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Stress-strain state of precast and cast-in place buildings

Напряжённо-деформированное состояние сборно-монолитного здания

A.A. Koyankin,
Siberian Federal University, Krasnoyarsk, Russia
V.M. Mitasov,
Novosibirsk State University of Architecture and Construction, Novosibirsk-8, Russia

Канд. техн. наук, доцент А.А. Коянкин,
Сибирский федеральный университет, г. Красноярск, Россия
д-р техн. наук, профессор В.М. Митасов,
Новосибирский государственный архитектурно-строительный университет, г. Новосибирск-8, Россия

Key words: life cycle; reinforced concrete structures; precast with cast-in place construction; genetic nonlinearity; phasing approach of assembling; phasing of the force application

Ключевые слова: жизненный цикл; железобетонные конструкции; сборно-монолитные конструкции; генетическая нелинейность; поэтапность монтажа; поэтапность приложения нагрузки

Abstract. Based on the stages of the construction period of the life cycle of the building, the authors examined the influence of gradual inclusion in the work, including the editing process, its individual building elements on the stress-strain state of a building and its individual design. Determined the nuances of the existence of the building (a separate structure), which should be taken into account at the design stage. These nuances are present in the real structure, but cannot be determined for calculations in the classical way (without changing the stress-strain state in process of erection and loading). Conducted numerical studies of the stress-strain state of a flat frame made from collapsible-monolithic reinforced concrete with account of the phased construction. Also fulfilled a comparative analysis of the obtained results with data of calculation of the same frame, but not taking into account phasing of construction of the structure.

Аннотация. Авторами статьи, исходя из этапов периода строительства жизненного цикла здания, рассмотрено влияние поэтапности включения в работу, в том числе в процессе монтажа, отдельных его элементов на напряжённо-деформированное состояние, как здания, так и отдельной его конструкции. Определены нюансы существования здания (отдельной конструкции), которые должны учитываться на стадии проектирования, присутствуют в реальном сооружении, но не могут быть определены при выполнении расчётов классическим способом (без учёта изменения напряжённо-деформированного состояния по мере возведения и нагружения). Проведены численные исследования напряжённо-деформированного состояния плоского каркаса из сборно-монолитного железобетона с учётом поэтапности возведения, а также выполнен сравнительный анализ полученных результатов с данными расчёта аналогичного каркаса, но не учитывающего этапность возведения.

Introduction

Modern building has reached a high level of development. Engineers are ready to offer to customer buildings of any form and size, including almost of one kilometer height [1–4]. There is a wide range of building materials for carcass construction and it’s finishing. The choice of these materials is defined by functional and constructive details of the building being erecting and by geographic and hydrogeological location of the construction site. The main types of materials used for load-carrying frame erection [5–10, 26], are reinforced concrete, metal, wood and stone. They can be classified basing on a technology of manufacturing used: cast-in place, precast and precast with cast-in-place reinforced concrete structures; rolled metal products and light steel thin-walled structures; solid wood and laminated wood structures; brick, blocks (various types) etc.

Construction design of buildings (foundations, columns, walls, slabs etc.), and also the constructive system developed from them (carcass, wall, mixed), combined with building materials used for their erection throughout the life cycle of the building, including the period of construction, experience different conditions, separated from each other by the appearing of a new factor. This leads to a quality change of

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stress-deformed state, as a separate construction, and the entire building as well. We define these states as “stage of the life cycle”. To these factors are referred: occurrence of additional, principally different from other forces; change of the structural design; change of mechanical-and-physical properties etc. We point out that the definition “stage of the life cycle” can be applied to a separate construction and the building in general as well.

It should be noted, there are not many works that are devoted to influence of the previous existence of the stress-deformed state at various “stage of the life cycles” on the stress-deformed state of building and/or separate structure. However, there is the conclusion about the impact on the stress-deformed state of construction of the earlier stages of its existence from already carried out works. In particular, Professor Perel'muter indicated in [11] “Most of the action done during assembly, leads to changes of the design scheme and/or the stress and deformed state of the system”. This fact was successfully confirmed in number of other scientific papers. In particular in [12, 13] devoted to the reinforcement of building structures under load. Within the individual element (beam), the impact of the stress-deformed state of construction in the previous stage to the stress-deformed state the subsequent stage has been shown not only numerically, but also experimentally. The authors of the works [14, 15] present the results of calculations (in linear statement) structures of buildings, qualitative difference evident between calculations made according to traditional methods. The methods corresponds to finished state of the object, and calculations carried out taking into account the phasing of construction of the building. Based on the calculations (flat bar system, a linear formulation of the problem), in [16–18] shows discrepancies in the efforts of the elements when performing calculations with and without allowance for the assembly process. On this basis, conclusions were made about the necessity of taking into account the stage of construction of the building when performing the structural design. Some foreign scientists [19–25] also conducted studies, which confirmed the necessity of taking into account the phased assembly of building structures when performing the calculation of load-bearing structures of the building.

As an example of time phasing for “the stages of the construction period of the life cycle” of a separate construction existence we consider a single-bay precast with cast-in-place two-story frame, with the following stages of construction:

1. Assembling of 1-st floor columns;
2. Assembling by use of a temporary conductors, unit beams of 1-st floor (pinned connection);
3. Post stressed reinforcement fixing on unit beams of the 1-st floor. Laying of high-tensile reinforcement on according channels of assembled part with its post tensioning “on concrete”. Unit beam is still pinned on the columns, but with tight clamping its ends by vertical lead-carrying elements. Additional load – force of clamping at the level of unit beams of 1-st floor;
4. Assembling of 2-nd floor columns;
5. Assembling by use of temporary conductors of 2-nd floor unit beams (pinned connection);
6. Stressed reinforcement fixing on 2-nd floor unit beams, similarly as in the 1-st floor beam. Additional load – force of prestressing clamping at the level of 2-nd floor unit beam.
7. Fixing of slab unit elements (slab-casing) and laying of cast-in-place concrete of 1-st and 2-nd floor. At this phase freshly placed cast-in-place concrete has not yet gained the required resistibility and, accordingly, as the load-carrying element is not considered. Unit beam pinned on the columns with tight clamping of the ends. Additional load – weight of built-up construction and weight of cast-in-place concrete.
8. Gaining of the required strength by the cast-in-place concrete. Cast-in-place concrete has gained strength, but until the moment additional force application, is unloaded and no tension occurs from external loads. Structural design of precast with cast-in-place beam does not change, and it becomes rigidly restrained beam;
9. Additional assembling load application (floor construction weight, dividing walls, load-bearing walls) and operation load on the slabs of 1-st and 2-nd floors.

Similarly there is a division into stages and other periods (exploitation, reconstruction, repair, dismantling, etc.) life cycle of the building.

Consideration of the existence of the building based on individual stages from different periods of the life cycle and including them in the design allows:

– to define the real stress deformed state (separate construction) at each stage of its life considering tension and deformation, occurred earlier. In practice [11] the professor Perelmunter A.V., using the definition “genetic nonlinearity”, clearly demonstrated a significant influence of assembly staging on stress deformed state of the building frame;

– to estimate the sufficiency of the load carrying ability, strength and crack resistance of a building (a separate construction) at each separate cycle considering phase by phase accumulated tensions and deformations;

– to use effectively the possibility of building constructions and developing from them at the stage of building systems erection with the purpose of labor and financial expenses minimization for construction, and also reducing the construction period. This effect is achieved by reducing the quantity of casing, reinforcement (more effective location considering the assembling), lack of necessity of waiting for required strength development of cast-in-place concrete of the lower floors for the assembling of the higher floors (common for hybrid precast/cast-in-place building) etc.;

– to regulate stress deformed state of the building (a separate construction) by means of assembling phasing, sequence of loading of erected constructions, change of structural design during strength development etc., that is addition to already known force regulators (reinforcement and its preliminary tension, prior arranged cracks).

Based on the above arguments and taking into account the earlier research [11–21] of various foreign and domestic scientists, the authors of this article defined the goal of studying the impact of the construction period of the life cycle of the building in its stress-deformed state. To achieve this goal have been formulated the following tasks, including: numerical study of a flat frame precast and cast-in place structure, carried out with and without taking into account the phased process of construction; analysis the stress-deformed state precast and cast-in place structure; analysis of phased "viability" of the frame construction for the possibility of perception of current loads.

Methods

The numerical investigations (taking into account the physical nonlinearity) were carried using the software package "Lira” out of the model above mentioned plane frame of precast and cast in place casing including (Figure 1): built-up column of cross-section 100x100 mm (concrete cl. B25) and precast and cast-in-place beams. Which are consisting from assembled part of cross-section 100x100(h) mm (concrete cl.B25) and cast-in-place part of cross-section 100x60(h) mm (concrete cl. B15). For allowance of work nonlinearity of the concrete and reinforcement, bi- and trilinear diagrams of deformation have been used, put to Russian Set of Rules SP 63.13330.2012. Calculations were performed in the following variants: with division for phasing of the construction according to above mentioned algorithm (P-1) and without division for stages of assembling, that is calculation of completely erected construction of the cross frame was performed. As a result of the subsequent analysis, in addition to the consideration of the strain state, considerable attention was given to consideration of the stress state in the body of the frame construction (in the above studies [11–21] analysis of efforts was carried out mostly in rod and flat items).

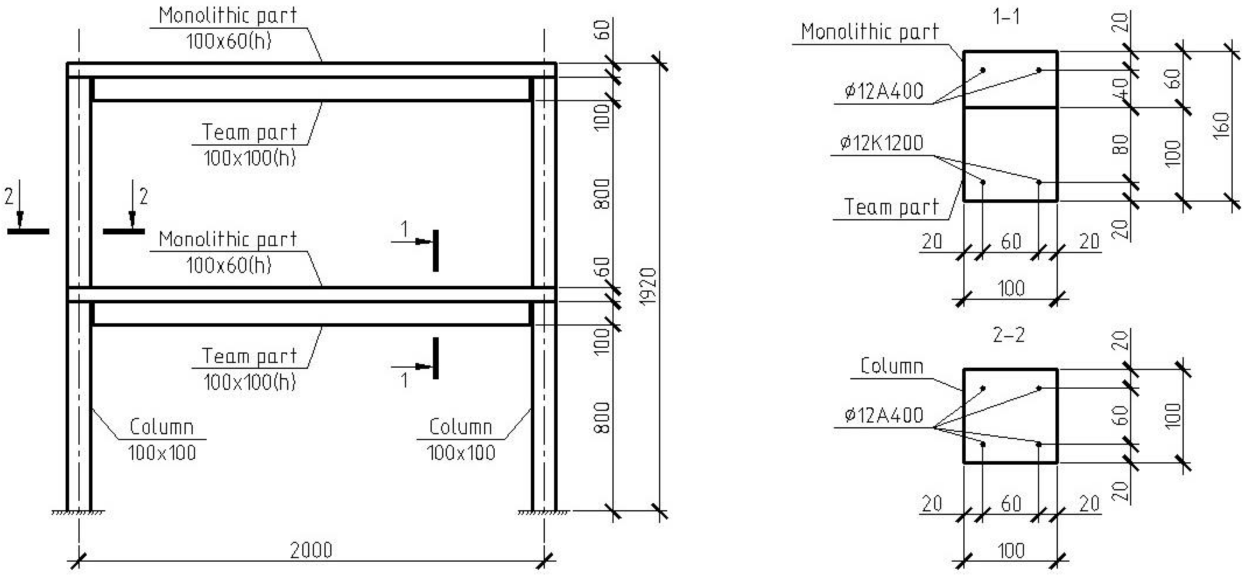

Figure1. The drawing of the numerical model

Results

Let us trace the character of the changes of a stress-deformed state of a precast with cast-in-place frame during its life at the example of model P-1. In the process of unit beams erection of a building upcoming framework, first of all floor-by-floor prefabricated frame construction is made, which consists from columns and leaned on them prefabricated beam parts. The prefabricated beam parts due to posttensioned reinforcement become pretensioned (Figure.2). Precast beam part initially bows under the effect of its own weight, and then bows outward in proportion to the preliminary tensioned steel stress. As the result, in the end of all framework unit beams erection and tensioning of the steel (stage 6), the cross section of the unit beam of the1-st floor is almost centrally pressed with a small difference in the tension at the upper and lower border at the bay center (1.98–2.03 MPa). The cross section of the upper beam is off-center pressed and bowed upwards with the most pressed lower zone in the center of the bay – 2.2 MPa and the less pressed upward zone – 1.68 MPa.

The stress rate in the frame elements do not exceed the admissible limit value, which is quite expectable, considering the fact of the construction loading only with the own weight and preliminary clamping. However, the pulling stress in the column, after the completion of the steel posttensioning have reached 1 MPa. It indicates the possibility of cracks development on the columns internal border at any tiny changes of the parameters of structural design (concrete class lowering, change of the steel posttension, change geometrical parameters of the scheme etc.). Due to that, it is required to pay attention to forces developing in the construction during the erection process, but unfortunately, the project designers do not always observe this.

It should be pointed out that at this stage despite not complete readiness of the frame construction, constructive scheme is already statically indeterminate and geometrically unchangeable system with rigidly restrained columns and pinned connection of beams with columns. This allows to use it successfully (frame) for further erection loads without any special holding equipment.

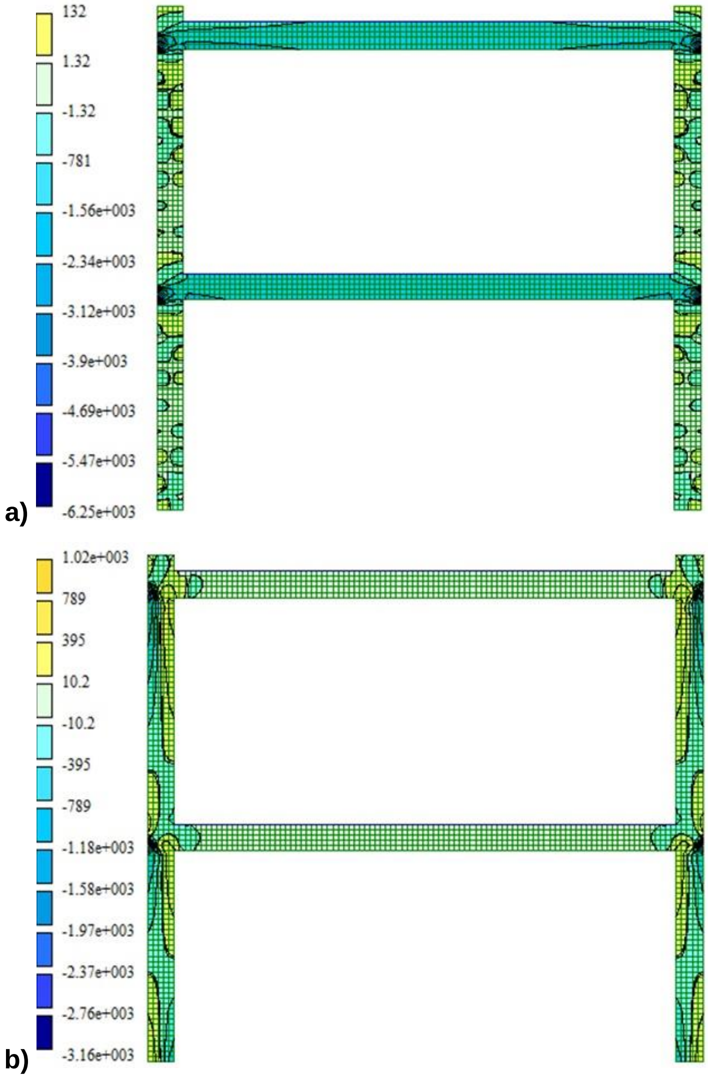

Figure 2. Strain state of the model P-1 at 6-th cycle loading a – Nx; b – Nz

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Applied further (stage 7) erection loads (weight of unit floor slab, weight of newly laid cast-in-place concrete etc.) lead to new change of strain distribution in the frame construction elements. Unit beams work already as flexible elements with strained and pressed zones (at the bottom strain reaching up to 0.2 MPa, on the top pressing together reaching 4.9 MPa). Upon that, their connection with the column is still pinned (Figure 3). The force of thrust and tight pressing by means of column pretension steel to the beam, force the column to deform from the flat area with development of exposed face strain up to 0.8 MPa and inner face press up to 2.4 MPa. The force in the lower longitudinal reinforcement are 11.6 kH. As the maximum tension stress in the concrete of the frame elements have not been reached, it can be concluded that cracks at this stage are not developed. Before additional erection load beams had upward bend – 0.15 mm, with further bend up to +0.61 mm.

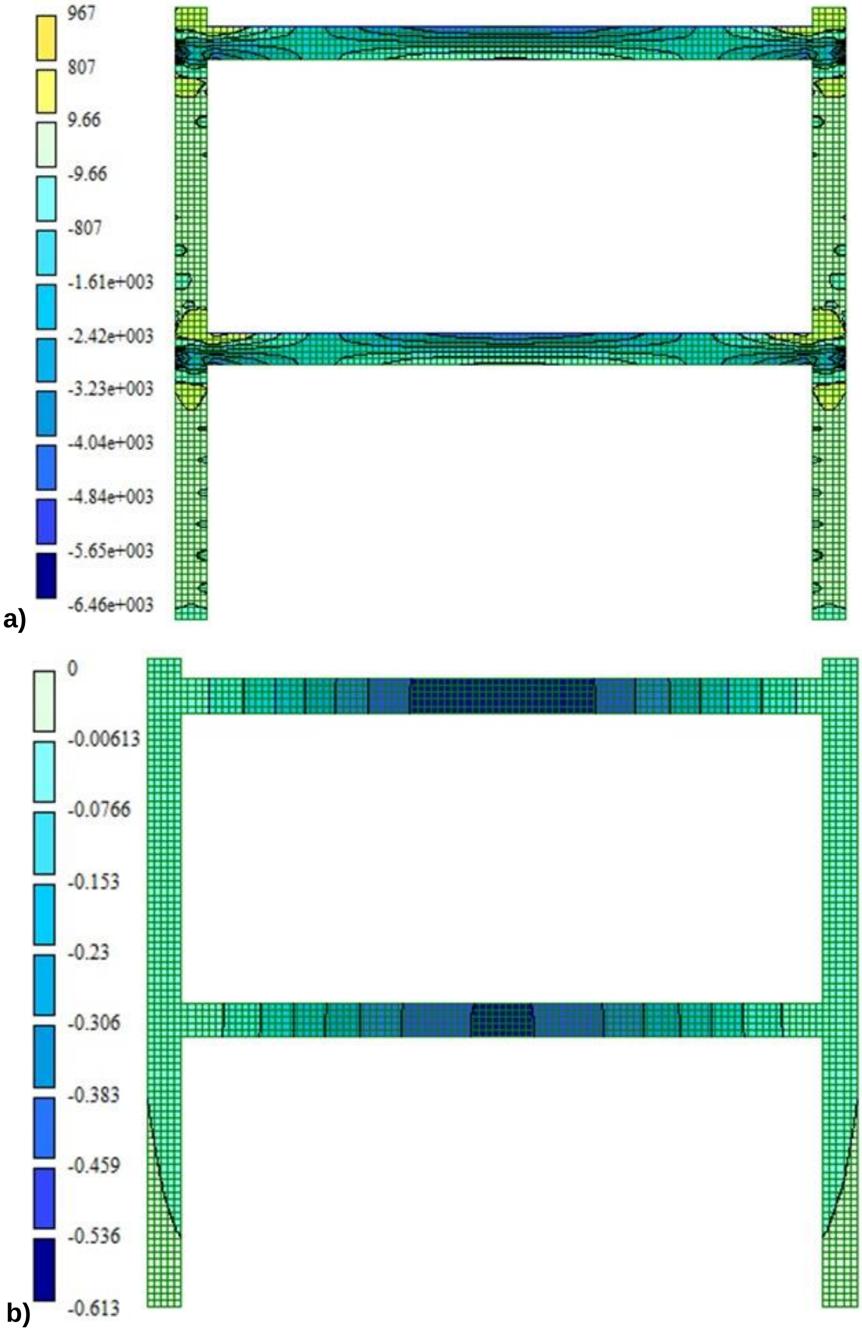

Figure 3. Stress deformed state of model P-1 at 7-th loading cycle: a – Nx; б – sags

From the moment of gaining of required resistibility, but without additional loading (stage 8), stress deformed state at precast parts of columns and beams is still kept. Meanwhile at site concrete tensioning has not yet developed (shrinkage-related and other primary stress are not taken into consideration). From this moment, the frame construction is also statically indeterminable system but with more rate of static indeterminateness by means of rigid connection of precast with cast-in-place beams with column. This frame is in full construction readiness can bear additional erection loading (weight of the floor, walls, carrying wall etc.), and also operational loads as well.

With the more loading (stage 9) stress deformed state again will be different from the previous stage and this results in complex stressed state of bending precast with cast-in-place element. Particularly, precast part with compressive stress, developed earlier, bears more stress (beam of the 1-st floor – 5.45 MPa and beams of the 2-nd floor – 6.6 MPa), than cast-in-place (beam of the 1-st floor – 4.51 MPa and the beam of the2-nd floor – 5.25 MPa). Despite the location of its outer compression area, inside of cross section (closer to the center) of precast with cast-in-place element. Similarly, basing on earlier involvement into operation of precast part and post strain availability, more stress is in the lower longitudinal reinforcement of the precast part (the beam of the 1-st floor – 16.5 kN and the beam of the 2-nd floor – 18.4 kN). Than in the higher pier support reinforcement of the cast-in-place part (the beam of the 1-st floor – 5.1 kN and the beam of the 2-nd floor – 1.4 kN).

Tensile stress in the support zone of the precast part of the beam cross section have not exceeded the limit value 1.05 MPa, that indicates of lack of cracks in this part (Figure 4). At the same time in the center of the bay of precast element cracks develop. Beams bending at this cycle reach up to 2 mm.

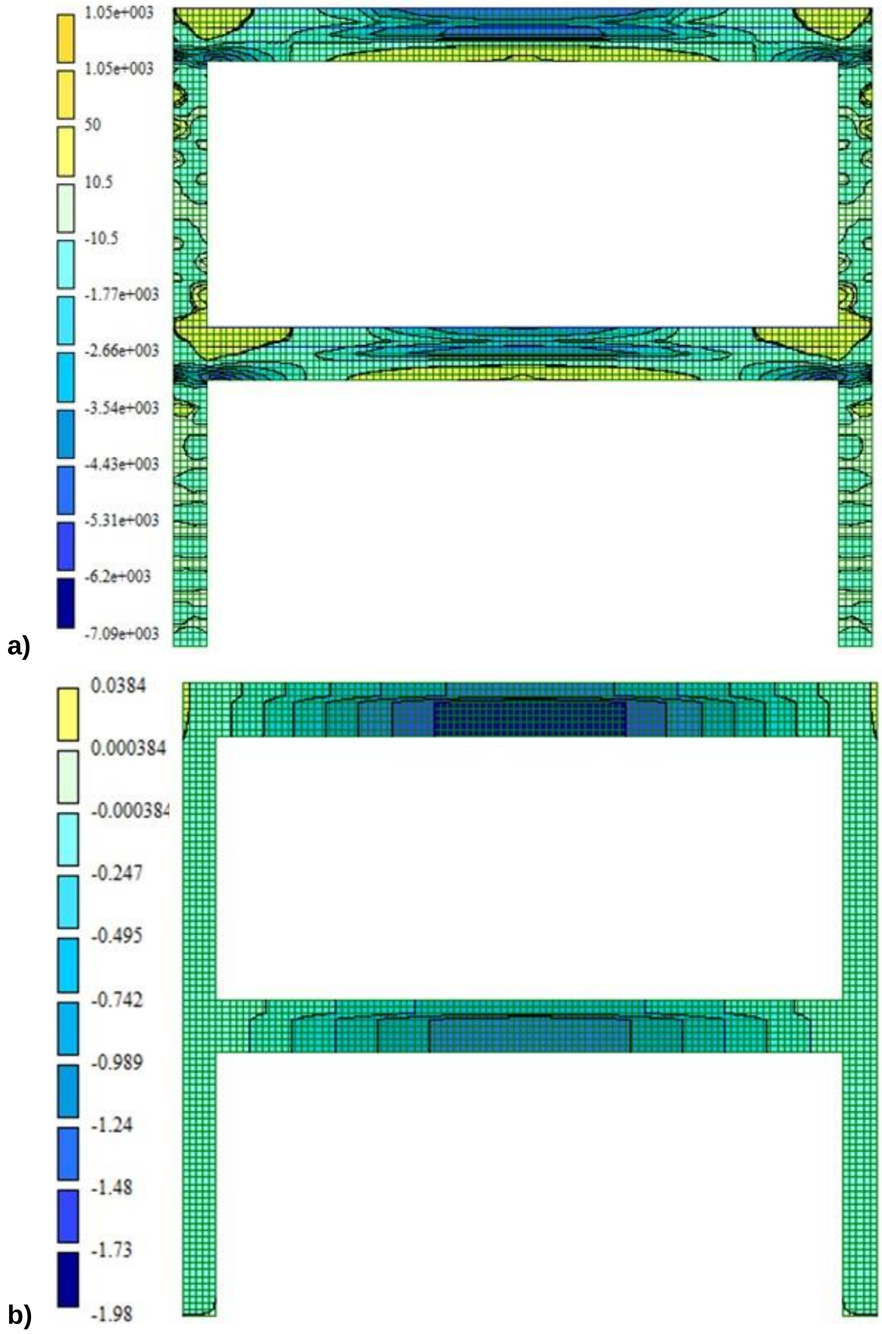

Figure 4. Stress deformed state of model P-1 with full loading : a – Nx; б – sags

Comparing the picture of stress in the models P-1 and P-2, but not analyzing at the level of numeral value, there is a considerate quality difference at stress deformed state of frame beams. It is indicated in that maximal strain, considering gradual construction in the concrete, is focused in the farthest compressed fiber of the precast unit. Meanwhile at standard classic estimation that is without assembling and with once applied loadings, maximal strain values will be in the farthest fiber of the cast-in place part (Figure 5). As in the model P-1 and in the model P-2 the strained is the lower edging of the precast part, where the extreme tension stress are 1.05 MPa. This indicates for the cracks development under the full loading of construction.

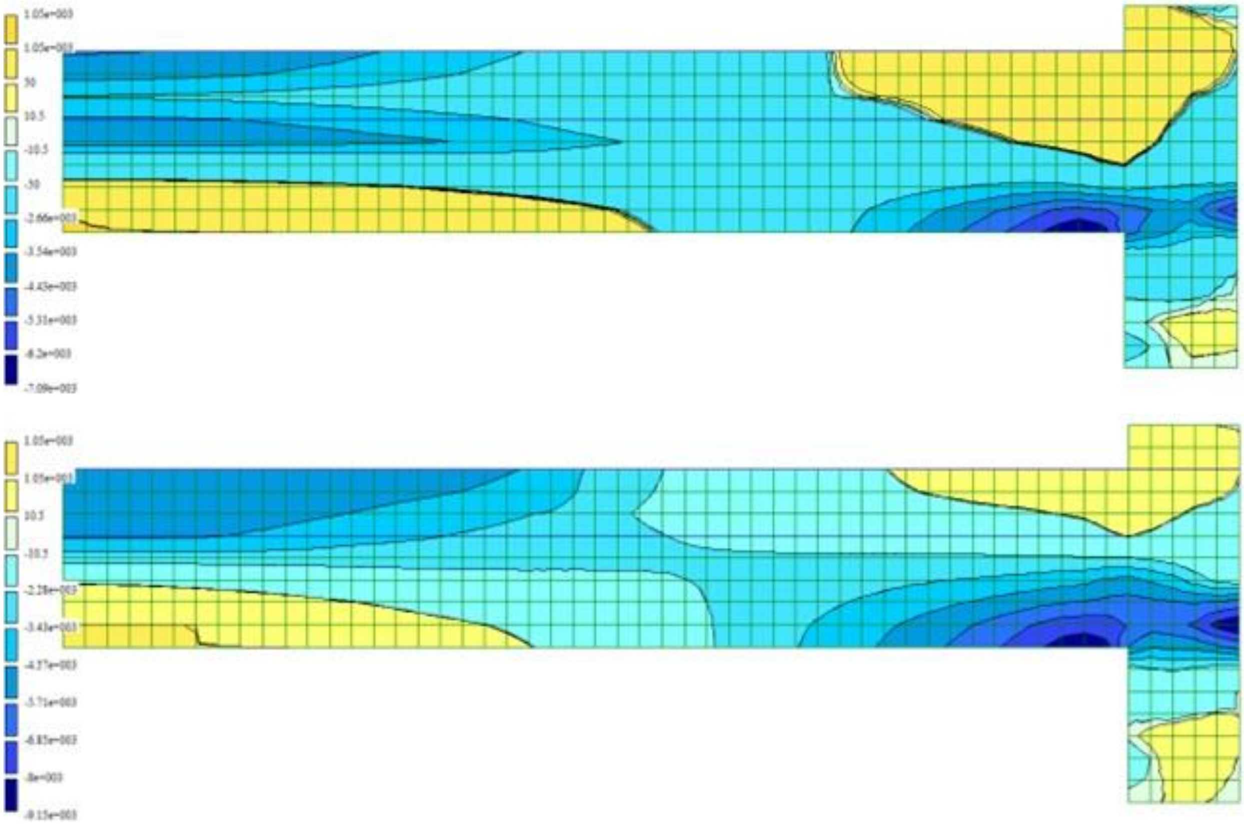

Figure 5. Stress deformed state of the 1-st floor under the full loading: a – P-1; b – P-2

In the model P-2 the maximal stress, developed on the surface of the upper edging of the cast-in place part, has reached the value of 0.6 MPa, meanwhile in the precast part the stress reach 4.53 MPa. In the case of dividing the construction existence for the individual stages of the life cycle the extreme values in the precast part of the beam reach 6.6 MPa, while in the cast-in place concrete the stress is lower and are 4.2 MPa. This fact is caused by that the precast concrete is involved into the process earlier, rather than cast-in place and by the time of gaining of the required strength by the cast-in place concrete and the beginning of the load bearing, in the precast concrete strong stress have already developed. Further, in the course of loading of the precast with cast-in place element, the strain in the precast part is increasing, although with the lower intensity. Thus the precast part is more stressed, that is demanding the proper engineering, and that forces in the cast-in place concrete are of the lower value considering the construction period, indicates the possibility of use of the concrete of the lower strength, including light concrete.

On the supporting structure the stretching forces in the upper zone, using the classic type of calculation and considering “life cycles” are approximately 0.7–0.8 MPa. Compressing stress in the beam concrete of the columns in the model P-1 are 8.7 MPa, and in the model P-2–7.27 MPa.

The real bendings in the construction while making estimations considering stages of the construction period are larger, than bendings, which were calculated at simultaneous readiness of the whole building and simultaneousness of the whole loading application. Particularly, considering the gradual assembling the extreme bendings have reached 1.98 mm, while without “life cycles” – 1.73 mm. This difference is explained by the earlier involvement into the process of the precast part, which has the lesser strength, than precast with cast-in place edging that leads to the accumulation of more size of the bendings until the moment of gaining the strength by the cast-in place concrete (this value in the example is 0.61 mm). Hereafter after the gaining of the required strength by the cast-in place concrete, the increase of the bending is not so significant, as the bending stiffness of the cross section has become higher (bending gain is 1.12 mm).

Comparing the results obtained by the authors of this article in the course of the study with the results obtained by other scientists [11–21], it is possible to note the generality of the conclusion about the execution of the calculation according to the classical technology. When the object is in a ready state, it introduces significant distortion in the stress and deformed state of the design scheme as the building as a whole and its individual structural elements. In particular, the pilot studies carried out in the framework of [12], showed a similar pattern of distribution of deformations along the height of the section, as the numerical study presented in this article. Namely, the later inclusion of the cast-in place concrete leads to the difference of deformations at the interface concretes. In this case, compressive stresses in the precast part is greater than in the monolithic part bending precast and cast-in place element.

Conclusions

1. In the calculations of bearing structures of buildings and subsequent design must take into account the prehistory of the work of the structure at an earlier stage, i.e. to develop the project of the building (a separate structure) taking into account the period of its life cycle. Otherwise, there is a significant distortion of the actual stress-deformed state of the building as a whole and its separate structures.
2. By analogy with requirements to precast concrete structures to make calculations at all stages (production, clamping, transportation, construction etc.) at precast with cast-in place frame erection, it is required to make checkup tests at each stage of the life cycle of the construction.
3. Considering the phasing of constructions erection will allow to avoid initial mistakes at estimation of stress calculation in the body, separate elements and the whole building as well.
4. The real picture of the stress state of precast with cast-in place (especially bending) element, received taking into account the prehistory of the existence of structure in the earlier stages, differs from the pattern of stress distribution. Moreover, these differences are not only quantitative but also qualitative (the maximum compression in the precast with cast-in place girders at the account stages of the life cycle is observed in precast part of the element, while in the traditional calculation – in cast-in place part).

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Alexander Koyankin,
+7(391)2934711; KoyankinAA@mail.ru

Valery Mitasov,
+7(391)2934711; KoyankinAA@mail.ru

Александр Александрович Коянкин,
+7(391)2934711; эл. почта: KoyankinAA@mail.ru

Валерий Михайлович Митасов,
+7(391)2934711; эл. почта: KoyankinAA@mail.ru

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