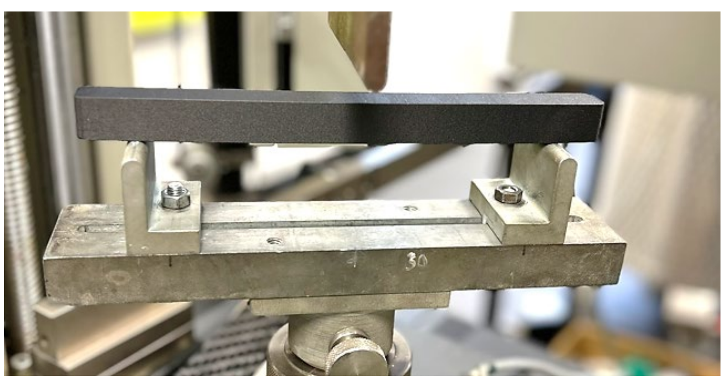
Totally 6 samples with sizes 20 x 20 x 250 mm were made by means of 3D printing machine type MakerBot Method X using the FDM technique. The next parameters were chosen based on the manufacturer's recommendation as well as a preliminary test and they were: nozzle diameter 0.4 mm; both the temperature of the basement and the temperature of the workspace area were 65 °C; the print speed was 35 mm/s and the layer thickness was set to 0.15 mm. The heat treatment of the samples was performed at 80 °C according to the 3D printer producer's recommendation for the given material.

Three-point bending tests were carried out by the Zwick 1456 testing machine at an ambient temperature of 20 °C with a humidity of 50 % according to the ISO 178:2019 standard. [7]

The samples were placed on supporting pins with a supporting span of 200 mm (Fig. 1). The orientation of the three samples during the experimental testing corresponded to the orientation of the sample formation (Fig. 1a), while three samples were oriented perpendicular to the layering plane (i.e., parallel to the direction of movement of the pusher as shown in Fig. 1b). The radius of the pusher was 5 mm and the speed of the cross-head was set at 20 mm/min.



a) parallel orientation b) perpendicular orientation



c) real view

Figure 1. Position of a sample during testing.

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Results and discussion

Within the preliminary study, the filament was tested by quasistatic tensile test according to ASTM D638 [8] standard to confirm its properties given by the datasheet. The experiments were realized employing a Testometric X350-5 testing machine (Fig. 2a) at an ambient temperature of 19 °C and a cross-head speed of 50 mm/min. Six pieces of fibre with a length of 100 mm were used, and the measured data are shown in Fig. 2b. The results (elongation at break 1.9 % and tensile strength 85.35 MPa) showed that the properties of the thermoplastic polymer correspond to the properties listed in the material sheet. [9,10]

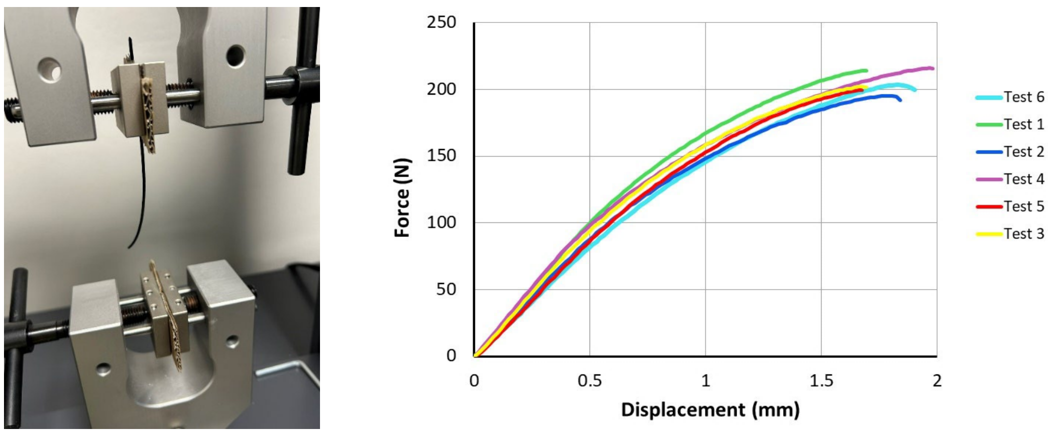
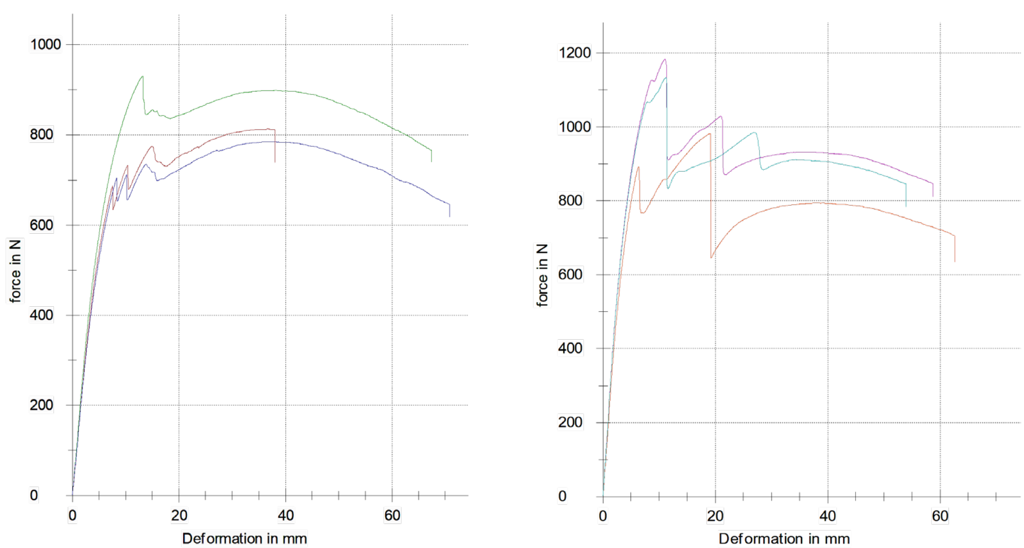


Figure 2. Preliminary test to verify the Nylon 12 CF filament properties

Using the Nylon 12 CF filament, the samples described in the previous section were produced, which were subjected to three-point bending testing. During the experimental investigation, the force-deflection dependencies were recorded and the measurements for the same sample orientation were plotted together, as shown in Fig. 3.



a) parallel position b) perpendicular position

Fig. 3 Measured force-deflection dependencies

The obtained data were statistically processed and based on them, the flexural yield strength and flexural elastic modulus were calculated according to the equations (1) and (2) respectively [11,12]

$$\sigma = \frac{M}{I} z \quad \text{(MPa)} \tag{1}$$

$$E = \frac{F_e l^3}{48 u_e I} \quad \text{(MPa)} \tag{2}$$

where σ is the resulting stress at a distance "z" from the neutral axis, I is the area moment of inertia, l is a supporting span and u_e is elastic deflection.

Moreover, the absorbed energies at break were also computed based on equation (3) which is represented by the area under the curve representing the force-deflection dependence: [13]

$$U = \int_0^l \frac{M^2}{2EI} dx. \tag{3}$$

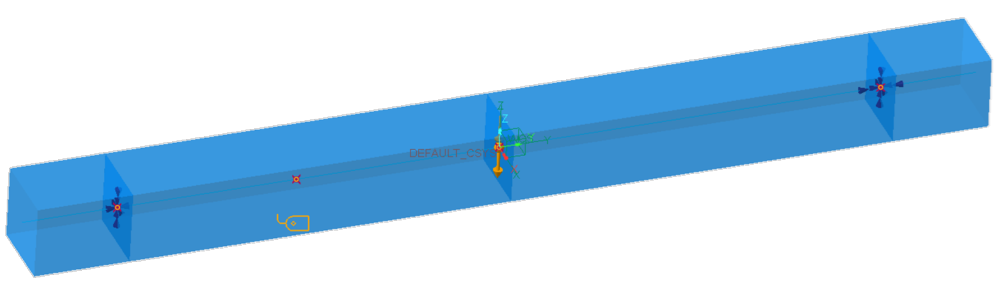
Average achieved values are listed in Table 1 and it can be seen that the difference between Young´s modulus is very high.

Table 1 Measured and calculated values of flexural characteristics

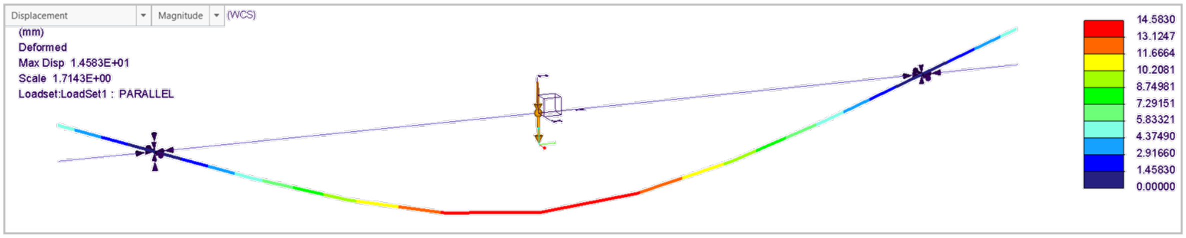
Orientation of the sample with respect to the layering plane	Elastic force (N)	Deflection at elastic force (mm)	Flexural modulus (MPa)	Yield strength (MPa)	Total absorbed energy (J)
Parallel	852	14.1	755	31.95	45.32
Perpendicular	1100	9.5	1408	40.125	47.85

Based on the obtained results it is clear that there are relatively big differences not only in flexural modulus (more than 85 %) but also in yield strength values (25 %), however, the total absorbed energy in both cases of orientation is almost the same.

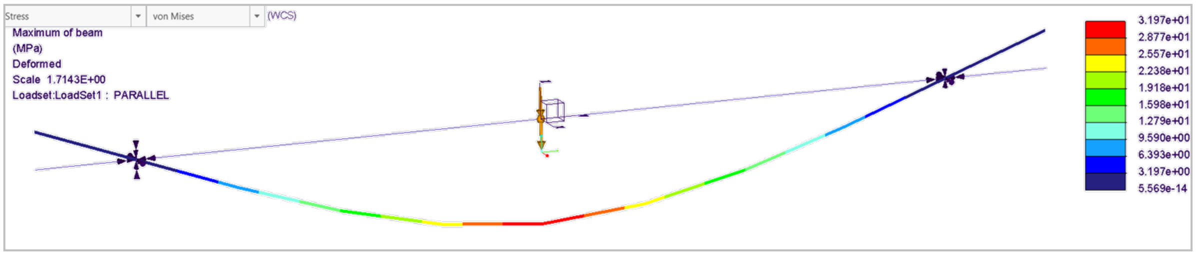
The experimental data were compared with the results solved by means of numerical analyses. Given that the beam is simple, a linear idealization was applied to the software PTC Creo 10. The beam with the constraints and a force load is shown in Fig. 4a, while Figures 4b and 4c show the results for the parallel orientation of the beam, and Figures 4d, and 4e show the results at the perpendicular beam orientation. They are summarized in Table 2, where also the comparison with experimental data can be found.



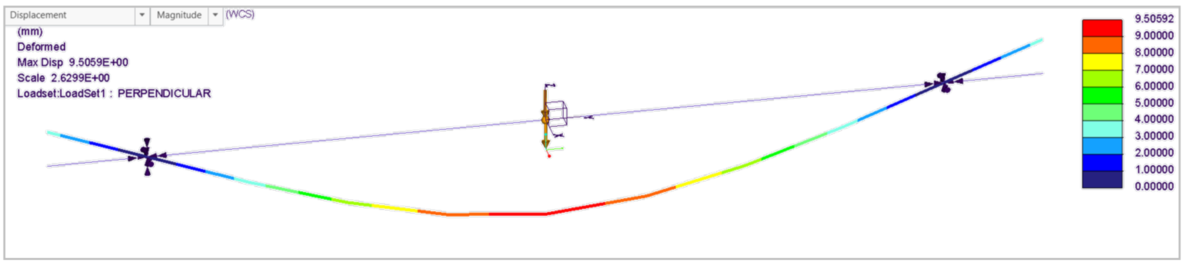
a) load set and constraints of FEA



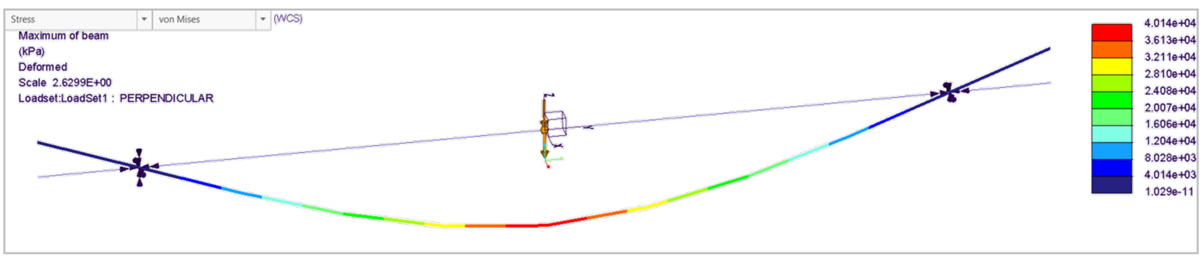
b) displacement at parallel orientation of a sample during testing



c) Stress von Mises at parallel orientation of a sample during testing



d) displacement at perpendicular orientation of a sample during testing



e) Stress von Mises at the perpendicular orientation of a sample during testing.

Fig. 4 Results of numerical analyses.

Table 2 Comparison of the measured/calculated data with numerical analysis results

Orientation of the sample with respect to the layering plane	Deflection at elastic force (mm)		Flexural yield strength (MPa)	
	FEM	Measured	FEM	Calculated
Parallel	14.58	14.1	31.97	31.95
Perpendicular	9.82	9.5	40.14	40.125

Based on Table 2, it is clear that the numerical analysis results are in high accordance with measured (calculated) values, however, the values of the samples´ flexural properties are very far from the values related to the filament flexural properties mentioned in datasheets. Stratasys FDM-Nylon 12 CF data sheet provides the flexural modulus values of the filament in two axes of 10.3 and 2.07 GPa [9,14] (obtained according to the ASTM D790 test method), and Ricoh Europe PLC [15] provides the value of a flexural modulus 10.62 GPa. It indicates that values of the Nylon 12 CF filament properties can not be used for the sample body behaviour simulation in a software application and should be first verified experimentally, also due to a big variety of material, production, testing and processing aspects that it is necessary to take into account during numerical analysis.

Summary

Additive technology is a rapidly developing way of the various parts production for a wide spectrum of usage and applications. This approach to manufacturing can provide the components with a lot of benefits, including sustainability, material savings and improving the environmental conditions. However, there are still a lot of challenges that need to be addressed and solved related to this technology.

Within the manuscript, the effect of sample orientation during testing regarding to the orientation during its production was studied. Six specimens produced at the same conditions were subjected to the three-point bending testing at two different orientations (rotated 90° to each other).

The results showed a big difference between the flexural modulus for the specimens oriented in parallel (755 MPa) and perpendicular (1408 MPa) ways regarding the layering during 3D printing, as well as relatively big differences between yield strengths (31.95 MPa at parallel orientation and 40.125 MPa at perpendicular orientation) but the amount of absorbed energies was almost the same (45.32 J at parallel orientation and 47.85 J at perpendicular orientation).

The obtained experimental values were in good agreement with the results obtained by the numerical analysis, however, the values indicate that the fibre characteristics are different from those characterizing the behaviour of the fabricated body/specimen.

In conclusion, it can be concluded that not only the orientation during 3D printing with respect to the subsequent load has a great influence on the mechanical properties of the components, but also other conditions such as the printing strategy, pre-, and post-processing of samples and the like, which subsequently influence the resulting properties of the part, also play a large role. and can affect its reliability and service life. In the near future, the authors would like to continue the research and study the effect of other aspects on the Nylon 12 CF behaviour under loading.

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