Materials Physics and Mechanics 34 (2017) 51-58 Received: October 3, 2017

DESIGN AND SIMULATION OF ADDITIVE MANUFACTURED STRUCTURES OF THREE-COMPONENT COMPOSITE MATERIAL

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Abstract. Modeling the microstructure of a three-component composite material obtained by layer-by-layer 3D printing is presented. The effect of the microstructure parameters on mechanical characteristics of the composite material created by 3D printing is studied. On the basis of multiscale simulations, an optimal configuration of the plate of composite material is designed and manufactured by 3D printer.

Keywords: composite, design, finite element, structure.

1. Introduction

A main tendency in the modern technology era is the transition from using traditional materials in the industry to using advanced materials with pre-defined properties such as composite materials. Nowadays, composite materials based on carbon fibers and polymer matrices are widely used in rocket-space and aviation engineering. The materials of such structures have high strength and low mass.

One of the modern approaches to creating composite materials is 3D printing or additive technologies. This manufacturing method allows obtain composite structures almost of any shape using different materials of binders and reinforcing fibers. An overview on 3D printing techniques of polymer composite materials and the properties and performance of 3D printed composite parts is given in Ref. [1]. A thermoplastic composite reinforced with long fibers and employed thermotropic liquid crystalline polymers is described in Ref. [2]. It was shown that the mechanical performance of the 3D printed thermosetting composites was superior to that of similar 3D printed thermoplastic composites and 3D printed short carbon fiber reinforced composites [3].

At the same time, the use of thermoplastic and thermosetting binders makes it possible to achieve good adhesion of the components while maintaining the inherent elasticity of the thermoplastics and maintainability of the material. The production of such three-component material is carried out in two stages during 3D printing. At the first stage, the carbon fibers are impregnated with a thermosetting binder and completely cured; at the second stage, the resulting microplastic is coated with a melt of a thermoplastic binder. When manufacturing composite products through the use of the described technology, a certain spread of microstructure characteristics arises inevitably, besides defects are also formed.

Studying and simulation of mesostructure and microstructure of a three-component composite material obtained by the 3D printing method, as well as studying the effect of a possible variation of the microstructure characteristics on mechanical properties of the material is described in Ref. [4]. Figure 1 shows an example of mesostructure of a real-scale sample manufactured by 3D printer [5]. Finite element (FE) models of the mesostructure we were used to simulate the behavior of composite material. The developed technique of modeling three-component composite materials allows also studying large-sized structures of any configuration.

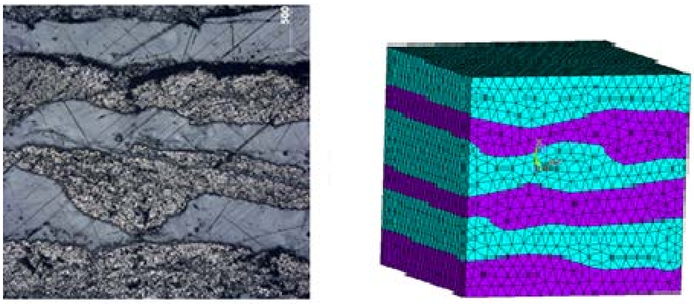


Fig. 1. Mesostructure of a three-component material and its FE model.

2. Optimization of lattice structures

Now lattice structures have become widespread in many areas. Their obvious advantage is the light weight and significant cost savings of a material. Application of unidirectional composite materials allows preserve the exceptional strength properties of composites in construction regardless of the loading direction. For this reason, the lattice composite structures are actively used in the aerospace industry.

The goal of this work is the study of the property change of lattice structures of three-component composite materials depending on their parameters, as well as the determination of optimal configurations of these structures. During the work, the software of finite element analysis ANSYS and the software modeFRONTIER for solving the tasks of criterion and multi-criteria optimization were used.

As an example of lattice structure, we considered construction of a plate type. The lattice structure element has the overall dimensions (200 ± 5) x· (200 ± 5) x· (22 ± 1) mm. A sample of a large-sized lattice structure should have the overall dimensions (1400 ± 5) (1400 ± 5) · (22 ± 1) mm. The initial configuration variants of the plate are shown in Figure 2.

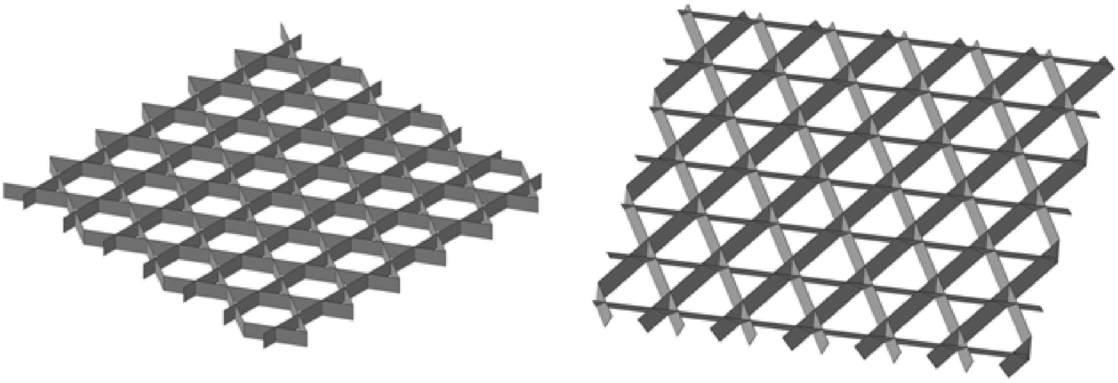
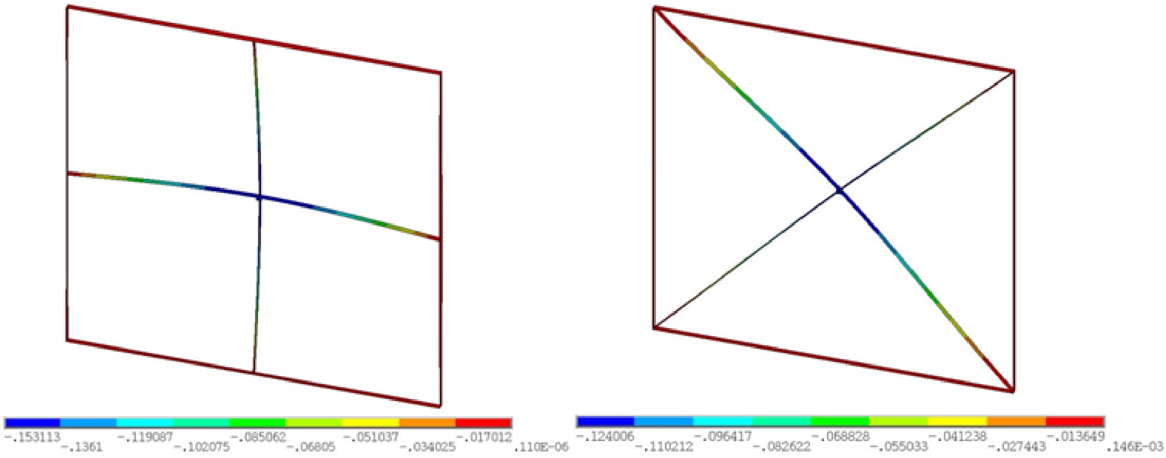


Fig. 2. Variants of the initial configuration of a plate.

The following set of optimization parameters is assumed: number of inclined ribs, number of horizontal/vertical ribs, inclination angle of the ribs to the horizontal axis in the plane of the plate, inclination angle of the diagonal ribs to the vertical axis perpendicular to the plate. The problem solution is considered in a 2-criterion formulation. The target functions are: weight of the structure, maximum deflection. Before performing parametric optimization the effect of each optimization parameter on the target functions is investigated to study the possibility of limiting the parameters and the range of their variation.

In order to determine the initial configuration of the plate, two simplified versions of the structure are considered: with one vertical and one horizontal edge (Fig. 3a) and with two diagonal edges (Fig. 3b). The maximum displacements under the action of a given load are shown in Figure 3 and in Table 1.



a b

Fig. 3. Maximum displacement (deflection) of the plate, m.

Table 1. Results of calculation of a simplified plate configuration.

	Straight	Diagonal
Deflection, mm	153.11	124.01
Plate weight, kg	0.34	0.385

In the case of the rib diagonal position, the deflection is less than 19%. At the same time, the weight of such design is higher by 11%. It is necessary to investigate the dependence of weight on deflection with the number increase of edges in both constructions. The results of this analysis are shown in Figure 4. From this it follows that the configuration of the plate with diagonal ribs is characterized by a smaller deflection with a smaller weight. It should be noted also that among the designs with inclined edges, the minimum deflection is fixed at the inclination angle of the ribs equal to 45°. Figure 5 shows the dependence of the plate deflection on the slope angle of the edges with a constant weight of the plate. Thus, the configuration of the inclined rib design becomes the basis for further investigation; the angle of ribs being no longer considered as an optimization parameter.

We have considered the addition of straight (horizontal and vertical) edges to the basic construction (with diagonal edges). Figure 6 shows the displacements of the construction with 36 diagonal edges and 16 additional straight edges (a quarter of the construction is shown). The deflection of the structure is 12.80 mm with the weight m = 4 x 0.55317 kg ≈ 2.21 kg.

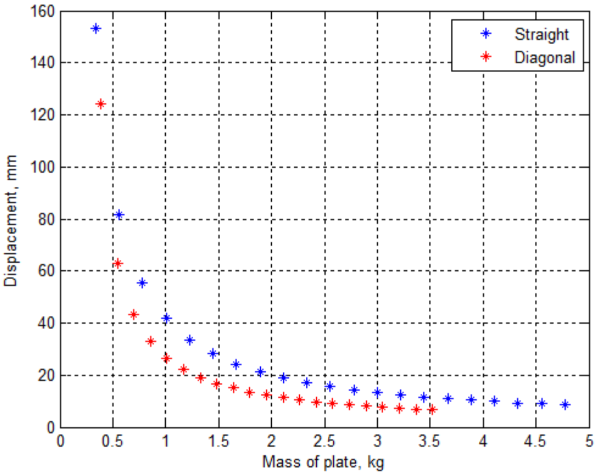


Fig. 4. Dependence of the deflection on the total mass of the plate for the straight and diagonal gratings.

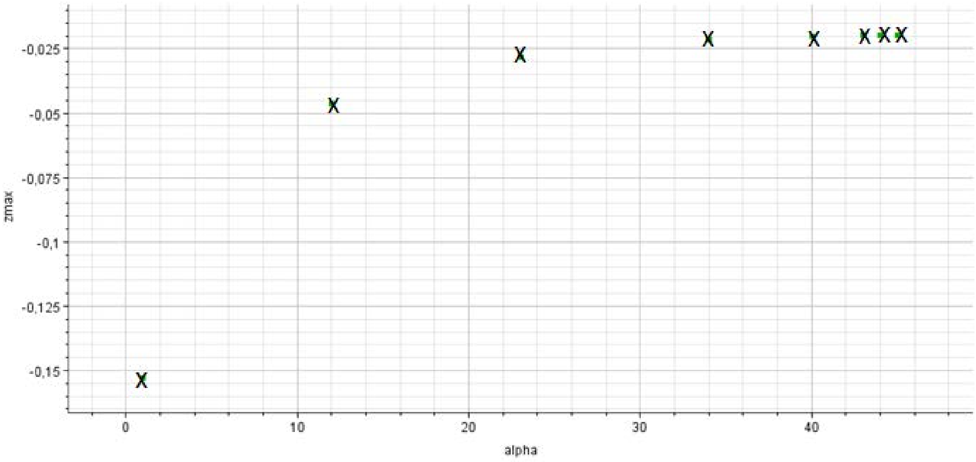


Fig. 5. The dependence of the deflection of the plate on the angle of inclination of the edges to the Ox axis.

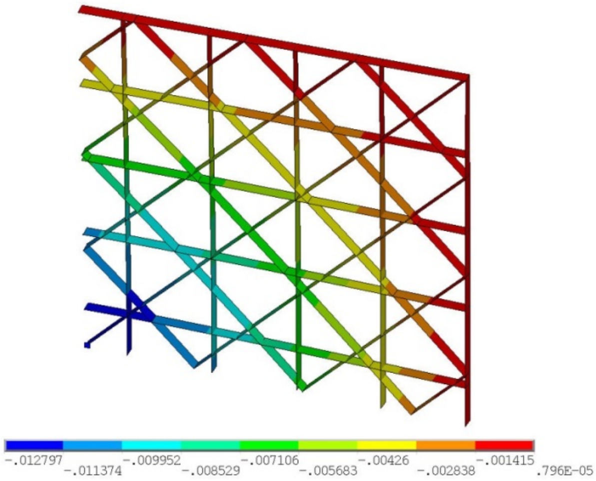


Fig. 6. Plate with additional horizontal ribs.

Figure 7 shows the dependence of the deflection of the structure with the increase in the number of straight edges at the fixed number of diagonal ones (36). Then we have studied the variation of the inclination angle of the ribs in the plane of the Oxy plate. For β = 0, the edges are perpendicular to Oxy; the values of β> 0 correspond to the inclination outward from the central edge. The central edge always remains normal to the Oxy plane; the value range -70 ≤ β ≤ 70 being considered. In Figure 8 the dependence of the inclination angle of the ribs β to the vertical is illustrated. The dependence has a different character with decreasing and increasing β; the minimum of deflection (9.61 mm) in this range of angles is reached when β = -70 (Fig. 9). The dependences obtained are asymmetric, since in the constructed model the edge rotation occurs around the lines lying in the Oxy plane, but not around the midline. However, this does not affect significantly on the results. It should be noted that the structure weight increases with increasing angle β.

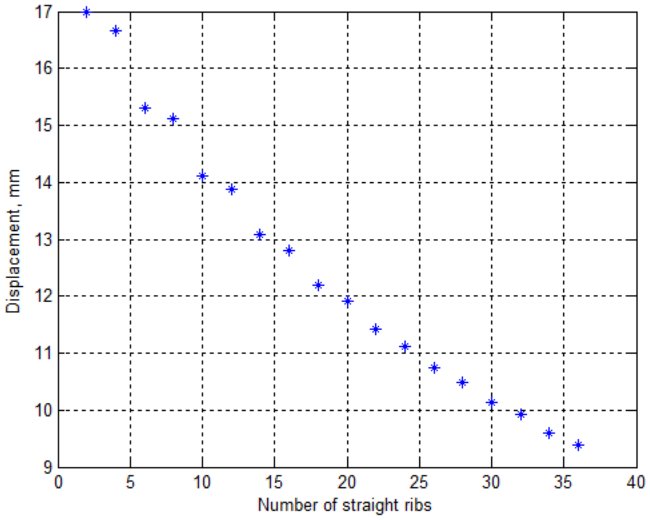


Fig. 7. Dependence of the plate deflection on the number of additional straight ribs.

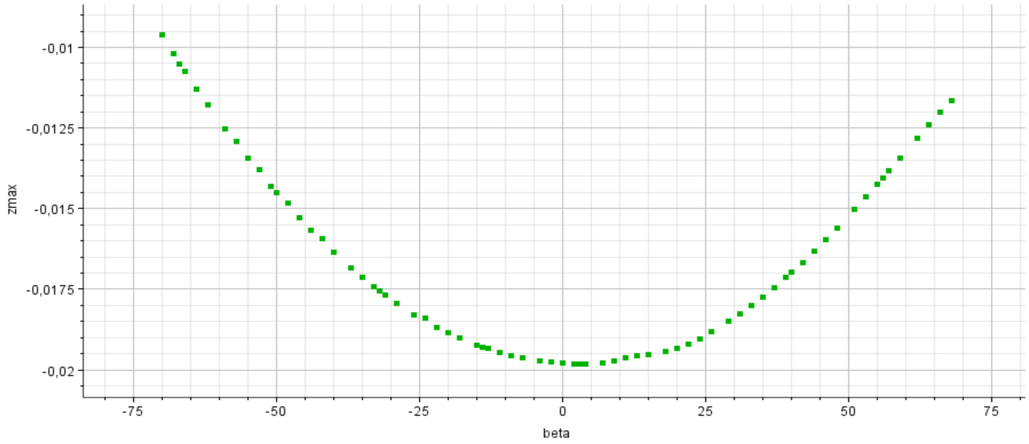


Fig. 8. Dependence of the deflection on the inclination angle of the ribs β to the vertical.

As the result of study, it was found that by changing the inclination angle of the ribs to the plate plane and by adding additional straight ribs, it is possible to obtain a deflection much less than in the initial configuration. It is obvious that the deflection can be reduced by simply increasing the number of diagonal ribs in the structure. Nevertheless, it is necessary to determine which of these three options is most effective. Figure 10 shows the dependence of the plate deflection on the slope angle of the edges at a constant mass of the plate.

The results indicate a low efficiency of the slope of the edges to the plate normal. In addition, it is seen that with a fixed mass, the best results are achieved in case 1, with a large number of diagonal ribs. However, the first point of graph 2 for a plate with additional straight edges corresponds to a smaller deflection value than in case 1 for the same mass of the plate. This point corresponds to the configuration with two straight edges passing through the plate center.

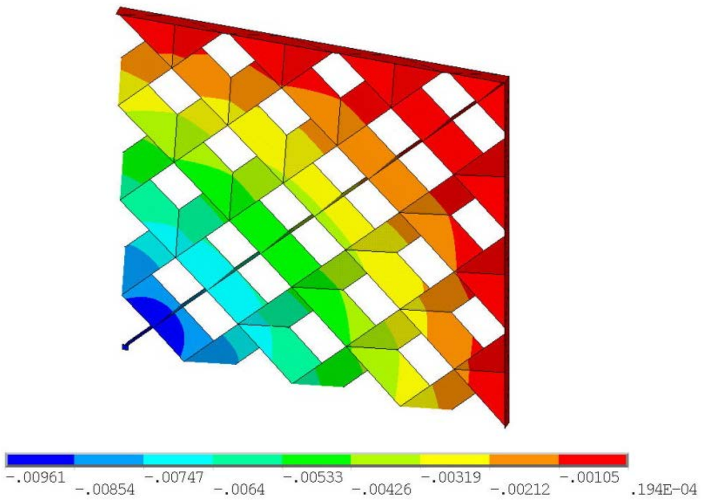


Fig. 9. Maximum deflection of the plate with the inclination angle of ribs -70° to the vertical in m.

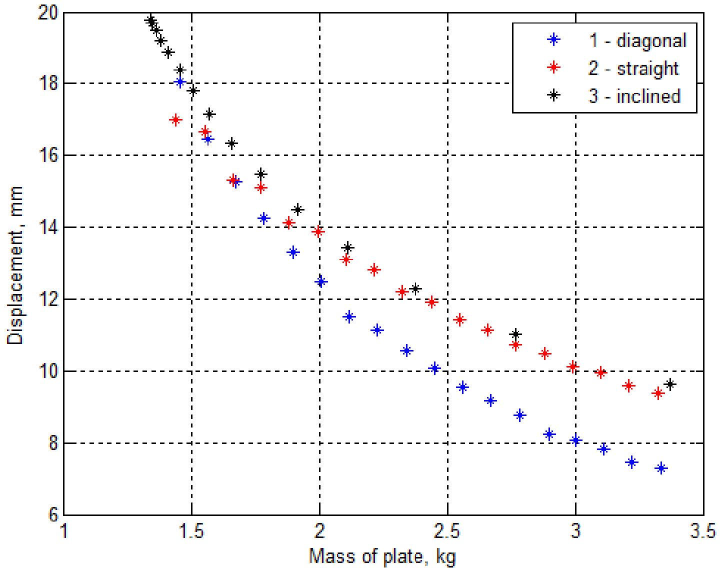


Fig. 10. Comparison of the dependence of plate deflection on the mass.

The solution of the parametric optimization problem is performed in the software modeFRONTIER. The geometrical model of the plate obtained during the optimization does not meet the technical requirements of the developed 3D printer. Therefore, an alternative version of the plate was designed to meet these requirements (Fig. 11). The presented configuration of the plate satisfies the limitations on the maximum deflection specified in the technical specification when the properties of a material determined by the results of full-scale tests of the samples; with the elements of the composite structure being consistent.

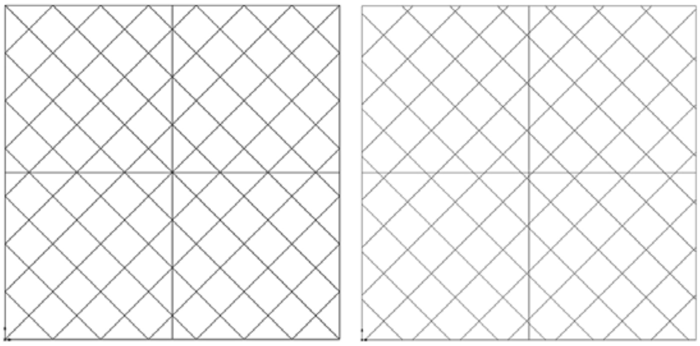


Fig. 11. Optimal and technologically-implemented plate configuration.

3. Full-scale experiment

The resulting plate configuration was printed on a developed 3D printer. Figure 12 shows the printing process and the printed plate. Virtual tests of the plate manufactured by 3D printing method is provided by the procedure of two-level submodelling described in Ref. [1] and correspond to full-scale tests carried out by the Testing Center «Polytechtest». The developed geometric and finite element models for the testing of the plate correspond to full-scale plate, taking into account the identified defects. In Figure 13, the full-scale test and the results of virtual tests are presented. The displacement values are reasonably close being 35.5mm in the case of full-scale test and 36mm in the case of virtual test.

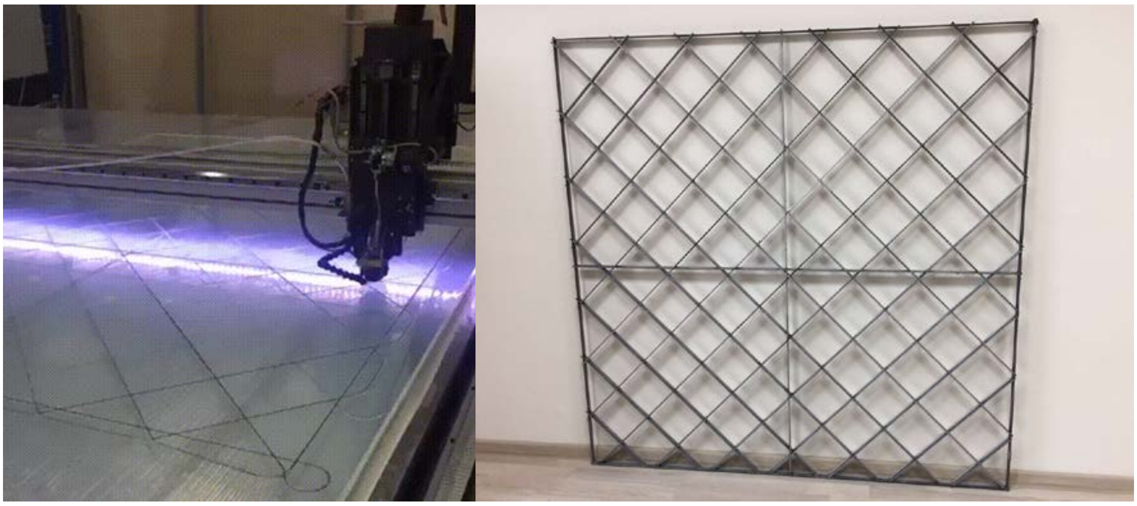


Fig. 12. 3D printed lattice structure.

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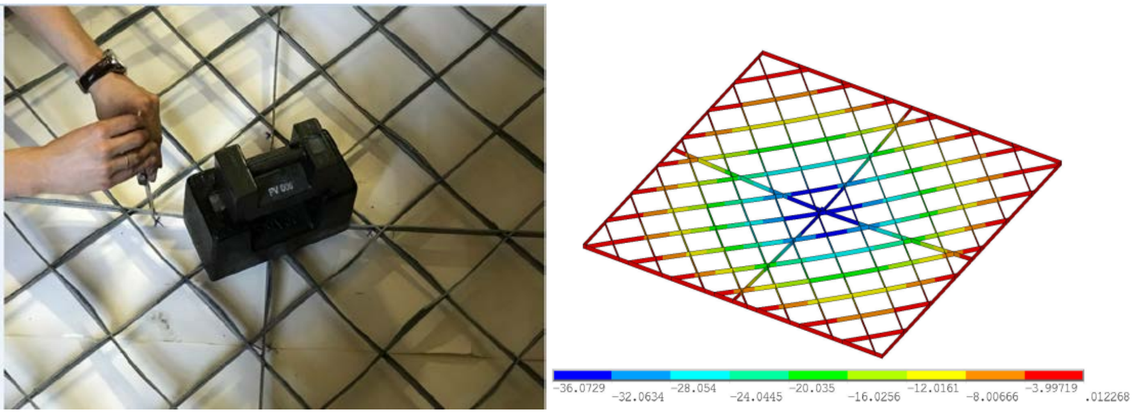

Fig. 13. Full-scale test and virtual test of plate

4. Conclusions

The parametric optimization of the lattice structure plate type is carried out. The dependences of the deflection and the first natural frequency on the plate mass are obtained, and a set of solutions optimal for the given criteria is determined. It is found that the minimum deflection is achieved at ??the inclination angle the ribs equal to 45^0 at a constant mass. There are strong grounds for believing that the variation of the inclination angle of the ribs to the plate plane is irrational.

Based on the results of solving the parametric optimization problem, among the quasi-optimal realizations, the variant with the maximum allowable deflection is selected. On the basis of multiscale simulations, an optimal configuration of the plate is designed and manufactured by 3D printer. The real-scale test results differ from the virtual nonlinear solution by 1%. The plate carried out the load; after removing the load the plate returned to its original configuration.

Acknowledgements

This work has been supported by RF Ministry of Education and Science (Contract No.14.581.21.0005, RFMEFI58114X0005).

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