Self-stressed steel-reinforced concrete floor slab stress-strain state numerical analysis taking into account the concreting stages

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Abstract. In steel-reinforced concrete floor slabs, structurally ensuring the joint operation of monolithic reinforced concrete slab and steel crossbars, a successful combination of its components positive qualities is realized at a high level: compression forces are perceived by monolithic slab, and tensile forces by steel beams. Reinforced concrete slabs in such structures have a relatively equal weight with a payload on interfloor slabs for public buildings. Having effectively developed the sequence of concreting the slab through the span in two stages, it is possible to create pre-stressing in the floor steel crossbars, located in the spans of the second concreting stage, and in monolithic reinforced concrete slab of the first concreting stage. In this sense, the term "self-stressed" is used in this work. By creating pre-stresses in the steel crossbars of the floor, it is possible to reduce their cross-section or to increase their span and to achieve savings in metal costs on the building frame. Pre-stressing of the monolithic reinforced concrete slab of the first concreting stage in the opposite to operational bending form, will increase crack resistance of the specified sites of a monolithic overlapping and will give the chance to reduce its reinforcement.

1. Introduction
Born as a building structure about a century ago, steel-concrete structure has recently become more widely used in various fields of construction, proof of which is the development of relevant regulations. Steel-concrete structures are made by a successful combination of steel, mainly rod elements and monolithic concrete. In some cases, to increase the overall load-bearing capacity of the combined cross section, flexible or rigid reinforcement rods are inserted into monolithic concrete, especially in the case of monolithic reinforced concrete beyond rigid reinforcement (for example, in steel-reinforced concrete floor slab). The number and cross section of such reinforcement is selected by a separate calculation only for the reinforced concrete floor slab [19].

In steel-reinforced concrete floor slabs (see figure 1), structurally ensuring the joint operation of monolithic reinforced concrete slab and steel crossbars, a successful combination of its components positive qualities is realized at a high level: compression efforts are perceived by monolithic reinforced concrete, and tensile efforts - by steel beams [8]. The high level of reliability, durability and resource saving during the construction and operation of such floor slabs is confirmed by the significant volume of its installation for both public and industrial buildings [13]. Quite often, to increase the manufacturability of such floor slab installation, a monolithic reinforced concrete slab is arranged on a fixed formwork from profiled flooring [6].

Monolithic reinforced concrete floor slabs in steel-reinforced concrete floor slabs have a relatively equal weight with a payload on interfloor slabs for public and civil buildings [15]. Having effectively developed the sequence of concreting the slab through the span in two stages, it is possible to create prestressing in the floor steel crossbars, located in the spans of the second concreting stage, and in monolithic reinforced concrete slab of the first concreting stage. In this sense, the term "self-stressed" is used in this work.
2. Analysis of recent research and publications

Based on the results of research in recent decades, today steel-reinforced concrete elements that work on the bend are calculated using an analytical apparatus for calculating similar reinforced concrete elements [3; 7; 9]. This analytical apparatus is based on the deformation method taking into account complete nonlinear real diagrams of material deformation [2]. The essence of the adaptation of reinforced concrete structures working on the bend calculation method, to the calculation of similar reinforced concrete elements is as follows [16]. The steel part of the calculated cross section is divided into separate "strips". Within the height of these "strips" stresses are considered constant, and the deformations distribution in the height of the steel element - according to a linear law. This approach allows you to depict a steel-reinforced concrete beam as a reinforced concrete with multi-row external reinforcement. Comparison of experimental and theoretical values of steel-concrete beams bearing capacity allows us to conclude that the considered analytical apparatus for calculating bending steel-reinforced concrete elements, fairly accurately assesses their stress-strain state and bearing capacity.

However, in most experimental and theoretical studies in this direction, the definition of parameters that characterize the initial (before inclusion in the joint work of the combined section) state - the initial deformations and stresses of both steel beams and monolithic concrete in steel-concrete floor slab, was not given due attention [1]. Therefore, the analysis of their influence on the overall stress-strain state of the structure is difficult. It is assumed that ignoring the initial conditions provides a margin of 10%. The calculated analytical apparatus, the essence of which is given above, take into account the initial conditions, such as pre-stresses and deformations of steel reinforcement [16].

A linear approach to taking into account the initial state of the elements of the composite floor slab can give errors that can lead to the destruction of the structure or, conversely, the design of structures with a large margin of safety [17]. Therefore, the application of such a linear approach, despite its simplicity and availability in terms of a relatively small amount of knowledge and skills to use it, is unjustified. An accurate study of the above problem requires nonlinear analysis [4]. This analysis takes into account nonlinear effects, such as nonlinear material properties [5], contacts, large deformations [10], loading history [18], etc.

For the preliminary analysis of the real stress-strain state taking into account the stage loading of the steel-reinforced concrete floor slab, was used the software package Femap 2020.2 with NX Nastran Trial Version Siemens Digital Industries Software with personal activation code 2827301401535961. This finite element analysis program has proven its reliability, accuracy, and speed many times over the course of about fifty years [14]. Due to a widely developed set of output parameters, this program is used by engineers in various fields of technology, in particular in mechanical engineering, construction, electro mechanics, thermodynamics and others. To solve the most complex nonlinear problems, including if you need to take into account the history of loading the structure, the Femap software package has a module of multi-step nonlinear solutions Multistep Nonlinear (SOL401 / SOL402) [11].
3. Formulating of the article’s goals
The aim of the article is to consider the algorithms of finite element modelling using computer software for the stages of two different materials inclusion in the work during the analysis of the stress-strain state of self-stressed steel-reinforced concrete floor slab at the stage of taking into account the stages of concreting monolithic reinforced concrete slab.

4. Description of the research problem
The object of research is a steel-reinforced concrete floor slab, arranged according to a three-span continuous scheme (see figure 2), the construction of which is shown in figure 1.

The subject of research is a distribution of stresses and strains along the height of the combined cross section of steel-reinforced concrete floor slab during two-stage concreting of a monolithic slab and, accordingly, its two-stage inclusion in the work.

As indicated in the introduction to this work, the own weight of steel-reinforced concrete floor slab is approximately equal to the payload on floor slabs in residential and public buildings. Therefore, during the construction of the building before its exploitation in the cross sections of steel-reinforced concrete floor slabs from its own weight will be quite significant stresses. Their level can reach 30...50% of the maximum design stresses. The authors propose to use this effect to create favourable pre-stressing components of steel-reinforced concrete floor slabs.

Creation of preliminary stresses is offered to realize by the following sequence of slab concreting in two stages. At the first stage concreting through span is carried out. That is, for the considered three-span scheme of floor slab – two extreme spans (see figure 2, a). At this stage, the steel beams of the extreme spans (spans of the first stage of concreting) are bent down from the weight of the freshly laid concrete mixture. In this position there is a setting (transformation) of the concrete mixture into a monolithic concrete stone. That is, the monolithic concrete floor slab in these spans has an initial negative bending, which repeats the bending of steel beams in these spans. The stress in the concrete at this level is zero. Steel beams in spans without concrete mix (for the considered three span scheme – average span) due to the inseparable scheme of work beams are bent upwards, then the preliminary self-stressed is created in them.

After setting the design strength by the concrete of the first stage of concreting, the second stage of concreting for other spans is performed. For the considered three-span scheme of floor slab – the average span (see figure 2, b). At this stage, the steel beam of the middle span (span of the second stage of concreting) bends down from the weight of the freshly laid concrete mixture. However, due to the inseparable scheme of beams and inclusion in the work the concrete shelves extreme spans the first stage of concreting, the beam deflection in the middle span is less than the deflections of the beams in the extreme spans. Thus, the effect of steel beams self-tension begins to be shown. Beams of the extreme spans (spans of the first stage of concreting) in the second stage of concreting begin to bend upwards towards the initial position. Thus, the concrete in these areas is stretched, which creates a preliminary self-stress.

By creating pre-stresses in the steel crossbars of the floor slab in the areas of the second stage of concreting, it is possible to reduce the cross-section of the latter and achieve savings in metal costs on the building frame. Another option for using the increased bearing capacity of pre-stressed crossbars is to increase their span. That is, to design the location of columns with a variable step through the span. Then the cost of metal on the building frame is saved by reducing the number of columns. Pre-stressing of the monolithic reinforced concrete slab of the first stage of concreting in the form of opposite to operational bending, will increase crack resistance of a monolithic floor slab specified sites and will give the chance to reduce its reinforcement.

Figure 2, c shows a deformed view of the steel-reinforced concrete floor slab in the operating position. Also, in figure 2 for clarity of the above statements about the creation of pre-tension of the steel-reinforced concrete floor slab elements, shows the expected plots of stress distribution in the corresponding sections at each stage of concreting.
5. Ways to solve the problem
The presence of pre-operational stresses in the components of the composite reinforced concrete floor with the simultaneous absence of stresses in other components during the finite element analysis in the software package Femap 2020.2 with NX Nastran may be considered in different ways. These include:
- initial tension (stress) of the steel floor beam (similar to the previous tension of bolted joints – Bolt Preload);
• loading of the composite reinforced concrete structure with the initial data (Output Load) of the preliminary calculations of the steel floor beams;
• installation of a preliminary gap between steel and concrete parts (Initial Gap);
• temperature effects on monolithic reinforced concrete in order to reduce to zero stresses in it at the time of concrete setting (Temperature Load);
• taking into account the stages of two materials (steel and concrete) inclusion in the work with the module of multi-step nonlinear solutions (Multistep Nonlinear).

The following is a brief overview, advantages and disadvantages of the above ways to solve the problem, some of which are quite cumbersome when creating a finite element model and may give calculation errors.

During bending of steel beams of floor from weight of a monolithic reinforced concrete plate, distribution of stresses on height of their section is uneven (see figure 2). For example, when the beam is bent down, the lower fibers are stretched and the upper ones are compressed. Therefore, to set the correct pre-tension of the Bolt Preload type, it is necessary to divide the steel cross-section into strips within which the stresses will be considered constant (see figure 3). This procedure leads to an unjustified increase in the time to create these bands, determine and set the pre-stresses in them, as well as to a significant increase in the number of finite elements of the steel beam model.

When loading the composite reinforced concrete structure with the initial data of the preliminary calculations of the steel floor beams, the concrete part of the structure is immediately included in the work (see figure 4). This process is not true, as in the concrete part of the section at the time of concrete set design strength until the next stage of concreting or other external load, no stress. This disadvantage is also present for the first of the above ways to solve the problem (pre-stress of the steel beam).

Since during bending of steel beams under the action of evenly distributed load from freshly laid concrete mixture their maximum deflection occurs in the middle of the span, and on the supports vertical displacements are zero (see figure 5), the establishment of an initial gap between concrete and steel parts of the composite structure is also time consuming. In this case, it is necessary to divide the beam along the length of the span into an infinite number of sections within which the deflections will be considered constant.

Setting different temperatures along the length of the concrete shelf in order to obtain temperature stresses in it, which would reset the stress at the time of the concrete mixture setting, is also time consuming. This is due to the different values of the bending moment and, consequently, the different level of stresses along the length of the beam axis. Therefore, it is necessary to divide the beam along
the length of the span into an infinite number of sections within which the bending moment will be considered constant. With the help of the last two ways to solve this problem, it is possible to achieve zero stresses in the concrete shelf with a stress-strain steel part of the composite structure.

The module of multistep nonlinear solutions Multistep Nonlinear gives the chance to create subcases of calculation by means of which materials of a composite design will be included in work at various necessary for the user stages of the investigated construction work.

6. Conclusion

Using the proposed two-stage technology of concreting a monolithic slab of steel-reinforced concrete floor structure by creating self-pre-stressed in the steel crossbars of the steel-reinforced concrete floor, it is possible to reduce their cross-section or to increase their span and to achieve savings in metal costs on the building frame. Pre-stressing of the monolithic reinforced concrete slab of the first concreting stage in the opposite to operational bending form, will increase crack resistance of the specified sites of a monolithic overlapping and will give the chance to reduce its reinforcement.

It is recommended to use the module of multi-step nonlinear solutions Multistep Nonlinear in Femap 2020.2 with NX Nastran to model by the method of finite elements of the stage of a monolithic concrete shelf inclusion in the work of steel-reinforced concrete floor slab, as in this case it is necessary to spend the least resources.

7. References

[1] Ametov U G 2014 Some aspects of the calculation of combined joints of steel-concrete composite structures Academic journal. Industrial Machine Building, Civil Engineering (Ukraine, Poltava: PolntTU) №3 (42) book 1
[2] Azizov T, Kochkarev D and Galinska T 2020 Reinforced concrete rod elements stiffness considering concrete nonlinear properties Lecture Notes in Civil Engineering (London: Chapman and Hall) volume 47 pp 1–6 https://doi.org/10.1007/978-3-030-27011-7_1
[3] Bachinsky V Ya, Bambura A N, Vatagin S S and Zhuravlyova N V 1985 Methodical recommendations for determining the parameters of the diagram "σ-ε" of concrete during short-term compression (Ukraine, Kiev) p. 15
[4] Basic Nonlinear Analysis User’s Guide 2014 (Siemens Industry Software) p. 144
[5] Bolotov A U and Karpenko A A 2017 Calculation of buildings of social housing by a deformation method based on time factor with using transformed diagram of concrete deformation Construction, materials science, mechanical engineering (Ukraine, Dnipro: PSACEA) No 99 pp 35–43
[6] Cherednikov V, Voskobinyk O and Cherednikova O 2017 Evaluation of the warping model for analysis of polystyrene concrete slabs with profiled steel sheeting Periodica Polytechnica Civil Engineering (Hungary: Budapest University of Technology and Economics) volume 61(3) pp 483–490
[7] Gasii G, Hasii O and Klimenko V 2020 Testing of the combined structural elements of support of a mine opening In E3S Web of Conferences (France, Les Ulis Cedex A) volume 168 00028
[8] Hudz S, Storozhenko L, Gasii G and Hasii O 2020 Features of operation and design of steel sloping roof purlin Proceedings of the 2nd International Conference on Building Innovations. ICBI 2019. Lecture Notes in Civil Engineering (Springer, Cham) volume 73 pp 65–73 https://doi.org/10.1007/978-3-030-42939-3_8
[9] Lazariev D, Avramenko Y, Zyma O and Pasichnyk P 2020 Experimental researches of concrete ultimate characteristics and strength of compressed and bended reinforced concrete elements Lecture Notes in Civil Engineering (Springer, Cham) volume 73 pp 133–141
[10] Liang K, Ruess M and Abdalla M 2016 An eigenanalysis-based bifurcation indicator proposed in the framework of a reduced-order modeling technique for non-linear structural analysis International Journal of Non-Linear Mechanics (Elsevier) volume 81 pp 129–138 doi:
10.1016/j.ijnonlinmec.2016.01.013

[11] Multi-Step Nonlinear User’s Guide (SOL 401 and SOL 402) 2018 (Siemens Industry Software) p. 292

[12] Pavlikov A M, Mykytenko S M and Hasenko A V 2018 Effective structural system for the construction of affordable housing International Journal of Engineering & Technology: Publisher of International Academic Journals: Science Publishing Corporation, RAK Free Trade Zone 7 (UAE, Al Mamourah Area) No 3.2 pp 291–298 doi:10.14419/ijet.v7i3.2.14422

[13] Pavlikov A, Harkava O, Prykhodko Y and Baryliak B 2019 Highly constructed precast flat slab frame structural system of buildings and research of its slabs Proceedings of the International fib Symposium on Conceptual Design of Structures (Torroja Institute, Madrid, Spain) volume pp 493–499

[14] Rudakov K N 2011 Femap 10.2.0. Geometric and finite element modeling of structures (Ukraine, Kiev: Igor Sikorsky Kyiv Polytechnic Institute) p. 317

[15] Semko O V, Hasenko A V, Kryuchenko V A and Sirobaba V O 2020 The rational parameters of the civil building steel frame with struts Proceedings of the 2nd International Conference on Building Innovations – Part of the Lecture Notes in Civil Engineering book series (LNCE) volume 73 pp 235–243

[16] Storozhenko L I, Semko O V and Pents V F 2005 Steel-reinforced concrete constrictions (Tutorial) (Poltava: PoliNTU) p 181

[17] Su Y Y and Gao X L 2014 Analytical model for adhesively bonded composite panel-flange joints based on the Timoshenko beam theory Composite Structures (Elsevier) vol 107 pp 112–118

[18] Titarenko F 2020 Simple about nonlinear finite element analysis Nanosoft blog (Electronic Materials)

[19] Vatulia G L, Lobiat O V, Deryzemlia S V, Verevicheva M A and Orel Y F 2019 Rationalization of cross-sections of the composite reinforced concrete span structure of bridges with a monolithic reinforced concrete roadway slab IOP Conference Series: Materials Science and Engineering (Bulgaria, Sozopol) volume 664 10 012014