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Experimental Study of the Stability of Layered Composite Plates

Bokhoeva Lyubov Aleksandrovna,
Bochektueva Elena Batorovna
Department "Strength of materials"
FSBEI HE ESSUTM
Ulan-Ude, Russia
bohoeva@yandex.ru, bochektueva.e@yandex.ru

Rogov Vitalii Evdokimovich
Laboratory of Polymer Chemistry
Baikal Institute of Nature Management SB RAS
Ulan-Ude, Russia
rogov54v@mail.ru

***Abstract* — This article presents the results of experimental studies of definition the mechanical characteristics of epoxy resin and hardener without adding nanopowder and with the inclusion of nanopowders. The stability and destruction process of laminated plates made of composite material with different numbers of layers without nano-additives and with nanopowders in the binder has been studied. The results of experimental studies of the stability and destruction process of laminated plates made of composite material are presented. Experimental and numerical methods are used to estimate the carrying capacity of laminated plates. A technique has been developed for the experimental study of the deformation and strength properties of composite materials using modern test equipment. It was established that the discrepancies between the values of the critical load of four-layer samples and the critical load of three-layer samples are 2-3%, therefore, to reduce the weight, products from composite materials can be made of three-layer plates. In the ANSYS system, two-layer, three-layer and four-layer plates were modeled. The results of numerical calculation by the finite element method are presented. Comparison of the obtained experimental results with numerical values is made, the possibility of using experimental data on the mechanical behavior of layered composite materials in the design and calculation of protective screen modules is estimated.**

Keywords* — *composite materials, samples, tests, plates, experiment

I. INTRODUCTION

The problem of littering near-Earth space with "space debris" arose when spacecraft and space stations became the most vulnerable target of such debris [1]. Protection against it is currently carried out by introducing into the design of space objects the modules of special protective shields. Design, testing and confirmation of the effectiveness of protective screens is an urgent and necessary task. The main difficulties in solving this problem are due to the reasons: rigid weight limitations of the screens and high speeds upon impact. Scientists are working to create methods to protect the surface of spacecraft from damage [2-6], to simulate the conditions for such emergencies in orbit and to form a new promising class of layered materials. Layered composite materials (CM) have a wide range and a unique combination of properties such as high strength, corrosion resistance, wear resistance [7-8]. A significant role in the process of creating new materials is played by an experimental study of the strength and stability of samples [9-10]. The use of epoxy polymers is due to the high manufacturability of epoxy resins and the unique combination of their performance characteristics [11]. Epoxy polymers are characterized by high static and impact strength, hardness, which allows them to be used as adhesives, compounds and various coatings. A special place is occupied by composite reinforced plastics, the carrying elements of which are high-strength fibers and fabrics [12]. However, protective shields require materials with improved operational and mechanical properties. Various nanopowders, compounds with unique physical and mechanical properties can be used in layered composite materials as reinforcing additives.

Nanoparticles impart new properties to materials, which are due to the fact that nanoparticle sizes are comparable to the characteristic sizes of nuclei (initiators) of the formation of defects (microcracks, voids, interlaminar delaminations) and therefore can affect their growth. In such dispersion-strengthened materials, the strength of the particles themselves is not used, these particles serve as a barrier in the path of movement of the crack in the matrix, and thus strengthen the initial phase. However, there is the problem of using such nanosystems in structural materials science, which consists in the tendency of nanoparticles to agglomerate due to excessively high surface energy, which does not allow achieving a uniform distribution of particles in the bulk of the composite.

The analysis of the works devoted to the creation of composites with the use of nanoparticles of various origin showed that the increase in mechanical parameters is observed in a rather wide range from 0.005 to 5.0 mass % of filling. The wide variation in the rational concentration of additives is likely due to the use of various technologies for combining the epoxy matrix with nanoparticles, the use of various methods of applying to reinforcing elements, due to the various technological factors. It was also found that the most promising technology for combining nano-objects with a matrix is the use of ultrasonic vibrations. Ultrasonic vibrations are used to disintegrate the agglomerates of nanoparticles and achieve their uniform distribution in the polymer matrix. The intense cavitation field of ultrasound provides not only the effective destruction of the agglomerates of nanoparticles, but also

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contributes to the formation of a suspension of nanoparticles with their uniform spatial distribution in the mixture.

II. Experimental Work

The results of experimental studies of definition the mechanical characteristics of epoxy resin and hardener without adding nanopowder and with the inclusion of nanopowders are presented. For experimental studies, ten samples were made of epoxy resin and hardener with the addition of nanopowder and without it in the form of protruding blades with dimensions according to GOST 11262-80. Polymerization was carried out at room temperature for four days. As a thermosetting matrix resin, an epoxy diane uncured resin of the brand ED-20 GOST 10587-84 was taken. As a thermosetting matrix resin, an epoxy diane uncured resin of the brand ED-20 was used (according to GOST 10587-84). Polyethylene polyamines (PEPA) (TU 2413-357-0203447-99) were used as a curing agent for this epoxy resin. In the study, nanodispersed powders of silicon dioxide – Tarkosil T-05 – with an average particle size of 24 nm were used. Silica powders were obtained at a pilot plant, created at the S.A. Khristianovich Institute of Theoretical and Applied Mechanics (Novosibirsk). Weighing the resin, hardener and nanopowder was carried out on an electronic analytical balance with an accuracy of 0.005 g. For uniform distribution of nanoparticles in the matrix was used ultrasonic bath "Sapphire", a volume of 4 liters and a capacity of 450 watts with an operating frequency of 35 kHz. The effect of the ultrasound field on the mixture lasted for 2 minutes through the aquatic environment. It is believed that the intensive cavitation field of ultrasound provides not only the effective destruction of the agglomerates of nanoparticles, but also contributes to the formation of a suspension of nanoparticles with their uniform spatial distribution in the mixture. After the operations, the mixture was poured into silicone molds and left under normal conditions for polymerization. For experimental studies, five samples were made of epoxy resin and a hardener without the addition of nanopowder (Fig. 1) and five samples with a nano-dispersed silica powder Tarkosil T-05 (Fig. 2, 3).

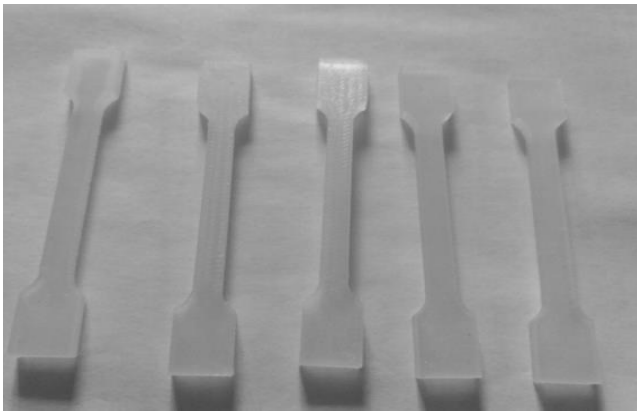

Fig. 1. Finished samples after curing.

For carrying out mechanical tests, an Instron 3367 electromechanical tensile machine was used with a force of 30 kN.

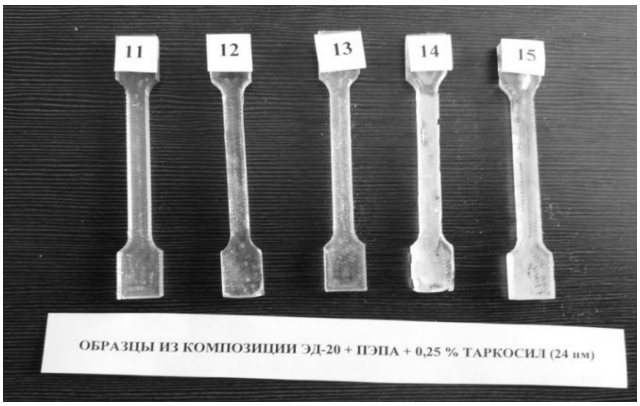

Fig. 2. Samples from the composition of ED-20 + PEPA + 0.25 % tarkosil (24 nm) before testing

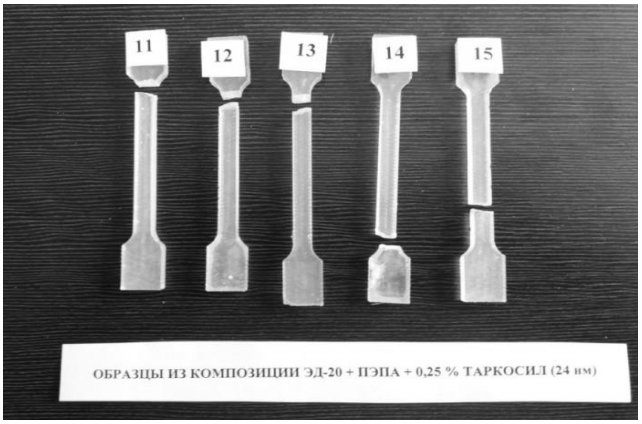

Fig. 3. Samples from the composition of ED-20 + PEPA + 0.25 % tarkosil (24 nm) after testing

The test results of the samples are presented in Tables I and II. The absence of experimental data in the tables indicates that either the sample collapsed when installed in a test machine, or the value is extremely low or large.

TABLE I. THE COMPOSITION OF ED-20 + PEPA WITHOUT NANOPARTICLES

No.	Tensile stress (MPa)	Tensile deformation (%)	Elastic modulus *E* (MPa)
1	–	–	–
2	–	–	–
3	47.03	5.74	926.4
4	40.64	5.18	892.65
5	47.29	5.75	951.16

The uniform distribution of Tarkosil nanoparticles with this technology of manufacturing samples is observed when the nanoparticles are filled with 0.25-0.3 % mass. The analysis of the obtained results showed that for all the fabricated samples no significant deviations were observed in strength properties,

the deformation of the ED-20 + PEPA + 0.25 mass % of nanoparticles (24 nm) samples is 20-30 % less than deformation of samples without nano-additives.

TABLE II. THE COMPOSITION OF ED-20 + PEPA + 0.25 MASS % OF NANOPARTICLES (24 NM)

No.	Tensile stress (MPa)	Tensile deformation (%)	Elastic modulus *E* (MPa)
1	40.17	4.00	970.38
2	39.24	3.95	969.22
3	41.22	2.48	937.29
4	39.47	3.35	910.49
5	40.94	4.05	843.01

ED-20 + PEPA + 0.25 mass % of nanoparticles (24 nm) samples have tensile stresses commensurate with the ED-20 + PEPA composite, which can be explained by the fact that in these samples the process of curing the composite did not completely pass, as evidenced by high deformation indicators. Samples were obtained by cold curing, the curing process can take a long time. Aging at room temperature for ninety-six hours is insufficient for curing. Based on the results obtained, studies on the effects of nano-dispersed additives will continue.

To study the stability and destruction process of layered plates made of a composite material without nano-additives and with nano-additives in a binder, samples were made. For experimental work there were made 10 samples from four layers; 10 samples from three layers of fiberglass; 10 samples from three layers of fiberglass with the inclusion in the binder of nano-dispersed silica powder Tarkosil T-05; 10 samples from two layers. The samples were made in the research and production laboratory "Reliability, strength of products and structures" of the East Siberia State University of Technology and Management. Samples were fabricated by contact molding by layering in a form lubricated with an adhesive coating, a reinforcing material (T-10 fiberglass) with simultaneous impregnation of each layer with a binder (epoxy resin with a hardener). After impregnation, additional rolling is carried out to eliminate air bubbles and distribute the resin uniformly. At the same time, it is very important to carry out thorough air removal, since subsequently interlayer defects appear in these places. After forming, the product dries and is machined. Then all the samples were numbered, and the cross-sectional measurements of the samples in the working section were measured. Using a micrometer and an electronic caliper, the width and thickness were measured in different sections of the sample. The deviations in width were ± 0.1 mm, in thickness ± 0.1 mm. Samples for the experimental determination of the mechanical characteristics of composite materials meet the following requirements [9]:

- implementation of standard loading schemes;
- simplicity and low cost of device for testing;
- ease of installation in a testing machine and testing;
- insensitivity to the method of attachment;
- reproducibility of experimental assessments of the characteristics studied.

Fig. 4 shows the production and preparation of samples for testing.

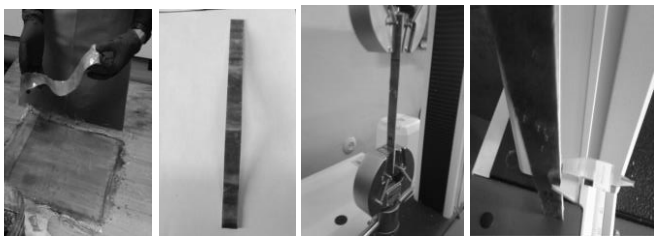

Fig. 4. Production and preparation of samples for conducting experiments.

Accurate determination of the mechanical characteristics of composite materials is possible with the use of modern equipment with high accuracy of recording loads and displacements. Experimental work was carried out on the universal machine Instron 3367. In compression tests, the test specimen is placed in the grips between the movable and fixed crossheads. The loading of the sample is carried out by moving the active grip in a given mode. In the process of testing, it is possible to implement modes of loading the sample with a constant change rate of stresses, forces, displacements of the active grip or deformations. The measured parameters (forces and displacements) are converted by the sensors and the control unit of the machine into electrical signals, which are displayed on the monitor screen of the control computer in the form of the corresponding stretching or compression diagrams. Fig. 5 shows photographs of testing equipment for compressing the plates.

Fig. 5. Instron 3367 testing machine.

III. THE RESULTS OF EXPERIMENTAL WORK

The first sampling consisted of ten four-layer plates of the following sizes: t = 2 mm, h = 19.6 mm, l = 170 mm. The plate was installed in the clamps and the load was set at a speed of v = 50 mm/min, when the critical force (Fig. 6) was reached, the plate lost stability, but continued to perceive the load until failure. The critical load and the load at the destruction of the sample were defined. The test results of four-layer samples are presented in Fig. 7.

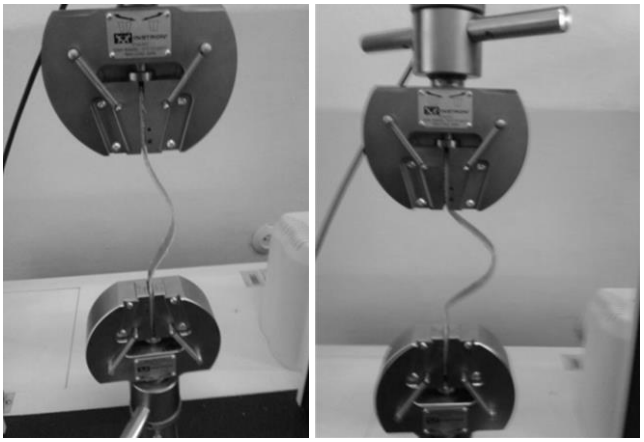

Fig. 6. Double layer plate compression test.

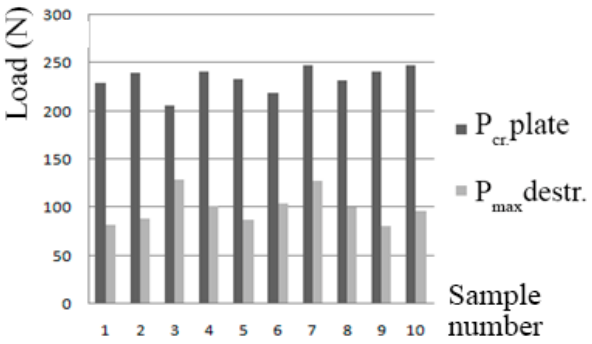

Fig. 7. The results of compression tests of four-layer samples with numbers 1-10.

The second sampling consisted of ten three-layer plates (samples No. 11 to No. 20) of the following sizes: t = 2.5 mm, h = 20 mm, l = 170 mm. The results are presented in Fig. 8, 9.

The third sampling consisted of ten three-layer plates (samples No. 36 to No. 45) with a nano-dispersed silica powder – Tarkosil T-05. The results are presented in Fig. 10, 11.

The fourth sampling consisted of ten two-layer plates (t = 1 mm, h = 20 mm, l = 110 mm, v = 50 mm/min), samples No. 26 to No. 35 are presented in Fig. 12, 13.

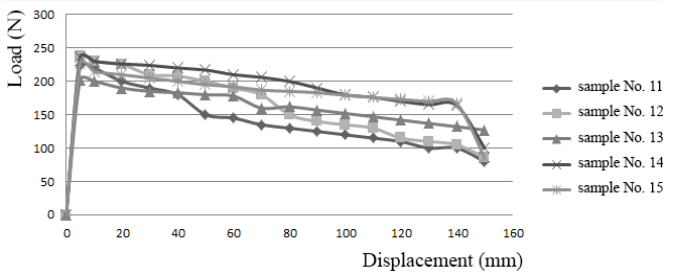

Fig. 8. The compression chart for three-layer samples with numbers 11-15.

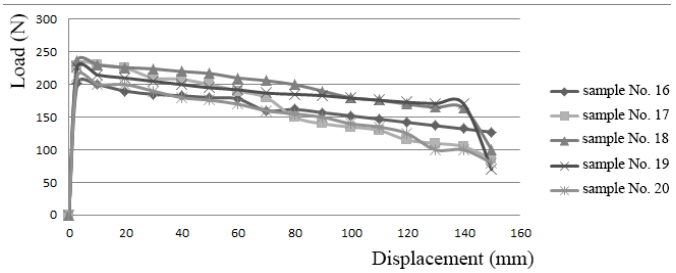

Fig. 9. The compression chart for three-layer samples with numbers 16-20.

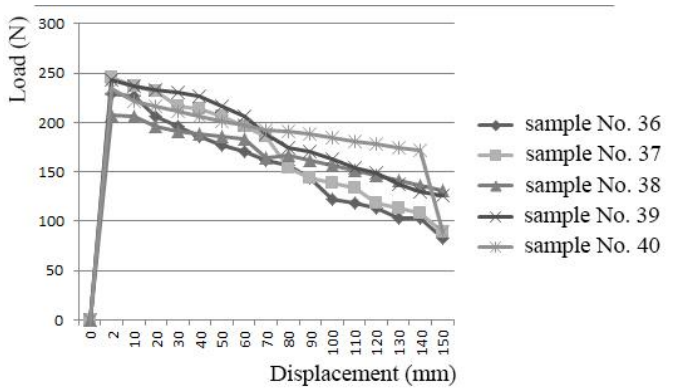

Fig. 10. The compression chart for three-layer samples with nano-dispersed silica powder – Tarkosil T-05 with numbers 36-40.

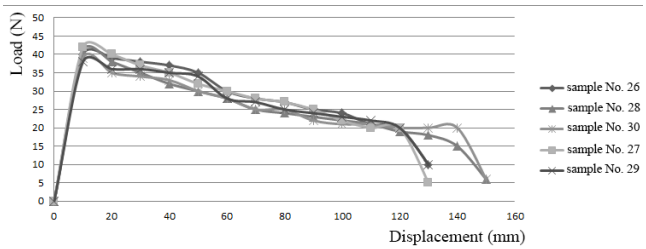

Fig. 11. The compression chart for three-layer samples with nano-dispersed silica powder – Tarkosil T-05 with numbers 26-30.

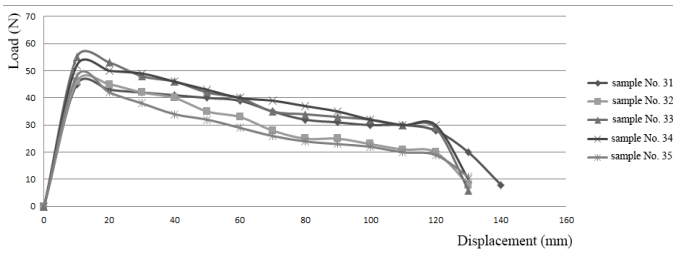

Fig. 12. The compression chart for two-layer samples with numbers 31-35.

The results of the experiments are presented in Table III. Sample critical load – $P_{cr.plate}$. Load at sample destruction – $P_{cr.destr}$.

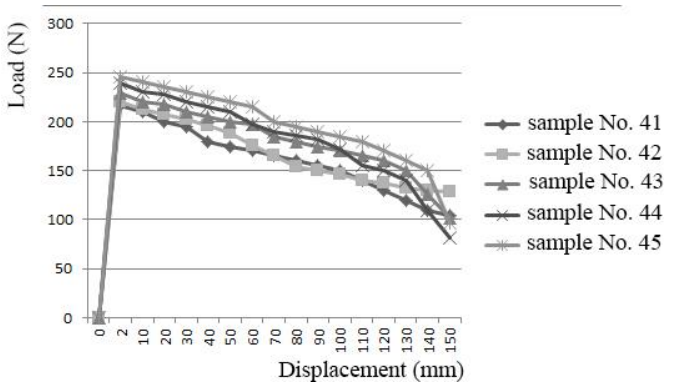

Fig. 13. The compression chart for two-layer samples with numbers 31-35.

IV. Computer Modeling of Layered Composite Plates

In the ANSYS system, two-layer, three-layer and four-layer plates were modeled. There are the results of numerical calculation by the finite element method: Fig. 14 presents the deformed state of a three-layer plate, Fig. 15 presents the stress state of a three-layer plate.

Table IV presents the experimental values of the critical load of the samples and the numerical values obtained by the finite element method in the ANSYS system. A good convergence of analytical and numerical values was obtained.

TABLE III. Sample Test Results

Four-layer samples without nanopowder			**Three-layer samples**						**Two-layer samples without nanopowder**		
			without nanopowder			**with nanopowder**					
Sample No.	***$P_{cr.plate}$ (N)***	***$P_{cr.destr}$ (N)***	***Sample No.***	***$P_{cr.plate}$ (N)***	***$P_{cr.destr}$ (N)***	***Sample No.***	***$P_{cr.plate}$ (N)***	***$P_{cr.destr}$ (N)***	***Sample No.***	***$P_{cr.plate}$ (N)***	***$P_{cr.destr}$ (N)***
1	230	82	11	223	80	36	233	88	26	40	10
2	240	89	12	238	86	37	244	87	27	42	5
3	206	130	13	202	127	38	243	130	28	41	6
4	241	102	14	236	100	39	208	103	29	38	11
5	234	87	15	227	86	40	229	89	30	39	6
6	219	105	16	213	102	41	217	105	31	45	8
7	248	128	17	216	125	42	246	97	32	46	8
8	232	100	18	225	98	43	229	102	33	55	6
9	241	81	19	236	78	44	220	128	34	52	10
10	248	97	20	241	94	45	239	81	35	48	11

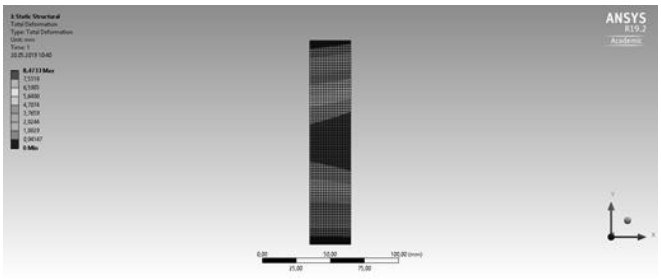

Fig. 14. Deformed state of a three-layer plate in the ANSYS system (mm).

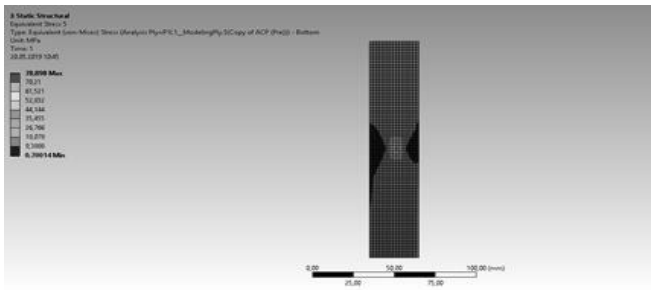

Fig. 15. Stress state of three-layer plate in ANSYS system (MPa).

TABLE IV. Experimental and Numerical Values of the Critical Load and Load at Destruction

Number of layers	**P_{cr} (N) (experimental value)**	**P_{cr} (N) (numerical value)**
2	45	48.6
3	223	239

V. Results

The complex of experimental work with samples from multilayer composite materials was performed and the following results were obtained:

1) Tests of samples from composite materials, consisting of four and two layers without nanopowder, and samples

consisting of three layers of fiberglass with the inclusion in the binder of nanodispersed silica powder – Tarkosil T-05 were carried out. The values of the critical load and the load at destruction are obtained.

2) A manufacturing method has been developed and samples have been tested. It was established that the discrepancy between the values of the critical load of four-layer samples and the critical load of three-layer samples with nanomaterials is 2-3%, therefore, to reduce the weight, products from composite materials can be made of three-layer plates with nanomaterials. The discrepancy between the values of the critical load of three-layer samples and the critical load of two-layer samples is 19-21%. The discrepancy between the experimental and numerical values is 7-8%.

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