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Key words: *buildings in 3D technology, 3D printing, outer wall, stress condition*
doi:10.5937/jaes0-28755

Cite article:
Gennadievna, E. P., Vladislavovich, P. M., Vladislavovich, O. E., & Balthazar, D. A. [2020]. Research of design parameters influence of building wall, constructed with the help of 3d printer, on its stress state. *Journal of Applied Engineering Science*, 18(4), 565 - 570.

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Istraživanja i projektovanja za privredu
Journal of Applied Engineering Science

Original Scientific Paper

doi:10.5937/jaes0-28755
Paper number: 18(2020)4, 728, 565-570

RESEARCH OF DESIGN PARAMETERS INFLUENCE OF BUILDING WALL, CONSTRUCTED WITH THE HELP OF 3D PRINTER, ON ITS STRESS STATE

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The article presents the research results of design parameters influence of outer wall of a building erected in 3D technology, namely: wavelength of inner wall diaphragm, displacement of lower wave relative to upper wave of inner wall diaphragm (displacement of wave crest) on the stress state of a wall fragment subject to the constancy of its cross-section area. The set of data for analysis has been obtained on the basis of calculations in the SCAD ++ computer complex. The dependences of relative stresses of wall fragments on the studied factors have been obtained and the interpretation of research results has been given.

Key words: buildings in 3D technology, 3D printing, outer wall, stress condition

INTRODUCTION

Due to rapid development of technologies, namely digital technologies, there has been a tendency to increase the automation of production processes in various industries, including construction in recent decades [1] to [3]. The latest innovation in construction is the application of 3D printing technology. The essence of this technology lies in the fact that a layer by layer of concrete mixture is applied by extrusion along the programmed contour of the building structure, thereby producing individual building structures of the building or "printing" the building as a whole [4] to [6].

At the moment this technology is being tested all over the world and more than a dozen buildings have already been erected using 3D printing [7] to [9]. One of the most recent examples of the use of 3D printing is the two-story office for a government agency of the United Arab Emirates, which was built in 2019, Fig. 1 [10]. This building has a total area of 6400 m^2 and a height of 9.5 m. It took the contractor 21 days to "print" the vertical structures. Only the walls of buildings were made by layer-by-layer "printing" using a 3D-printer (Fig. 1). This project was implemented by Apis Cor [10].

It is known that the outer walls of heated buildings must have the required strength and heat-protective qualities. The analysis of fragments of the horizontal section of walls erected in 3D technology [12] to [14] has shown that this issue is not resolved on the level, and if attempts to optimize the structural solutions of external walls from the standpoint of thermal protection of buildings are underway [12], [15], [16], then studies aimed at the influence of design solutions walls on their load-bearing capacity is not enough.

Figure 1: Two-story building erected by APISCOR in Dubai in 2019 [10], [11]

MATERIALS AND METHODS

As an example, discussed further in the study, we give a fragment of the wall section of Contour Crafting Company (Fig. 2) [17]. For a fragment of this section measuring 0.3 x 1 m^2, the area of the bearing part has been calculated, which is 0.186 m^2. The share of the bearing part

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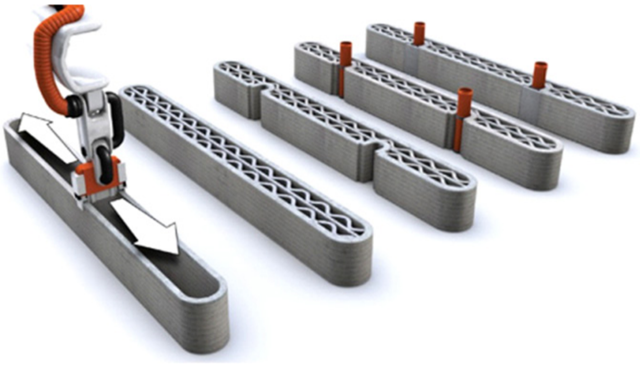


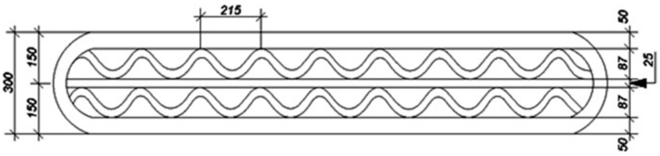


Figure 2: Schematic of a horizontal wall section by Contour Crafting [17]

in the total cross-section area is 62%. The walls have a hollow structure. The thickness of the walls of the bearing part of the section ranges from external 30 ... 50 mm, to internal 15 ... 30 mm.

Despite the fact that filling the voids of outer walls should be carried out with heat-insulating material in the study carried out in this article, the authors consider the constructive solution of the outer wall without filling its voids with heat-insulating material due to its low rigidity.

A fragment of the outer wall of a building erected in 3D technology from concrete of class B20 with a length of lст=1.00m, thickness dст=0.30m and a height of h=3.00m is taken as the object under study. The variants of the fragment models differ among themselves in configuration and geometric parameters of the voids in the section (Fig. 3).

The initial condition for all considered configuration options is the constancy of the cross-section area of the bearing part of the wall, which is 62% of the total cross-section area of the wall fragment, as recommended in [17]. The condition for the mandatory presence of 62% filling of the cross-section bearing material has contributed to the creation of options with different configurations of voids, but with the same cross-section areas of the bearing part, which are 0.30 x 0.62 = 0.186m^2. In order to simplify the generation of the studied parameters, it has been decided to take the thicknesses of the inner and outer parts of the walls under study by 0.04 m, and the thickness of the diaphragms (waves and partitions) to be taken as variables, depending on their configuration. The thickness of the waves and intermediate partitions is taken the same from the practice experience and is determined by the results of cutting, knowing the total area, thickness of the outer walls and the length of the diaphragms in accordance with the condition of the constancy of the cross-section area of the bearing part of the wall, adopted according to the condition of ensuring strength.

In the study, the wavelength of the inner wall diaphragm l, [m] varied at three levels and is taken equal to 0.500, 0.200 and 0.125 m, and the displacement of the lower wave relative to the upper wave of the inner wall diaphragm Δ, [wave] (displacement of the wave crest) is taken within 0, 1/4 and 1/2 waves. Figure 3 shows the investigated variants of the outer wall and the generated dimensions of the thicknesses of the stiffening diaphragms.

To determine the influence of the investigated factors on the stress state in the computer complex SCAD ++, models of external walls have been created using spatial isoparametric six-node and eight-node finite element grids (Fig. 4). Loading of the model upper surface has been carried out with a load equal to 10kN/m^2 distributed ac-

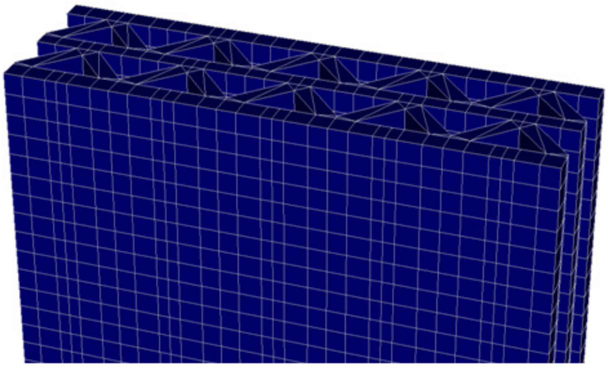


Figure 4: Fragment of the design model of wall element

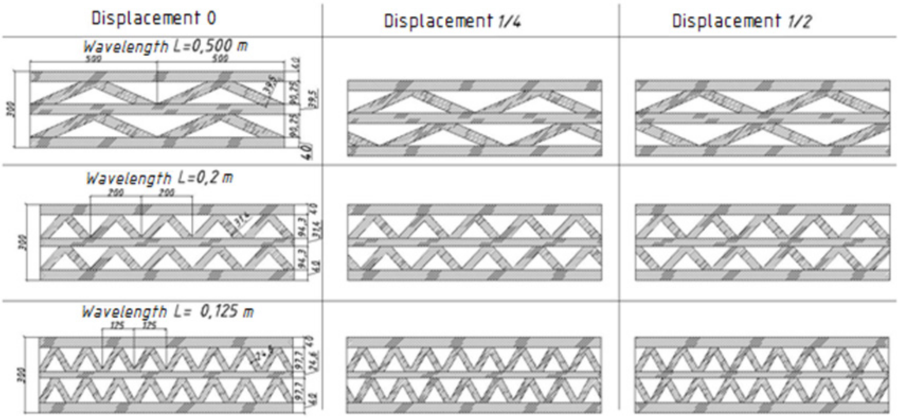


Figure 3: Variants of a wall fragment in 3D technology with different configurations of voids in cross sections

cording to the law of a triangle (along the wall thickness). The boundary conditions assumed the possibility of horizontal displacements of the nodes of the wall model at its ends.

The calculation of the maximum and minimum relative stresses in the direction of the Z axis (in the direction of height) has been calculated by the formula:

$$\overline{\sigma_z} = \frac{\sigma_z}{q} \tag{1}$$

where σ_z - normal stresses in the direction of local axes of coordinates Z; q = 10kN/m^2 distributed load on a wall fragment.

RESULTS

The calculation results are shown in Table 1 and Figure 5. Examples of stress distribution are shown in Figures 6-7.

Table 1: The results of calculating the maximum and minimum relative stresses in the direction of the Z axis (in the direction of height)

№	l, [m]	Δ, [waves]	$\overline{\sigma}_{zmax}$	$\overline{\sigma}_{zmin}$
1	0.5	0	-2.937	-0.184
2	0.2	0	-2.592	-0.346
3	0.125	0	-2.711	-0.37
4	0.5	1/4	-2.986	-0.227
5	0.2	1/4	-2.601	-0.362
6	0.125	1/4	-2.701	-0.359
7	0.5	1/2	-2,972	-0.337
8	0.2	1/2	-2.609	-0.393
9	0.125	1/2	-2.696	-0.362

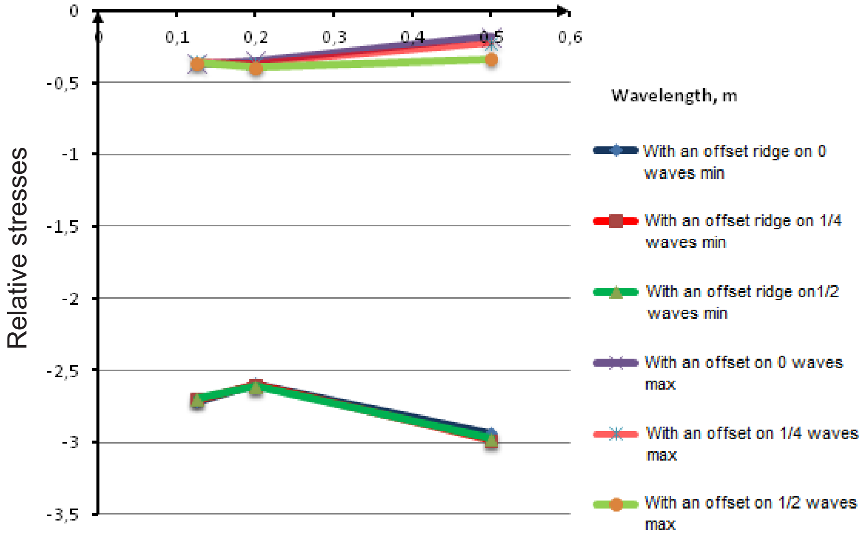


Figure 5: Dependence of relative stresses σ_z of wall fragments on wavelength l, [m] and displacements of the wave crest Δ, [waves]

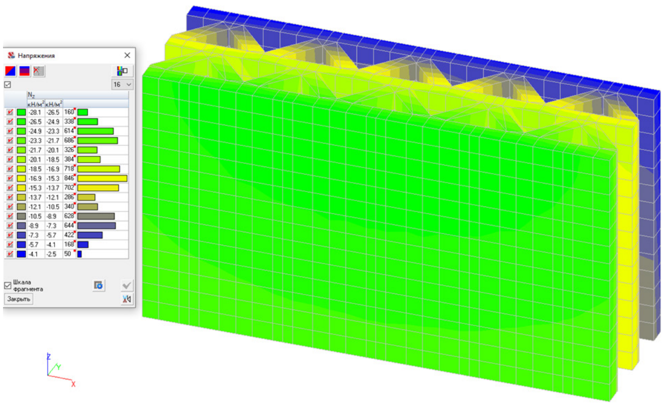
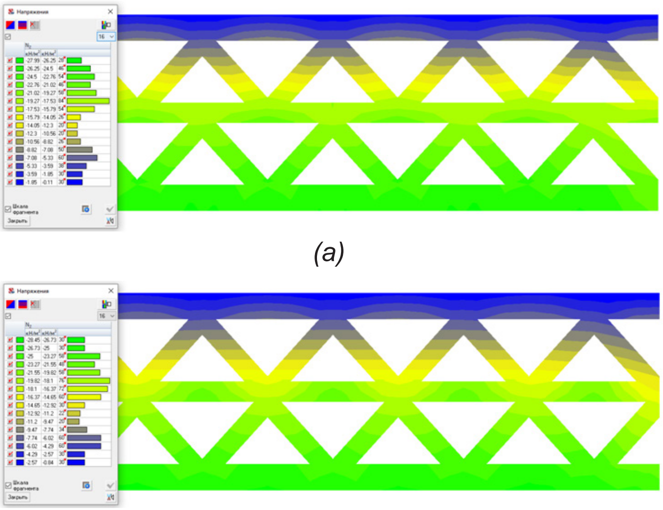


Figure 6: An example of stress distribution σ_z along the wall height



(a)

(b)

Figure 7: Distribution of stresses σ_z along the wall thickness at wavelength of l=0.2 m, and displacements of the wave crest Δ equal to (a) 0 and (b) 0.5

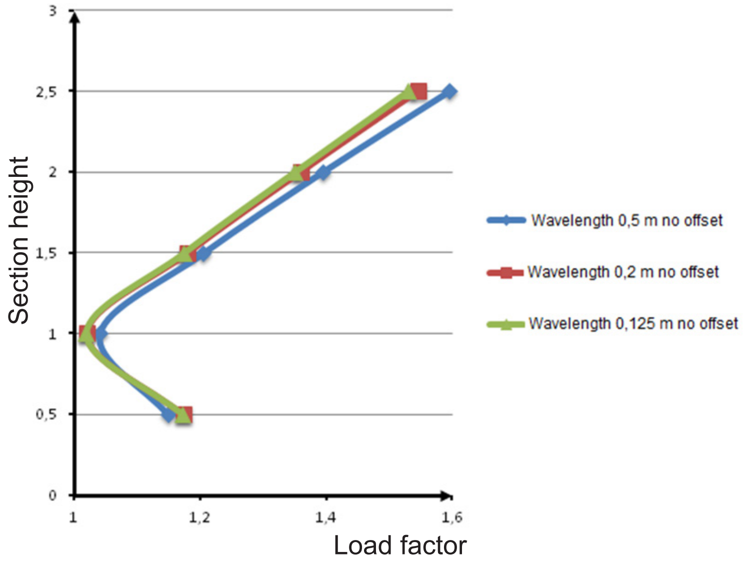


Figure 8: Dependence of the coefficient of unevenness on the height of the section H

The research results have shown that all structures have practically the same distribution patterns of maximum and minimum relative stresses in the direction of the wall height (Z axis). It is found that at the initial stage of increasing the wavelength of the inner wall diaphragm (l) to 0.2 m, there is a slight increase in the relative minimum stresses in some structures and a decrease in the minimum stresses (from -2.711 to -2.592 in the design solutions of the walls without wave displacement; from - 2.701 to -2.601 when the crest is shifted by ¼ wave and from -2.696 to -2.609 when shifted by ½ wave). An increase in the wavelength to 0.5 m leads to an increase in the maximum (up to 13%) and a decrease in the minimum stresses. The maximum relative stresses change from -2.592 to -2.937, from -2.601 to -2.986, and -2.609 to -2.972 for the design without displacement, with ¼ and ½ wave crest displacement.

The displacement of waves almost has no effect on the values of the maximum and minimum stresses (Fig. 7), which are observed mainly at the places of load application and at the places where the wall rests on the foundation. All stress values are obtained at the centers of finite elements.

The unevenness of the stress state in the walls and section waves has been estimated using the stress unevenness coefficients, determined by the formulas:

$$K_{n1} = \frac{\sigma_{z,max}}{\sigma_{z,m}} \qquad (2)$$

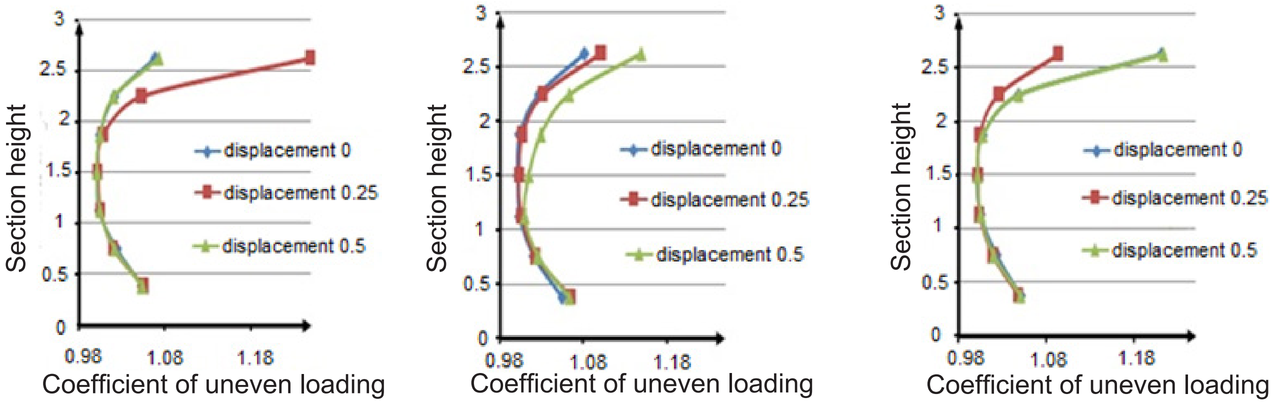
$$K_{n2} = \frac{\sigma_{z,max}}{\sigma_{z,min}} \qquad (3)$$

where $\sigma_{z,m}$, $\sigma_{z,max}$, $\sigma_{z,min}$ - average, maximum and minimum normal voltages.

The values of the K_{n1} coefficient are determined for the entire section, and the K_{n2} coefficient only for the sections of the piers.

The minimum stress unevenness in terms of intensity (Fig. 8) is noted in the lower part of the wall fragment (range 0.5-1.5 m from the place of support) and practically does not depend on the wavelength and displacement of the wave.

Stress unevenness in the cross-section walls (Fig. 9) is essentially manifested in the upper part of the wall fragment (range 2.0-3.0 m from the place of support) and depends on the magnitude of the wave displacement.



(a) (b) (c)

Figure 9: Dependence of the coefficient of unevenness K_{n2} on the height of the section H: a) for the inner pier of wall; b) for the middle pier of wall; c) for the outer pier of wall

In the considered range of influencing parameters, the most favorable is the stress state at a wavelength of l = 0.2 m and a displacement of the wave crest Δ = 0.

CONCLUSION

The study has shown that when erecting buildings in 3D technology, an important aspect is the constructive solution of the outer walls, on the selected parameters of which not only their heat engineering, but also their strength properties depend. It is found that with a constant area of the bearing part of the wall section, by varying such parameters of the outer wall as the wavelength of the inner diaphragm and the displacement of the lower wave relative to the upper wave of the inner wall diaphragm, one can influence the stress-strain state of the entire wall structure.

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Paper submitted: 07.10.2020.
Paper accepted: 09.11.2020.