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APPLICATION OF 3D PRINTING TECHNOLOGY FOR MECHANICAL PROPERTIES STUDY OF THE PHOTOPOLYMER RESIN USED TO PRINT POROUS STRUCTURES

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Abstract

In the field of numerical research there are various approaches and methods for structures of porous materials modeling. The solution is the use of fractal models to develop the porous structure.

In the case of modeling the geometry of natural (random) materials, there is a problem of compatibility of the FE model geometry and real one. This is a source of differences between the results of calculations and experimental ones. Application of 3D printing technology will allow to receive a real structure in a controlled manner, which exactly reflects the designed structure and is consistent with the geometry of the numerical model. An experimental research on the standard samples made of photopolymer resin using 3D printing technique was presented in the paper. The aim of the research was to determine the base material properties and, consequently, to select the constitutive model, which is necessary to carry out numerical analyses.

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Introduction

The "3D printing" was originally referred to a process that deposits a binder material onto a powder bed with inkjet printer heads layer by layer. More recently, the term is being used to encompass a wider variety of additive manufacturing techniques. United States and global technical standards use the official term *additive manufacturing* for this broader sense.

3D printing technology is any of various processes in which material is joined or solidified under computer control to create a three-dimensional object, with material being added together (such as liquid molecules or powder grains being fused together). The process consists of printing successive layers of materials that are formed on top of each other. This technology has been developed by Charles Hull in 1986 in a process known as stereolithography (SLA), which was followed by subsequent developments such as powder bed fusion, fused deposition modeling (FDM), inkjet printing and contour crafting (CC). 3D printing, which involves various methods, materials and equipment, has evolved over the years and has the ability to transform manufacturing and Logistics processes. Additive manufacturing has been widely applied in different industries, including construction, prototyping and biomechanical. The uptake of 3D printing in the construction industry, in particular, was very slow and limited despite the advantages e.g. less waste, freedom of design and automation (NGO et al. 2018).

The growing consensus of adapting the 3D manufacturing system over traditional techniques is attributed to several advantages including fabrication of complex geometry with high precision, maximum material savings, flexibility in design, and personal customization. A wide range of materials that are currently used in 3D printing include metals, polymers, ceramics and concrete. Polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS) are the main polymers used in the 3D printing of composites. Advanced metals and alloys are typically utilized in the aerospace sector because traditional processes are more time consuming, difficult and costly. Ceramics are mainly used in 3D printed scaffolds and concrete is the main material employed in the additive manufacturing of buildings.

However, the inferior mechanical properties and anisotropic behavior of 3D printed parts still limit the potential of large-scale printing. Therefore, an optimized pattern of 3D priming is important to control flaw sensitivity and anisotropic behavior. Also, changes in the printing environment have an influence on the quality of finished products (IVANOVA et al. 2013).

Methods of additive manufacturing (AM) have been developed to meet the demand of printing complex structures at fine resolutions.

Rapid prototyping, the ability to print large structures, reducing printing defects and enhancing mechanical properties are some of the key factors that have driven the development of AM technologies (Fig. 1). The most common

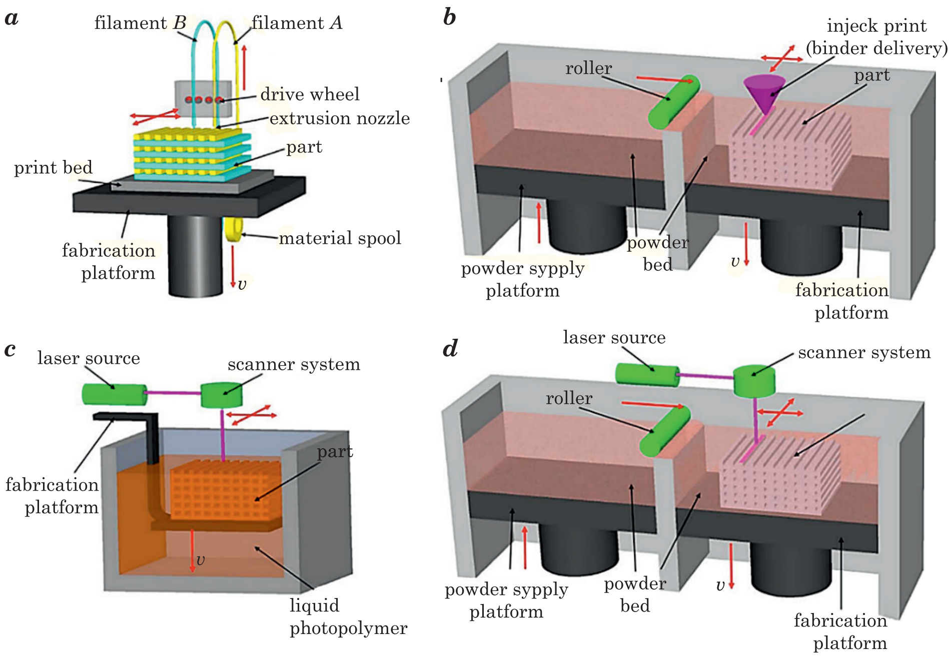

Fig. 1. Scheme of main methods of additive manufacturing: *a* – fused deposition modelling; *b* – inkjet printing, *c* – stereolithography, *d* – powder bed fusion
Source: based on WANG et al. (2017).

method of 3D printing that mainly uses polymer filaments is known as fused deposition modelling (FDM). In addition, additive manufacturing of powders by selective laser sintering (SLS), selective laser melting (SLM) or liquid binding in three-dimensional printing (3DP), as well as inkjet printing, contour crafting, stereolithography, direct energy deposition (DED) and laminated object manufacturing (LOM) are the main methods of AM (BHUSHAN, CASPERS 2017).

SLA (Stereolitography)

Stereolithography (SLA) is an additive manufacturing — commonly referred to as 3D printing — technology that converts liquid materials into solid parts, layer by layer, by selectively curing them using a light source in a process called photopolymerization. SLA is widely used to create models, prototypes, patterns, and production parts for a range of industries from engineering and product design to manufacturing, dentistry, jewelry, model making, and education.

The polymerization process

Plastics are made out of long carbon chains. The shorter the chain, the less solid or viscous the plastic. Resin is a plastic composed of short(er) carbon chains —from 1 carbon to a few thousand carbons. It has all of the components of the final plastic, but hasn't been fully polymerized yet. When the resin is exposed to UV light, the chains join together to create much longer and therefore stiffer chains (Fig. 2). When enough chains have reacted, the result is a solid part (*The ultimate guide*... 2017).

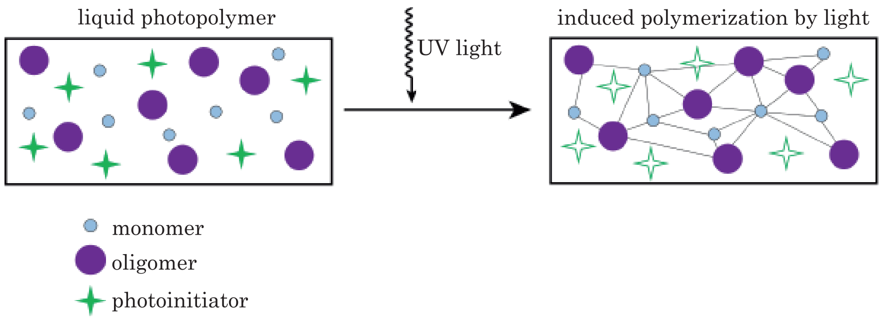

Fig. 2. Steps of the polymerization process
Source: based on FOUASSIER et al. (2003).

The monomer and oligomer chains in the resin have active groups at their ends. When the resin is exposed to UV light, the photo initiator molecule breaks down into two parts, and the bond holding it together becomes two very reactive radicals. These molecules transfer the reactive radicals to the active groups on the monomers and oligomer chains, which in turn react with other active groups, forming longer chains. As the chains get longer and create cross-links, the resin begins to solidify. The entire process, from liquid to highly polymerized solid state, takes place in a matter of milliseconds (*The ultimate guide*... 2017).

Polymers

Polymers are considered as the most common materials in the 3D printing industry due to their diversity and ease of adoption to different 3D printing processes. Polymers for additive manufacturing are found in the form of thermoplastic filaments, reactive monomers, resin or powder. The capability of employing 3D printing of polymers and composites has been explored for several years in many industrial applications, such as the aerospace, architectural, toy fabrication and medical fields.

Photopolymer resins can polymerize when activated by UV light in stereolithography 3D printing. According to the annual industry survey conducted by Wohlers Associates, nearly 50% of the 3D printing market in the industrial sectors is attributed to generated prototypes using photopolymers (LIGON et al. 2017). However, the thermomechanical properties of photopolymers should still be improved. For instance, molecular structure and alignment of 3D printed polymers depend on the thickness of the layers because of the gradient in UV exposure and intensity (GUNDRATI et al. 2018a, b) On the other hand, plastic for selective laser sintering (SLS) is reported to be the second most important class for 3D printing. Among SLS polymers are polystyrene, polyamides and thermoplastic elastomers (LIGON et al. 2017).

Printing of test samples

In presented work, photoreactive resin with trade name Clear Resin, belonging to the group of plastics is analyzed.

This resin is a mixture of methacrylic acid esters and photoinitiator and is used in Formlabs printer Form 1, Form 2.

Standard samples for experimental tensile test were developed using rapid prototyping technology. SLA 3D printing method was implemented using Formlabs Form 2 printer. The steps of preparing objects by SLA method are as follows:

– preparation of the geometric model of the object for printing in dedicated PreForm software (Fig. 3);

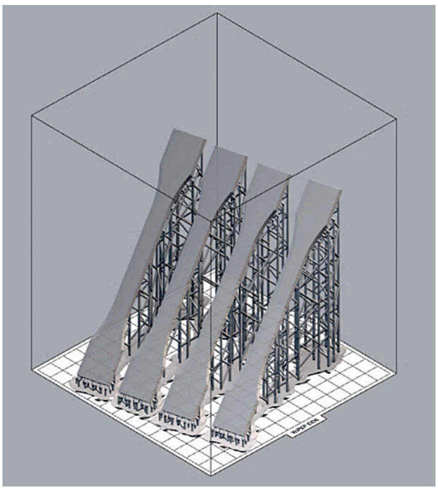

Fig. 3. Model for printing design

– the printing process of the object in the SLA printer (Fig. 4);

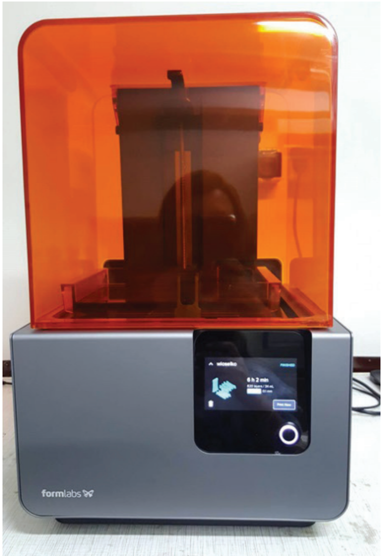

Fig. 4. Form 2 desktop 3D printer

– finishing sections:
- washing to excess a liquid resin from the parts' surfaces and cavities,
- post-curing with light and heat (Fig. 5). Post-cured parameters to assure the best strength properties of developed samples were presented in Table 1.

a *b*

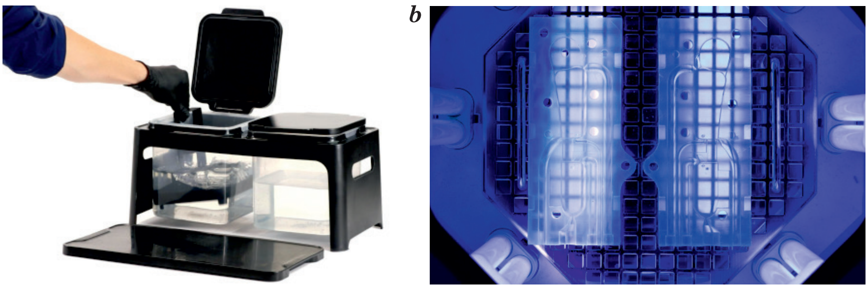

Fig. 5. Washing equipment (*a*), UV lamp (*b*)

Table 1

Post-cured properties for Clear Resin

Material	Temperature of curing [°C]	Time of curing [min]	Wavelength of UV lamp light [nm]
Clear Resin	60	60	405

Tensile testing

Tensile testing is a fundamental materials science and engineering experimental method in which a sample is subjected to a controlled uniaxial tension until failure. Properties that are directly measured via this test are: ultimate tensile strength, breaking strength, maximum elongation and reduction in gauge length cross-sectional area.

The conditions and the method of performing the tensile testing of plastics are described in the PN-EN ISO 527 standard. The sample for testing is flat and "paddle" shaped (Fig. 6). The dimensions of the sample were as follows: thickness $h = 4.0 \pm 0.2$ mm, width of narrow portion $B1 = 10 \pm 0.2$ mm and overall length $L3 > 150$ mm. The cross-section dimension $B1$, h were presented in Table 2.

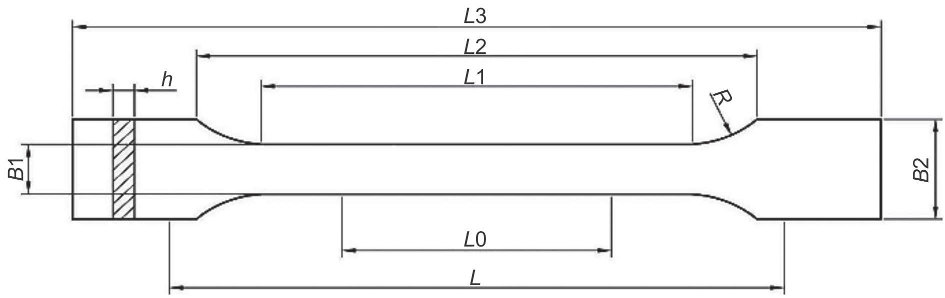

Fig. 6. Test specimen scheme according to PN-EN ISO 527 standard

Table 2

The cross-section dimensions of the samples in the gauge length for the Clear Resin

Number of samples	Dimension $B1$ [mm]	Dimension h [mm]	Cross-section area [mm^2]
Sample 1	10.03	4.04	40.47
Sample 2	10.02	4.05	40.56
Sample 3	10.04	4.03	40.45
Sample 4	10.07	4.07	40.97
Sample 5	10.00	4.04	40.38
Average value	10.04	4.05	40.61

Tensile test was carried out using Zwick Roell Kappa 500 testing machine (Fig. 7), at a room temperature of 20°C. The stand was equipped with a videoextensometer, which allows non-contact measurement of deformation of the sample in various axes. Thanks to special modules, it allows measuring the narrowest or the widest place of the sample, the angle of deflection, the distribution of deformations in a given axis.

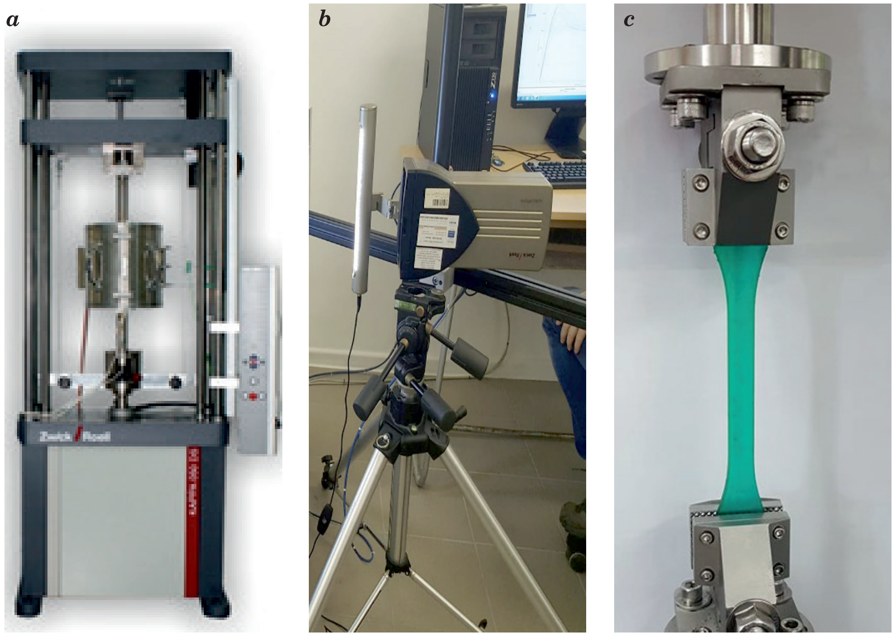

Fig. 7. Zwick Roell Kappa 500 testing machine (*a*), videoextensometer (*b*), sample in the machine's clamps (*c*)

The experiment conditions were as follows:
– 5 standard samples were researched in tensile test;
– The samples were loaded with displacement of 5 mm/min;
– The reaction force was measured on the strength machine head;
– Tensile tests were carried out to sample damage.

Results and discussion

On the base characteristic of force – displacement of the traverse were obtained (Fig. 8). Stress-strain curves were determined (Fig. 9).

The forces and displacements obtained from the experiment were converted into engineering stresses and engineering deformations according to the following relations:

– engineering stress

$$\sigma_{\mathrm{eng}} = \frac{P}{A}\,[\mathrm{MPa}] \tag{1}$$

– engineering strain

$$\varepsilon_{\mathrm{eng}} = \frac{\Delta l}{l_0}\,[-] \tag{2}$$

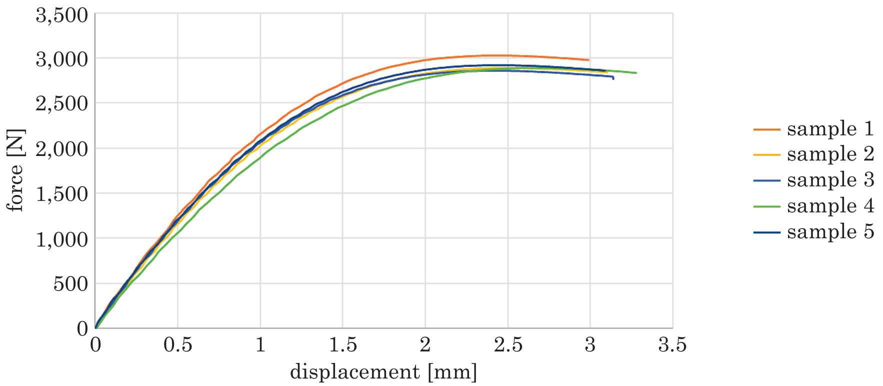

Fig. 8. Force –displacement curves for Clear Resin tensile test

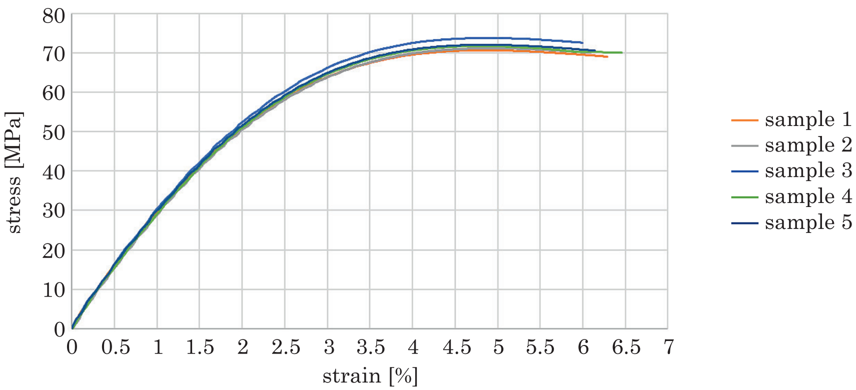

Fig. 9. Stress – strain curves for Clear Resin tensile test

On the base of obtained curves Young's modulus, elongation at break and tensile strength were determined. These data are summarized in Table 3.

Table 3

Material properties of Clear Resin determined from the experiment

Samples	Young's Modulus [MPa]	Elongation at failure [%]	Tensile Strength [MPa]
Sample 1	2,893.91	6.35	71.71
Sample 2	2,892.94	6.29	70.64
Sample 3	2,980.49	5.99	73.78
Sample 4	2,881.01	6.64	71.16
Sample 5	2,921.86	6.13	72.04
Average value	2,914.04	6.28	71.86

The method of determining material data from the experiment according to the standard (Tab. 3) was as follows:

– Modulus of Elasticity was calculated by extending the initial linear portion of stress-strain curve and dividing the difference in stress corresponding to any segment of section on this straight line by the corresponding difference in strain. All elastic modulus values were computed using the average initial cross-sectional area of the test specimens in the calculations;

– Tensile Strength was calculated by dividing the maximum load in newtons by the original minimum cross-sectional area of the specimen in square meters;

– Percent Elongation was calculated by reading the extension (change in gauge length) at the moment the applicable load is reached. The extension was divided by the original gauge length and multiply by 100.

Material data for Clear Resin given by the producer were presented in Table 4.

Table 4

Material data for Clear Photopolymer Resin given by the producer

Mechanical properties	Young's Modulus [MPa]	Elongation at failure [%]	Ultimate Tensile Strength [MPa]
Post-cured	2,800	6.2	65
Standard	ASTM D 638-10	ASTM D 638-10	ASTM D 638-10

Comparing the values obtained in the experiment (Tab. 3) to the values given by the producer (Tab. 4) it can be seen that the values of both Young's modulus and elongation at failure are consistent, while the ultimate tensile strength is larger in the case of experimental tests.

Summary

As it was mentioned the results of the tensile test for Clear Resin will be adopted in numerical modeling of fractal porous structure.

Comparing the values obtained in the experiment to the values given by the producer it can be seen that they are similar, which proves that the process of producing samples was carried out correctly. The tensile strength is larger for the experimental samples. Values of the tensile strength are depending of the variable condition parameters. Printing samples and post-cured processes could change the finally structure of the samples, in the small range. It caused the minor differences in obtained values.

Future implementation of presented research

It should be noted that the main idea of the work is to develop a numerical research methodology whose behavior can be fully controlled. The next step will be numerical research of the natural structures whose construction creates problems in their modeling.

The proposed numerical models of the selected porous structure will be based on the geometry of the Menger cube (Fig. 10). This geometry is commonly used for fractal media simulations.

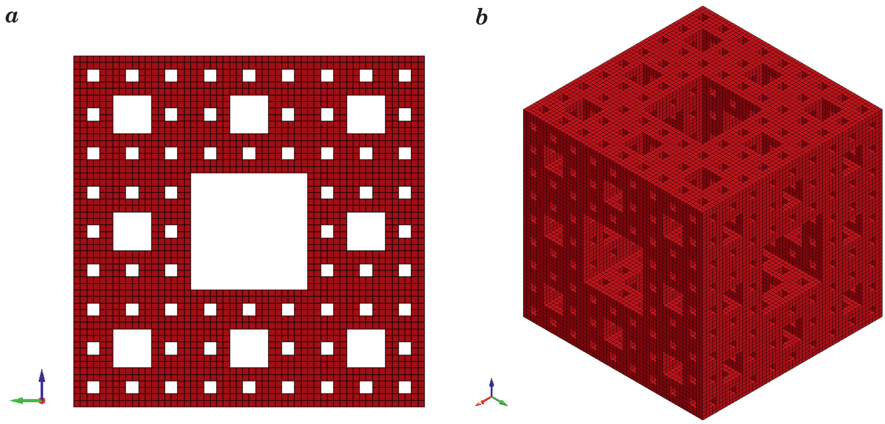

Fig. 10. Numerical model: *a* – 2D, *b* – 3D Menger's structure, as the basic fractal model

The idealistic structure (Fig. 10) will be modified to break the symmetry of the sample. The example of such modification (Fig. 11) was developed by introducing the directivity of structure by multiplying the geometry in one direction.

In addition the presented research will be used to constitutive material model selection in the chosen FE computer code.

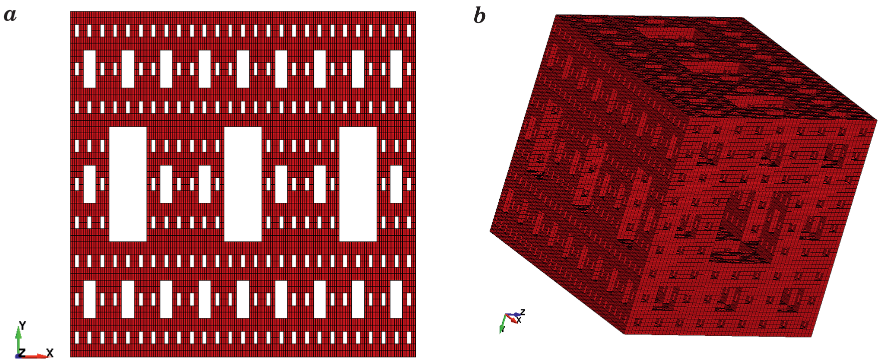

Fig. 11. Proposed numerical model: *a* – 2D, *b* – 3D of Menger's structure after modification

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