UDC 624.072.2

Voskobiinyk O.P.*, ScD, Senior Scientist*
ORCID 0000-0002-8547-762X elenvosko@gmail.com
Cherednikova O.V., *post-graduate*
ORCID 0000-0003-4684-9870 al.chered108@gmail.com
Poltava National Technical Yuri Kondratyuk University

LIGHT CONCRETE COMPOSITE SLAB WITH FLEXIBLE REINFORCEMENT STRESS-STRAIN STATE MODELING BY FINITE ELEMENT METHOD

The light concrete (polystyrene concrete) composite slab with profiled steel sheeting was considered. In this slab, the flexible reinforcement (PMA-2) was used as strengthening. Previous experimental studies have shown that this slab has increased carrying capacity in 2.4 times compared with a similar slab without additional anchoring means. The finite element method (FEM) was used for a detailed study of the PMA-2 slab work and its components. The calculations of light concrete composite slab allowed to investigate the work of profiled steel sheeting, material contact, their bundles, as well as the work of the reinforcement and its influence on the stress-strain state parameters of polystyrene concrete and profiled steel sheeting. Comparison by FEM calculations with experimental data confirmed the accuracy and adequacy of the developed model for PMA-2 slab.

Keywords: *light concrete composite slab, profiled steel sheeting, polystyrene concrete, reinforcement, deformation property, load, finite element method (FEM).*

Воскобійник О.П.*, д.т.н., с.н.с.*
Череднікова О.В., *аспірант*
Полтавський національний технічний університет імені Юрія Кондратюка

МОДЕЛЮВАННЯ НАПРУЖЕНО-ДЕФОРМОВАНОГО СТАНУ ЛЕГКОБЕТОННОЇ КОМБІНОВАНОЇ ПЛИТИ З ГНУЧКИМ АРМУВАННЯМ МЕТОДОМ СКІНЧЕННИХ ЕЛЕМЕНТІВ

Розглянуто легкобетонну (полістиролбетонну) комбіновану плиту з профільованим настилом, у якій як підсилення використовувалося гнучке армування (ПМА-2). Виявлено з попередніх експериментальних досліджень, що така плита має збільшену у 2,4 раза несучу здатність порівняно з аналогічною плитою без додаткових засобів анкерування. Застосовано метод скінченних елементів (МСЕ) для детального вивчення роботи плити ПМА-2 та її компонентів. Досліджено роботу профнастилу, контакту матеріалів, їх розшарування, а також роботу арматури та її вплив на параметри напружено-деформованого стану полістиролбетону і профнастилу з проведених розрахунків легкобетонної комбінованої плити. Підтверджено точність та адекватність побудованої моделі для плити ПМА-2 порівняннями розрахунків за МСЕ з експериментальними даними.

Ключові слова: *легкобетонна комбінована плита, профільований настил, полістиролбетон, армування, деформативність, навантаження, метод скінченних елементів (МСЕ).*

Problem statement. The question of using efficiently structures in construction is particularly relevant for Ukraine and for any another country now. Considering this factor, light concrete composite slabs with profiled steel sheeting [10] are taken as structures that have not only high design qualities, but also thermal insulation. Ideally, the slabs of the coating and the ceiling should be light, but along with it they are strong, have low deformability and a low coefficient of thermal conductivity. Light concrete composite slabs where light concrete will work together with profiled steel sheeting can combine all of the qualities mentioned above. The question is the next – what type of connection is better to use in such slabs and how to carry out analytical calculations that can describe the work of different types of light concrete composite slabs with profiled steel sheeting under load.

Analysis of recent research and publications. Scientists in the field of construction work carried out on the application of various types of anchoring and reinforcement in beam steel reinforced concrete structures. But mainly heavy concrete was used in these constructions. Such studies were conducted by Skyba O., Belyaeva S., Darienko V. and others [1 – 4]. Polystyrene concrete samples depending on the concrete strength class investigation, considering the stability of the profile in the steel reinforced concrete samples, are given in the works of Avramenko Yu. and Semko O. [5, 15].

A question that has not been considered by previous scientists, but that is relevant in connection with the expansion of energy efficient structures use, is in the investigation of the stress-strain state of light concrete (polystyrene concrete) composite slabs with profiled steel sheeting by the finite element method under applying as heat-insulating and structural building element.

It can be assumed that the analytical methods for calculating steel-reinforced concrete slabs [10] do not fully describe the work of the considered slabs. It is due to the fact that different assumptions or hypotheses about the slabs deformation nature are used to obtain finite equations. In addition, engineering methods do not allow to investigate the stress-strain state of both reinforcement and concrete, since they are intended only for strength and deformability verification.

The numerical methods deprived most of these deficiencies and based on direct solution of theory of elasticity. Depending on the discussed tasks, these methods can be used both for the slabs stress-strain state study and for their simplified engineering calculations. Composite slabs and profiled steel sheeting modeling using finite element method is involved by many foreign scientists [14, 17]. In their studies, they solve a variety of specific tasks, such as the development of finite elements, approaches to applying boundary conditions, overlay nets depending on the materials type, loading type etc. [7, 8, 11, 12, 18].

There are many software complexes implementing structures calculations by the finite element method. The most common ones among them are «ANSYS» by «ANSYS Corporation», «FEMAP» (NASTRAN) by «Siemens PLM Software», «ABAQUS» and «COSMOS» by «Dassault Systèmes Simulia Corporation», «LIRA» by «LIRA soft», «LS-DYNA» by «Livermore Software Technology» and others. Each complex has its own set of finite elements that simulate the structure stress-strain state depending on the material, load, deformation type etc. FEMAP software package is one of the most convenient in use. It has intuitive interface, pre- and post-processing, a large number of finite elements that allow to create models of high degree of complexity. Therefore, it is well suited for scientific research. In most cases, these software systems are used for calculating and investigating the stress-strain state of existing building structures types and new ones [13, 16].

Selection of unsolved question. The question that is relevant in the study of the stress-strain state of light concrete (polystyrene concrete) composite slabs with profiled steel sheeting by finite elements method is the creation of an adequate model for slab type calculating. This model must have finite elements that correspond to the properties of the construction materials (concrete, steel). The contact layer among the materials, which is responsible for modeling the fracture at the time of material bundle, should be correctly displayed in the model. The construction of finite elements grid, the application of loads and boundary conditions should consider all the conditions where the investigated structure is located.

Purpose and objectives of the research. The main purpose of the research is to develop approaches to modeling the stress-strain state of composite steel-reinforced concrete slabs (CSRS) by finite element method (FEM).

The set goal requires the solution of the following tasks: creation of three-dimensional geometric models of profiled steel sheeting, polystyrene concrete and contact; definition of physical and mechanical models of materials and contact work; building of finite elements grid; applying loads and boundary conditions; determination the calculation type and obtained data analysis.

The main part of the research. In previous experimental studies, two rational types of anchoring were identified - the anchoring in the form of flexible (PMA-2 slab) and horizontal (PMA-3 slab) reinforcement. The flexible reinforcement use (PMA-2) as anchoring makes it possible to increase the carrying capacity in 2.4 times compared to the slab without any means of anchoring, and horizontal reinforcement (PMA-3) makes it possible to reduce deformation for 8% under a load of $0.6M_{ult,\ exp.}$ The studies by finite element method are presented exactly for the PMA-2 slab with flexible anchoring.

An experimental and analytical study of a PM-1 slab without anchoring and reinforcing has been carried out earlier and are described in details in [6, 9].

All types of FE were used to calculate the slabs - linear, flat and volumetric. Geometric models for the composite slabs were constructed according to the FE type. Three-dimensional bodies were used for a concrete array and contact; the extreme lower planes of the already constructed contact - for profiled steel sheeting; the lines formed at the intersection of the jagged planes - for reinforcement. The profile of profiled steel sheeting was used as basis for the construction where the necessary planes of slab cross-section were formed. After that, the plane «pulled» in the base bodies, which were the basis for the slab models construction. Further transformations of the base geometric bodies are in their partition into pentagons and hexagons in accordance with the shape and location of the specific slabs reinforcement.

Modeling of materials and contact was based on the results of experimental determination of physical and mechanical characteristics and on the material behavior during loading. Work model was considered for each material and depended on the expected conditions of its work. Profiled steel sheeting and reinforcement were set as isotropic nonlinear elastic-plastic material; polystyrene concrete and contact - as non-linear elastic material. Diagrams of materials deformation, that was accepted for the calculation by FEM, were given in the form of two-linear functions $\sigma - \varepsilon$, the horizontal section of which corresponded to the limit of strength or durability of the materials.

The types of FE and their properties were determined before the beginning of the finite element (FE) grids construction. Thus, the linear, flat, voluminous and completely rigid FE was used for the slabs modeling. The main condition for the correct calculation was the connectivity of the grids in the nodes that combine different materials and types of FE. The grids were imposing on all geometric body of model determining its size and configuration. Figure 1 shows the complete FE model of the PMA-2 slab.

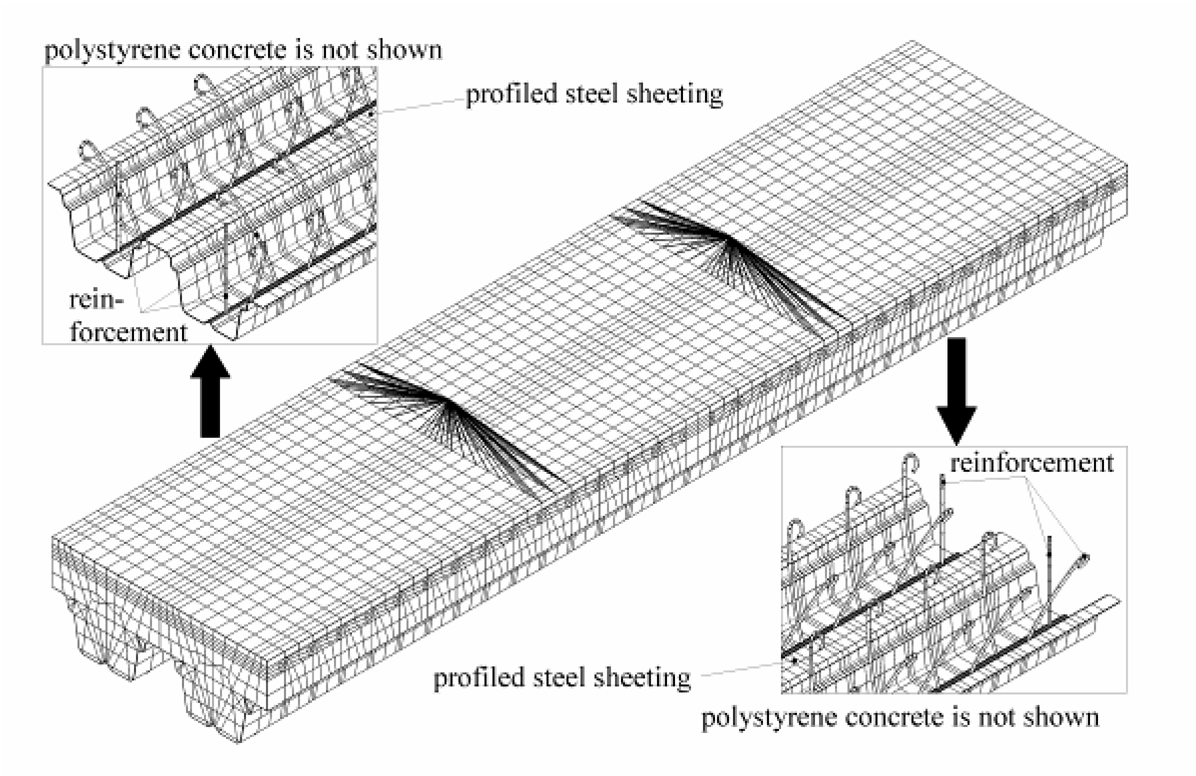

Figure 1 – Complete FE model of the PMA-2 slab

Placements of loading loads, their size and configuration corresponded to the experimental data. Concentrated loads through boards located on the upper surface of polystyrene concrete were applied in the experiment for PMA-1...PMA-5 slabs. The load was applied through complete rigid FE (Figure 1) for adequate modeling of these conditions. The total load value for the PMA-2 slab was equal to 21480 H.

Support nodes of all slabs and profiled steel sheeting were modeled using completely rigid FE. In all cases, the following degrees of freedom are accepted: on the one site of model the support bracket forbade linear displacement along the axes x, y, z, and the angular displacement around the z axis; on the other site the support bracket forbade displacement along the axes x and y and angular displacement around the z axis. Additionally, the nodes of vertical plane were forbidden to move in the direction of the vertical axis in areas of support slabs.

Linear and nonlinear static calculations were performed for all models. During the linear static calculation, the nonlinear properties of materials and the geometric nonlinearity of the construction were ignored. The calculation is based on the initial modules of elasticity. Nonlinear calculation provided applying the load in a few steps with increasing from zero to its maximum value. The values of intersecting elastic module were calculated at every step of loading according to the charts of materials deformation. This process ended when the maximum load was reached, or when the structure was transformed into a mechanism – appearance of plastic hinges, loss of local or general stability, etc. There were 20 steps of load in all nonlinear calculations, but not all slabs reached the maximum load value. The maximum experimental load was not achieved during calculating for both the PMA-2 and PMA-1 slabs. Calculation was ended on value $0{,}8F_{max}$. The results of nonlinear calculation of PMA-2 slab at maximum load are shown in Figures 2-7. The maximum deflections determined in the middle of the span at the location of the defibrillator are given in Table 1.

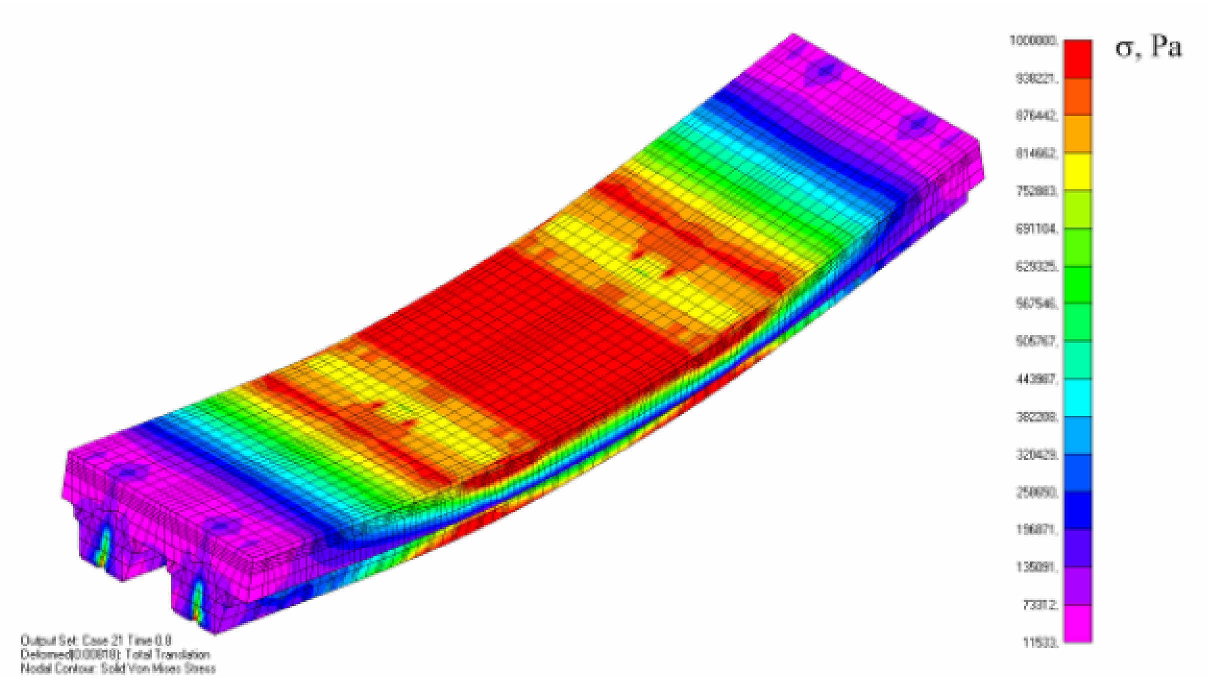

Figure 2 – Chart of Mises stress distribution and deformation of polystyrene concrete when nonlinear calculating PMA-2 slab

The chart of Mises stress distribution and deformation of polystyrene concrete with nonlinear calculating PMA-2 slab is shown in Figure 2. Small concentrations of stresses are observed on the upper surface of the polystyrene concrete in the locations of the reinforcement. There are also concentration stresses from the effects of loads through complete rigid FE. The polystyrene concrete is pressed by reinforcement at the ends of the PMA 2 slab. Maximal stresses arise in the middle of span on the upper part of slabs, and under concentrated forces in lower part of the slab. This distribution is explained by the action of concentrated forces and distribution of reinforcement on all-area of the slab.

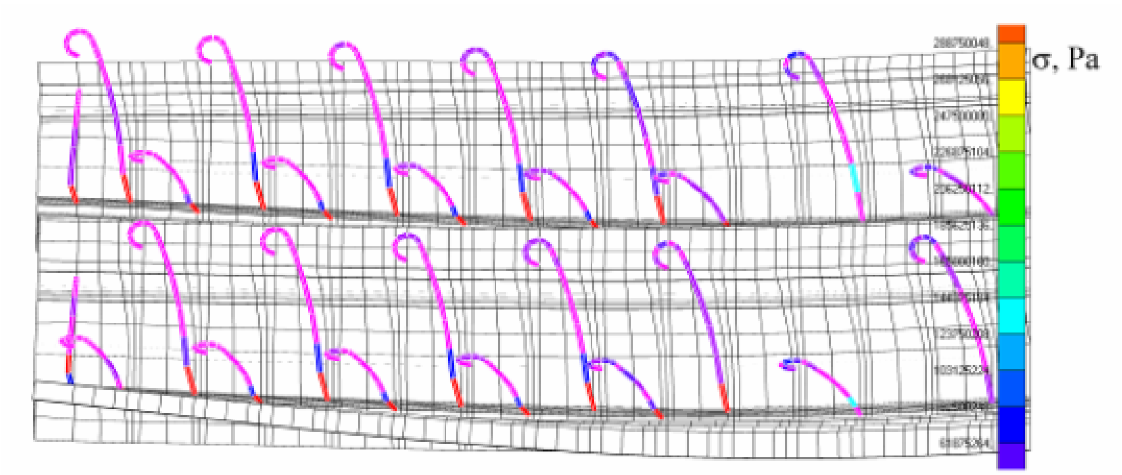

Figure 3 – Chart of Mises stress distribution and deformation of reinforcement with nonlinear calculating PMA-2 slab

Reinforcement work is shown in Figure 3. As it is shown, all reinforcement is reached with yield strength in the contact zone of profiled steel sheeting at maximum load. It undergoes the greatest deformation in bearing zones.

The effect of reinforcement on the stress state of polystyrene concrete is shown in Figures 4-6. The location of reinforcement at different angles causes a chain change in the stresses in the lower central depression of polystyrene concrete that depends on the angle of the reinforcement. The reinforcement located at different angles helps to avoid the occurrence of a longitudinal crack (Figure 4).

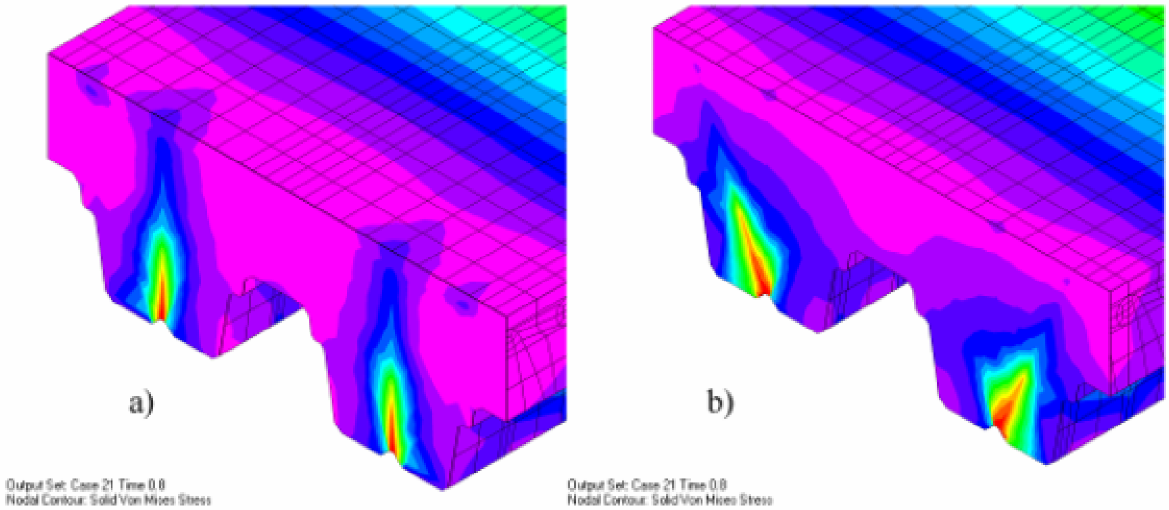

Figure 4 – Effect of vertical and inclined reinforcement at stress state of the PMA-2 slab: a) cross-section at vertical reinforcement; b) cross-section at inclined reinforcement.

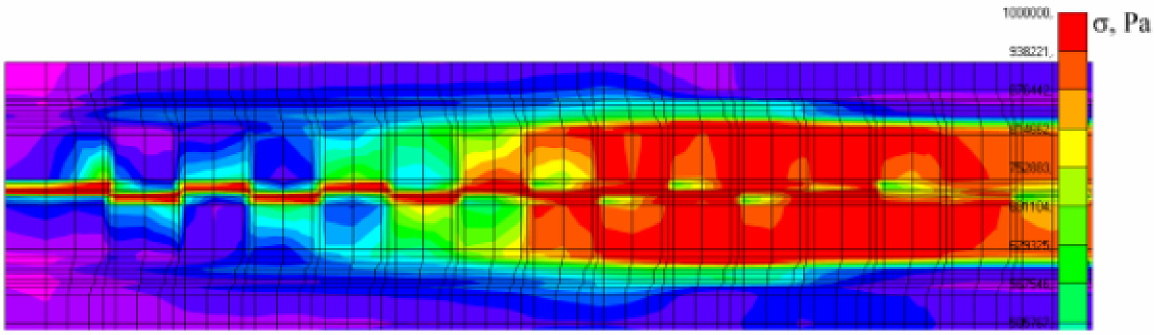

Figure 5 – Effect of the reinforcement on the stress state of polystyrene concrete (bottom view) for the PMA-2 slab

Figure 6 a) shows the distribution of stresses along a longitudinal vertical section through vertical reinforcement. The zones of boundary stress is clearly observed in places of its location that caused by bending of the reinforcement and subsequent bulging of concrete up to the ends of the slab.

Figure 6 b) shows the distribution of stresses along the longitudinal slope section through the inclined reinforcement. In this case, the location of the reinforcement does not cause a continuous zone of boundary stresses in lower part of polystyrene concrete, which improves the mutual work of reinforcement with polystyrene concrete. Distribution of stresses in the zones of inclined reinforcement location is the same but a little bit changes when approaching the middle of the slab. Small circular stress reduction areas are observed in the upper part of the inclined cross-section corresponding to the corner radius at the ends of the inclined reinforcement. The reinforcement works only in the lower part of slab height, causing the corresponding perturbations. Stress distribution does not change in the middle and upper slab parts in zones of reinforcement location.

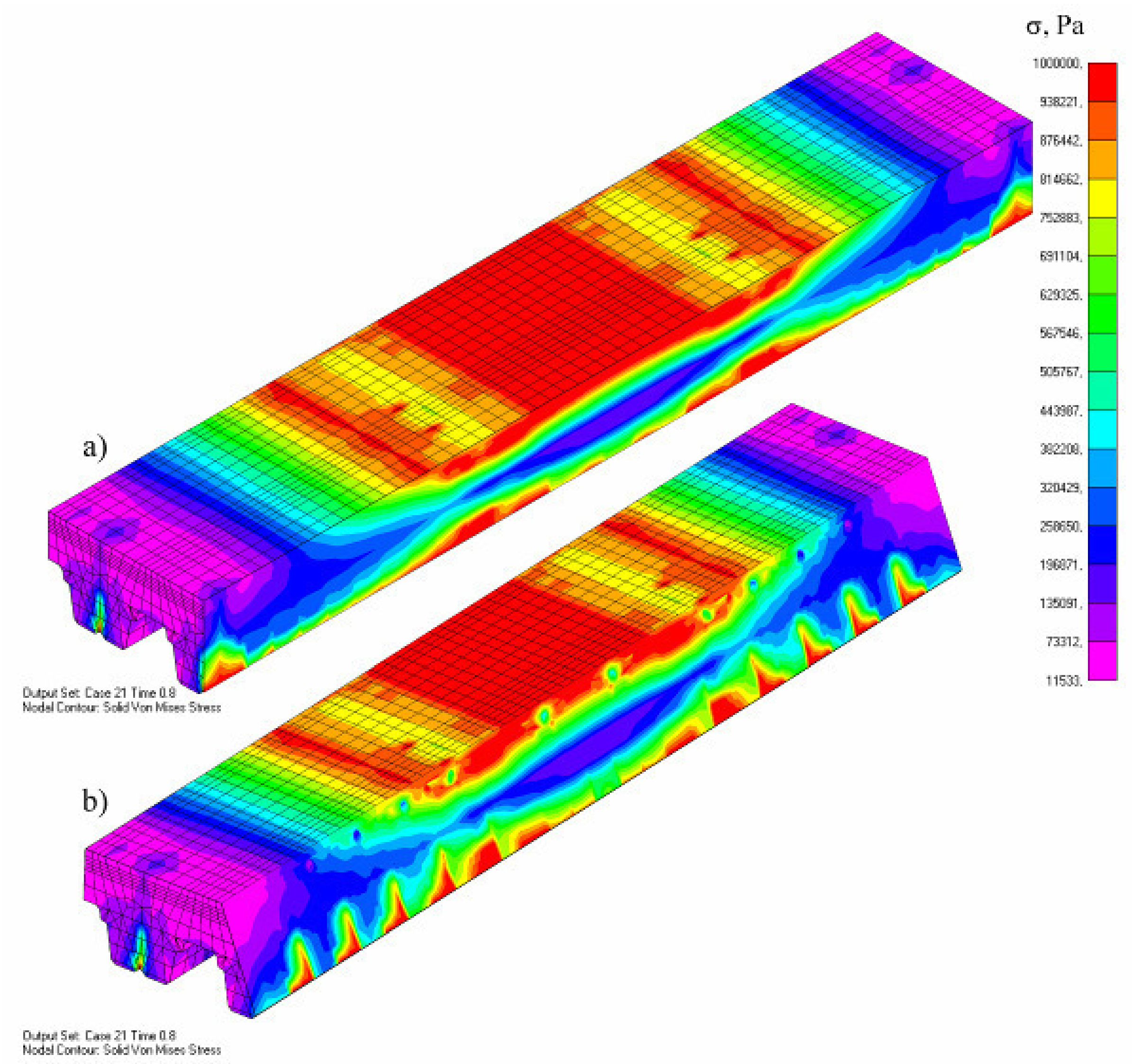

Figure 6 – Effect of vertical and inclined reinforcement on the stress state of the PMA-2 slab: a) longitudinal vertical section on reinforcement; b) longitudinal inclined cross-section along the inclined reinforcement

Contact area between polystyrene concrete and profiled steel sheeting decreased with load increase, ranging from supporting and central zones and ending with lateral surfaces of profiled steel sheeting in the middle of slab span. Full separation of materials occurs at a load of about 5000 H. Further deformation of slab components occurred differently for different zones of the slab. For example, the separation of profiled steel sheeting from concrete increased in support areas, while both materials are equally deformed in the middle span, although they are not connected. Their final separation occurred only when load is 12000 H. In this case, the left shelf of profiled steel sheeting began to lose local stability.

In Figure 7, according to Table 1, PMA-2 slab deformation graph was constructed. The main difference slabs with other types of anchoring research results is that the process of separation was practically free of deformation jumps. This is due to the increased slab stiffness. Separation of profiled steel sheeting from polystyrene concrete begins at load of 12000 H, and the distance between adjacent nodes begins to increase according to increase of load.

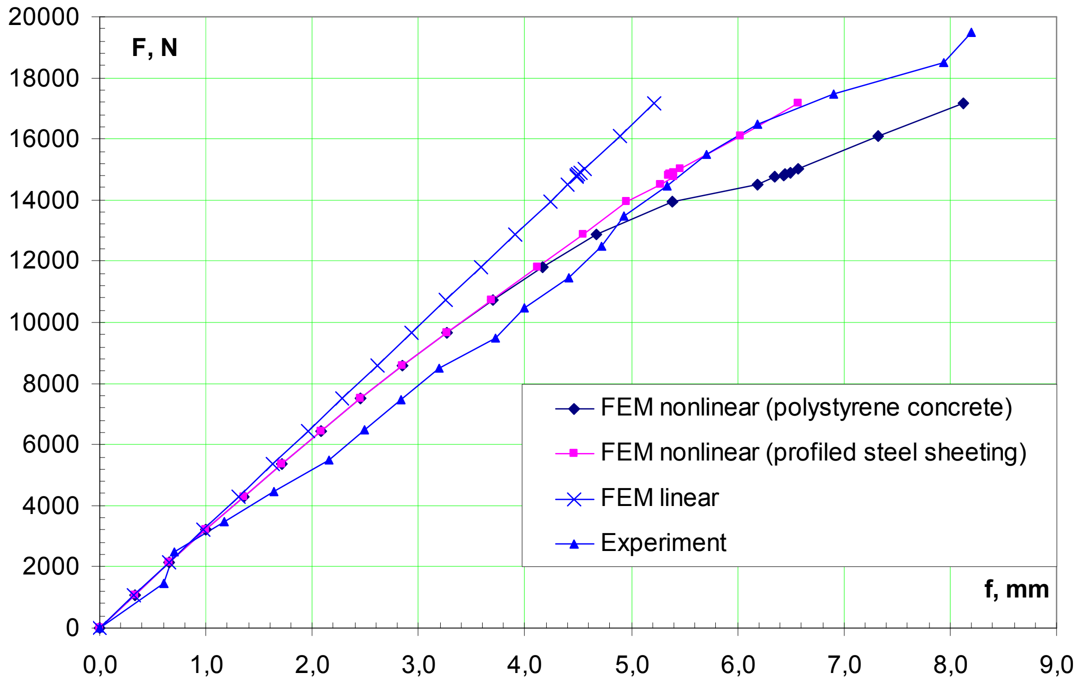

Figure 7 – Comparison of the deflections for the PMA-2 slab by FEM, with experimental data

Table 1 – Results of deflection calculations for PMA-2 slab

Load step	Load, N	Deflection, mm		
		Polystyrene concrete	Profiled steel sheeting	Linear calculation
0	0	0,00	0,00	0,00
1	1074	0,33	0,33	0,33
2	2148	0,66	0,66	0,65
3	3222	1,00	1,00	0,98
4	4296	1,35	1,35	1,30
5	5370	1,72	1,72	1,63
6	6444	2,08	2,08	1,96
7	7518	2,46	2,46	2,28
8	8592	2,85	2,85	2,61
9	9666	3,26	3,26	2,93
10	10740	3,70	3,69	3,26
11	11814	4,17	4,12	3,59
12	12888	4,68	4,55	3,91
13	13962	5,38	4,96	4,24
14	14499	6,19	5,28	4,40
15	14768	6,35	5,40	4,48
16	14801	6,43	5,35	4,49
17	14835	6,45	5,37	4,50
18	14902	6,49	5,40	4,52
19	15036	6,57	5,46	4,57
20	16110	7,33	6,03	4,89
21	17184	8,12	6,57	5,22
–	21480	–	–	6,52

Conclusions. The calculations of the profiled steel sheeting and the slabs by finite element method allowed to investigate the work of the profiled steel sheeting, the contact of the materials, their bundles, as well as the work of the reinforcement and its influence on the parameters of the stress-strain state of polystyrene concrete and profiled steel sheeting. The error in experimental data and calculation by FEM does not exceed 8.4% for nonlinear calculations and 21% for linear ones. The anchoring method used in the PMA-2 slab can be recommended for use in cases where it is necessary to increase bearing capacity significantly due to a slight decrease in deformation properties of the slab. Modeling methods for PMA-2 slab and its components, used in calculations by FEM, can be recommended for application in the finite-element models of steel-reinforced concrete structures development.

Practical recommendations for light concrete slabs with profiled steel sheeting by FEM modeling and calculation, including the foundation for choosing FE type for the rofiled steel sheeting modeling is occurred according to the research.

References

1. *Беляева С. Ю. Экспериментальные исследования железобетонных плит, армированных стальным профилированным настилом / С. Ю. Беляева // Збірник наукових праць Донбаського технічнічного університету. – Алчевск: «Ладо» ДГМІ, 2005. – Вип. 20. – С. 344 – 348.*
   Belyaeva S. Yu. Eksperimentalnyie issledovaniya zhelezobetonnyih plit, armirovannyih stalnyim profilirovannyim nastilom / S. Yu. Belyaeva // ZbIrnik naukovih prats Donbaskogo tehnIchnIchnogo unIversitetu. – Alchevsk: «Lado» DGMI, 2005. – Vip. 20. – S. 344 – 348.
2. *Коваль М. П. Дослідження роботи монолітних залізобетонних плит зі сталевим профільованим настилом Н80А та болтовими опорними анкерами при дії статичного й високорівневого малоциклового навантаження / М. П. Коваль, І. О. Кондрюкова // Збірник наукових праць. Серія: Галузеве машинобудування, будівництво. – ПолтНТУ, 2015. – Вип. 1(43). – С. 170 – 177.*
   Koval M. P. Doslidzhennya roboti monolitnih zalizobetonnih plit zi stalevim profilovanim nastilom N80A ta boltovimi opornimi ankerami pri diyi statichnogo y visokorivnevogo malotsiklovogo navantazhennya / M. P. Koval, I. O. Kondryukova // Zbirnik naukovih prats. Seriya: Galuzeve mashinobuduvannya, budivnitstvo. – PoltNTU, 2015. – Vip. 1(43). – C. 170 – 177.
   http://journals.pntu.edu.ua/index.php/znp/article/view/121.
3. *Семко О. В. Дослідження напружено-деформованого стану залізобетонних ребристих плит покриттів в розрахунковому комплексі NASTRAN / О. В. Семко, О. А. Крупченко, В. В. Дарієнко, М. І. Глінкін // Проблеми розвитку дорожньо-транспортного і будівельного комплексів : зб. статей і тез Міжнар. наук.-прак. конф. (3-5.10.2013 р). – К-д, 2013. – С. 358 – 363.*
   Semko O. V. Doslidzhennya napruzheno-deformovanogo stanu zalizobetonnih rebristih plit pokrittiv v rozrahunkovomu kompleksi NASTRAN / O. V. Semko, O. A. Krupchenko, V. V. Darienko, M. I. Glinkin // Problemi rozvitku dorozhno-transportnogo i budivelnogo kompleksiv : zb. statey i tez Mizhnar. nauk.-prak. konf.. – K-d, 2013. – S. 358 – 363.
4. *Семко О. В. Експериментальні дослідження обетонованих сталезалізобетонних балок з вигинами / О. В. Семко, О. В. Скиба, Є. В. Гутник // Проблеми розвитку дорожньо-транспортного і будівельного комплексів : зб. статей і тез Міжнар. наук.-прак. конф. (3-5.10.2013 р). – К-д, 2013. – С. 363 – 366.*
   Semko O. V. Eksperimentalni doslidzhennya obetonovanih stalezalizobetonnih balok z viginami / O. V. Semko, O. V. Skiba, E. V. Gutnik // Problemi rozvitku dorozhno-transportnogo l budlvelnogo kompleksiv : zb. statey i tez Mizhnar. nauk.-prak. konf. – K-d, 2013. – S. 363 – 366.
5. *Семко О. В. Легкий бетон для заповнення порожнин сталевих тонкостінних конструкцій / О. В. Семко, Д. М. Лазарєв, Ю. О. Авраменко // Зб. наук. праць. – К. : ДП НДІБК, 2011. – № 74. – С. 659 – 666.*
   Semko O. V. Legkiy beton dlya zapovnennya porozhnin stalevih tonkostInnih konstruktsIy / O. V. Semko, D. M. Lazarev, Yu. O. Avramenko // Zb. nauk. prats. – K. : DP NDIBK, 2011. – № 4. – S. 659 – 666.

6. *Чередніков В. М. Про визначення параметрів напружено-деформованого стану сталезалізобетонних балочних елементів / В. М. Чередніков, О. П. Воскобійник, О. В. Череднікова // Збірник наукових праць. Серія: Галузеве машинобудування, будівництво. – ПолтНТУ, 2012. – Вип. 3(33). – С. 279 – 287.*
CherednIkov V. M. Pro viznachennya parametriv napruzheno-deformovanogo stanu stalezalizobetonnih balochnih elementIv / V. M. Cherednikov, O. P. Voskobiynik, O. V. Cherednikova // Zbirnik naukovih prats. Seriya: Galuzeve mashinobuduvannya, budivnitstvo. – PoltNTU, 2012. – Vip. 3(33). – C. 279 – 287.
7. *Akpoyomare A. I. Virtual testing of composites: Imposing periodic boundary conditions on general finite element meshes / A. I. Akpoyomare, M .I. Okereke, M. S. Bingley // Composite Structures. – 2017. – № 160. – P. 983 – 994.*
https://doi.org/10.1016/j.compstruct.2016.10.114.
8. *Carrazedo R. Triangular based prismatic finite element for the analysis of orthotropic laminated beams, plates and shells / Rogério Carrazedo, Humberto Breves Coda // Composite Structures. – 2017. – № 168. – P. 234 – 246.*
https://doi.org/10.1016/j.compstruct.2017.02.027.
9. *Cherednikov V. Evaluation of the warping model for analysis of polystyrene concrete slabs with profiled steel sheeting / V. Cherednikov, O. Voskobiinyk, O. Cherednikova // Periodica Polytechnica Civil Engineering. – 2017. – 61(3). – P. 483 – 490.*
https://doi.org/10.3311/PPci.8717.
10. *Designers' Guide to Eurocode 4: Design of composite steel and concrete structures : 2th editions / Roger P. Johnson. – 2011. – 310 p.*
11. *Buckling and free vibration of shear-flexible sandwich beams using a couple-stress-based finite element / B. R. Goncalves, A. Karttunen, J. Romanoff, J. N. Reddy // Composite Structures. – 2017. – № 165. – P. 233 – 241.*
https://doi.org/10.1016/j.compstruct.2017.01.033.
12. *Han J.-W. Improved finite element viscoelastic analysis of laminated structures via the enhanced first-order shear deformation theory / J.-W. Han, J.-S. Kim, M. Cho // Composite Structures. – 2017. – № 180. – P. 360 – 377.*
https://doi.org/10.1016/j.compstruct.2017.07.099.
13. *Kaliakin V. N. Analysis of concrete beams reinforced with externally bonded woven composite fabrics/ V. N. Kaliakin, M. J. Chajes, T. F. Januszka // Composites. – 1996. – Vol. 27B, Part B. – P. 235 – 244.*
14. *Laim L. Experimental and numerical analysis on the structural behaviour of cold-formed steel beams / L. Laim, J. P. C. Rodrigues, L. S. da Silva // Thin-Walled Structures. – 2013. – № 72. – P. 1 – 13.*
15. *Semko V. Effect of Bracing Systems on Overall Stability and Deformability of Cold-Formed Steel Roofing Structures / V. Semko, D. Prohorenko // Design, Fabrication and Economy of Metal Structures: International Conference Proceedings 2013, Miskolc, Hungary, April 24 – 26, 2013. – Berlin: Springer Berlin Heidelberg, 2013. – P. 229 – 234.*
https://link.springer.com/chapter/10.1007%2F978-3-642-36691-8_35
16. *Static flexural response of members pretensioned with multiple layered aramid fiber tendons / M. A. Shahawy, T. Beitelman, M. Arockiasamy, K. S. Sandepudi // Composites. – 1996. – Vol. 27B, Part B. – P. 253 – 261.*
17. *Teng X. Nonlinear finite element analyses of FRP-strengthened reinforced concrete slabs using a new layered composite plate element / X. Teng, Y.X. Zhang // Composite Structures. – 2014. – № 114. – P. 20 – 29.*
https://doi.org/10.1016/j.compstruct.2014.03.040
18. *A linear smoothed quadratic finite element for the analysis of laminated composite Reissner–Mindlin plates / D. Wan, D. Hu, S. Natarajan, S. P. A. Bordas, T. Long // Composite Structures. – 2017. – № 180. – P. 395 – 411.*
https://doi.org/10.1016/j.compstruct.2017.07.092.

Received 26.08.2017