DOI:10.22337/2587-9618-2023-19-2-51-59

SELECTION OF THE RATIONAL PARAMETERS OF THREE-LAYER REINFORCED CONCRETE STRUCTURES WITH MONOLITHIC BONDING LAYERS BY THE METHOD OF COMPUTER MODELING

Elena A. Korol, Yulia O. Kustikova

National Research Moscow State University of Civil Engineering, Moscow, RUSSIA

Abstract. For the selection of the rational physical, mechanical and geometric parameters of three-layer reinforced concrete structures with monolithic bonding layers, it is necessary to have numerous data on the stress field and patterns of their deformation upon loading, changes in the energy parameters of the strength of concrete and the thickness of the layers. The important condition for the analysis of the stress-strain state by computer simulation is verification with experimental studies. This research is a confirmation of the reliability of the partitioning of the model into finite elements, the choice of their size and configuration. Modeling of three-layered enclosing structures with overall dimensions of attic overlappings allows obtaining strains and deformations in the outer and middle layers at different levels of loads and performing their comparison with limiting values. Due to the high rigidity of the three-layered enclosing structures with a monolithic bond of the layers and the use of structural concrete in the outer layers, the strength of which is more than 10 times higher than that of the middle layer, there are no cracks in the operating loads. In order to recommend considering the stress-strain state, there are more dimensional three-layer coating plates with monolithically bonded layers with different geometric and strength parameters, with different degrees of reinforcement and levels.

Keywords: three-layer reinforced concrete structures, monolithic binding layers, computer modeling, deformations, stress-strain state, enclosing structures, concrete strength

ВЫБОР РАЦИОНАЛЬНЫХ ПАРАМЕТРОВ ТРЕХСЛОЙНЫХ ЖЕЛЕЗОБЕТОННЫХ КОНСТРУКЦИЙ С МОНОЛИТНЫМИ СВЯЗУЮЩИМИ СЛОЯМИ МЕТОДОМ КОМПЬЮТЕРНОГО МОДЕЛИРОВАНИЯ

Е.А. Король, Ю.О. Кустикова

Национальный исследовательский Московский государственный строительный университет (НИУ МГСУ); г. Москва, РОССИЯ

Аннотация. Для выбора рациональных физико-механических и геометрических параметров трехслойных железобетонных конструкций с монолитными связующими слоями необходимо располагать многочисленными данными о поле напряжений и закономерностях их деформации при нагружении, изменениях энергетических параметров прочности бетона и толщины слоев. Важным условием для анализа напряженно-деформированного состояния с помощью компьютерного моделирования является верификация экспериментальными исследованиями. Это исследование является подтверждением надежности разделения модели на конечные элементы, выбора их размера и конфигурации. Моделирование трехслойных ограждающих конструкций с учетом габаритных размеров чердачных перекрытий позволяет получать напряжения и деформационные сдвиги во внешнем и среднем слоях при разных уровнях нагрузок и проводить их сравнение с предельными значениями. Благодаря высокой жесткости трехслойных ограждающих конструкций с монолитным соединением слоев и использованию конструкционного бетона во внешних слоях, прочность которого более чем в 10 раз выше, чем у среднего слоя, при эксплуатационных нагрузках трещины отсутствуют. Для того чтобы рекомендовать учитывать напряженно-деформированное состояние, существуют пластины с трехслойным покрытием большего размера с монолитно соединенными слоями с различными геометрическими и прочностными параметрами, с разной степенью усиления и уровнями.

Ключевые слова: трехслойные железобетонные конструкции, монолитные связующие слои, компьютерное моделирование, деформации, напряженно-деформированное состояние, ограждающие конструкции, прочность бетона

1. INTRODUCTION

This research is aimed at studying the development of methods for calculating multi-layer reinforced concrete structures, that based on the use of the results of both experimental and theoretical studies, including computer modeling.

Multilayer structures consisting of materials with different physical and mechanical characteristics have a contact layer on the contact boundary, the influence of which on the construction of computational models has been investigated by numerical methods [1-7].

The experimental results reflect within the limits of the accuracy of the experiment the actual parameters of the stress-strain state of the structures and are associated with the correct development of physical models.

As shown by the theoretical and experimental studies, which were carried out earlier by the author [8-10], the stresses in the stretched zone of the investigated three-layer reinforced concrete structures under the operational load do not reach the ultimate tensile strength, therefore formation of cracks does not occur. This is the basis for accepting the work of concretes of the middle and outer layers of the structure under such elastic loads. However, when analyzing the results of model calculation, it is necessary to consider the ratio of the obtained values of tensile stresses for each layer of concrete and the corresponding design tensile strength. When these values approach or exceed the first one above the second one, it is necessary to correct the model taking into account the cracking.

2. MATERIALS AND METHODS

The cross-section of the investigated three-layer bending reinforced concrete structures consists of two types of concrete. Their outer layers are made of structural concrete of class B12.5 - B30, and the middle layer is made of structural and heat-insulating class B1.5 and less.

After preliminary analysis for further work, the ZSOIL software package developed by Zace Service Ltd. (Switzerland). The possibilities of this program are allowed to enter various material parameters without their mutual dependence. The program allows you to set the data and generate the grid CE in manual mode. This software allows the use of flat, isoparametric and subparametric finite elements of the second order.

To approximate a three-layer structure from different types of concrete with a monolithic bond of layers, as preliminary studies have shown, rectangular or triangular flat finite elements are most suitable. The dimensions of the final elements were correlated with the thickness of the layers of the structure, the smallest of which was 40 mm. In order to be able to compare the results of the simulation with the actual picture of the deformation of the tested three-layer reinforced concrete beam-type samples, the parameters of the layers of beam samples were taken for the first model [8] based on the results of previous experimental studies. In the first approximation, taking into account the rare arrangement of the reinforcement and the low percentage of reinforcement (up to 0.05%), the beam reinforcement was not taken into account in the calculation.

In the first version of the model, the three-layer construction was represented by rectangular finite elements - the lower and upper layers in one row, the middle one in the form of 4 rows of finite elements (Fig. 1, a).

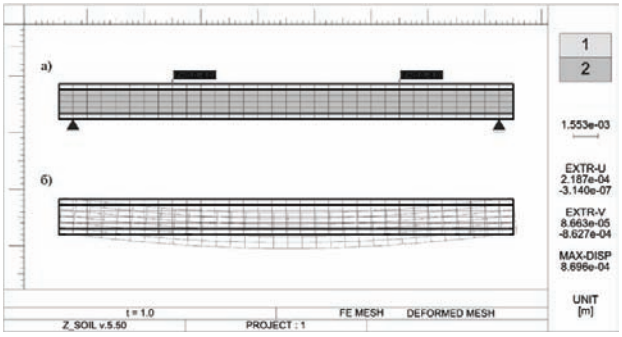


Figure 1. FE model of beam with rectangular grid: a) scheme for grid layout of FE model; b) beam deformations

The parameters of the finite elements (FE) and the characteristics of the concrete layers of the structure are given in Table 1.

Table 1

Construction layer	External	Internal
The size of rectangular elements, m	0,04×0,10	0,0425×0,10
Prismatic strength of concrete R_b, MPa	10,1	1,15
Strength of concrete for tensile strength R_{bt}, MPa	1,02	0,35
Initial modulus of elasticity E0, MPa	10400	950
Poisson's ratio $\nu = 0.00189 \mid R_b \mid + 0.12$	0,139	0,122
The shear modulus $G = E_0 / 2(1 + \nu)$, MPa	4570	423
Average density of concrete, kg / m3	1700	440

The results of the calculation for a load corresponding to the elastic stage of operation of a beam sample are shown in Fig. 1 and Fig. 2.

As the calculation results showed, the deflections of beam models correspond to the results of full-scale tests with an accuracy of up to 95%. The magnitudes of the principal stresses in the layers of the elements are also close to those experienced at the corresponding load levels. However, the direction of the main tensile and principal compressive stresses, shown in adjacent finite elements on opposite diagonals, somewhat distorts the true picture of the stress field. Therefore, the representation of the structural layers by rectangular finite elements with a length more than two times the height of the element is not convenient in deriving the calculation results in the form of principal stresses.

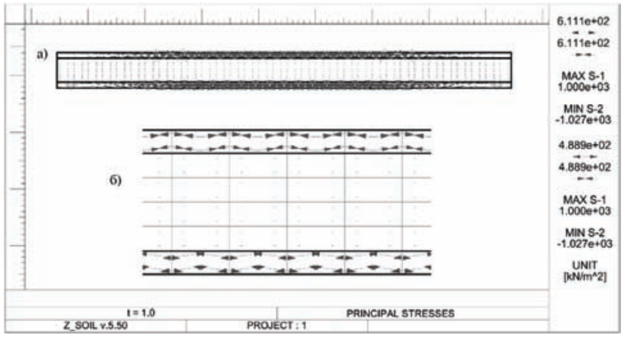


Figure 2. Pattern of the distribution of principal stresses in model 1
a) general diagram of the location of the principal stresses along the length of the beam;
b) enlarged fragment in the middle of the span

In the second model, the length of the rectangular finite elements is reduced to 0.05 m. Fig. 3 shows the main stresses in the middle of the beam model. With a decrease in the size of the final element by half, the overall picture of the stresses did not change, but the angle of inclination of the principal stresses decreased somewhat. Differences in stress level do not exceed 0.1% upwards.

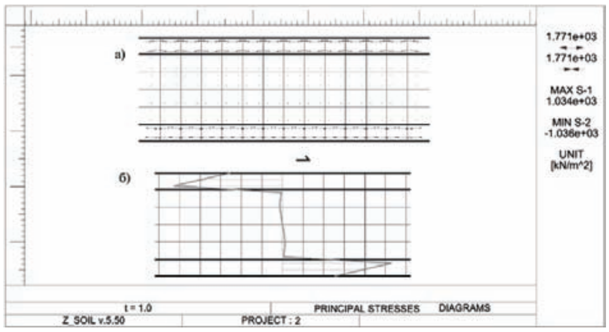
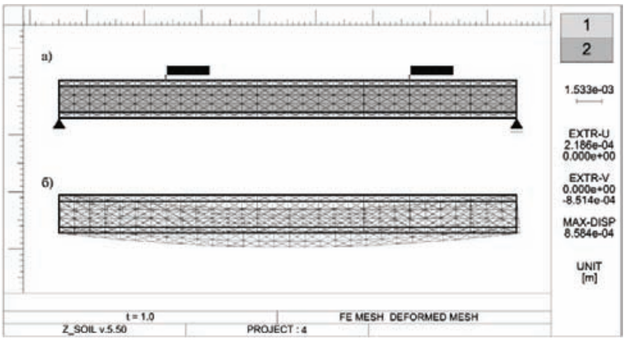
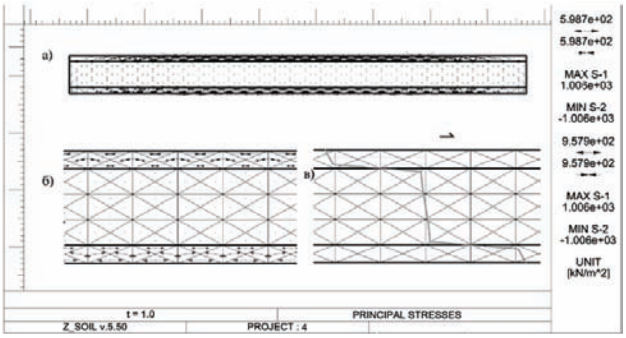


Figure 3. Stresses in the beam by model 2
a) enlarged fragment of the main stresses in the middle of the span;
b) diagram of normal stresses in the middle of the span

In the third model, the same construction is represented in the form of triangular finite elements (Figure 4), that is, each rectangular FE with a width of 0.1 m is replaced by four triangular elements, dividing it by diagonals. In this case, we obtain triangular FEs of two types-with the side of the parallel lines separating the layers (1a) and with the side perpendicular to these lines (1b).
The properties of the materials are taken from Table. 1. As the analysis shows (Fig. 4, Fig. 5), the transition to smaller triangular FEs clarifies the results downwards by about 1.3%. In this case, the diagram of normal stresses in the middle of the span of the beam completely corresponds to the experimental data.



<u>Figure 4.</u> FE model of beam with triangular grid
a) scheme for grid layout of FE model;
b) beam deformations



<u>Figure 5</u>. Stress distribution pattern in model 3
a) distribution of principal stresses along the length of the beam; b) enlarged fragment of principal stresses along the length of the beam; c) diagram of normal stresses in the middle section of the beam

The reliability of the model, when the beam is divided into triangular FEs, has a significant importance. Comparison of the calculation results with the experimental data on deflections, strain measurements along the direction of the main stresses in the middle of the span and on the landing areas gives a convergence in the range 95-97%.
In general, the analysis of the operation of the three-layer beam element model without longitudinal reinforcement shows that the bulk of the effort is assumed by the outer layers of the construction made of structural concrete, and in the middle layer of low strength concrete, the level of maximum stresses is lower by an average of 15 times. The destruction of the structure will occur starting with the outer layers, and on the average, a layer of internal destruction and excessive deformation is not observed.
In this research there is also well-considered issue, how the introduction into the stretched zone of the beam of longitudinal reinforcement will affect the operation of the layered structure. For this, in the middle of the height of the lower layer of the beam we arrange the reinforcement layer. In this case, for the possibility of comparing the results of the characteristics of reinforcement and concrete layers, we take as previous tests of beam samples [8] (Table 2).

<u>Table 2</u>

Construction layer	External	Internal
The size of rectangular elements, m	0,04×0,10 0,02×0,10	0,0425×0, 10
Prismatic strength of concrete R_b, MPa	21,0	1,01
Strength of concrete for tensile strength R_{bt}, MPa	1,75	0,28
Initial modulus of elasticity E0, MPa	12000	890
Poisson's ratio $\nu = 0.00189 \mid R_b \mid + 0.12$	0,16	0,122
The shear modulus $G = E_0 / 2 (1 + \nu)$, MPa	5172	397
Average density of concrete, kg / m3	1800	440
Modulus of elasticity of reinforcement, MPa	200000	

The reinforcement was adopted with a diameter of 8 mm in increments of 15 cm, the reinforcement percentage was 0.29%. The FE model grid and the results of the the loading of beam calculations are shown in Fig. 6 - 8.

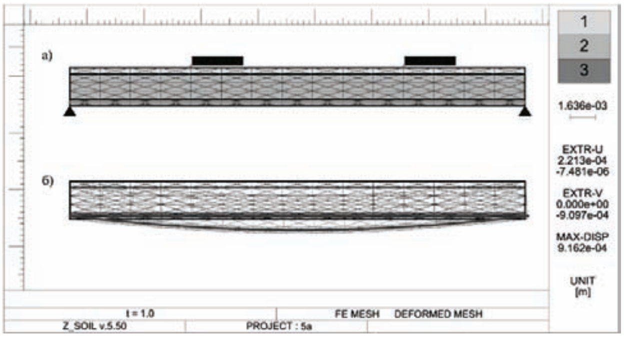


Figure 6. Model of a beam with longitudinal reinforcement
a) scheme of grid layout of the FE model 4;
b) deformation of the beam

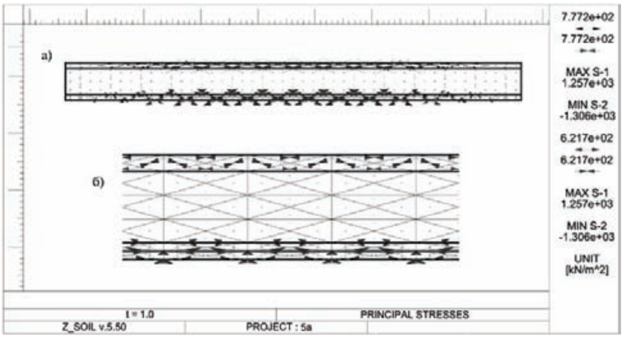


Figure 7. Pattern of the distribution of principal stresses in a model with longitudinal reinforcement: a) distribution of principal stresses in the model; b) enlarged fragment of principal stresses

As shown by the calculation results, the deflections of the models of beam samples (Fig. 6) correspond to the results of the tests with an accuracy of up to 96%, the deformations in the middle layer of the beam near the supports (Fig. 8b) are also close to those experienced at this stage of loading. The effect of reinforcement on the operation of such rigid beams at such a low percentage of reinforcement (0.29%) is very slight. The difference in the absolute values of the boundary compressive and tensile stresses in the considered models without reinforcement is from 0 to 0.3%, and in the reinforced sample this difference amounts to 3.75%.

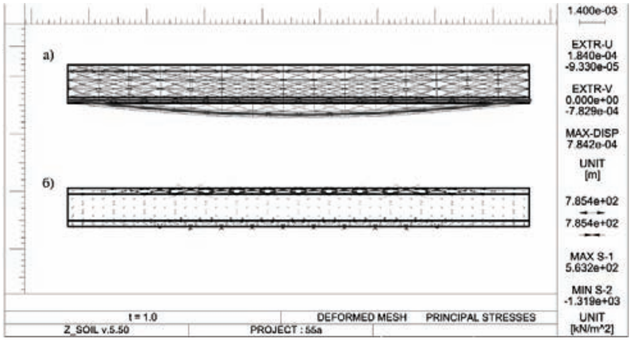


Figure 8. The field of distribution of the relative deformations of concrete in the beam of model 4
a) along the length of the beam; b) enlarged fragment near the support

In this study the following model of the effect of increasing the degree of reinforcement on the work of a three-layer structure was considered. With an increase in the percentage of reinforcement to 3% and a decrease in the strength of the concrete of the outer layers to the value indicated in Table. 1, the stress field in concrete changes and the reinforcement will have a significant effect on the design work (Figure 9). The main tensile stresses in the lower zone of the beams in the middle of the span are below the boundary compressive stresses by 57.3%.

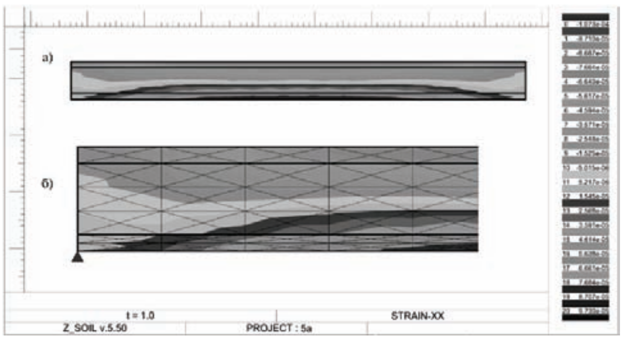


Figure 9. Beam model with an increased percentage of reinforcement
a) deformation of the beam; b) distribution of principal stresses

Comparison of the results of experimental studies of three-layer beam elements with their models developed with the help of the ZSOIL software complex showed that it is possible to reproduce with sufficient accuracy the modeling of the operation of a multilayer element using plane triangular cells with dimensions close to the thickness of the layers.

3. RESULTS

In the practice important means has studying the work of the slabs and attic overlaps of a three-layer structure with a monolithic bond of layers: a slab of a 6.0 m length and a thickness of 50 cm with external layers of structural concrete 8 and 4 cm thick and a medium layer of low strength concrete - 38 cm; minimum allowable reinforcement level of 0.05% (a reinforcement with a diameter of 8 mm step of 15 cm). The total calculated value of the uniformly distributed load from the roof mass and the temporary snow load is 2.2 kN / m^2.

The model with the bottom layer of concrete 8 cm thick is divided in height into two rows of FE - 2 cm and 6 cm, reinforcement is provided between layers 2 cm and 6 cm thick, was composed in this researching. Further, the middle layer of 38 cm thick is represented by three rows of FE with a height of 5.6 cm. The upper layer 4 cm thick is single-row. The length of the element is divided into 15 sections, i.e., the maximum length of the FE is 20 cm. The FEs are triangular (Fig. 9 and Fig.10).

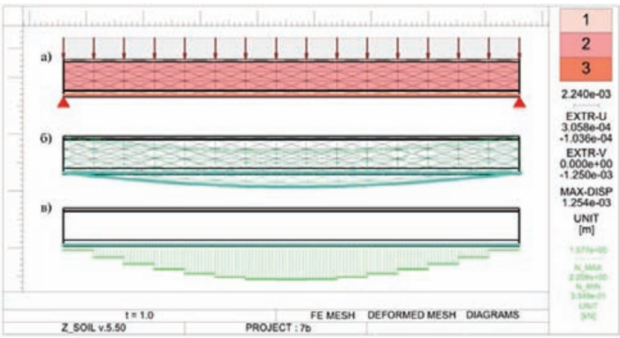


Figure 10. Model of a plate of a covering: a) scheme of splitting on final elements; b) deformation of the plate; c) diagram of the distribution of longitudinal forces in the reinforcement

Deflections, the pattern of distribution of principal stresses, the diagram of normal stresses and also the distribution fields of normal stresses and relative deformations of concrete are shown in Fig. 10 – 12. The maximum vertical deflection of the structure was 0.125 cm. As can be seen in Fig. 11, at such value of ratio of the layers thickness, the tensile force in the middle layer practically does not arise.

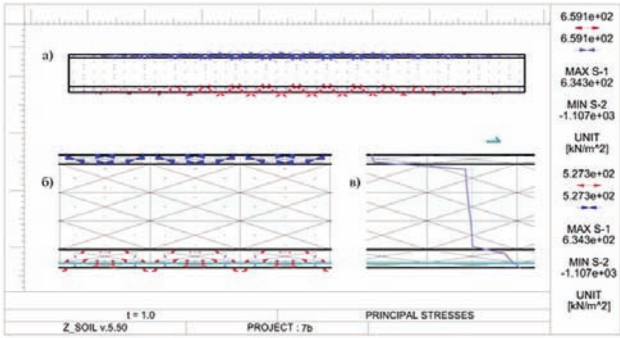


Figure 11. The pattern of stress distribution in the plate model: a) the main stresses along the length of the plate; b) enlarged fragment of principal stresses; c) diagram of normal stresses in the middle section of the plate

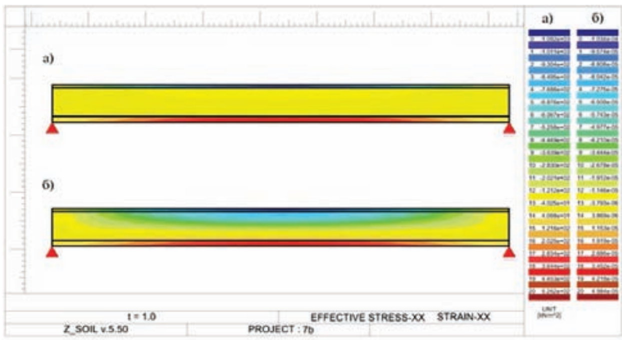


Figure 12. distribution of stresses and strains in the model plate: a) field distribution of normal stresses in the plate; b) field of distribution of the relative deformations

In addition, the cross section in the middle of the span of the plate was considered. In the 5 upper triangular cells of the cross-section 1, normal compressive stresses of the level of 0.086-0.012 MPa (at Rb = 1.15 MPa) act in the middle of the slab of the structural concrete layer; and only in the lower FE there is an insignificant stretching of 0.022 MPa (at Rbt = 0.35 MPa). Such a distribution of efforts will positively affect the reliability of the work of such a design. Efforts in the outer layers of the plate are as follows: in the stretched zone 0.259-0.526 MPa (at Rbt = 1.02 MPa); in the compressed zone 0,96 - 1,1 MPa (at Rb = 10,1 MPa).

The stress diagram for the reinforcement, shown in Fig. 10, shows that the effect of reinforcement due to the rigidity of the structure is insignificant, since at the design load the ratio of the maximum force in the armature (2.2 kN) to the design (18.34 kN) is 12%.

As the calculation of the design model with the dimensions of the offered full-scale plates has shown, the concrete of the middle layer of such boards will experience compressive stresses of 85% of the thickness that do not exceed 8% of the prismatic strength of concrete, while the remaining part exhibits insignificant tensile stresses that do not exceed 6% of the tensile strength of the concrete.

4. CONCLUSIONS

The well convergence of the experimental and calculated results makes it possible to recommend considering the stress-strain state of large-sized layered slabs with different thicknesses of monolithically bonded layers at different reinforcement levels and loading levels on the recommended finite element models.

The use of modern calculating software on the basis of the finite element method (FE) makes it possible to simulate the stress-strain state of a reinforced layered structure with monolithically bonded layers. It is recommended to use flat triangular cells with dimensions close to the thickness of the layers.

The analysis of the operation of three-layer beam structures shows that the middle layer of low-strength concrete undergoes insignificant stresses, which are close to the operational ones, 5-10% of the design tensile strength of concrete, which confirms the rational layout of the section from the point of view of the stress-strain state, These researches with application of a computer modeling method allow to vary in a wide range by changing the design parameters (thickness of layers, strength properties of concrete, types of reinforcement and the degree of reinforcement) and, ultimately, to choose a rational design solution.

REFERENCES

1. **Andreev V.I., Barmenkova E.V., Matveeva A.V.** The Stress State in Inhomogeneous Elastic Beam at Combined Strength // Applied Mechanics and Materials. 2014. Vols. 501-504. pp. 645-648.
2. **Andreev V.I., Barmenkova E.V**. The modeling of the real building objects by using the model of a two-layer beam of variable rigidity on an elastic basis // Applied Mechanics and Materials. 2012. Vols. 204-208. pp. 3596-3599.
3. **Vladimir I. Andreev, Robert A.** Turusov, Nikita Yu. Tsybin Application of the Contact Layer in the Solution of the Problem of Bending the Multilayer Beam // Procedia Engineering, Volume 153, 2016, Pages 59-65.
4. **Vladimir I. Andreev, Elena V. Barmenkova, Ivan A. Potekhin.** Way of Optimization of Stress State of Elements of Concrete Structures. Procedia Engineering, Volume 153, 2016, Pages 37-44.
5. **Vladimir Andreev, Robert Turusov and Nikita Tsybin.** The edge effects in layered beams //FORM 2018 IOP Conf. Series: Materials Science and Engineering 365 (2018) 042049
6. **Andreev V.I., Turusov R.A.** The contact layer method in the problem of bending of a multilayer beam. Fourier series solution: 2nd International Conference on Mechanics, Materials and Structural Engineering (ICMMSE 2017).
7. **Elena Korol, Vu Dinh Tho and Yuliya Kustikova**. Model of stressed-strained state of multi-layered reinforced concrete struc-

ture with the use of composite reinforcement IOP Conference Series: Materials Science and Engineering, Volume 365, Reliability Of Buildings And Constructions.
8. **Korol E.A.** Three-layer enclosing reinforced concrete structures made of lightweight concrete and features of their calculation. M., ASV, (2001)
9. **Bujnak I., Korol E. A., Latushkin V. E.** Design model from three-layer composite reinforcement of reinforced concrete structures. Communication, T. 14, № 1, P. 101-105 (2012)
10. **Korol E. A. and Kharkin Yu. A.** To the question of choosing a software package for modeling the stress-strain state of three-layer reinforced concrete elements and structures with a monolithic bond of layers. Scientific and technical journal on construction and architecture (The Bulletin of MGSU). № 3. p156-163 (2010)
11. **Korol E. A., Pugach E. M. and Kharkin-ua A.** The influence of technological factors on the formation of communication layers of multi-layered enclosing structures. Scientific and technical journal on construction and architecture (The Bulletin of MGSU). № 3. p67-75 (2014)
12. **Korol E.A.** Deformation model for calculating three-layer reinforced concrete elements. News of higher educational institutions. Bulletin of MGSU. № 5. p11 (2004).
13. **Korol E.A.** and Kharkin Yu. A. Investigation of stress-strain state of three-layer reinforced concrete elements and monolithic section constructions by computer simulation Bulletin of MGSU. 117-120 (2010)
14. **Korol E.A.** Analysis the operating conditions of the polystyrene in the middle of three layer structures // Loaf. No 2.- P. 5-7 (2000)

СПИСОК ЛИТЕРАТУРЫ

1. **Andreev V.I., Barmenkova E.V., Matveeva A.V.** The Stress State in Inhomogeneous Elastic Beam at Combined Strength // Applied Mechanics and Materials. 2014. Vols. 501-504. pp. 645-648.
2. **Andreev V.I., Barmenkova E.V**. The modeling of the real building objects by using the model of a two-layer beam of variable rigidity on an elastic basis // Applied Mechanics and Materials. 2012. Vols. 204-208. pp. 3596-3599.
3. **Vladimir I. Andreev, Robert A.** Turusov, Nikita Yu. Tsybin Application of the Contact Layer in the Solution of the Problem of Bending the Multilayer Beam // Procedia Engineering, Volume 153, 2016, Pages 59-65.
4. **Vladimir I. Andreev, Elena V. Barmenkova, Ivan A. Potekhin.** Way of Optimization of Stress State of Elements of Concrete Structures. Procedia Engineering, Volume 153, 2016, Pages 37-44.
5. **Vladimir Andreev, Robert Turusov and Nikita Tsybin.** The edge effects in layered beams //FORM 2018 IOP Conf. Series: Materials Science and Engineering 365 (2018) 042049
6. **Andreev V.I., Turusov R.A.** The contact layer method in the problem of bending of a multilayer beam. Fourier series solution: 2nd International Conference on Mechanics, Materials and Structural Engineering (ICMMSE 2017).
7. **Elena Korol, Vu Dinh Tho and Yuliya Kustikova**. Model of stressed-strained state of multi-layered reinforced concrete structure with the use of composite reinforcement IOP Conference Series: Materials Science and Engineering, Volume 365, Reliability Of Buildings And Constructions.
8. **Korol E.A.** Three-layer enclosing reinforced concrete structures made of lightweight concrete and features of their calculation. M., ASV, (2001)
9. **Bujnak I., Korol E. A., Latushkin V. E.** Design model from three-layer composite reinforcement of reinforced concrete structures. Communication, T. 14, № 1, P. 101-105 (2012)

10. **Korol E. A. and Kharkin Yu. A.** To the question of choosing a software package for modeling the stress-strain state of three-layer reinforced concrete elements and structures with a monolithic bond of layers. Scientific and technical journal on construction and architecture (The Bulletin of MGSU). № 3. p156-163 (2010)
11. **Korol E. A., Pugach E. M. and Kharkin-ua A.** The influence of technological factors on the formation of communication layers of multi-layered enclosing structures. Scientific and technical journal on construction and architecture (The Bulletin of MGSU). № 3. p67-75 (2014)
12. **Korol E.A.** Deformation model for calculating three-layer reinforced concrete elements. News of higher educational institutions. Bulletin of MGSU. № 5. p11 (2004).
13. **Korol E.A.** and Kharkin Yu. A. Investigation of stress-strain state of three-layer reinforced concrete elements and monolithic section constructions by computer simulation Bulletin of MGSU. 117-120 (2010)
14. **Korol E.A.** Analysis the operating conditions of the polystyrene in the middle of three layer structures // Loaf. No 2.- P. 5-7 (2000)

Elena A. Korol – Doctor of Technical Sciences, Professor, Head of the Department of Housing and Communal Utility; Moscow State University of Civil Engineering (National Research University) (MGSU); 26 Yaroslavskoe shosse, Moscow, 129337, Russian Federation; professorkorol@mail.ru.

Kustikova Yulia Olegovna – Candidate of Technical Sciences, Associate Professor, Associate Professor of the Department of Housing and Communal Complex, National Research Moscow State University of Civil Engineering (National Research University MGSU); 26 Yaroslavskoe shosse, Moscow, e-mail: KustukovaYO@mgsu.ru, 8(926)179-20-74.

Елена Анатольевна Король – доктор технических наук, профессор, заведующая кафедрой жилищно-коммунального комплекса; Национальный исследовательский Московский государственный строительный университет (НИУ МГСУ); 129337, г. Москва, Ярославское шоссе, д. 26; professorkorol@mail.ru.

Кустикова Юлия Олеговна – кандидат технических наук, доцент, доцент кафедры Жилищно-коммунальный комплекс, Национальный исследовательский Московский государственный строительный университет (НИУ МГСУ) ; 129337, г. Москва, Ярославское шоссе, д. 26; e-mail: KustukovaYO@mgsu.ru, 8(926)179-20-74.