Validation of Methodology for Numerical Modeling of 3D Printed Structures Reinforced by Long Carbon Fibers

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Abstract: This paper describes the main experimental and numerical results gained for 3D printed composites prepared by FDM technology. The matrix is considered from onyx – short carbon fiber reinforced nylon. In a dual nozzle system, long carbon fibers are prepared in the required orientation. Realized tensile tests were used to identify the elastic properties of the matrix and long carbon fibers. Gained experimental stiffness of the shear specimen under three loading modes was used to verify the proposed numerical strategy, making possible the introduction of contour lines of carbon fibers in the computational structural analysis.

Keywords: 3D print; carbon; electronic speckle pattern interferometry; digital image correlation; FEM.

1 Introduction

Additive Manufacting (AM), the main technology behind manufacturing of these structures is the method of linking materials to result in a 3D model. This technology makes it easier to construct larger ranges of prototypes or components with much complex geometrical structures or those structures which are quiet complex to be manufactured by conventional methods. There are various techniques used behind Additive Manufacturing, but in this case, the Fused Deposition Modelling (FDM) technique is used to fabricate the parts due to its low wastage and ability for material change post-fabrication [1]. There are many industrial applications of 3D printed composites due to their excellent strength-to-weight and stiffness-to-weight ratios.

The 3D printed composite materials bring the required properties. Mark forged X7 printer offers a unique possibility of printing composites, in which a plastic matrix, applied using FDM technology and a reinforcing fiber is continuously inserted into it through a dual nozzle. The laser unit controls the quality and height of the layer during printing to ensure the highest possible dimensional accuracy. 3D printer offers combining a matrix material in the form of nylon, nylon reinforced with short carbon fibers (Onyx), or nylon with additives against burning (Onyx-FR) or electrostatic discharge (Onyx-EDS) with carbon, glass, or aramid long fibers. Parts can be printed as solid or filled with a honeycomb structure. Structural parts with high demands on accuracy and durability can be produced. However, the elastic properties and numerical modeling approaches of 3D printed composites are still open questions. Some useful results obtained for onyx were published in [2–4]. Mechanical properties of 3D printed composite materials with carbon fibers were tested in tension [5] as well as flexural and indentation conditions [6].

This contribution presents the current state of mechanical testing realized on specimens made of onyx reinforced by long carbon fibers (CF) at VSB-Technical University of Ostrava. Tensile tests were realized considering different fiber volume fractions to estimate the elastic properties of the matrix and fibers. Then, a shear-type specimen was used in the measurements via optical methods to gain a basis of validation data for developing a suitable numerical modeling approach.

2 Analytical approach for tensile load

Analytical approach is an easy and quick way of Young's modulus calculation for various volume fractions. Estimation of Young's modulus for longitudinal and lateral loading of a unidirectional fiber composite are depicted below.

2.1 Expression for longitudinal loading

Let us consider the tensile load of F_c acting along the vertical direction in the longitudinal fiber direction as shown in the Fig. 1. The Fig. 1 shows the blue region which is the carbon fiber orientation direction, and the white region is the Onyx region. Because of the application of the tensile load, the composite tends to elongate with the distance of δL as shown in the Fig. 1. Crucial idea is that both the fibers and the matrix are experiencing the same elongation along the loading direction, which leads to establish the relation as follows.

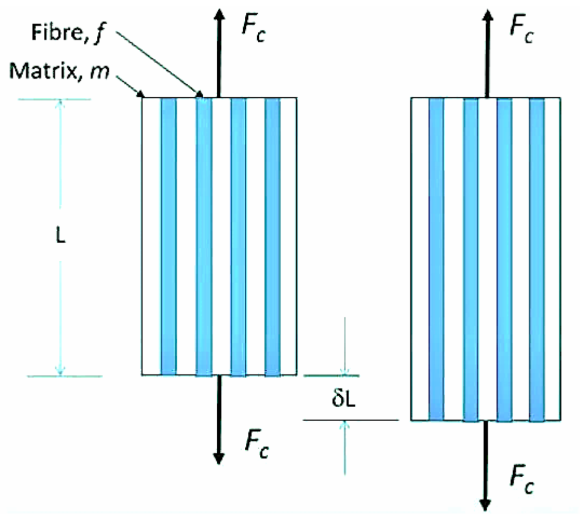


Fig. 1: Unidirectional fiber in Longitudinal direction.

Equilibrium of the forces is described by the equation

$$F_C = F_F + F_M, \tag{1}$$

where F_C, F_F and F_M are the total force in composite, the force in carbon fibers, and the force in the matrix, respectively. After substituting the relationship between an axial stress and corresponding cross-sectional area

$$\sigma_C A_C = \sigma_F A_F + \sigma_M A_M, \tag{2}$$

where $\sigma_C, \sigma_F, \sigma_M$ are stresses acting in matrix, fiber and composite respectively, and A_C, A_F, A_M are cross-sectional areas of composite, long fibers and matrix, respectively. Due to the geometrical constraints total strain in the composite ε_C is the same as in fibers ε_F and matrix ε_M, i.e.

$$\varepsilon_C = \varepsilon_F = \varepsilon_M. \tag{3}$$

The stress-strain relationship is given by

$$\begin{aligned} \sigma_c &= E_C \varepsilon_C \\ \sigma_F &= E_F \varepsilon_F \\ \sigma_M &= E_M \varepsilon_M \end{aligned} \tag{4}$$

where E_M, E_F, E_C is Young's modulus obtained in matrix, fiber and composite respectively, By combining the Eqs. 4 with the Eq. 2, we get

$$E_C \varepsilon_C A_C = E_F \varepsilon_F A_F + E_M \varepsilon_M A_M. \tag{5}$$

The volume fraction of fibers can be expressed by

$$V_F = \frac{v_F}{v_C} = \frac{A_F}{A_C}\frac{L}{L} = \frac{A_F}{A_C}, \tag{6}$$

where v_F, v_C are volumes of fibers and the whole composite respectively. The volume fraction of matrix V_M could be expressed analogously considering the volume of matrix v_M. Then, considering V_M, V_F as volume fractions of matrix and fibers respectively, the rule of mixture can be stated

$$E_C = E_F V_F + E_M V_M. \tag{7}$$

Similarly, strength equation

$$\sigma_C = \sigma_F V_F + \sigma_M V_M \tag{8}$$

and the equation for ultimate strength

$$\sigma_{C,ult} = \sigma_{F,ult} V_F + \sigma_{M,ult} V_M, \tag{9}$$

where $\sigma_{M,ult}, \sigma_{F,ult}, \sigma_{C,ult}$ are the ultimate stresses obtained in matrix, fiber and composite respectively.

2.2 Expression for transversal loading

Let us consider the tensile load of F_C acting along the vertical direction perpendicular to that of the fiber direction (Lateral direction) as shown in the Fig. 2. The Fig. 2 shows the blue region which characterizes the carbon fiber orientation direction, and the white region is the Onyx region. Both the fibers and the matrix are experiencing the same force and stress along the loading direction, which leads to establish the relation analogously as for the longitudinal direction.

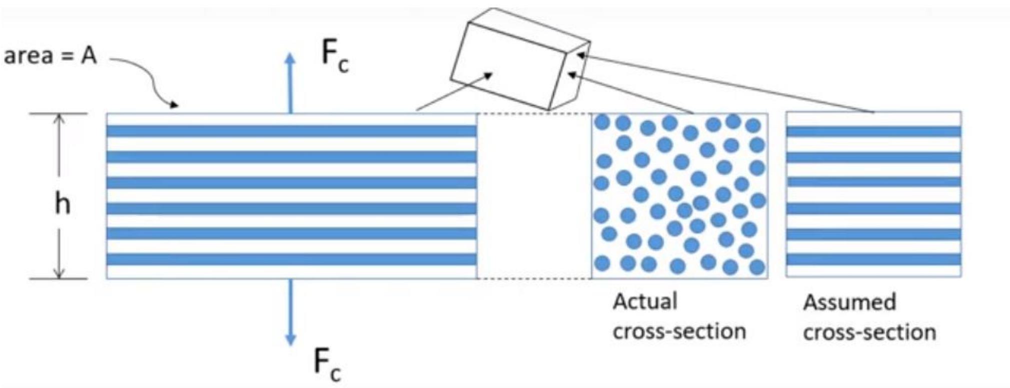


Fig. 2: Unidirectional fiber in Transversal direction.

Equilibrium of the forces:

$$\begin{aligned} F_C = F_F &= F_M, \\ \sigma_c = \sigma_F &= \sigma_M. \end{aligned} \tag{10}$$

Geometry of deformation: Total strain in the composite can be written as

$$\varepsilon_C = V_F \varepsilon_F + V_M \varepsilon_M. \tag{11}$$

The stress-strain relationships are given by

$$\begin{aligned} \sigma_C &= E_C \varepsilon_C, \\ \sigma_F &= E_F \varepsilon_F, \\ \sigma_M &= E_M \varepsilon_M, \end{aligned} \tag{12}$$

where $\varepsilon_M, \varepsilon_F, \varepsilon_C$ are strains obtained in Matrix, Fiber and composite respectively; $\sigma_M, \sigma_F, \sigma_C$ are stresses obtained in Matrix, Fiber and composite respectively; E_M, E_F, E_C is Young's modulus obtained in Matrix, Fiber and composite respectively; V_M, V_F, V_C are volume fractions obtained in Matrix, Fiber and composite respectively.

Combining the above Eqs. 12 with the Eq. 11, we get

$$\frac{\sigma_C}{E_C} = \frac{\sigma_F V_F}{E_F} + \frac{\sigma_M V_M}{E_M}. \tag{13}$$

Axial stress is the same in each cross-section

$$\sigma_C = \sigma_F = \sigma_M. \tag{14}$$

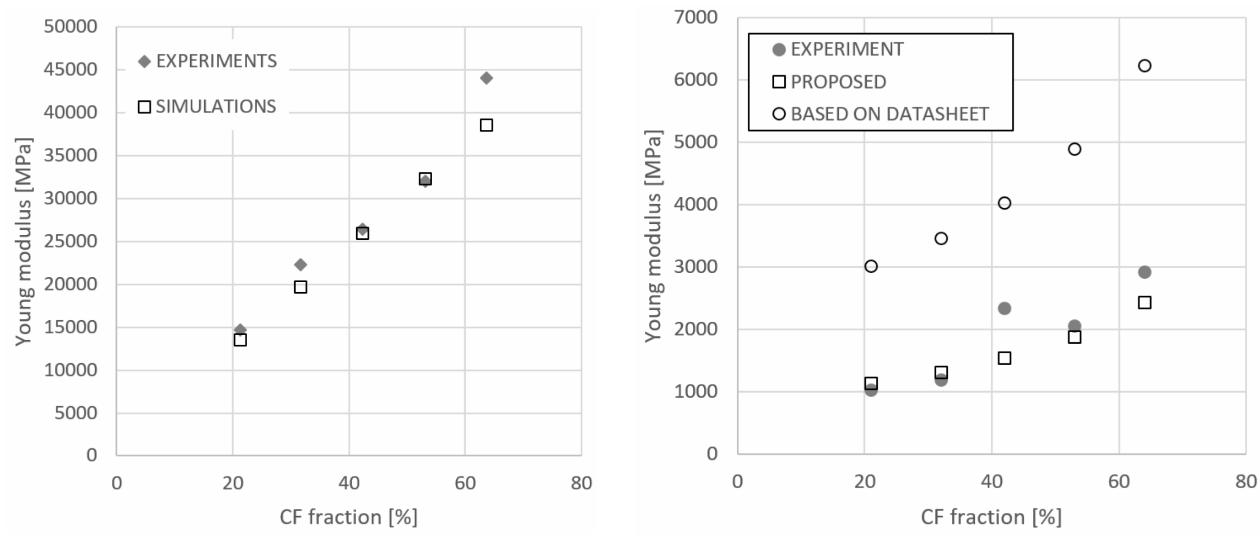
Therefore, the rule of mixture

$$E_C = \frac{E_F E_M}{V_M E_F + V_F E_M}. \tag{15}$$

The above Eqs. 7 and 15 are used to perform the analytical prediction of Young's Modulus particularly for unidirectional fibre reinforced composite.

3 Experiments in tensile mode

All mechanical tensile tests were performed using LabControl 100kN/1000Nm testing machine in accordance with ASTM D3039 standard [7]. Young's modulus obtained for the longitudinal and transversal direction of fibers was evaluated for different long fiber volume ratios, see Fig. 3.



(a) Longitudinal

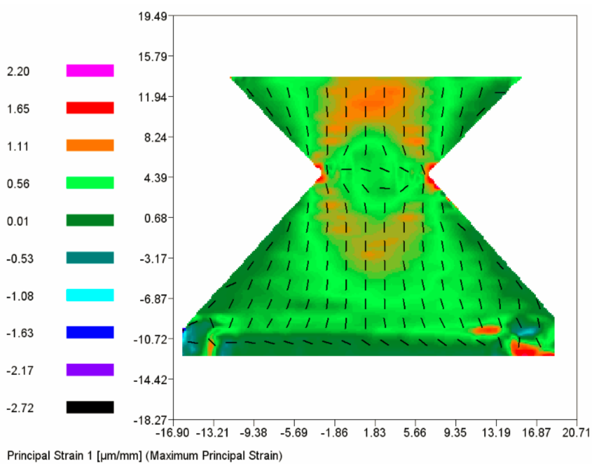
(b) Transverse

Fig. 3: Dependency of Young's modulus of Onyx+CF composite on the CF fraction.

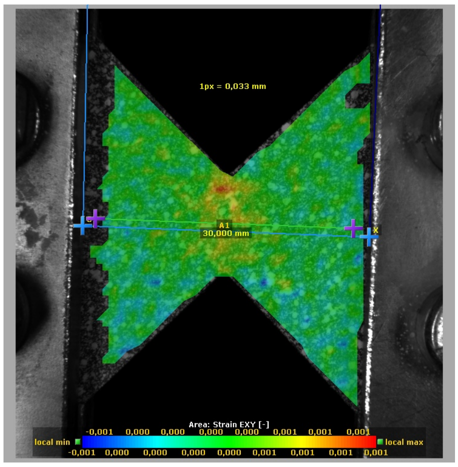
Fig. 3 shows that the correlation is very good for all loading cases for proposed simulation in case of longitudinal loading. In case of transversal loading, the proposed and experimental correlations are good but the datasheet values are giving poor results. The proposed values from our experiment are reliable in case of transversal loading. The Young's modulus of fiber and matrix utilized in the prediction is 60,000 MPa and 900 MPa respectively.

4 Experiments on shear specimen

Based on the ASTM D7078 Standard [8], the shear testing specimen was designed, 3D printed and tested. Two contours carbon fibers were created around the perimeter in Eiger software. The shear-type specimen has been tested on Testometric 50CT-500 universal testing machine. All tests were conducted capturing full field data by Digital Image Correlation (DIC) system Mercury RT. Dantec Dynamics Electronic Speckle Pattern Interferometry (ESPI) system Q100 was used for verification on a shear-type specimen subjected to tensile load. The stiffness of specimen considering line with the length of 27.4 mm was 1864.2 N/mm as measured by ESPI and 1795 N/mm as measured by DIC. In other two loading cases, the stiffness of specimens made of onyx + two contour lines of CF was studied based on DIC data only.



(a) ESPI – tensile load (F = 41 N)

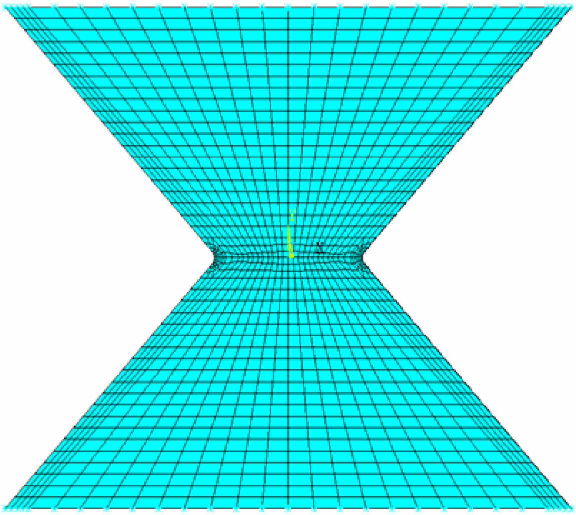


(b) DIC – shear load (F = 22 N)

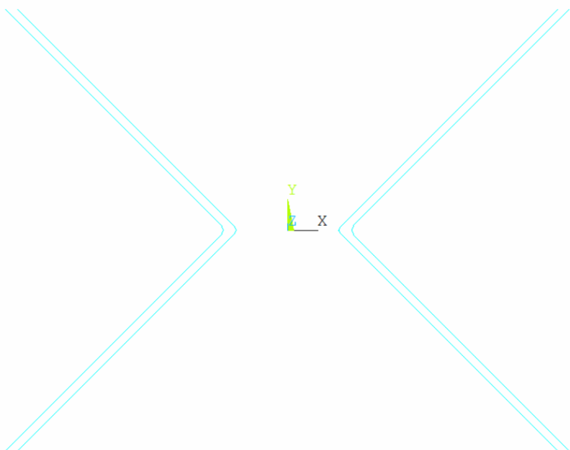
Fig. 4: Strain contours from full-field measurements on Onyx+CF composite.

5 Numerical modeling

FE modeling was performed in ANSYS 2020R1. The mesh prepared for the shear specimen is shown in the Fig. 4. In total, 4956 of solid185 elements were used for characterization of matrix and 216 of BEAM188 elements were used for long carbon fibers creation.



(a) solid elements – matrix



(b) beam elements – carbon fibers

Fig. 5: FE model of shear specimen characterizing Onyx+CF composite.

Specimen model was subjected to tensile, shear and combined loading using Ansys APDL macro. All nodes on the bottom area were fixed. Appropriate boundary conditions were applied on all nodes lying on the top area. Comparison of numerical and experimental results is done in Tab. 1.

Tab. 1: Comparison of experimental and numerical results of specimen's stiffness.

Loading mode	Experiment [N/mm]	FEM [N/mm]	Error [%]
tensile	1,795	1,890	5
shear	904	977	8
combination	2,354	2,474	5

6 Conclusion

All experiments realized on tensile specimens were used to identify the elastic properties of Onyx and carbon for subsequent Finite Element modeling. The most important parameter is Young's modulus. In order to reach good correlation of mixture rule with experiments for the longitudinal and transversal direction of fibers evaluated for different long fiber volume ratios its optimized value for matrix and fibers has been found: E_M = 900 MPa and E_F = 60,000 MPa.

Numerical results of shear specimen simulations for three loading modes are in good correlation with performed experiments. The developed computational strategy is based on solid elements usage for matrix and beam element application for long carbon fibers. Authors focused on linear elastic structural analysis, which is important for engineering applications. However, Onyx is a viscoplastic material and it is necessary to take it into account in the case of higher loads [4].

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