CONCERNING THE RATIO BETWEEN THE ADHESIVE AND MECHANICAL STRENGTH OF BUILDING STRUCTURES – 3D PRINTING PRODUCTS OBTAINED BY FUSED DEPOSITION MODELING OF THERMOPLASTIC MATERIALS

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Abstract

Introduction: 3D printing represents a very promising area in the construction industry. However, the lack of a theoretical framework, which makes it impossible to control the quality of structures obtained, prevents it from being used in mass production. **Methods:** Adhesion properties largely depending on the cross-section area are one of the most important elements of the technology, which in some cases limit the strength characteristics of a resulting structure. Therefore, it is necessary to know adhesive strength characteristics (besides mechanical ones) of items manufactured using this technology. The paper addresses strength characteristics of a joint between the layers of the extruded material when a structure is manufactured by 3D printing. The authors experimentally determine a dependency of the ratio between the adhesive and mechanical strength on the layer printing time. **Results:** The practical result of the study is in the revealing of a general relationship in 3D printing both in the area under consideration and in the construction field, and the improvement of the theoretical framework for further development of the technology in the construction industry.

Keywords

Polymer materials, additive manufacturing, fused deposition modeling, mechanical strength, adhesive strength, construction 3D printing.

Introduction

Construction 3D printing moved beyond theoretical studies and scientific papers long ago. Currently, layer-by-layer extrusion (or fused deposition modeling) is the most commonly used method in the area under consideration, and concrete is the basic material (Demidenko, Kulibaba, Ivanov, 2017).

As a result of technology improvement, Shanghai WinSun Decoration Design Engineering Co. improved the performance of printed buildings in comparison with that of buildings constructed according to the traditional technology. Printed buildings are 2 times efficient in terms of the construction and installation cost, 2.5 times efficient in terms of material consumption, and 5 times efficient in terms of labor intensity (http://robotrends.ru/pub/1718/top-6-stroitelnych-printerov-dlja-3D-pechati-domov, accessed on: 01.12.2018). These results apply to buildings up to five stories high. This indicates that construction 3D printing is developing and expanding in civil engineering, taking the place of the traditional technology and competing with it in the sphere of low-rise construction.

As a result of layer-by-layer extrusion of a construction mix in 3D printing, we get a structure “covered” with concrete joints. However, a joint obtained as a result of extrusion is not equivalent to a cold joint. According to Paragraph 5.3.12 of the Set of Rules SP 70.13330.2012 Load-Bearing and Separating Constructions, it is possible to proceed with concreting when at least 1.5 MPa strength is gained, which cannot be ensured during 3D printing. Therefore, a joint obtained (hereinafter referred to as “’printing” joint) cannot be considered as a cold joint. According to Paragraph 5.3.9 of the Set of Rules SP 70.13330.2012, the next layer of a construction mix shall be laid prior to the setting of concrete in the previous layer. Therefore, a printing joint cannot be considered as a homogeneous material in design.

Thus, in terms of the regulatory framework covering joint analysis, printing joints represent a topic that has not been addressed yet. The lack of a regulatory framework makes it impossible to use the technology in the Russian Federation for the construction of buildings and structures, design documentation of which shall be reviewed by

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expert examination authorities, i.e. buildings with more than three stories and a total area exceeding 1500 m2 (Urban Development Code of the Russian Federation, Federal Law No. 190-FZ dd. 29.12.2004). This limits the development and application of the technology.

It seems that to perform the analysis of structures manufactured using layer-by-layer extrusion it is necessary to know the relationship between the layer printing time and strength characteristics represented as a ratio between the adhesive strength and the mechanical strength of a 3D printing product.

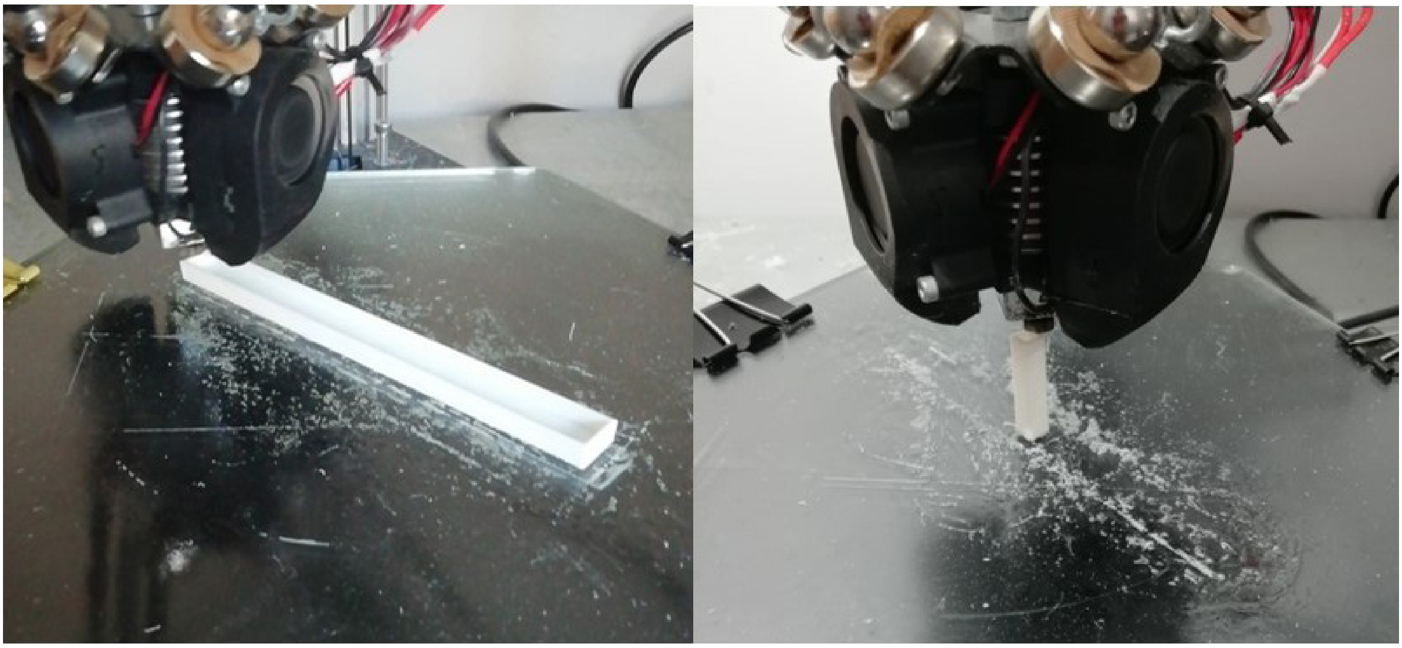
Theoretical studies in this area (in particular, with respect to concrete) are performed with regard to the mechanics of accreted solids. However, such studies address not the strength characteristics of a joint material but the effect of concrete creep on a structure (Rashba, 1953; Kharlab, 1966) and the stress-strain state of a structure during accretion (Kharlab, 2014).

As can be seen, the issue of finding a relationship between the adhesive strength and the mechanical strength in a printing joint is insufficiently studied. Therefore, the purpose of this study is to determine the type of empirical relationship between the parameters mentioned. Results of the study and its further development can significantly expand the scope of construction 3D printing application in the Russian Federation due to the formation of the regulatory framework for the analysis of buildings and structures constructed using a 3D printer.

Methods

Due to the scale factor and specifics of materials applied, it is time-, cost-, and labor-consuming to study the effect of various conditions on the quality of a final product (building structure) and its properties. It seems possible to establish a similarity rule for physical processes in construction and mechanical engineering 3D printing. As for the latter, products and their structural elements have significantly smaller cross-sections. In this paper, items manufactured from polylactide (PLA) by Fused Deposition Modeling (FDM) are considered as a model for 3D printed building products.

Such products are characterized by anisotropy of properties along and across the filaments: under the load along the filaments, the filaments resist; under the load across the filaments, the joints between them resist. In his paper (Petrov et al., 2017) demonstrate that to calculate the mechanical strength of 3D printing products it is required to use samples manufactured horizontally, and to calculate the adhesive strength it is required to use samples manufactured vertically (Figure 1).



a) b)

Figure 1. Arrangement of samples on the table of a 3D printer: horizontal (on the left), vertical (on the right)

The samples are represented by hollow square prismatic bars with a length of 128 mm, wall thickness t_w = 1.2 mm, and sides of 3.2, 4.8, 6.4, and 12.8 mm, respectively (Figure 2). The printing speed is the same for all samples (45 mm/s).

The samples were manufactured using a 3D Quality printer (Prism Mini V2 printer with air cooling of the hot end). The filament was manufactured by Best Filament. It had a diameter of 1.75 mm, white color, and a shelf life of 12 months. The filament was stored under normal conditions within 1 month. The printing temperature was 230°C, and the temperature of the table was 70°C.

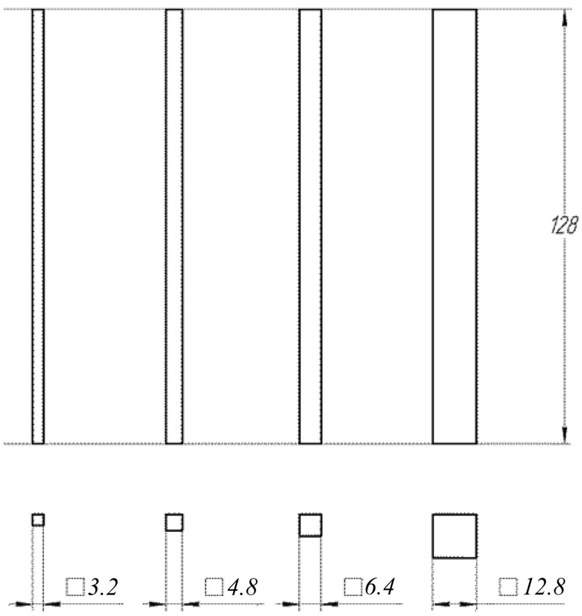


Figure 2. Test samples

The samples were printed horizontally ("h" samples) and vertically ("v" samples). Each batch corresponding to a particular combination of two parameters had five samples.

Each sample was analyzed under axial tension. To test the samples, the authors used an INSTRON 5966 universal electromechanical testing machine.

Based on the analysis of the structure of the "h" and "v" samples, it possible to construct a model linking the load-bearing capacity of the samples F_h and F_v with the mechanical strength σ_m and adhesive strength σ_a of the material, respectively. The model can be represented by equations (1) and (2):

$$\sigma_m = \frac{F_h}{P \cdot t_w} \tag{1}$$

$$\sigma_a = \frac{F_v}{P \cdot t_w} \tag{2}$$

where *P* is the perimeter of the cross-section across the centerline of the wall.

The printing time of one layer was taken as a parameter affecting the strength characteristics. The printing time can be determined by equation (3):

$$t_l = \upsilon \cdot 3 \cdot 2 \cdot (a - 2.4mm + b) \tag{3}$$

where v is the printing speed; a, b are the dimensions of the sample cross-section parallel to the table;

$2 \cdot (a - 2.4mm + b)$ is the centerline of the cross-section parallel to the table; 3 is the wall line count.

Results

Statistical processing of the test results was performed in accordance with an algorithm described in Paragraph 4 and Appendix 3 of State Standard GOST 14359-69 (Plastics. General requirements of the methods of mechanical testing (as amended on 10.04.2018)).

A hypothesis of normal distribution was accepted at the confidence level α = 0.99. As there are five tests in each series, it does not seem possible to compare the obtained distributions with the normal one. Processed results are given in Tables 1 and 2.

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Table 1. Test results in case of the horizontal arrangement of the samples on the 3D printer table

Test No.	Layer printing time $t_{l, i, s}$	No.	F_h, N	Cross-section area, mm^2	σ_{mj}, N/mm^2
1	16.11	3.2h-1	418.39	10.56	39.62
		3.2h-2	429.49	10.70	40.12
		3.2h-3	424.37	10.68	39.74
		3.2h-4	426.53	10.46	40.76
		3.2h-5	435.95	10.49	41.57
				Strength:	40.36 ± 2.11
2	16.32	4.8h-1	723.5	17.74	40.79
		4.8h-2	732.77	17.40	42.11
		4.8h-3	735.66	17.69	41.59
		4.8h-4	751.03	17.59	42.69
		4.8h-5	691.36	17.57	39.35
				Strength:	41.31 ± .39
3	16.53	6.4h-1	1025.41	25.13	40.81
		6.4h-2	1036.29	25.22	41.08
		6.4h-3	1046.44	25.25	41.45
		6.4h-4	1034.4	25.08	41.24
		6.4h-5	971.88	24.84	39.13
				Strength:	40.74 ± 2.44
4	17.39	12.8h-1	2034.78	56.18	12.8h-136.22
		12.8h-2	2160.62	56.62	38.16
		12.8h-3	2048.24	56.14	36.49
		12.8h-4	2009.83	56.16	35.79
		12.8h-5	2014.65	56.18	35.86
				Strength:	36.50 ± 2.53

Table 2. Test results in case of the vertical arrangement of the samples on the 3D printer table

Test No	Layer printing time $t_{l, i, s}$	No.	F_v, N	Cross-section area, mm^2	σ_{aj}, N/mm^2
1	0.53	3.2v-1	376.67	10.49	35.91
		3.2v-2	370.00	10.51	35.20
		3.2v-3	376.93	10.22	36.87
		3.2v-4	371.85	10.30	36.12
		3.2v-5	383.43	10.32	37.15
				Mean:	36.25 ± 2.04
2	0.96	4.8v-1	540.78	16.94	31.92
		4.8v-2	504.12	16.91	29.82
		4.8v-3	510.45	17.02	30.00
		4.8v-4	529.16	17.14	30.88
		4.8v-5	511.03	17.02	30.03
				Mean:	30.53 ± 2.29

3	1.39	6.4v-1	661.75	24.74	26.74
		6.4v-2	602.92	24.58	24.53
		6.4v-3	585.59	24.55	23.85
		6.4v-4	620.96	24.48	25.37
		6.4v-5	576.00	24.69	23.33
				Mean:	24.76 ± 3.51
4	3.09	12.8v-1	1175.76	55.20	21.30
		12.8v-2	1046.19	55.22	18.94
		12.8v-3	1170.43	55.34	21.15
		12.8v-4	1000.17	55.32	18.08
		12.8v-5	1141.35	55.18	20.69
				Mean:	20.03 ± 3.76

The coefficient of correlation between the layer printing time $t_{l,\ i}$ and mechanical strength $\sigma_{mj,\ mean}$ is $r_{x,\ y}$ = -0.913. At $|r_{x,y}|$ from 0.9 to 0.99 on the Chaddock scale, the qualitative assessment demonstrates that the strength of the relationship between these two parameters is very high (https://math.semect.ru/corel/cheddor.php, accessed on: 01.12.2018). It is assumed that the relationship is linear. The coefficient of correlation between the layer printing time $t_{l,\ i}$ and adhesion strength $\sigma_{aj,\ mean}$ is $r_{x,\ y}$ = -0.915, i.e. the qualitative assessment demonstrates that the strength of the relationship between these two parameters is very high. It is assumed that for the "v" samples the relationship is power-law.

To determine equations of the relationship, the least square method is used. Dependency diagrams for the parameters and equations of the approximating relationships are shown in Figure 3.

The obtained mathematical models were checked for informativeness using the Fisher criterion. The calculated value of the Fisher criterion is determined by equation (4):

$$F_{calc} = \frac{S_{res}^2}{S_{av}^2 \cdot (N - p)} \quad (4)$$

where p is the number of assessed model regression coefficients (p = 1 both for the linear and power-law models); N = 4 is the number of test series.

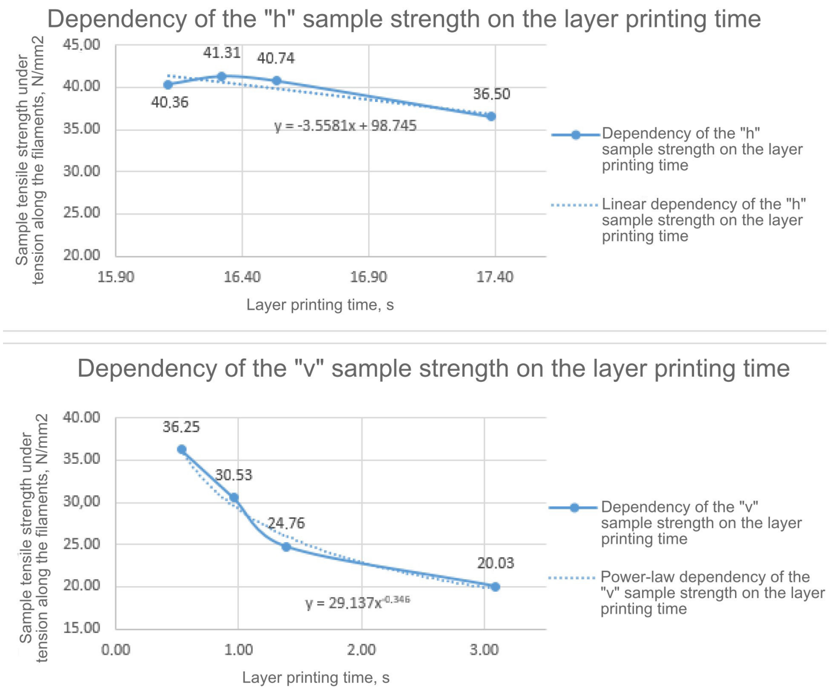

Figure 3. Dependency of σ_m on t (above – for the "h" samples, below – for the "v" samples)

Average response variance is calculated by equation (5):

$$S_{av}^2 = \sum_{i=1}^{N=5} \frac{(y_i - Y)^2}{N-1} \qquad (5)$$

Residual variance is calculated by equation (6):

$$S_{res}^2 = \sum_{i=1}^{5} \frac{(y_i - y_\iota)^2}{N-p}, \qquad (6)$$

where $\hat{y}_\iota$ is the output value calculated by the regression equation for the i[th] basic test.

The calculated values of the Fisher criterion for the tests of the "h" and "v" samples are equal to 0.055 and 0.006, respectively. The critical value of the Fisher criterion (https://Studfiles.net/prtviev/1740888/, accessed on: 01.12.2018) F_{cr} = 26.83. As $F_{cr} > F_{calc}$ for both mathematical models, then both obtained empirical equations can be considered having informational value.

Dependency k of the actual ratio between the adhesive and mechanical strength on tl is shown in Figure 4. With the use of the least square method, an approximating power-law dependency was obtained. It can be represented by equation (7):

$$k(t) = 0.1907 \cdot t_l^{-1.236} + 0.5 \qquad (7)$$

where t_l is given in seconds.

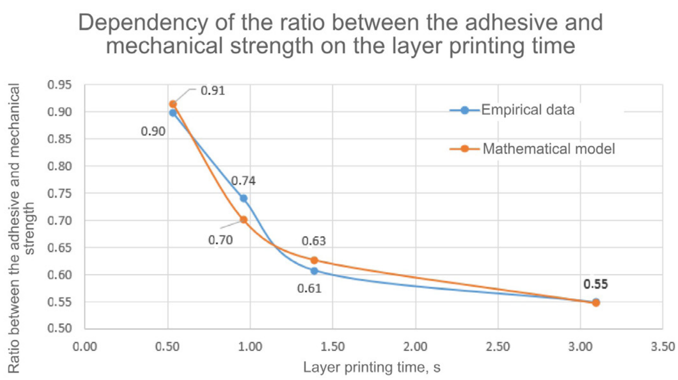

Figure 4. Dependency of the ratio between the adhesive and mechanical strength on the layer printing time

Discussion

The results of the studies confirmed the assumption on the significant effect of time during fused deposition modeling of thermoplastic materials on the adhesive strength of a product (anisotropic material).

The obtained dependency regarding the ratio between the adhesive strength of printing joints and the mechanical strength of the material makes it possible to conclude the following:

1) With an increase in the relative layer printing time, the value of the ratio between the adhesive and mechanical strength decreases according to a law that can be approximated by a power-law function with a sufficient probability.

2) In case of the short relative layer printing time, the strength of adhesive bonding approximates the strength of cohesive bonding (mechanical strength), and with an increase in the layer printing time, it approximates the strength of one-sided connections between hardening and hardened filaments.

Based on the results obtained, it is possible to give practical recommendations and determine paths of further studies:

1. the process of printing several products arranged on the table simultaneously decreases their adhesion strength significantly;
2. during 3D printing, it is required to adjust the printing speed based on the cross-section of the item; the algorithm of control program generation shall provide the possibility of setting the variable printing speed;
3. it is required to perform additional studies to analyze the effect of such process factor as the ratio between the layer printing time and solidification time on the resistance to the shearing of the filaments and solve the following tasks:

- to study the effect of the mentioned process factor on components of the strength tensor in the obtained anisotropic material;
- to develop a method to calculate the printing time and trajectory of the hot end relative to the reference surfaces of the item obtained based on the requirements for its minimum weight, fulfillment of strength conditions in each point, and in accordance with the requirements for printing productivity and technological efficiency of products.

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К ВОПРОСУ СООТНОШЕНИЯ АДГЕЗИОННОЙ И МЕХАНИЧЕСКОЙ ПРОЧНОСТИ СТРОИТЕЛЬНЫХ КОНСТРУКЦИЙ – ИЗДЕЛИЙ 3D-ПЕЧАТИ, ПОЛУЧАЕМЫХ ПОСЛОЙНЫМ НАПЛАВЛЕНИЕМ ТЕРМОПЛАСТОВ

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Аннотация

Введение. В строительной отрасли применение 3D-печати является весьма перспективным направлением, но одним из препятствий к внедрению её в массовое производство является недостаточность теоретической базы, вследствие чего управление качеством получаемых конструкций становится невозможным. **Методика испытаний.** Адгезионные свойства, во многом зависящие от площади сечения - важнейшая составляющая этой технологии, подчас лимитирующая прочностные свойства результирующей конструкции. Вследствие чего необходимо достаточно точно знать помимо механических ещё и адгезионные прочностные свойства изделия при данной технологии. В работе рассматриваются прочностные свойства шва между слоями экструзируемого материала при выполнении конструкции по технологии 3D-печати, а также экспериментально определяется зависимость отношения адгезионной к механической прочности от времени печати одного слоя. **Результаты испытаний.** Практический результат настоящего исследования состоит в выявлении общей зависимости для технологии 3D-печати как в исследуемой, так и в строительной сферах, а также в совершенствовании теоретической базы для развития данной технологии в строительной сфере.

Ключевые слова

Полимерные материалы, аддитивные технологии, послойное наплавление, механическая прочность, адгезионная прочность, строительная 3D-печать.