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Finite element simulation of tensile test of composite materials manufactured by 3D printing

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Abstract. A principle of 3D printing is based on formation of continuous layers of materials up to a formation of the final shape. Materials for production of given components are composite materials, especially on the basis of so-termed CFRP, CRP, (carbon fibre – so-termed polymers reinforced by carbon fibres). The objective of this paper is to predict the deformation length of carbon/onyx composite laminates using Finite Element Analysis (FEA) and compare with universal testing machine INOVA FU 160 deformation results through the tensile load. Specimen were printed at raster orientation angles of 0°, 45° and 90° to test orientation effects on part strength. 16 ply CFRP specimens with various stacking sequences were analysed for their strength and displacements. A shell model has been established for simulation of the tensile test composite specimen which enables to understand the mechanical strength and strain at failure of the composite materials. The simulations of experiment are provided in FEM program ANSYS and ANSYS/Workbench.

1. Introduction

Additive technologies (AT) belong to one of the most progressive technological methods for manufacturing dimensionally contoured and complex construction components [1, 2]. A principle of manufacturing is based on formation of continuous layers of materials up to a formation of the final shape. Materials for production of given components are composite materials, especially on the basis of so-termed CFRP, CRP, (carbon fibre – so-termed polymers reinforced by carbon fibres). At present additive technologies (AT) are a solid part of ferrous and non-ferrous composites. The present development of materials enables to form new types, e.g., Composite Filament Fabrication (CFF) which enables to form structures of carbon, glass and kevlar fibres. Mechanical properties of the mentioned materials far outreach properties of polymers based on ABS and it is possible to compare them with aluminium alloys (durals) or common construction steels [3].

The present-state research of evaluation of materials and construction components formed by AT is aimed at an evaluation of mechanical properties, geometrical accuracy based on metrological productional requirements as well as machinability of the stated materials with metal and non-metal elements [4, 5].

AT enable to form a component without more striking limits of a shape or a function. When designing, it is possible to consider all requirements of functionality of a component regardless shape limits. They find their applications mainly in modern and progressive branches such as aviation, automobile industry or medicine [6, 7].

There are several excellent books, articles, web pages, etc., describing the invention and development of 3D printers [8–10].

2. Materials and testing methods

In present investigation two different materials are used. The material of matrix is Onyx and its material properties is given in table 1. Onyx filament is part nylon, part chopped carbon fibre. It is a proprietary Markforged material [11] that offers greater stiffness and better dimensional stability than engineering grade nylon, with twice the strength of traditional engineering-grade thermoplastics, such as Acrylonitrile butadiene styrene (ABS), Polylactic or polylactide (PLA) and even tough resins. Carbon Fibre CFF (Table 2) has the highest strength-to-weight ratio of all Markforged materials. It has a tensile strength of 700 MPa and a flexural strength of 470 MPa; greater than HSHT Fibreglass by 100 MPa and 50 MPa respectively. It also has a compressive strength of 320 MPa, which is more than twice the compressive strength of regular fibreglass. With carbon fibre, you can 3D print the strongest possible parts. Markforged have an extensive range of composite 3D printing materials that boast extreme abrasion resistance, heat deflection temperatures, impact resistance and strength. For example printing with some of these materials yields parts with a higher strength-to-weight ratio than 6061-T6 aluminium.

Table 1. Material properties of Onyx [12].

Material	Modulus of elasticity E [GPa]	Poisson´s ratio μ	Density ρ (g cm^{-3})
Onyx	1.4	0.3	1.2

Table 2. Material properties of carbon fiber [12].

Material property	Value
Modulus of elasticity of lamina in the direction of fibers E_1 (GPa)	64.7
Transverse modulsof elasticity E_2 (GPa)	22.4
Shear modulus of elasticity of the lamina G_{12} (GPa)	22.1
Shear modulus of elasticity of the lamina G_{23} (GPa)	8.3
Poisson´s ratio μ_{12}	0.3
Poisson´s ratio μ_{23}	0.35
Density ρ (g cm^{-3})	1.4

A schematic overview of the material feeding system of the Markforged 3D printers is shown in figure 1. Both the Nylon filament spool and the fibre filament spool supply the materials through separate tubes to their respective nozzles on the printer head [13]. It should be noted that the Markorged printers will only print one type material at a time. The printer is either depositing matrix material or fibre filament, never both at the same time. The nylon filament system (green) and the fibre filament system (yellow) are both practically the same except for the fact that the fibre system has a cutting tool, that cuts the fibre filament at a required length. The nylon spool is fed to the extruder, which then pulls the filament from the spool into the tube leading to the print head. In the print head, the nylon gets heated to 265 °C, which is above the melting temperature, making the nylon ready to be deposited. The red area in the print head (figure 2) indicates the area that is heated.

Figure 1. 3D printer MarkTwo [14].

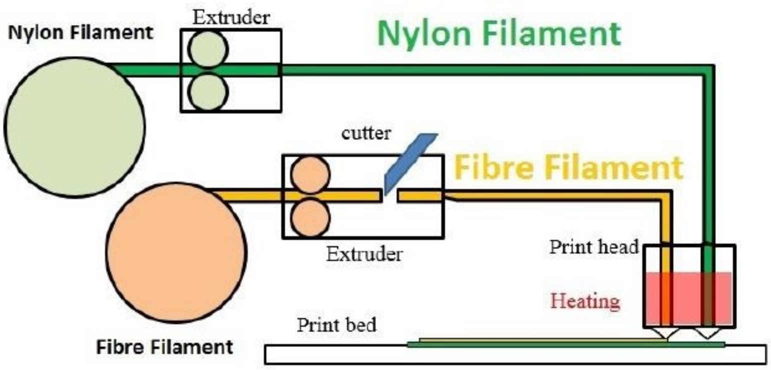

Figure 2. The scheme of the nylon and fibre feeding system of the MarkForged3D printers.

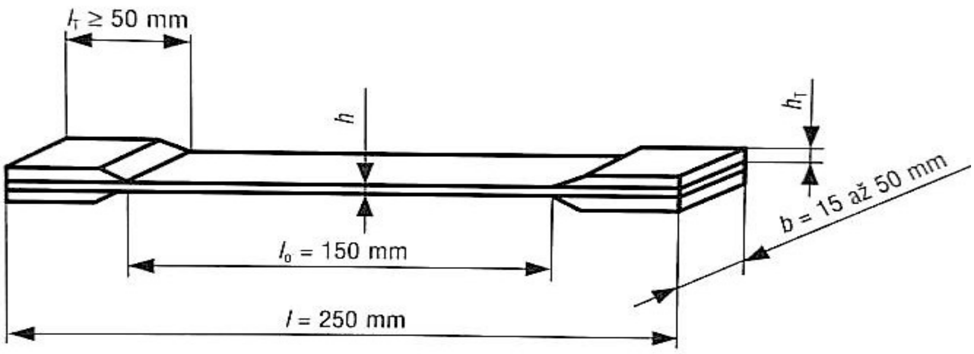

Figure 3. Specimen specification [15].

Tensile test specimens were fabricated in accordance to ASTM D 3039 standards using 3D printer Mark Two as shown in figure 3. In accordance with STN EN ISO 527 - 5, we have printed specimens of dimensions 250 × 25 × 1.875 mm (length x width x thickness) for the tensile test.

For 3D printing we used software the Eiger [15] for uploading the stl-files to the printer. It is important to note that Eiger software does not allow a print to start with a fibre reinforced layer, nor to end with one. These outer layers need to be of matrix material. The specimens are composed from 15–16 layers containing Onyx and carbon fibers (figures 4 and 5) and detailed description is in the figures 6–8. The red colour is onyx and the black coloris carbon fibers. We analysed three specimens and fiber arrangement is in the table 3.

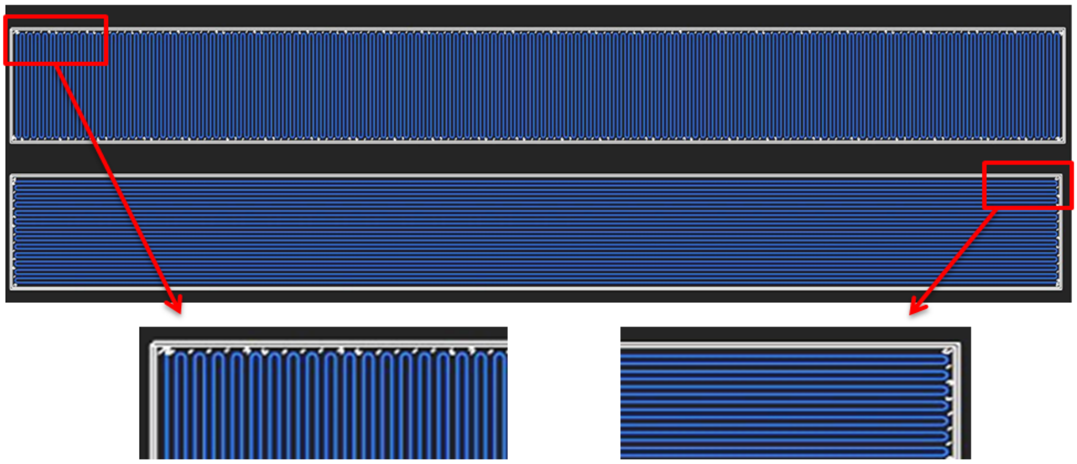

Figure 4. Orientation of carbon fibers in layers (above 90°, down 0°).

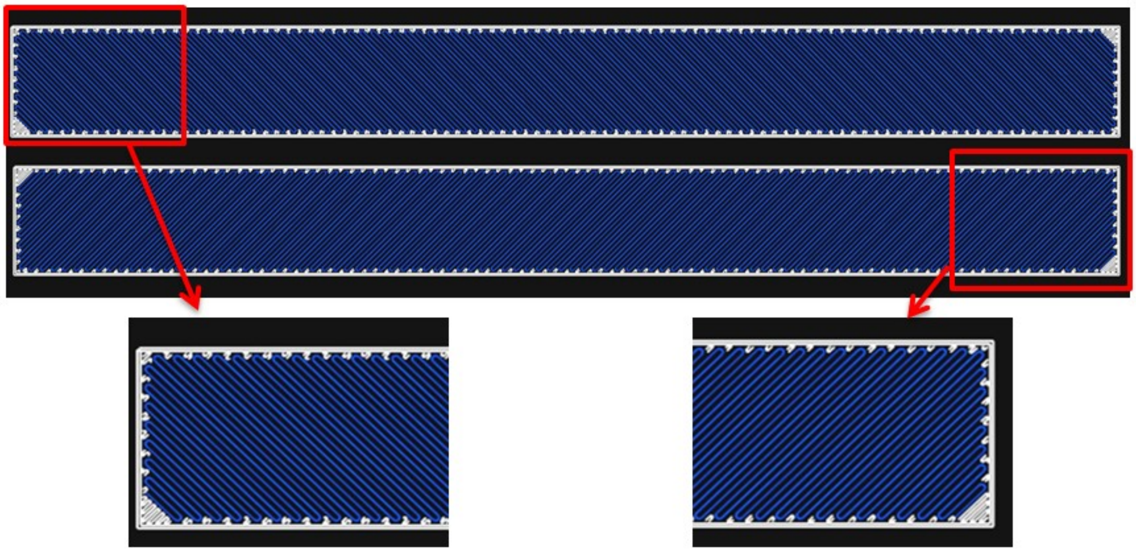

Figure 5. Orientation carbon fibers in layers (above 45°, below -45°).

Table 3. Ply sequence of composite test specimens.

Specimen number	Onyx orientation	Carbon fiber orientation
1	45°/ - 45°	90°
2	45°/ - 45°	45°/ - 45°
3	45°/ - 45°	0°

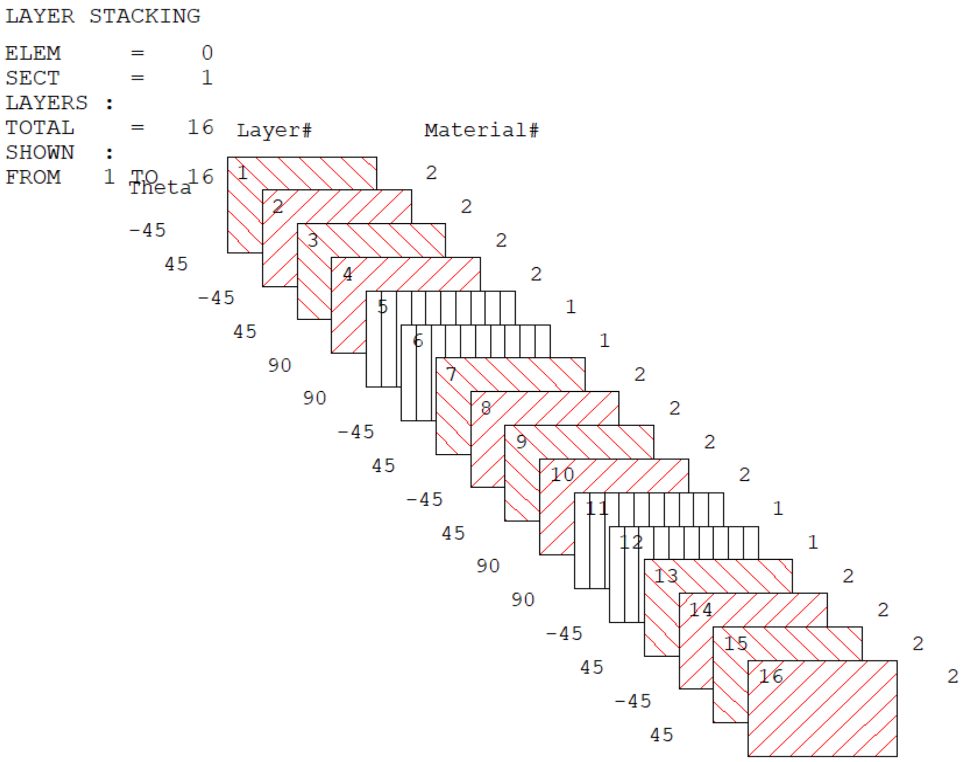

Figure 6. Layer stacking sequence of specimen no. 1 (90° fiber orientation).

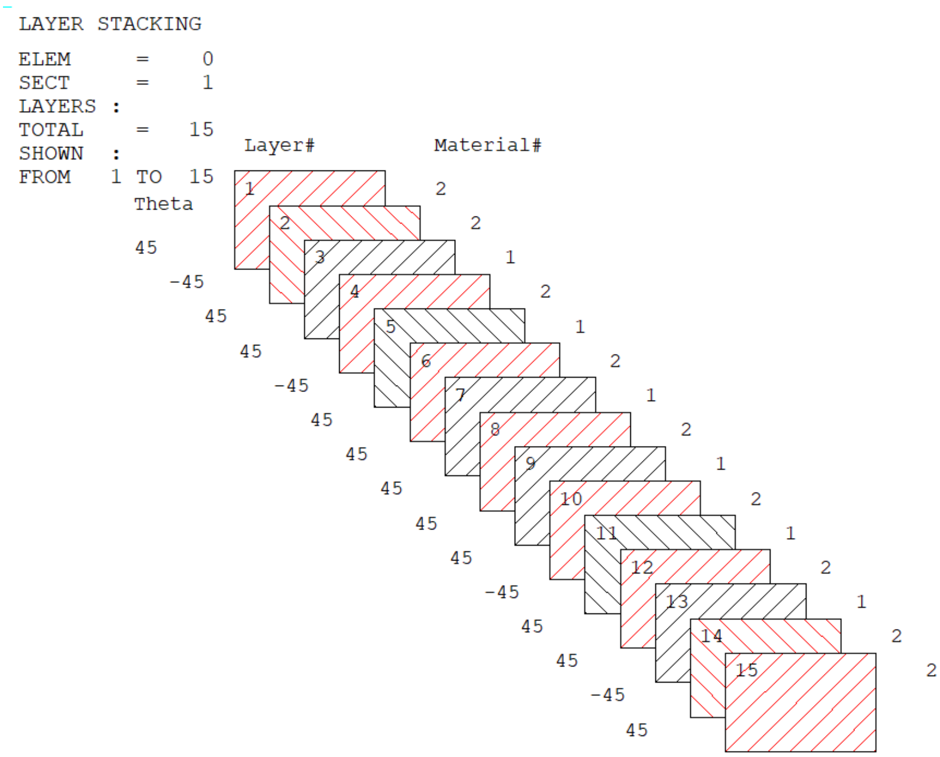

Figure 7. Layer stacking of specimen no. 2 (45° fiber orientation).

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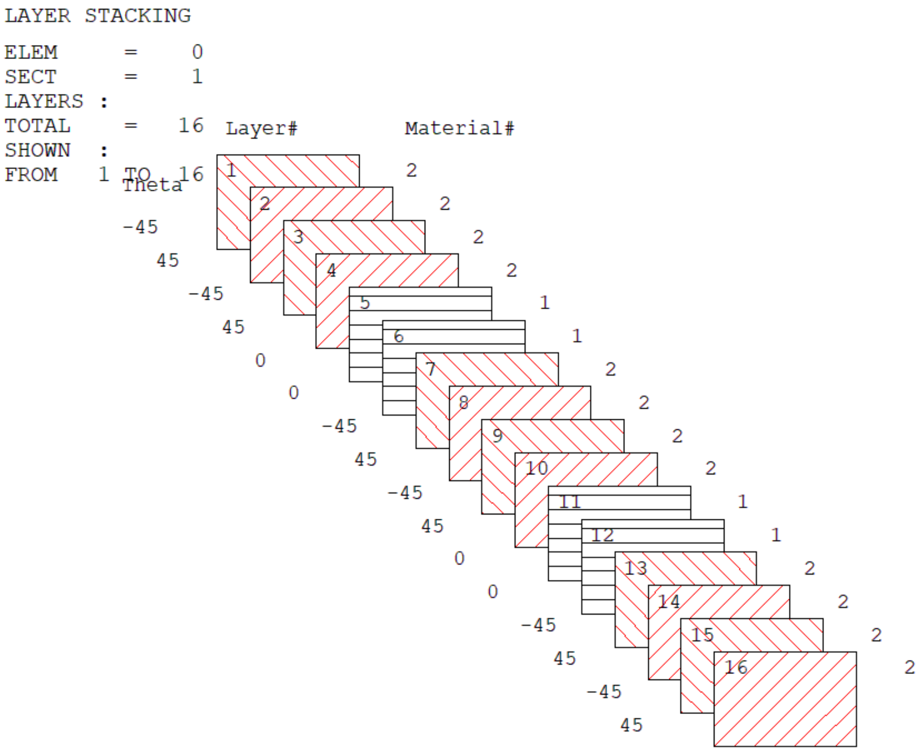

Figure 8. Layer stacking of specimen no. 3(0° fiber orientation).

3. Finite element modeling

Real tests of specimens were simulated with finite element analysis software ANSYS Workbench. Modelling of composite architecture was performed using software ANSYS Composite Pre/Post (ACP) [16]. For specimens meshing four nodes shell finite element SHELL181 was used. After some preliminary simulations in ANSYS APDL adequate size of finite element was determined for which simulation results converge.

This validation of software is necessary to have greater confidence in subsequent simulation results of parts modelled from tested composite materials. In calculation methodology of finite element stiffness matrix the following assumptions relating to material are considered [17]:

- material behaves linear ideal elastic. i.e. for each individual layer is applied law of linear elasticity;
- theory does not include cracks, air pockets etc.;
- lamina from composition laminates are orthotropic, parallel and perfectly stuck together;
- fibers are not examined isolated of matrix nor adhesive layer (interface effects are neglected);
- individual layers are bonded ideally to each other. In case of loads application relative slip doesn't appear.

In the present study the FEM simulation was carried out on a CFRP tensile specimen using commercially available software ANSYS Workbench which solve complex engineering problems ranging from linear to non-linear behaviour. The finite element model of composite specimen under static load was modelled and stress analysis was carried out. The geometry of the test specimen is rectangular with length 250 mm, width 25 mm, thickness 1.875 and margin of 57 mm from each ends for gripping as depicted in figure 9. In order to replicate there altensile test the boundary and loading conditions are applied as similar to the actual tensile test experiment. The lower grip of specimen was kept as fixed in all direction while the upper grip was kept as fixed in all directions but unconstrained in longitudinal direction i.e. free in the direction of load applied. The figure 10 shows geometric model and figure 11 shows FE model of test specimen with specified boundary conditions. The upper grip was loaded with a surface traction load recalculated to nodes: F = 1500 N for specimen no. 1, F = 3600 N for specimen no. 2 and F = 9600 for specimen no. 3 (tables 4–6).

Figure 9. Testing specimen.

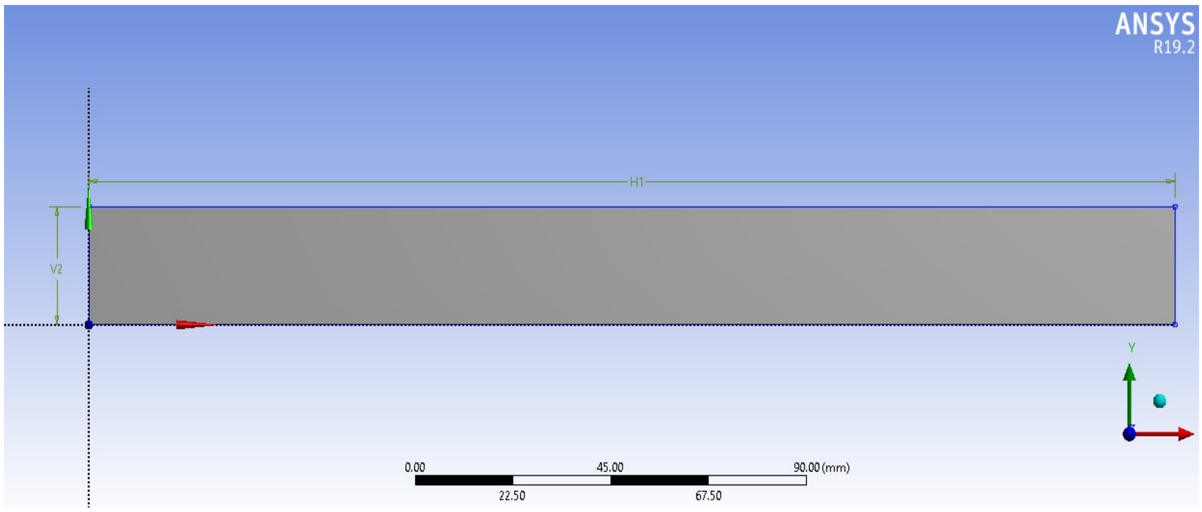

Figure 10. Geometric model of the rectangular test specimen.

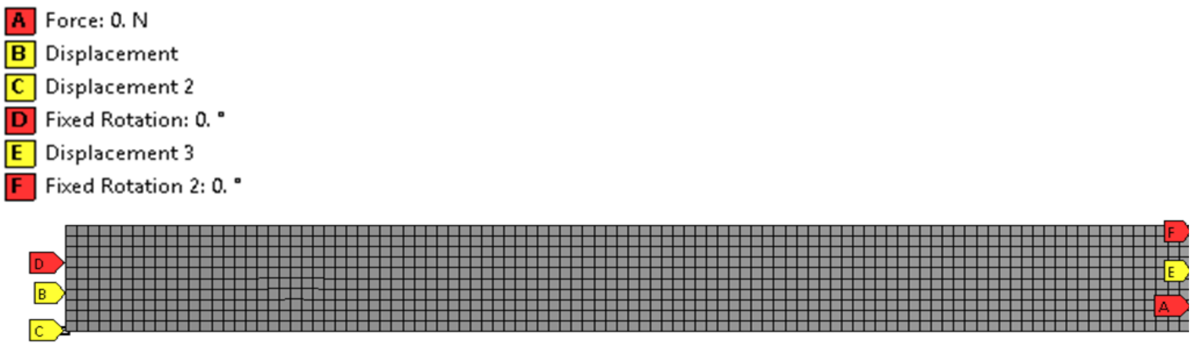

Figure 11. FE model of test specimen with boundary and load conditions.

4. Results

The tensile specimens obtained from the laminates are subjected to uni-axial tension using machine INOVA FU 160 (figure 12).

From figures 13 and 14 we can see that in the specimen no. 1 (90° fiber orientation) and specimen no. 2 (45° fiber orientation) the fracture surface corresponds to the carbon fiber orientation. Specimen no. 3 in figure 15 (0° fiber orientation) exhibits a similar fracture area as in specimen no. 1. The tensile strength was calculated for all specimens. As excepted specimen no. 1 has the lowest strength because the load was transferred by the Onyx matrix, which contains a high proportion of nylon. In tables 4–6 are evaluated basic parameters from tensile test results. The specimen with 90° orientation shows the greatest deformation (38 %) and at the same time has the lowest tensile strength R_m = 28.841 MPa.

In figure 14 is a tensile test diagram of a specimen having a fiber orientation of 45°. This graph is linear, unlike the previous one, which is typical of composites. The number of all layers is 15 and must be placed symmetrically from the plane of symmetry to prevent torsion twisting when tearing. For the same reason, the layers containing the fiber reinforcement are oriented at both 45° and -45°. As shown in figure 14, fracture runs along the fibers at an angle 45°.

Figure 12. The Inova test machine.

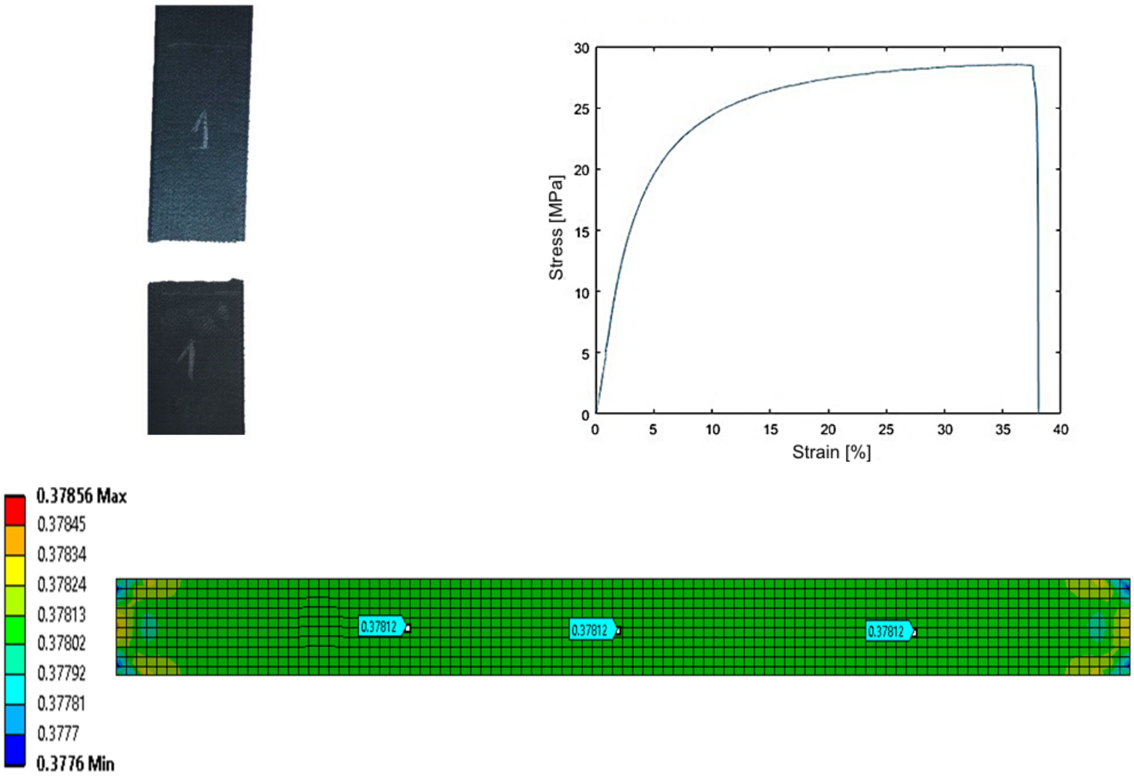

Figure 13. Tensile test and FEM results for specimen 1.

Table 4. Tensile test results for specimen no. 1.

Parameter	Specimen no. 1.1	Specimen no. 1.2
Max. force *F* (N)	1442.051	1405.278
Tensile strength R_m (MPa)	28.841	28.105
Elongation L_u (mm)	19.035	18.932
Deformation ε (%)	38.070	37.864
Elasticity modulus *E* (MPa)	0.757	0.742

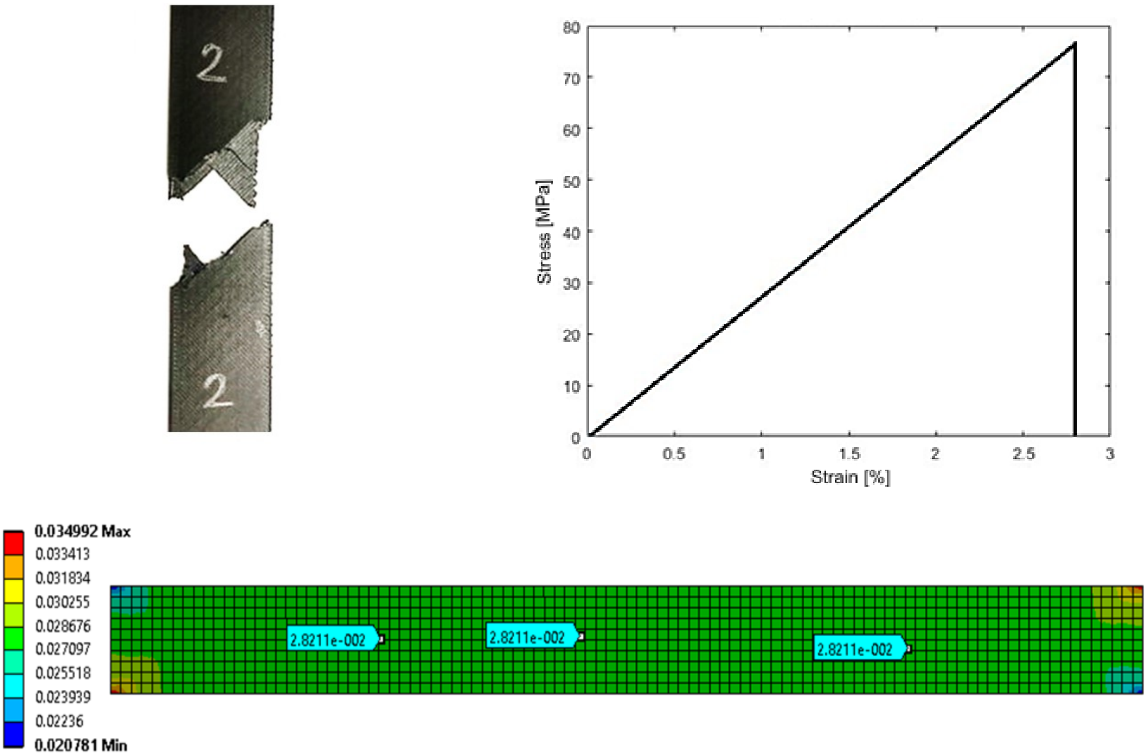

Figure 14. Tensile test and FEM results for specimen no. 2.

Table 5. Tensile test results for specimen no. 2.

Parameter	Specimen no. 2.1	Specimen no. 2.2
Max. force *F* (N)	3521.998	3440.779
Tensile strength R_m (MPa)	75.136	73.403
Elongation L_u (mm)	1.399	1.391
Deformation ε (%)	2.798	2.782
Elasticity modulus *E* (MPa)	26.853	26.385

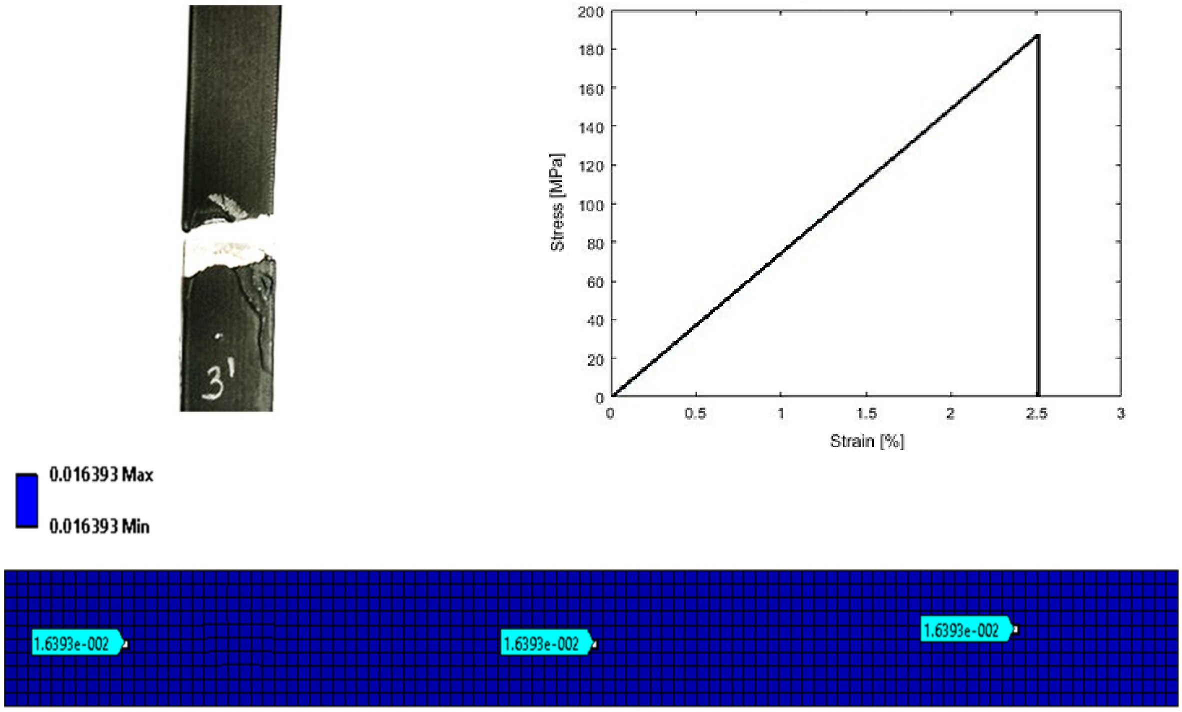

Figure 15. Tensile test and FEM results for specimen no. 3.

Table 6. Tensile test results for specimen no. 3.

Parameter	Specimen no. 3.1	Specimen no. 3.2
Max. force *F* (N)	9390.253	9578.020
Tensile strength R_m (MPa)	187.805	191.60
Elongation L_u (mm)	1.208	1.243
Deformation *ε* (%)	2.416	2.486
Elasticity modulus *E* (MPa)	77.34	77.055

In FEM simulations, we investigated the deformations of the specimens and results were compared with the results of the performed tensile test. In ACP software we also compared the stresses in the individual layers where Onyx was located and the layers that were reinforced with carbon fibers. Table 7 shows a comparison of the deformation results in the experiment and the simulation and the difference between them is calculated.

Table 7. Comparison of results.

Specimen	Deformation experiment ε (%)	Deformation simulation ε (%)	Difference (%)
1	38.070	37.812	0.682
2	2.798	2.821	0.815
3	2.486	1.639	34.071

5. Conclusion

Three types of composite specimens composed from two materials were used in the experiment: matrix and reinforcement-carbon fiber. The specimens had a rectangular shape with dimensions of 250 × 25 × 1.875 mm and differed in the angular orientation of the reinforcement. The specimens also differed in thickness, where two specimens contained 16 layers (4 reinforced) with one specimen containing layers 15 (6 reinforced). The thickness of one layer was 0.125 mm. We used 3D printing technology to prepare test specimens. The specimens also differed in the angular orientation of the carbon fibers in the layers. Specimen no. 1 had carbon fibers pressed at 90°, specimen no. 2 at 45° and the last specimen, specimen no. 3, the fibers had an angle of 0°.

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