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Anisotropy of 3D Printed Materials in Tension

Testing protocol and chain of activities

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The first attempts to use additive manufacturing civil engineering are successful. Additive printing can be used to print precast elements, building envelope elements or to print whole structure using contour crafting. The main goal of this research is to be a sort of bootstrap step, allowing us to have a grip on the whole chain of activities, protocols, and tools: creation of computer models of printed parts, 3D printing, mechanical properties testing, raw results storage and processing. The aim of the work was to determine the anisotropy of material behavior in tension for 3D printed materials and preparation the testing protocol for digitally manufactured cementitious building products. Samples for tensile strength determination were printed in FDM technology with three space fill (printing densities) and three different layer orientations.

Keywords—3D printing, FDM, ABS, anisotropy

I. Introduction

Beginning of 3D printing technology starts at late 1980s. 3D printing allows to create spacial models consisting of layers of molten material. This process begins when a CAD model is created. The next step is to convert the model into 'slices' and finally into the paths of printing head that either deposits of process printed material [1]. 3D printing technology makes possible to form compound mock-ups and miniature models of design structures for civil engineering. However there is also a very active research of the subject of applying 3D printing concepts for manufacturing full scale building components and complete structures.

The first attempts to use additive manufacturing civil engineering are successful. One of the examples of 3D printed buildings are located in China where WinSun company is using 3D printed precast elements, assembled on site. The company has recently achieved five-storey apartment building erected in 2015. The building has 1,100 square meter (11,840 square foot). The walls contains of 3D printed elements which contains empty spaces for reinforcement and insulation [3].

The last but not least example of using 3D printing in civil engineering is project Apis Cor – 38 square meters (409 square foot) ground-floor house. The innovative side of this project is the application of contour crafting technology directly on site. The technology consist in extruding the cement mortar through and extrusion head connected to small crane. The project was realized at the end of 2016, near Moscow in Russia by Apis Cor. The entire construction process of took 24 hours, which make this technology one of the most promising techniques in nowadays building industry [4].

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There are numerous advantages coming from application of 3D printing technology in construction. The most important ones are [3]:

- Lower costs – the cost of printing construction elements of houses is much lower than traditional construction methods, because material transportation and storage on sites is limited;
- Environmental friendly construction processes and the use of raw materials with low embodied energy (i.e. construction and industrial wastes);
- Wet construction processes are minimized, so that building erection process generate less material wastes and dust compared to traditional methods;
- Time savings – time required to complete the building can be considerably reduced.

As 3D printing differs much from other manufacturing techniques, one of the key aspect of applying it for creating not only prototypes but also final product is the assessment of strength and durability properties of printed elements. This requires both development of theoretical models of printed materials behavior as well as comprehensive experimental validation and calibration of such models. In presented research we aim at establishing the whole pipeline of such experimentation.

Technology used in this research is FDM (Fused Deposition Modelling). The main aim of this technology is to embed molten thermoplastic material ABS (Acylonitrile Butadiene Styrenein) to the platform which could move along Z axis. FDM technology requires usage of two different materials: the support material and the printing material. The first one is responsible for connecting platform with finished model. The second one is printing material which creates a form of the product [2].

The experimental setup presented in this paper is rather standard one and described in many references. It is exactly the reason why it was selected, because besides particular results described in section III, the parallel main goal of this research is to be a sort of bootstrap step, allowing us to have a grip on the whole chain of activities, protocols, and tools: creation of computer models of printed parts, 3D printing, mechanical properties testing, raw results storage and processing. Obtained results and their agreement with references show that we are ready to tackle much more complex task, both in terms of complex geometries as well as boundary and load conditions.

II. Samples preparation and the test method

A. Preparation of geometric models

For preparing geometric models and exporting them to STL format we have used OpenSCAD modeling program [5]. The ability to describe models parametrically in OpenSCAD programming language makes easy to create many variants of the samples. The samples presented in this paper were generated by the following program:

```
// Paddle dimension
tLen = 150;   // total length
h = 4;        // thickness
tWidth = 20;  // ends width
mWidth = 10;  // middle part width
mLen = 80;    // middle part length
R = 22.5;     // arcs' radius

// Paddle derived dimensions
mDy = mWidth;
Cx = (tLen-mLen)/2;
Cy = R + mWidth/2;

// Cylinder resolution parameter
$fn = 48;

// The model
difference() {
  cube([tLen, tWidth, h], center=true);
  union() {
    for(my = [-1,1]) {
      translate([0,my*mDy,0]) cube([mLen, mWidth, 2*h], center=true);
     for(mx = [-1,1])
       translate([mx*(tLen/2-Cx),my*Cy,0]) cylinder(2*h, R, R, center=true);
    }
  }
}
```

As a preparatory step for numerical studies meshing of the created models with Netgen mesh generator has been tested.

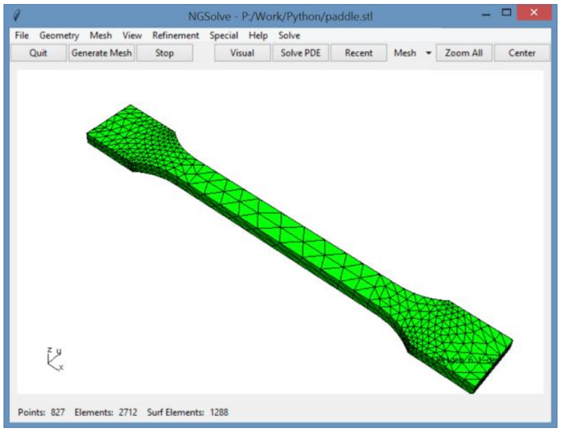

Figure 1. Paddle-shape sample dimensions.

B. Printing and molding samples

For sample preparation we used 3D Stratasys uPrint printer. The printing process using this device is based on melting model material – ABS and supporting material which are layered on the platform. Materials reaches temperature up to 300ºC (572ºF). 3D printer used in this project allows to print samples in three densities. First of them is solid which provides filling he space with the material at nearly 99%. The second option in sparse high fill which density is estimated at 75%. The last one is sparse fill which is the most porous type of printout approx. 50%.

In this research paddle-shape samples of dimensions 150x20 millimeters (5,9x0,8 inches) were printed for testing mechanical behavior in tension.

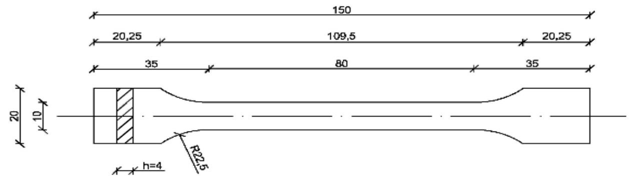

Figure 2. Paddle-shape sample dimensions.

After sending STL model to the printer it is possible to select the print plane. There is three different orientation of printout. The first one is flat – XY, the second on edge – XZ, the third upright – YZ.

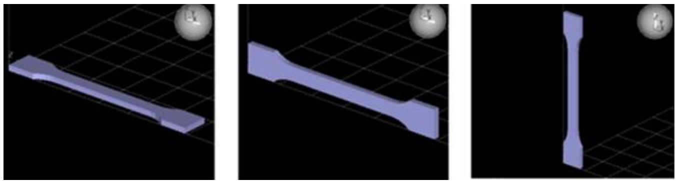

Figure 3. Samples orientation XY, XZ, YZ.

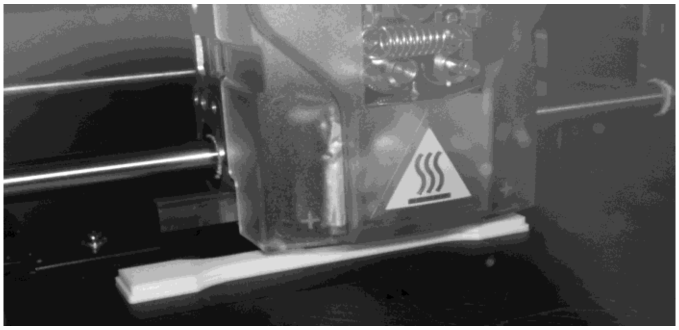

Figure 4. 3D printing process.

C. Physical properties of printouts

The porosity of the printouts was evaluated on the cubic samples (a=3 cm). The geometry of samples and mass was determined. Apparent density and total porosity was calculated taking into account the ABS density of 1.07 g/cm3. The highest difference in porosity compared with manufacturer data was noted for solid specimen and the difference reached 6%. In case of sparse high and solid differences were of 1% and 6.5% respectively (Table 1). The graph present density of samples depending on the fill of the printed space.

Porosity of samples

Porosity [%]	Type of sample		
	Solid	*Sparse High*	*Sparse*
According to manufacturer	1	25	50
Porosity testing results	7.3	23.9	56.5

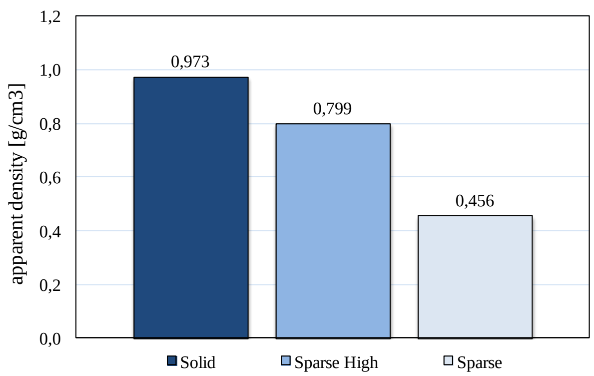

Figure 5. Density of sample.

D. *Testing method*

The sample was mounted in the jaws of the testing Zwick/Roell Z010 testing machine. The pre-force of 0.01 MPa was applied. Test speed was adjusted to the standard requirements (EN 527-1) and was set at 5 mm/min. The elongation measurement (Δl) was carried out on the base of l_0=50 mm using an extensometer affixed on the surface of the specimen. The samples view and testing machine is shown in Figure 6.

Figure 6. Tensile strength test on 3D printed specimens.

The purpose of the study was to determine the behaviour in tension of the prints and determination of stress strain curves according to PN-EN 527-1. The yielding stresses and the elongation at yielding point as well as elongation at the rupture were determined differences in the behaviour of the samples depending on their orientation in the coordinate system and the filling of the printed space with the material. The samples were printed in three type: solid, sparse high and sparse. Samples of each type were printed in the XY, XZ and YZ planes in relation to the coordinate system. A total of 22 samples were tested.

Designation and number of samples

	Type of sample						
	Solid			*Sparse High*		*Sparse*	
Plane	XY	XZ	YZ	XY	YX	XY	YZ
No.	5	3	3	3	3	3	2
Dessig nation	Solid XY	Solid XZ	Solid YZ	Sparse high XY	Sparse high YZ	Spar se XY	Spars e YZ

E. *Tested strength parameters*

This paper presents the strength properties in a static tensile test. The tests allowed us to determine the tensile strength σ_M, the yield point σ_y, the relative elongation at the maximum tensile stress ε_M, the elongation at break ε_B, the elongation at the yield point ε_y and the tensile modulus E_t.

Tensile strength σ_M as determined as the maximum tensile stress transmitted by the specimen during the tensile test. The yield point σ_y is the first stress at which the increase in elongation does not increase the stress and may be less than the maximum stress achieved. Values of tensile strength and yield point are expressed in [MPa]. The relative elongation at break ε_B is recorded when the rupture of the sample occurs. The elongation at the yield point ε_y is the relative elongation recorded at the yield point. Relative elongation values are expressed in [%].

III. The results

The following figures present stress strain relationships for solid (Figure 7), sparse high (Figure 8) and sparse (Figure 9) prints. In the following tables the strength properties of tested printouts for different material fills: solid, sparse high, sparse.

For all cases the differences in properties between the orientation of printout was evaluated. The following configurations of printouts was studied flat – XY, on edge – XZ, upright – YZ

Experimental results of Solid sample

Average vales	Orientation		
	XY	*XZ*	*YZ*
tensile strength σ_M	27.0 MPa	28.5 MPa	22.3 MPa
relative elongation at the maximum tensile stress ε_M	2.49%	2.26%	1.19%
elongation at break ε_B	4.26%	3.71%	1.19%
elongation at the yield point ε_y	1.57%	1.45%	1.19%
tensile modulus E_t	1.54 GPa	2.34 GPa	2.05 GPa

Tables III-V give the average values of tensile strength σ_{M}, relative elongation at the maximum tensile stress ε_{M}, elongation at break ε_{B}, elongation at the yield point ε_{y}, tensile modulus E_{t}.

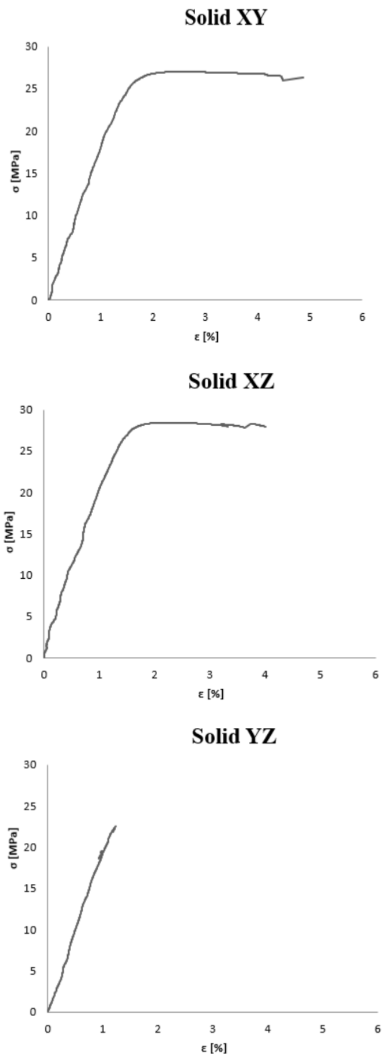

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Figure 7. Average stress strain curve - solid XY, XZ and YZ.

EXPERIMENTAL RESULTS OF SPARSE HIGH SAMPLE

Average vales	Orientation	
	XY	***YZ***
tensile strength σ_M	21.4 MPa	29.5 MPa
relative elongation at the maximum tensile stress ε_M	4.95%	2.04%
elongation at break ε_B	6.40%	3.96%
elongation at the yield point ε_y	1.41%	1.21%
tensile modulus E_t	1.73 GPa	2.39 GPa

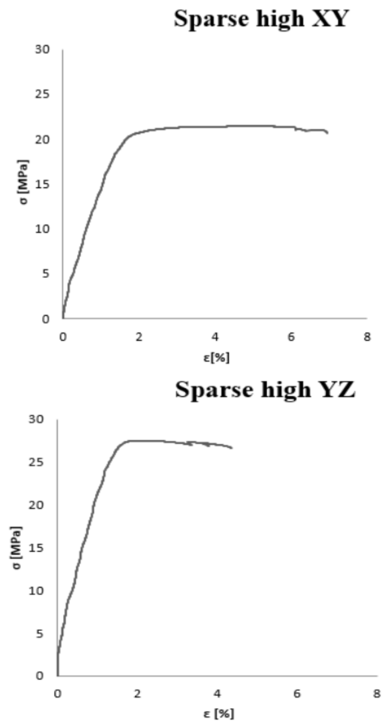

Figure 8. Average tensile strength - sparse high XY YZ.

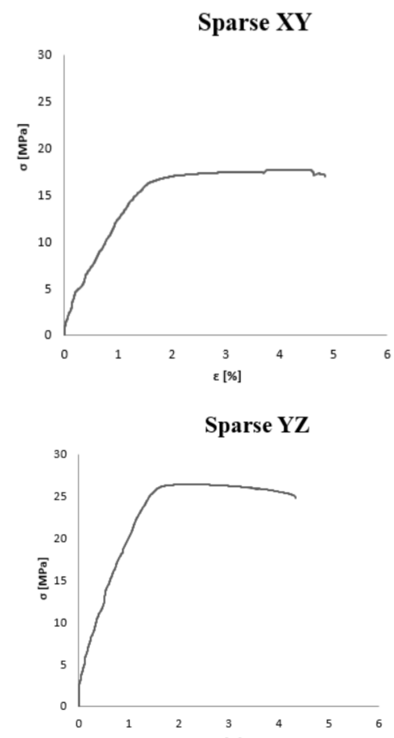

Figure 9. Average tensile strength - sparse XY and YZ.

EXPERIMENTAL RESULTS OF SPARSE SAMPLE

Average vales	Orientation	
	XY	***YZ***
tensile strength σ_M	15.9 MPa	26.4 MPa
relative elongation at the maximum tensile stress ε_M	3.86%	2.00%
elongation at break ε_B	4.32%	4.09%
elongation at the yield point ε_y	1.51%	1.32%
tensile modulus E_t	1.62 GPa	2.37 GPa

The results obtained during the tensile strength test confirmed the differences in properties depending on the filling of the printed space but also depending on the results show that the prepared samples behave in a repetitive and comparable manner which confirms the assumption that the 3D printer performs precisely and accurately. Moreover, the figure 10 give an overview of the tensile strength results in increasing order.

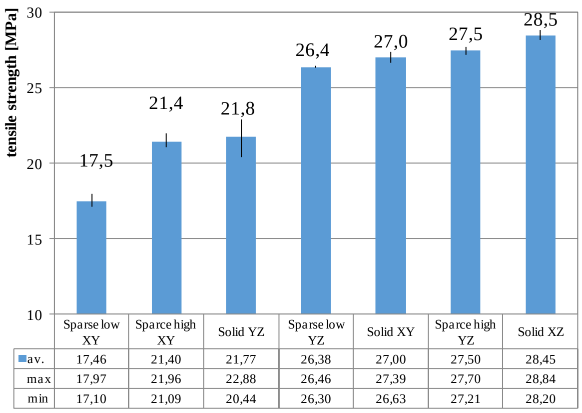

Figure 10. Average tensile strength in increasing order.

The highest tensile strength was observed, as expected for solid samples, characterized by the lowest porosity. The best results were obtained from solid samples printed in XZ plane. The average tensile strength of those samples was of 28.5MPa. The weakest of this group was Solid YZ samples which amounted to 21.8 MPa.

During the tests, the necking of samples was observed for samples printed in the XY and XZ planes, samples printed in the YZ plane did not present this behaviour and break without necking.

The yield point σ_y of the solid samples printed in the XY plane was 1.45 MPa less than σ_y for the XZ plane. For solid YZ samples no yielding was observed. Sparse high samples achieved approximately the same yield strength. The difference between the results for the XY and YZ planes was of 8.05 MPa.

The largest relative elongation at the maximum tensile stress ε_M is characterized by samples printed in the XY plane. The sparse high sample was the most ductile while the smallest elongation was observed for all solid samples

The highest strength had printed samples with orientation according to the YZ axes for samples with 75% and 50% space fill. Sparse YZ samples presented 51% higher tensile strength than Sparse XY.

The highest tensile modulus E_t is characterized samples printed in the YZ plane. Sparse high samples obtained the highest value of the elastic modulus while Solid samples presented the lowest E_t .

The greatest elongation at fracture ε_B was observed for sparse high samples oriented in the XY plane. The elongation has reached almost 7% while the samples of other groups were oscillating around 4-5%.

IV. Conclusion

For elements created by additive manufacturing processes one will observe high degree of anisotropy. Selection, calibration and experimental validation of material models must be done carefully, watching many factors that can influence the results. The testing protocol and obtained data presented in this paper, can be used as a bootstrap procedure and first calibration point, on the way to obtain sound and reproducible results.

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