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Determination of Shear Properties of 3D Printed Composite

P. Pavlíček [1, a], M. Fusek [1], M. Šofer [1]

[1] *Technical University of Ostrava*
[a] *pav0151@vsb.cz*

Abstract: Determination of mechanical properties in shear is important for defining the material model of composite. In this paper, the authors focus on the comparison of two types of shear experiment method when every method gave different result. From reason 3D is apparent non-homogenic structure of sample which have influence on mechanical property of composite. Standards of testing composite material do not take into account necessity removal of first layer of onyx. Understanding behavior of composite material under shear loading gave information about usability of tested method and for future research.

Keywords: 3D printing; Composites; Material model; DIC.

1 Introduction

This work is focused on methodology of testing 3D printed composites and obtain mechanical properties of composite under shear loading. For shear loading was written many standards but between these standards is significant differences between results and test procedure. In next case current standards neglect layers of material which must be removed. in 3D printed parts. These parts are more non-homogenic with comparison of traditional composite. This non-homogeneity of sample has significant dependency on mechanical property of composite Behavior under shear loading is important for define material model of composite and use inappropriate method has significant influence on interpretation of results.
Work is focused to comparation of these two experimental methods:

- ISO 527-4 [1],
- ASTM D5379 [2].

Understanding of behavior composite under shear loading is necessary for define suitability of testing method and for modification of standard for specifics of 3D printed composites. Accounting these influences into standards cause reduction of bad interpretation of results and raise of quality of measurement.

2 Material properties

Sample was printed on 3D printer Markforged X7 with accordance described above, material of sample is:

- Onyx composition of nylon and short carbon fibre,
- Carbon fibre.

Mechanical properties of used composite materials are written in tab. 1. Mechanical property of composite was measured with accordance ISO 527-4.

Tab. 1: Mechanical property of composite

Property	Value
Young modulus [GPa]	23.586
Yield stress [MPa]	194
Maximum stress [MPa]	714
Elongation [%]	4.21
Density $\left[\frac{g}{cm^{-3}}\right]$	1.4

3 Definition of Standards

3.1 Iso 524 – 4 Standard

Iso 527-4 is method of testing composites when is testing is done with unidirectional tension (compression). Shear testing in this method is done with orientation of fibers $\pm 45°$. Shape of sample is described in Fig.1 with indicated fibre orientation.

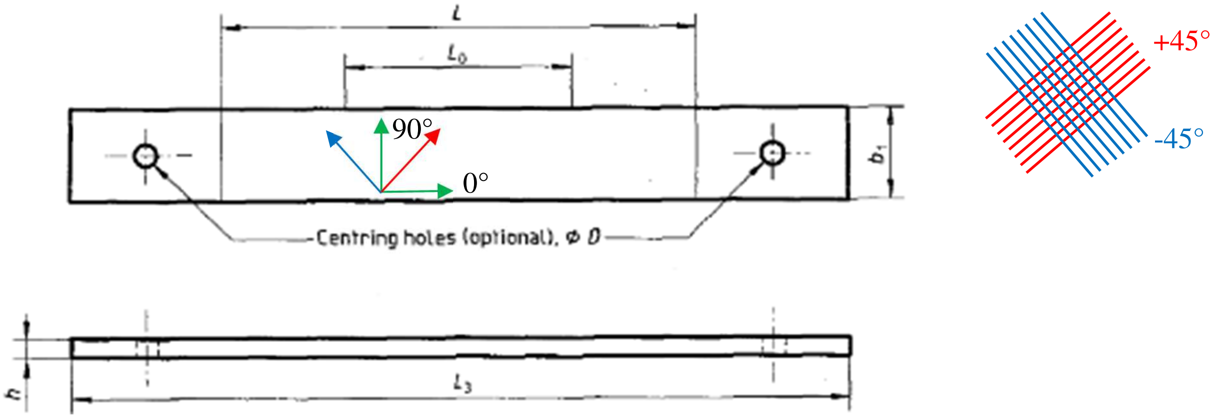

Fig. 1: Shape of sample and fibre orientation

Specimen shape is rectangular from reason even laying of fibers. In case of T-bone specimen, fibers are in the specimen deformed and this cause concentration in stress in transitional area. This standard defines equations for calculation mechanical properties when is important calculate stress, Shear modulus and strain. When stress was equated with formula (1).

$$\tau = \frac{F}{A} \tag{1}$$

When:

- F = force [N],
- A = area [mm^2],
- τ = shear stress [MPa].

When strain was equated with formula (2):

$$\gamma_{xy} = \frac{\epsilon_x - \epsilon_y}{2} \tag{2}$$

When:

- $\epsilon_{x(y)}$ =strain in fibre direction [−],
- γ_{xy} = shear strain [−].

Shear modulus was equated with formula (3):

$$G = \frac{\tau}{\gamma_{xy}} \quad (3)$$

When:

- G = shear modulus [MPa].

3.2 ASTM D5379 Standard

This method determines shear properties of composite materials reinforced with high modulus fibres. With this method can determined mechanical properties in all shear material planes. Specimen of ASTM D5379 standard is V-notched beam. which is represented in fig. 2 with shown fibres direction. On the left figure is measurement of strain on the specimen.

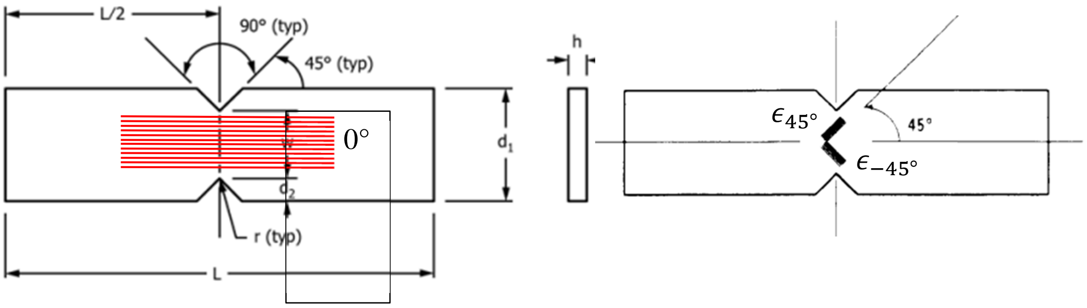

Fig 2: Specimen ASTM D5379 and laying of fibers

This method is more complex than ISO 527-4 for this method is need fixture for clamping and loading the specimen. Equations are same as in case ISO 527-4 but only with difference in indexes in equation (2).

3.3 Preparation of specimens

Specimen before test must be modified with use of milling machine when must be necessary remove surface layer of onyx. This layer has significant dependency on mechanical property of specimen. In the graph 1 is represented dependency on mechanical property of specimen.

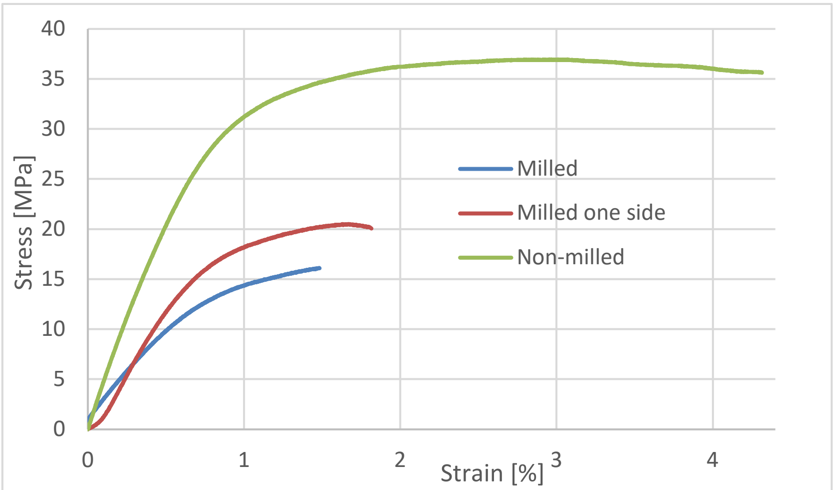

Fig 3: Behavior milled and non-milled sample

Milling of onyx layer has significant influence on mechanical property of sample mainly if the fiber in the sample has orientation 45°- 90 °. If the fibers are oriented with direction of loading effect of milling was neglected. Sample with fibers oriented in 90° direction has sample 2:25x times higher ultimate stress than milled sample. For correct testing of 3D printed composite materials is important remove onyx layers.

4 Homogeneity of composite

Homogeneity and structure of composite sample was measured with digital Microscope VHH 7000 with 200x magnification. On the figure 4 is represented homogeneity of composite sample. In the picture one is visible these findings:

ratio of fibres to matrix is $50 \pm 10\%\%$,

composite sample show inhomogeneous structure, with clusters of fibres when in the cluster have structure maximum fibre representation 80%,

inhomogeneous structure has significant effect on material parameters,

in zone out the cluster fibres has 20% representation,

diameter of single fiber is 4 nm,

composite layer does not contain onyx material.

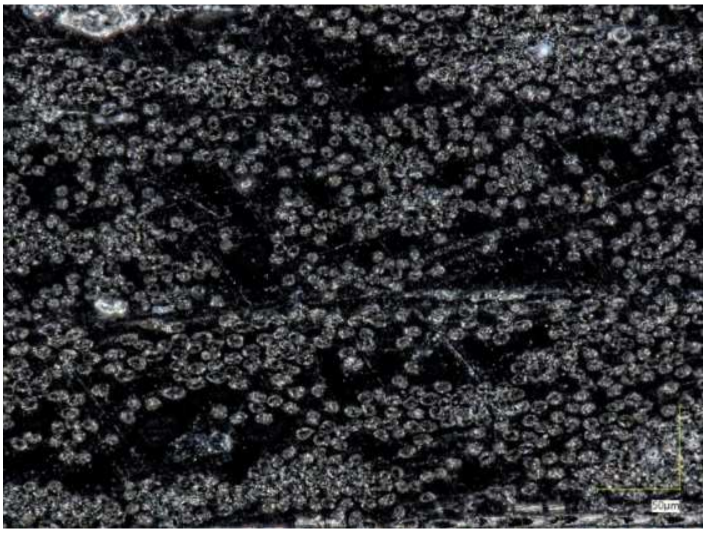

Fig 4: Sample homogeneity

Next investigation of homogeneity is focused on homogeneity of layering of fibres. Layering of fibres has influence of mechanical property of composite mainly if are fibres are not oriented in vector of loading. In 3D printing is presence of voids between fibres when voids are presented in fig.5.

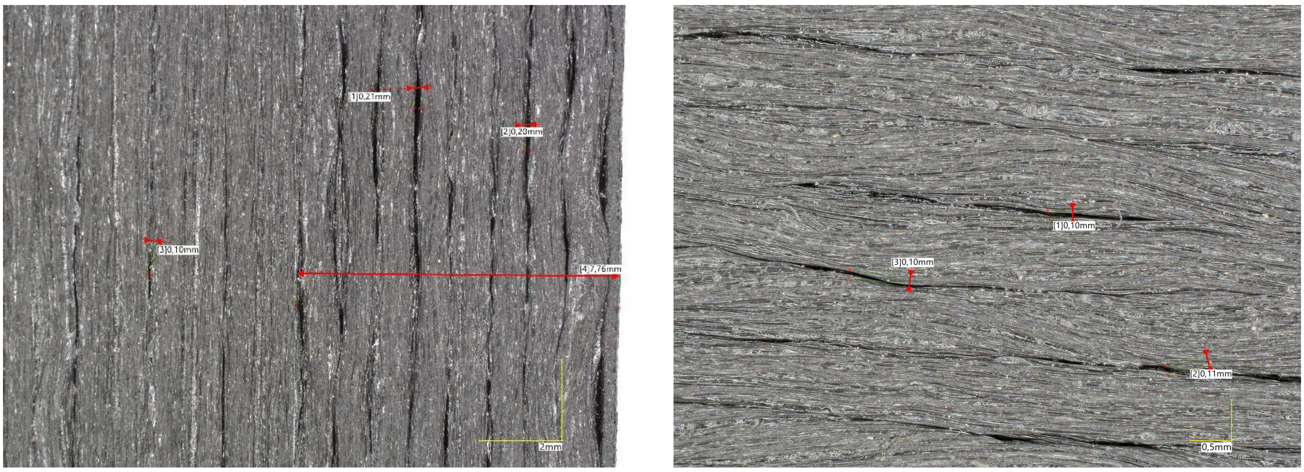

Fig. 5: Void presence

From the microscopy picture is visible presence of void when voids have size 0.1mm from the 7.75mm distance of the edge of sample. If are bellow this distance presence of void is higher than up to distance and size of void have value 0.2 mm. This zone is affected by 3D printing and has significant effect on mechanical properties of composite.

5 Test Procedure

Composites was tested on universal tensile machine Testometric MC-500 with 50kN force sensor. Test procedure was done with accordance ISO527-4 and ASTM D5379. On specimens before the test must be applied pattern with white chalk aerosol spray. Deformation of the sample was measured with DIC method with 3 frame per second. Specimen after clamping was preloaded with 100N. Test conditions are same for both methods, when test speed was 2 mm/min. On figures 6 and 7 are presented tested method.

Fig. 6: ISO 527-4

Fig. 7: ASTM D5379

6 Results

From experiment was obtained test data which are written in tab. 2 and fig 8 and 9. Data was evaluated with accordance ISO 2602 [3]. From the test was visible dispersion of data in ISO 527-4 test. This dispersion was not visible in ASTM D5379 test.

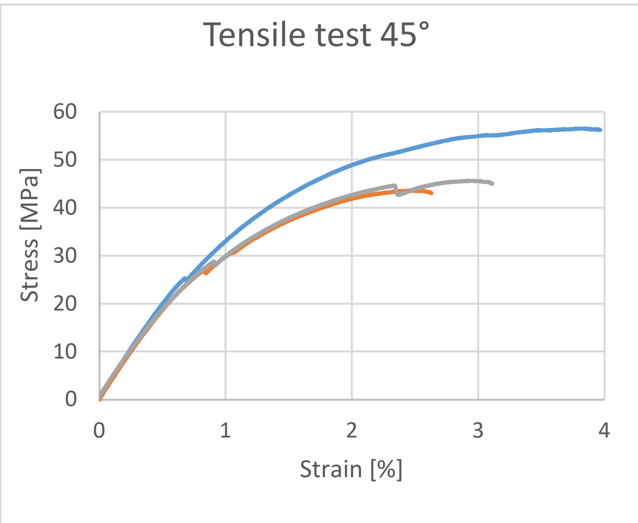

Fig. 8: ISO 527-4 Test

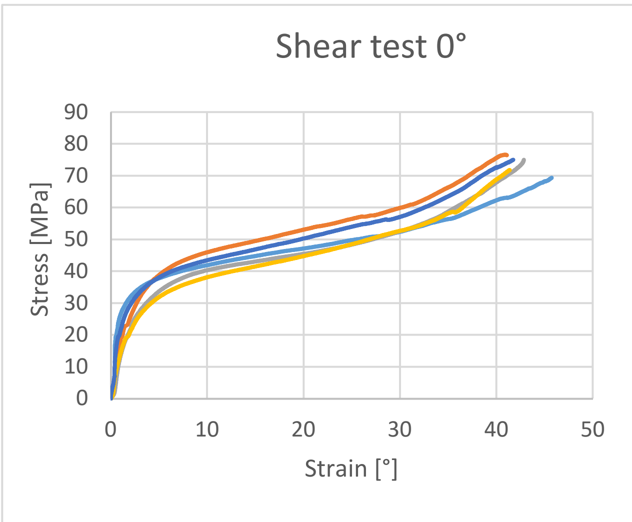

Fig. 9: ASTM D5379 Test

Tab. 2 Comparison mechanical properties

r	ISO 527-4	ASTM D5379	Difference [%]	Unit
Young modulus	3562 ± 142	2671 ± 172	35	MPa
Strength	48 ± 5.6	62 ± 4.4	29	MPa
Elongation	3.86 ± 0.8	36 ± 3.8	947	%
Yield Stress	26.6 ± 2.9	15.5 ± 2.2	42	MPa

From the results is visible difference in the graphs when ASTM D5379 gave higher results than ISO 527-4. These results are mainly visible in elongation when ASTM D5379 has different type of failure than ISO 527-4 test. Dispersion of data in ISO 527-4 test are caused by voids in the layer and with non-homogenic structure. Fracture in ISO 524-4 is mainly caused by interlaminar shear. In ASTM D 5379 has sample different fracture model when mainly fail fibers. From these results ISO 524-4 is more suitable for interlaminar shear test in composite than shear test.

7 Results of Fem Analysis

Fem analysis was done in Nastran 2022 and Marc 2022 model was modelled with shell Quad4 element with element size 1mm. Material model in analysis is orthotropic linear material. Element was check on mesh quality criteria. Model was evaluated through all layers with maximum value of stress.
Result of FEM analysis test ISO 524-4 is represented in fig.7.

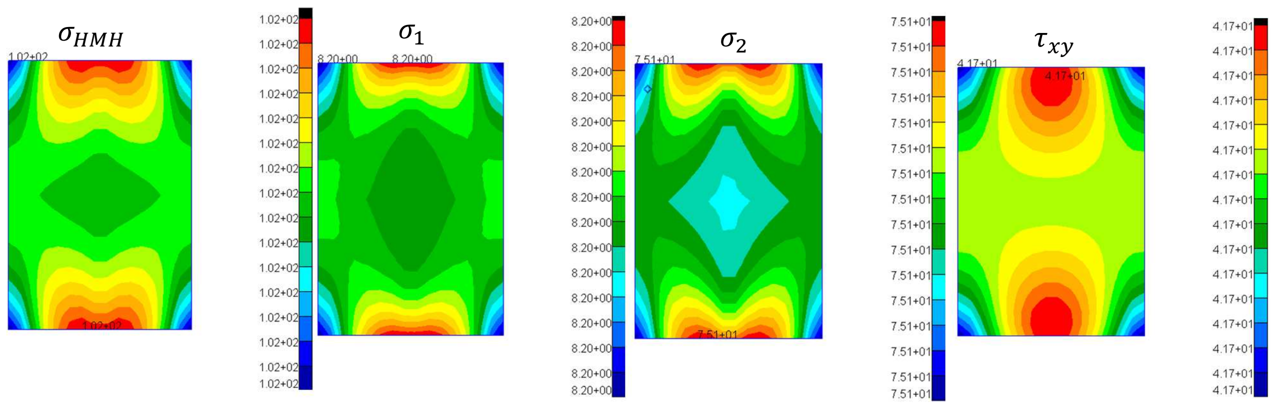

Fig. 7: Stress distribution ISO 524-4

From the fig. 7is visible stress in the center of the sample when maximum stress is distributed around center of sample. Shear distribution in the sample respond to simplified shear distribution. Results of FEM analysis from ASTM D5379 are represented in fig 8.

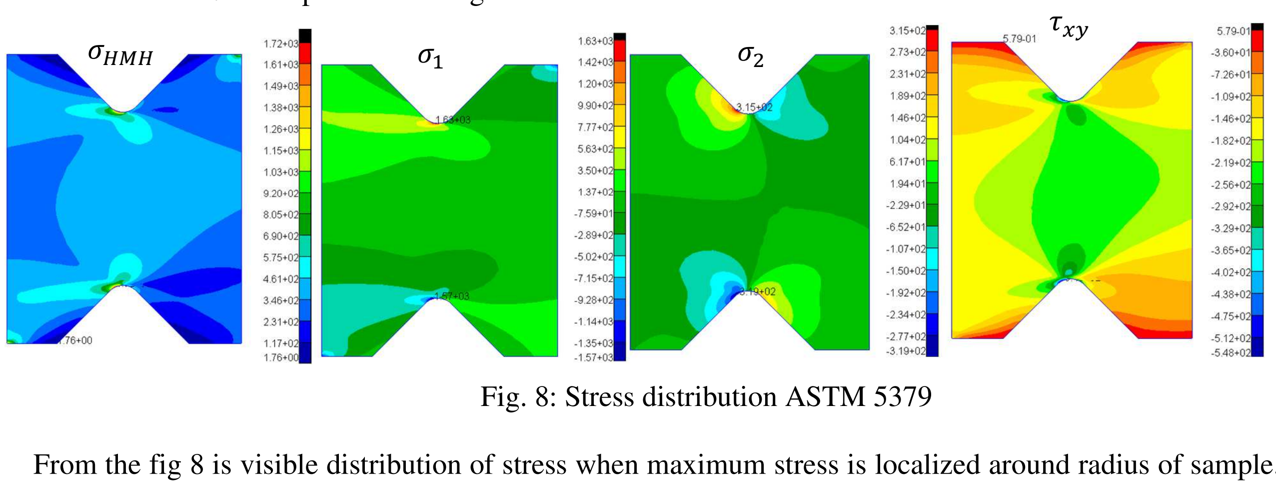

Fig. 8: Stress distribution ASTM 5379

From the fig 8 is visible distribution of stress when maximum stress is localized around radius of sample. Shear distribution in the sample respond to nonlinear shear distribution and is valid with shear theory. Secondary stress is cause by fibers bending and tension. This stress is valid with the test, From the both analysis is visible biaxial stress on sample when from the fem result is biaxial state is higher in ASTM D 5379 method.

8 Fracture under shear loading

From microscopy was found type of fracture from test ASTM 5379 when fracture is cause by shear and tension in the fibers. Detail of fracture is represented in fig. 16. From the picture are visible fractures of composite which are highlighted in red rectangular frame. 3D print in the root area has non-homogenic structure. This defect in homogeneity has significant effect on test and mechanical properties of material. Void between fibers is around 0.1 mm Failure of composite correspond to usual failure mode of CFRP composite under shear loading.

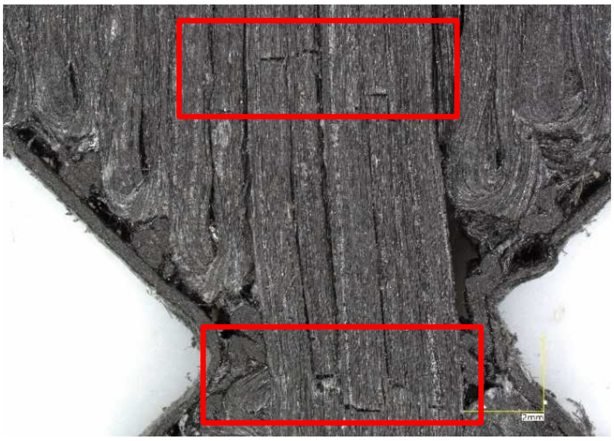

Fig. 16: Fracture under loading

9 Conclusion

From the results presented above was not found correlation between ASTM D5379 and ISO 527.4 both methods gave different results. Mean error between these methods is around 35%. Main difference between these two types of tests is in the different type of failure and stress distribution. 3D printing composite has:

- ratio matrix fiber around 50 ± 10%,
- 3D printed composite has non-homogenic structure,
- testing 3D printed composite without remove onyx layer has significant dependency on test results.

From the FEM results ASTM D5379 give more accurate results than ISO 527-4 method. ASTM D5379 is with compliance with shear theory. From the investigation ISO 527-4 is not recommended for testing composite under 45°, results from this test are only indicative and is usable for interlaminar shear test. ASTM D5379 give more accurate results and this method is recommended for shear testing. From the result of microscopy was found these results:

- print more likely desk and from the desk prepare samples, than printing samples,
- don’t use composite 8 mm from the edge from higher occurrence of voids,
- don’t print composite sample with complex shapes.

From the results of this work is necessary modified current standards for 3D printed composites, because don’t reflect this type of technology. Concurrently if will not be considered assumptions of this work, results of the testing they will be error burdened. Future research of these problems is important for understanding of influences which influence measurement.

Acknowledgement

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