ДОСЛІДЖЕННЯ, ПРОЕКТУВАННЯ ТА ЗАПРОВАДЖЕННЯ РЕСУРСОЕКОНОМНИХ КОНСТРУКЦІЙ, БУДІВЕЛЬ ТА СПОРУД

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THE FRACTURE TOUGHNESS OF THIN-WALLED COVER SHELLS HYPERBOLIC PARABOLOID SHAPED OF FERROCEMENT AND STEEL FIBER CONCRETE UNDER THE ACTION OF OPERATING LOADS

ТРІЩИНОСТІЙКІСТЬ ТОНКОСТІННИХ ОБОЛОНОК ПОКРИТТЯ У ФОРМІ ГІПЕРБОЛІЧНОГО ПАРАБОЛОЇДА З АРМОЦЕМЕНТУ ТА СТАЛЕФІБРОБЕТОНУ ЗА УМОВ ДІЇ ЕКСПЛУАТАЦІЙНОГО НАВАНТАЖЕННЯ

Andriichuk O.V., Ph.D., associate professor (ORCID 0000-0002-6275-097X)**, Uzhehov S.O. professor assistant,** (ORCID 0000-0001-6976-1279) Lutsk National Technical University, Lutsk)

Андрійчук О. В., к.т.н., доцент, **Ужехов С. О. асистент професора**, (Луцький національний технічний університет, м. Луцьк)

Experimental research of new materials and structures with improved parameters of strength, fracture toughness, bearing capacity and their lifetime in comparison with typical elements is an actual problem of building science.

Nowadays there is a trend to design and use for buildings covering the new design solutions as the thin shells. One of the types of thin shells are Gaussian shells with negative curvature. It's worth to note that in the last decade, a considerable number of researches of thin-walled structures made of steel fiber reinforced concrete were conducted, which confirmed the efficiency of its use to enhance their hardness, fracture toughness and thus longer life.

The article presents the results of the authors' experimental studies of fracture toughness of thin-walled cover structures with Gaussian negative curvature in the shape of hyperbolic paraboloid made of ferrocement and steel fiber reinforced concrete under the action of the operating load.

The load application was carried out for ten steps, after each step the pause was for 15...20 min, during which the data of the strain-gauge station VNP-8 was recorded, using a microscope were measured and recorded the width of the cracks, deflections of the structure were measured etc.

The external force was evenly-distributed to its applications and the impact was simulated according to the real conditions of construction use.

The experimental part of the research was conducted at the laboratory of building materials and structures of Lutsk National Technical University. In scientific work carried out mapping and comparison of the obtained experimental results, carried out processing and analysis, presents the conclusions.

During the researches it was found that the fracture toughness of thin-walled shell cover with Gaussian negative curvature in the shape of a hyperbolic

paraboloid with dispersed reinforcement (steel fiber reinforced concrete) is higher than in the shell made of ferrocement. Accordingly, it can be argued about the increasing of the lifetime of steel fiber reinforced concrete shell covering in comparison with the ferrocement shell.

У статті наведено результати експериментальних досліджень тріщиностійкості тонкостінних оболонок покриття у формі гіперболічного параболоїда з армоцементу та сталефібробетону за умов дії експлуатаційного навантаження.

Key words: Shell, hypar, ferrocement, steel fiber reinforced concrete, SFRC, fracture toughness
Оболонка, гіпар, армоцемент, сталефібробетон, СФБ, тріщиностійкість

For the last years among the building designs used as a covering of buildings and constructions, tendencies to application of new constructive decisions in the form of thin-walled covers are observed [1, 2]. One of the types of thin-walled shells, considered in the article, is the shell of negative Gaussian curvature in the form of hyperbolic paraboloid. Experimental studies of shells with increased fracture toughness are of considerable scientific interest. They acquire wide application in construction at designing of buildings and constructions from the point of view of technical and economic efficiency. To increase crack resistance of thin-walled shells steel fiber reinforced concrete is used, which is a promising and not yet fully studied material [3 - 12].

The purpose of this work is experimental studies of crack resistance of thin-walled ferrocement and steel fiber reinforced concrete shells in the form of hyperbolic paraboloid under the action of operational load.

To carry out the tests, thin-walled shells in the form of hyperbolic paraboloid with dimensions in the plan 2250×3500 mm, thickness 30 mm and angle lift 500 mm were designed (Fig. 1).

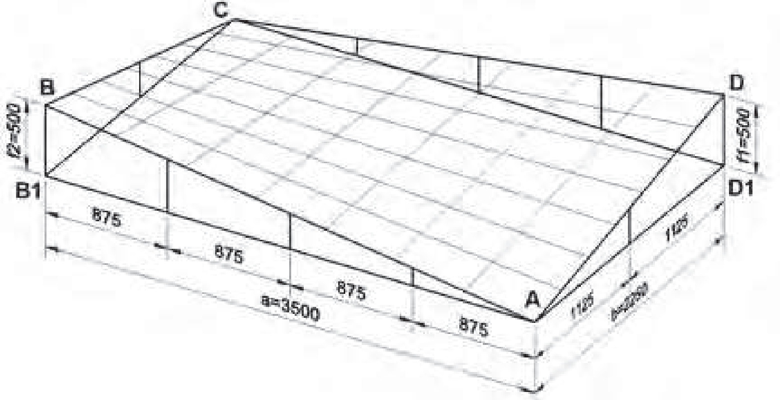


Fig. 1. Scheme of the hyperbolic paraboloid coating

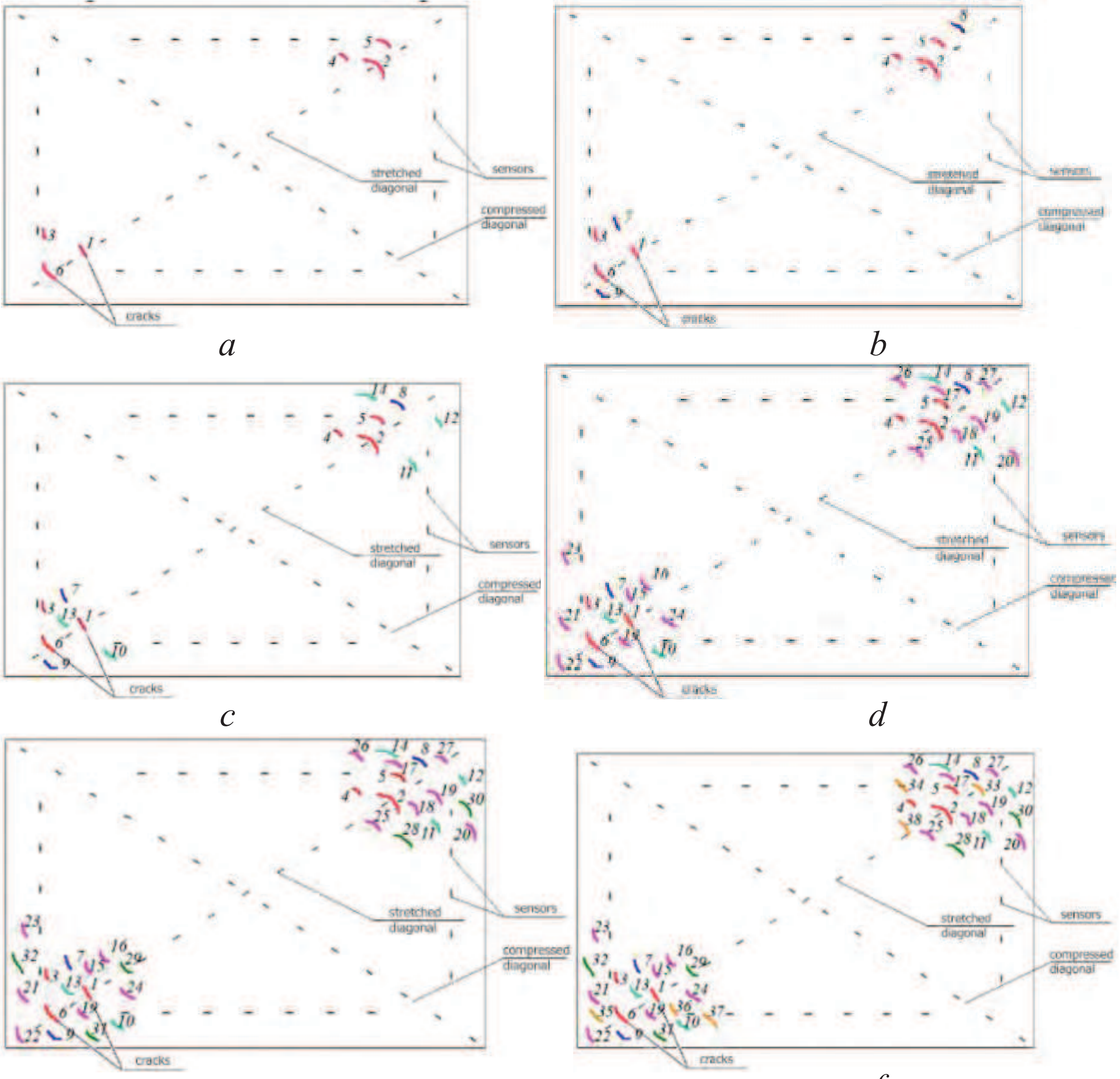
Detailed information about the materials used, the process of designing and producing of shells, and the application of load is described in [13, 14].

The design of the experimental shell of the coating in the form of hyperbolic paraboloid made of ferrocement, which is operated under environmental conditions, belongs to the second category of crack resistance [15]. The maximum allowable width of short-term crack opening for this case is $a_{crc,short}$= 0,05 mm, and the maximum allowable width of the long-term crack opening is $a_{crc,long}$= 0,03 mm.

The width of crack opening was determined by the MPB-3 microscope with a scale division of 0.02 mm. In order to improve visual observation of crack formation, a lime mortar was applied to the lower surface of the thin-walled shell in the form of a hyperbolic paraboloid. Crack formation was fixed visually and marked graphically (by pencil) on the lower edge of the shell, and their opening width was measured at the place of maximum opening.

Investigation of the process of crack formation and increase in the models of thin-walled coating structures in the form of hyperbolic paraboloid were carried out on ferrocement samples: 1H-F-1 and 2H-F-1 and steel-fiber concrete samples: 1H-SFRC-1 and 2H-SFRC-1.

With the application of uniformly distributed load up to the ferrocement shell 1H-F-1, cracks in the stretched zone began to appear at the 5th stage of loading, when the forces at 1H-F-1 reached F_H = 1,345 kPa. At the 6th stage of loading F_H= 1,505 kPa the number of cracks increased. There was also an increase of the width of cracks. At the next stages of loading (№7...№10) new cracks and opening of existing ones were recorded (Fig. 2).



a *b*

c *d*

e *f*

Fig. 2. Cracking process in sample 1H-F-1 during loading:
a – F_H = 1,345 kPa (stage 5); b – F_H = 1,505 kPa (stage 6*);*
c – F_H = 1,665 kPa (stage 7); d – F_H= 1,825 kPa (stage 8*);*
e – F_H= 1,985 kPa (stage 9*); f* – F_H= 2,145 kPa (stage 10*)*

Detailed process of crack formation in the ferrocement shell 1H-F-1 on 5...10 stages of loading are presented in Table 1 and in Fig. 3. Cracks are numbered due to their appearance.

Table 3

Crack opening width (mm) at different load levels

Crack number	Loading stage					
	5	6	7	8	9	10
	1345 Pa	1505 Pa	1665 Pa	1825 Pa	1985 Pa	2145 Pa
1	0,01	0,02	0,04	0,05	0,10	0,20
2	0,01	0,01	0,02	0,04	0,09	0,17
3	0,02	0,03	0,03	0,05	0,11	0,21
4	0,01	0,02	0,03	0,04	0,08	0,19
5	0,02	0,02	0,02	0,03	0,07	0,18
6	0,01	0,02	0,02	0,04	0,09	0,22
7	-	0,01	0,02	0,02	0,04	0,09
8	-	0,02	0,03	0,03	0,06	0,18
9	-	0,01	0,02	0,03	0,07	0,18
10	-	-	0,03	0,04	0,10	0,23
11	-	-	0,01	0,02	0,04	0,10
12	-	-	0,01	0,02	0,03	0,08
13	-	-	0,02	0,02	0,05	0,11
14	-	-	0,03	0,04	0,09	0,20
15	-	-	-	0,05	0,11	0,24
16	-	-	-	0,05	0,12	0,27
17	-	-	-	0,03	0,07	0,16
18	-	-	-	0,02	0,05	0,12
19	-	-	-	0,02	0,04	0,08
20	-	-	-	0,03	0,09	0,20
21	-	-	-	0,04	0,08	0,18
22	-	-	-	0,03	0,07	0,17
23	-	-	-	0,04	0,08	0,20
24	-	-	-	0,03	0,08	0,12
25	-	-	-	0,02	0,04	0,07
26	-	-	-	0,03	0,06	0,09
27	-	-	-	0,04	0,07	0,13
28	-	-	-	-	0,03	0,06
29	-	-	-	-	0,02	0,05
30	-	-	-	-	0,03	0,06
31	-	-	-	-	0,02	0,06
32	-	-	-	-	0,02	0,07
33	-	-	-	-	-	0,05
34	-	-	-	-	-	0,09
35	-	-	-	-	-	0,08
36	-	-	-	-	-	0,07

37	-	-	-	-	-	0,06
38	-	-	-	-	-	0,09
Average	**0,013**	**0,018**	**0,024**	**0,033**	**0,066**	**0,133**

During the study it was fixed that with the addition of next stage to the element 1H-F-1 the number of new cracks increases by 40 ... 50%, and the width of opening of existing (a_{crc}) cracks increases approximately twice.

On the graphs shown in Fig. 3 the dependencies on the applied load at the stages and the number of cracks (a) in the structure of ferrocement shell 1H-F-1 and their average width (b) are clearly presented.

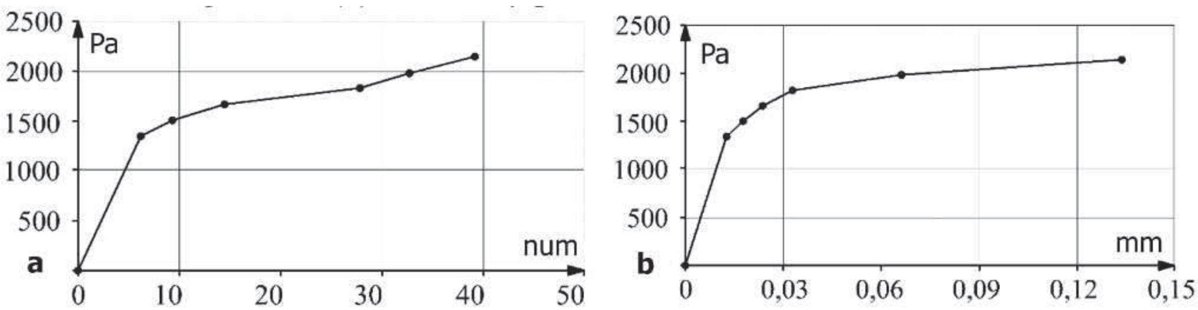


Fig. 3. Crack formation process in 1H-F-1:
a - quantity of cracks formed at the stages of load application;
b - average width of crack opening, mm

During the application of uniformly distributed load of single action to the steel fiber reinforced shell 1H-SFRC-1 the first cracks in the stretched shell zone were registered at the 8th stage at F_H=1,825 kPa. At the next stages of loading (№9 and №10) new cracks and opening of existing ones were fixed. In Fig. 4 the scheme of arrangement of cracks with numbering is presented according to their appearance in a shell.

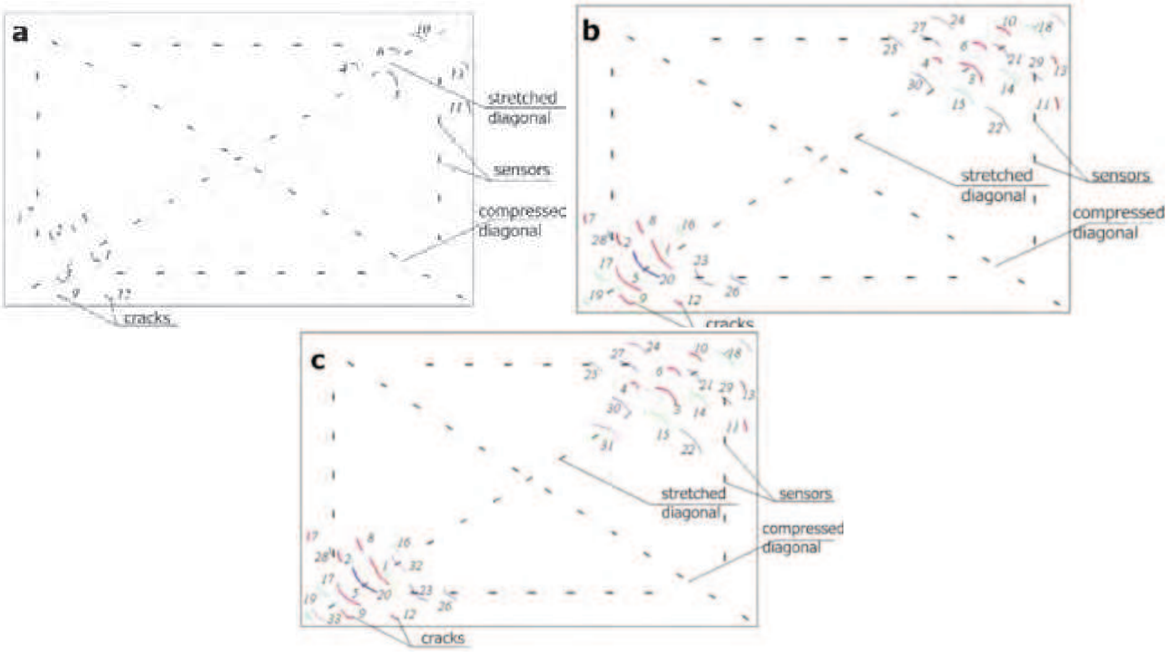


Fig. 4. Cracking process in 1H-SFRC-1 sample during loading:
a - F_H = 1,825 kPa (stage 8); b - F_H = 1,985 kPa (stage 9);
c - F_H = 2,145 kPa (stage 10);

It is fixed that at each stage the number of new cracks increases by 50...80 %, and the width of opening of existing cracks increases by 2-2,5 times. Detailed process of crack formation in steel fiber reinforced concrete shell 1H-SFRC-1 by 8 times ... 10 stages of loading are presented in Table 2 and in Fig. 5.

Table 2

Crack opening width (mm) at different load levels

Crack number	Loading stage		
	8	9	10
	1825 Pa	1985 Pa	2145 Pa
1	0,02	0,07	0,16
2	0,01	0,02	0,06
3	0,03	0,07	0,18
4	0,03	0,04	0,09
5	0,02	0,06	0,15
6	0,03	0,07	0,14
7	0,01	0,02	0,05
8	0,02	0,04	0,10
9	0,01	0,02	0,06
10	0,03	0,06	0,13
11	0,01	0,02	0,05
12	0,01	0,02	0,06
13	0,01	0,02	0,05
14	-	0,06	0,12
15	-	0,06	0,13
16	-	0,05	0,10
17	-	0,03	0,09
18	-	0,03	0,09
19	-	0,01	0,03
20	-	0,09	0,19
21	-	0,08	0,16
22	-	0,04	0,09
23	-	0,06	0,14
24	-	0,03	0,07
25	-	-	0,04
26	-	-	0,03
27	-	-	0,04
28	-	-	0,03
29	-	-	0,04
30	-	-	0,06
31	-	-	0,05
32	-	-	0,06
33	-	-	0,05
Average	**0,018**	**0,045**	**0,089**

On the graphs shown in Fig. 5 the dependencies on the applied load at the stages and the number of cracks (a) in the SFRC shell 1H-SFRC-1 and their average width (b) are clearly presented.

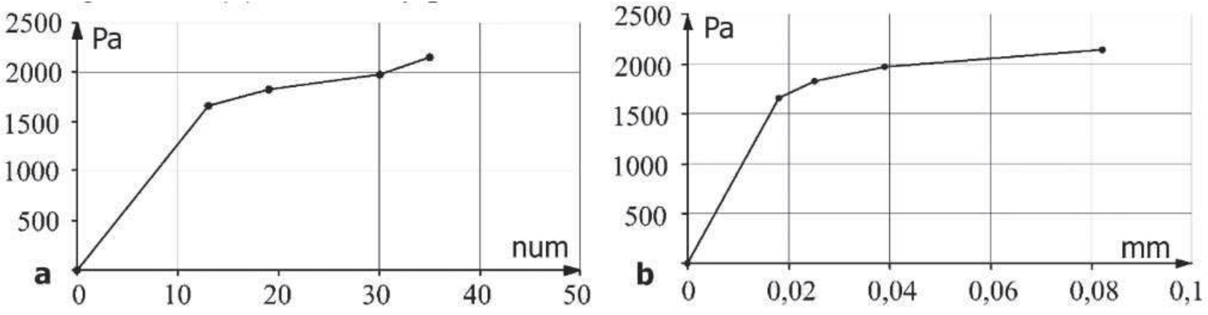


Fig. 5. Crack formation process in 1H-SFRC-1:
a - quantity of cracks formed at the stages of load application;
b - average width of crack opening, mm

In the experiment it was determined that during the application of repeated loads of the operational level (η=0.7) to the steel fiber reinforced concrete shell 2H-SFRC-1, the appearance of the crack formation process was not fixed. And in the thin-walled shell made of ferrocement 2H-F-1 under the same repeated loads along the concave were observed forming cracks and their opening.

It is proved that thin-walled shells of negative Gaussian curvature of "hyperbolic paraboloid" type, which are made of steel fiber reinforced concrete with the percentage of reinforcement of 1.5%, exceed the corresponding indicators of bearing capacity and crack resistance of standard reinforced concrete (ferrocement) thin-walled shells and at the same time reduce the usage of materials.

After the analysis of the research materials presented in this article, it can be concluded that thin-walled shells in the form of hyperbolic paraboloid of steel fiber reinforced concrete by the indicators of crack resistance at disposable and repeated loads have significant advantages over similar elements made of ferrocement and steel fiber reinforced concrete as an effective material is appropriate for the produce of thin-walled shells of negative Gaussian curvature coating in the form of hyperbolic paraboloid.

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