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THE EFFECT OF HOLLOW STRUCTURE PARAMETER ON THE 3D-PRINTED WALL BEARING CAPACITY. EXPERIMENTAL MODEL

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Abstract. We present the results of experimental studies and modelling of the evaluation of the bearing capacity of hollow 3D-printed walls with the printed shell performing bearing functions. The bearing capacity of hollow 3D-printed walls was experimentally assessed depending on the ratio of the void areas and casting layers in the wall structure. It was established that in case of central loading, a 3D-printed wall with bearing casting layers can serve as a bearing wall similar to traditional types of masonry construction without filling voids with structural concrete and reinforcement. We established the value of strength reduction of hollow 3D-printed walls, which amounted to ~0.1 – 0.25 MPa per 1 % of the increased area of voids. The limit value of the hollow structure parameter was determined, which must not exceed K = 0.75 in order to ensure the bearing capacity of self-bearing and non-bearing 3D-printed walls. We obtained an experimental model of the relationship between the hollow structure parameter and the bearing capacity, which allowed predicting the bearing capacity of a 3D-printed wall under central loading. It was suggested to take into account the hollow structure parameter K when calculating the elements of unreinforced 3D-printed walls under central compression according to the first group of limit states.

Keywords: 3D-build printing, bearing capacity, strength, wall, experimental model

ЭКСПЕРИМЕНТАЛЬНАЯ МОДЕЛЬ ВЛИЯНИЯ ПУСТОТНОСТИ НА НЕСУЩУЮ СПОСОБНОСТЬ СТЕН, ПОЛУЧЕННЫХ ПО АДДИТИВНОЙ ТЕХНОЛОГИИ

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Аннотация. Представлены результаты экспериментальных исследований и моделирования оценки несущей способности пустотелой 3D-напечатанной стены, в которой печатная оболочка выполняет несущие функции. Экспериментально оценена несущая способность 3D-печатных пустотелых стен в зависимости от соотношения площади пустот и печатных слоев в конструкции стены. Установлено, что 3D-напечатанная стена с несущими аддитивными слоями в случае центрального нагружения может выполнять роль несущей стены аналогично традиционным видам каменной кладки без заполнения пустот конструкционным бетоном и армирования. Определена мера снижения прочности 3D-напечатанной стены, которая составляет ~0.1 – 0.25 МПа на 1 % увеличения площади пустот. Установлено предельное значение параметра пустотности, которое не должно превышать K = 0.75, для обеспечения несущей способности самонесущих и ненесущих аддитивных стеновых конструкций. Получена экспериментальная модель взаимосвязи пустотности и несущей способности, которая позволяет прогнозировать несущую способность 3D-напечатанной стены при центральном нагружении в зависимости от параметра пустотности K. Предложено учитывать параметр пустотности K при расчете элементов неармированных аддитивных стеновых конструкций при центральном сжатии по первой группе предельных состояний.

Ключевые слова: строительная 3Д-печать, прочность, стена, экспериментальная модель

INTRODUCTION

The most common option of the wall structure in 3D-build printing is in the form of two straight layers connected by a sinusoidal lintel as a diaphragm stiffness [1-3]. Such a wall is actually a space truss with parallel belts, which means that the internal and external parts of the wall are interconnected by a spatial structure in the form of triangles [4]. The rationality of using such walls can be explained by the need to minimise the “idle” movement of the extruder of a construction printer, which ensures the continuity of the printing contour [5]. Precast lintels are installed above window and door frames. Channels are provided in the door profiles for the placement of utility systems and a hollow to be filled with a heat-insulating material [6,7].

In all implemented projects with 3D-build printing objects, the construction of walls includes the following steps:

- 3D printer prints the wall shell;
- Wall cavities are reinforced manually;
- Wall cavities are filled with structural concrete and (for external walls) insulation.

This approach is also typical for the manufacture of precast structural elements of complex curvilinear geometry [8].

The main disadvantage of this practised approach is that the printed shell acts as a fixed formwork and does not have a constructive function. Examples is 3D printed walls made using WinSun technology, CyBe technology, etc.[9-11]., The most operations in these technologies are performed manually, excluding the printing of fixed formwork. It was noted in [12] that the traditional technology of concrete casting was actually used in the formwork instead of the innovative printing technology, Today, this determines the high labour intensity of the process. This approach is an over-simplification of the idea of 3D-build printing as a robotic intelligent construction technology and may lead to its discreditation. From an economic point of view, the use of a printed shell only as a fixed formwork is also inefficient due to its obviously high cost as compared to traditional formworks.

However, in a number of studies it was confirmed that hollow 3D-printed walls that were not filled with structural concrete have sufficient bearing capacity due to the high strength of the material used and the more homogeneous strength properties of the obtained structure as compared to traditional masonry. For example, in [13], a compressive strength of 2.3 MPa was determined as a result of testing a 3D-printed concrete segment. The effective area of the wall with the deduction of the hollow was approximately 60% of the total area. That is confirmed that the hollow3D-printed wall shell carries out bearing function. So, the influence of the hollow parameter on the bearing capacity of 3D-printed walls needs to study in order to use it in design of 3D printed wall. According to the requirements of SP 15.13330.2020 “Masonry and reinforced masonry structures”, this corresponds to the strengths that are traditional in the Russian Federation [14] for the following types of walls:

- Masonry of M150 ceramic bricks on an M100 mixture,
- Made from B7.5 cellular concrete blocks on an M100 mixture,
- Made from M150 solid gypsum concrete blocks on an M150 mixture.

Thus, there is a possibility of using a hollow 3D-printed wall as a bearing and self-bearing wall in low-rise construction. This requires sufficient bearing capacity of the hollow wall structure, while their internal space should be used for creating heat-insulating layers instead of being filled with structural heavy concrete. The hollowness of the 3D-printed wall will allow their material consumption and reduce the costs of manual labour in the course of construction. In order to do this, the allowable area of voids per unit area of the wall must be determined as the current regulatory document SP 15.13330 does not in any way regulate the design of 3D-printed structures.

The goal of the study was to justify the requirements to the effective cross-section area of hollow 3D-printed walls by the criterion of ensuring its bearing capacity based on experimental studies and modelling.

Research objectives:

- Evaluating the bearing capacity of hollow 3D-printed walls depending on the ratio of the void areas and casting layers in the wall structure;
- Obtaining an experimental model of the influence of a hollow structure 3D-printed wall on its bearing capacity;
- Making suggestions for calculations on the strength of 3D-printed walls taking into account their hollow structure.

MATERIALS AND METHODS

The object of the study is a hollow 3D-printed wall with a sinusoidal lintel (Fig. 1). To assess the bearing capacity, we used the model and full-size 3D-printed wall segments the sizes of which are presented in Table 1.

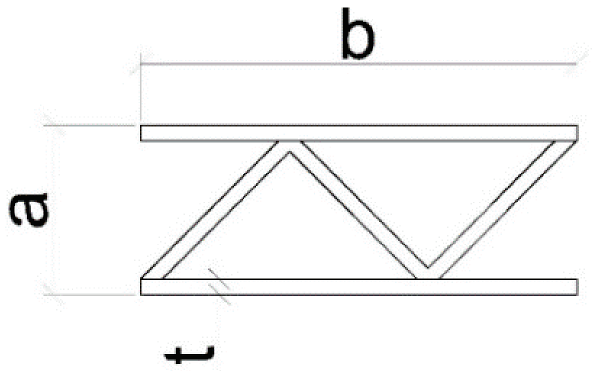

Figure 1. Cross-section of 3D-printed wall

Table 1. Size of experimental samples

Sample	a, mm	b, mm	t, mm	h, mm
3D-printed wall model segment				
IBW -75	75	155	15	150
IBW -90	90	200	15	180
IBW -105	105	245	15	210
EBW -135	135	335	15	270
EBW -150	150	380	15	300
EBW -165	165	425	15	330
3D-printed wall full-size segment				
IBW -75-f	250	520	50	500
IBW -90-f	300	670	50	600
IBW -105-f	350	820	50	700
EBW -135-f	450	1120	50	900
EBW -150-f	500	1270	50	1000
EBW -165-f	550	1420	50	1100

Note: Code EBW-135 means the following: the thickness of the bearing external wall is 135, IBW is the internal bearing wall, index "f" stands for a full-size construction.

The relative effective cross-sectional area A_c/A_{cs}, the ratio of concrete area (A_c) to cross-sectional area ($A_{cs} = a \times b$), was chosen as a variable parameter.

It is reasonable to assume that the following inequality must be satisfied for the relative effective area:

$$X < A_c / A_{cs} \leq 1, \quad (1)$$

where 1 is the value of a layered conventionally monolithic sample,

X is the minimum value of the relative effective cross-sectional area allowable to ensure the bearing capacity.

The range of values of the relative effective cross-sectional area A_c/A_{cs} of the 3D-printed wall segment used in the experiment is presented in Table 2.

Table 2. Parameters of experimental samples

Sample	Concrete area A_c, mm^2	Cross-sectional area ($A_{cs} = a \times b$), mm^2	Relative effective cross-sectional area A_c/A_{cs}	Hollow structure parameter K
3D-printed model wall segment				
IBW -75	7530	11625	0.65	0.35
IBW -90	9825	18000	0.55	0.45
IBW -105	12165	25725	0.47	0.53
EBW -135	16755	45225	0.37	0.63
EBW -150	19050	57000	0.33	0.67
EBW -165	21345	70125	0.30	0.70
3D-printed full-size wall segment				
IBW -75-f	83800	130000	0.64	0.36
IBW -90-f	109450	201000	0.54	0.46
IBW -105-f	134950	287000	0.47	0.53
EBW -135-f	186250	504000	0.37	0.63
EBW -150-f	211750	635000	0.33	0.67
EBW -165-f	237400	781000	0.30	0.70

Materials and 3D-printed wall segment preparation. The cement-sand mixture, patented by the author's team [15], was used for the printing wall model segments. The strength characteristics of the hardened cement-sand mixture are presented in Table 3.

Table 3. Strength test results

Compressive strength (axial), MPa	47.0
Compressive strength (cube), MPa	60.0
Flexible strength (four-point bending), MPa	2.8
Splitting interlayer bond strength, MPa	3.0

Sand-based concrete of B40 strength class was used to obtain a 3D-printed wall full-size segment.

Model and full-scale walls were printed on laboratory and industrial printers, respectively, with similar conditions for manufacturing and curing:

- Constant print speed 2 cm/s,
- Constant distance between nozzle and layer – 2 cm;
- Printing time gap < 1 min;
- Curing for 28 days in the same environment (T = 20 ± 2°C, RH = 60-70 %).

Figure 2 presents an example of 3D-printed model wall segment.

Figure 2. 3D-printed model wall segment after printing

Test conditions of 3D-printed wall segment. The printed hollow wall segments were tested for axial compression with a central load application according to GOST 32047-2012 "Masonry. Method of compressive test". The choice of the test pattern was due to the following. Testing methods for wall and other structures regarding 3D-build printing are not currently regulated. We analysed the experience [13] of a compression test of a 3D-printed wall segment 730 × 530 × 504 mm in size with a layer size of 12 × 35 mm. This pattern corresponding to the methodology of GOST 32047-2012 was accepted as adequate. Series of 3 samples were manufactured and tested for each type of a 3D-printed wall segment. 3D-printed wall segments prepared for testing and installed in the testing machine are presented in Figures 3 and 4.

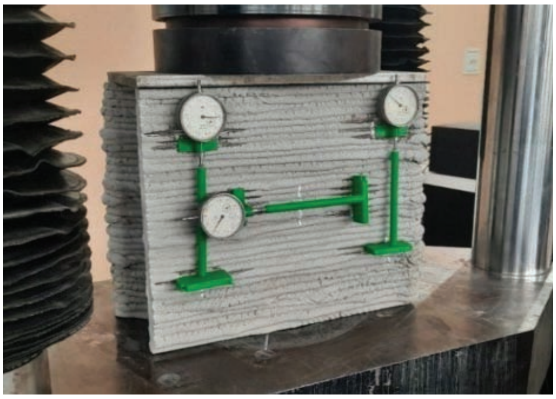

Figure 3. A 3D-printed model wall segment prepared for testing

Figure 4. General view on 3D-printed full-size wall segments before testing

EXPERIMENTAL RESULTS

Test results of 3D-printed wall segments are presented in Table 4.

The nature of destruction of the model and full-size wall segments upon central compression was identical and was characterised by the formation of vertical cracks that crossed the layers without any changes in the crack path. With an increase in the load, the number of cracks increased (Figures 5 and 6).

Table 4. 3D-printed walls axial compression test results

Sample	Cross-sectional area A_{cs}, mm^2	Concrete area A_c, mm^2	Relative effective cross-sectional area A_c/A_{cs}	Force N, kN	Strength of the model wall, related to the sectional area (considering hollows) N/ A_{cs}, MPa	The strength of the model wall, related to the concrete area N/A_c, MPa
3D-printed model wall segment						
IBW -75	13825	11678.3	0.84	126.14	9.10	10.85
IBW -90	20333	15840.4	0.78	191.41	9.37	11.85
IBW -105	29400	18621.3	0.63	223.50	7.60	12.00
EBW -135	49800	28218.5	0.57	279.35	5.59	9.87
EBW -150	62300	33871.1	0.54	384.35	6.25	12.17
EBW -165	73800	36924.0	0.50	407.37	5.54	11.06
3D-printed full-size wall segment						
IBW -75-f	134900	91500.0	0.68	1389.00	10.30	15.18
IBW -90-f	207162	112000	0.54	1380.00	6.66	12.32
IBW -105-f	285363	142630	0.50	1411.00	4.94	9.89
EBW -135-f	490757	172080	0.35	984.00	2.01	5.72
EBW -150-f	633775	199870	0.32	1017.00	1.60	5.09
EBW -165-f	771584	242160	0.31	1121.00	1.45	4.63

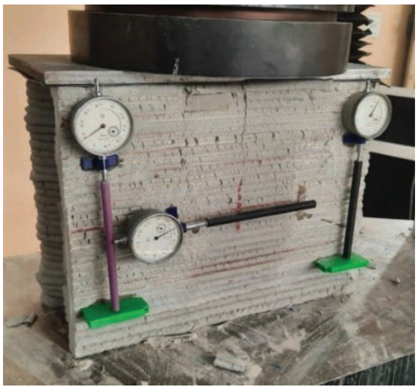

Figure 5. Representative example of the 3D-printed model wall segments during the compressive strength test

The effect of the hollow structure on the strength of walls was assessed quantitatively. With an increase in the size of the 3D-printed model wall segments, the ratio of the concrete area to the total cross-sectional area of the A_c/A_{cs} wall decreased within the range from 0.9 to 0.5, while the hollow structure, accordingly, increased from 0.1 to 0.5. The compressive strength of model walls classified as part of the total cross-sectional area N/A_c (which means, taking into account the hollow structure) naturally decreased and changed within the range of 5.5 – 9.4 MPa. The strength values of the bearing layers of concrete remained almost the same for all types of 3D-printed model wall segments and were in the range of 10 – 12 MPa. This showed that the bearing layers used their structural potential equally, regardless of the changes in the usable cross-sectional area of the wall.

Figure 6. A representative example of the 3D-printed-size wall segments during the compressive strength test

With an increase in the size of the model and full-size wall segments, the ratio of the concrete area to the total cross-sectional area of the A_c/A_{cs} wall decreased within the range of 0.7 – 0.3, while the hollow structure increased from 0.3 to 0.7, accordingly. The compressive strength of full-size walls classified as part of the total cross-sectional area N/A_c (which means, taking into account the hollow structure) naturally decreased and changed within the range of 1.45 – 10.3 MPa. The strength values of bearing concrete layers of full-size walls decreased and were within the range of 5 – 15 MPa. This indicated that the structural potential of the bearing layers depended on the change in the useful cross-sectional area of the wall and the scale factor as part of the central loading. The reduction in the strength of full-size wall segments as compared to model segments can be explained by the scale factor. With an increase in the size of the walls, their flexibility of straight layers increased, and as a result, the stability of the 3D-printed full-size wall segment on the whole decreased.

According to the obtained data, it can be stated that the bearing capacity of 3D-printed walls is determined by the following factors:

- The ratio of the concrete area to the total cross-sectional area of the wall or its hollow structure.
- The scale factor and especially its effect on the flexibility and stability of the structure.

The results of the assessment of the bearing capacity of hollow 3D-printed walls were correlated with the requirements to the bearing capacity of masonry from small-piece wall products, regulated by SP 15.13330.2020 “Masonry and reinforced masonry structures”. It can be explained by the fact that the working conditions for masonry and 3D-printed structures in internal and external bearing and self-bearing walls are similar. In the studied range of changes of the concrete area A_c/A_{cs} = 0.3-0.9 in the section of a hollow 3D-printed wall with bearing printed layers, the strength range was 1.45-10.3 MPa. In case of central loading these values corresponded to and, in most cases, exceeded the requirements of SP 15.13330.2020 to the calculated compressive strengths of typical forms of masonry for house construction. In particular, the strength values obtained in experiments corresponded to the strength of masonry from solid concrete, gypsum concrete, and natural stones, which was within the range of 0.38-13.0 MPa in accordance with the requirements of Table 6.5 of SP 15.13330.2020 (with a masonry layer height of 200-300 mm).

EXPERIMENTAL MODEL

The values of 3D-printed model and full-size wall segments were generalised depending on the hollow structure parameter (Figure 7).

$$K = 1 - A_c / A_{cs} \qquad (2)$$

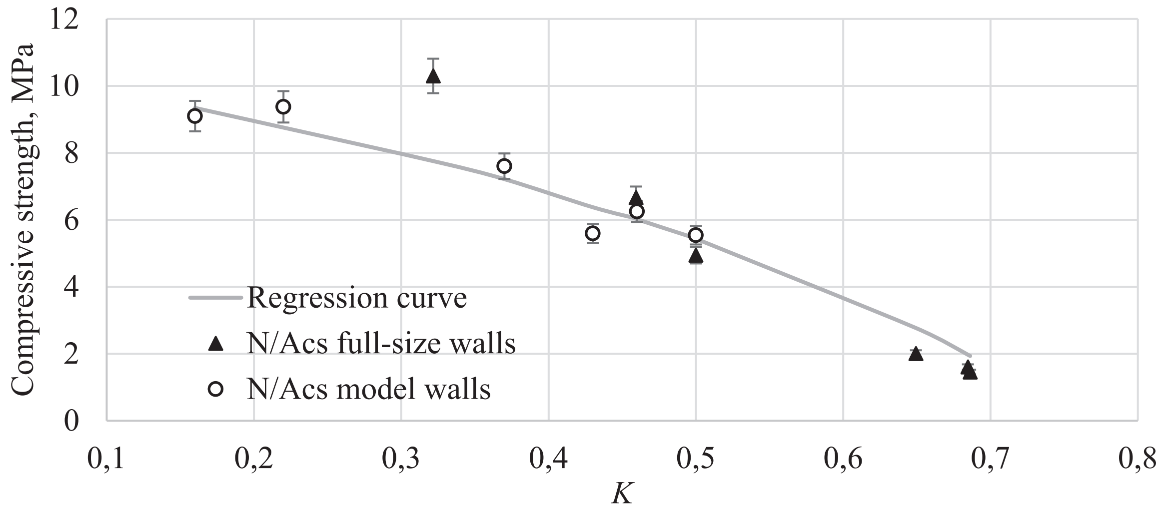

Figure 7. The effect of hollow structure parameter K on the 3d-printed wall bearing capacity.

Based on the regression analysis of experimental data, we obtained an equation that predicted a change in the bearing capacity of 3D-printed walls depending on their hollow structure.

$$N = \ln(1-K)^{7.94 A_{cs}} + 10.89 \cdot A_{cs} \qquad (3)$$

The reliability coefficient of the experimental data approximation was 0.9 for the obtained regression curve (eq. (3))

Therefore, it can be stated that the obtained experimental model described by equation (3) allowed predicting the bearing capacity of 3D-printed walls upon central loading depending on the hollow area in the section. The solution of this equation also allowed determining the minimum allowable boundary of wall void content by the criterion of ensuring enough bearing capacity in case of central compression. Taking into account the root of equation (3), the following inequality is true:

$$0 \le K < 0.75 \quad (4)$$

High convergence of the experimental data with the calculated data allowed proposing the hollow structure parameter K to be used for the calculation of strength of hollow 3D-printed walls according to the standard method SP 15.13330.2020 “Masonry and reinforced masonry structures”. The hollow parameter in this standard is used for masonry blocks. At the same time, in some foreign standards for building blocks the filling ratio is normalized in the range from 40% to 75%, vice versa the hollow of the building blocks is from 25% to 60%. It is corresponded to investigated hollow structure range of 3D-printed wall segments.

When designing 3D-printed walls, the calculations for the first group of limit states were allowed to be performed using existing standard methods, which are regulated in SP 63.13330 “Concrete and reinforced concrete structures. General provisions”, SP 15.13330 “Masonry and reinforced masonry structures”.

When using the specified standard methods, it is suggested to calculate the bearing capacity upon central compression of an unreinforced hollow 3D-printed wall using the following improved formula:

$$N \le m_r \cdot (1-K) \cdot m_g \cdot \varphi \cdot R \cdot A, \quad (5)$$

where N is the calculated longitudinal force; R is the calculated compressive strength of 3D-printed layered concrete, determined by new parametric rows; A is the wall cross-sectional area in geometric axes, K is the hollow structure parameter, m_g is the coefficient taking into account the impact of a long-term load, φ is the buckling coefficient.

At the same time, it is proposed to introduce the coefficient m_r into relation (5) which takes into account a decrease in the strength potential of 3D-printed layered concrete in the structure. Systematic studies must be performed in order to determine it. Extended experimental studies are also required to determine the impact of such parameters as concrete class, reinforcement, and wall configuration in combination with hollow structure on the bearing capacity of 3D-printed walls.

CONCLUSION

1. It was established that in case of central loading the strength of an unreinforced hollow 3D-printed wall corresponded to and/or exceeded SP 15.13330.2020 “Masonry and reinforced masonry structures” and amounted to 1.45–10.3 MPa within the range of a hollow structure 0.15–0.75. Therefore, in case of central loading a hollow 3D-printed wall can serve as a bearing wall similar to traditional types of masonry with no need to fill the voids with structural concrete and reinforcement.
2. According to the test results of model and full-size 3D-printed walls, it was established that the main factor determining their bearing capacity was the hollow structure. We determined the value of strength reduction of 3D-printed walls, which was ~0.1 – 0.25 MPa per 1% of the increased area of the hollow structure.
3. An experimental model was obtained that allowed predicting the bearing capacity of 3D-printed walls upon central loading depending on the hollow structure parameter K. According to the obtained model, the calculated value of the hollow structure parameter should not exceed 0.75 in order to ensure the bearing capacity of self-bearing and non-bearing 3D-printed walls. Thus, it is suggested to perform the calculation for the first group of limit states of the bearing capacity of unreinforced hollow 3D-printed walls upon central compression using the hollow structure parameter K.

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