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The compatibility of deformation of the hollow-core slab with beams

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Abstract. The features of deformation of the key joint of a hollow core slab with precast-monolithic (monolithic) beam of a frame constructive system, including the Saret series. Experimental studies have been performed and numerical research of the stress-strain state of the slab and beam precast monolithic frame joint are carried out. Based on the obtained data, a comparative analysis of the results of numerical studies with experimental research has been performed, which showed a satisfactory convergence of results. As a result of the conducted researches new data concerning design features of the joint of the hollow slab with the beam have been obtained. Conclusions are given about the bearing capacity, stiffness and crack resistance of the structural solution of the joint node. The “weak points” associated with the design and operation of the joint of the slab with the beam are indicated. Technical solutions have been proposed to address the identified shortcomings, such as installation of the upper reinforcement in the hollow plate in longitudinal and transverse directions or exclusion of the key rigid joint to improve the structural reliability of the building.

1. Introduction

Precast-monolithic housing is widely used in modern world construction. The technology of precast-monolithic house-building has become the main one with most of the major developers, which confirms the ease of its application for the erection of buildings of various functional purposes operated in difficult climatic conditions [6, 7, 9, 15]. For example, quite popular became the versions of the floor disk with hollow plates, interfaced with precast-monolithic or monolithic beams, as well as the execution of the floor disk with the use of a prefabricated formwork plate and subsequent pouring with monolithic concrete [1, 3, 6, 7, 10, 15]. At the same time, if the floor disk panels, as a rule, are performed without prestressing, the beams are often prestressed. In addition, a variant of the overlap device with hollow blocks of lightweight concrete is known [2], stacked on precast concrete beams with subsequent filling with monolithic concrete.

Significant development of precast-monolithic reinforced concrete has lead to the necessity of research of peculiarities of stress-strain state of precast-monolithic structures. In this regard, researchers worldwide are actively pursuing those and other studies, allowing to assess both the specifics of individual design solutions and components, and systems in general, by the frames constructed in precast-monolithic design. In particular, the results of experimental studies of precast-monolithic slabs on bearing capacity, crack resistance and deformability are presented in [3, 13].

Full-scale tests of a fragment of a composite monolithic frame of the system with flat floors showed the reliability of the proposed system [4]. In the dissertation work [16], the issues of joint deformation of flat plates and hidden beams in prefabricated monolithic cages, which are quite common in the world construction practice, were studied. Partially ribbed precast monolithic overlap with cellular concrete blocks is presented in [19], where, in addition to the description of the design solution, analytical and numerical comparative calculations were performed that showed greater accuracy of the results when performing calculations in a software package based on the finite element method. However, the studies were performed in the linear formulation of the problem, which alienates their accuracy from the actual construction with the physical nonlinearity inherent in reinforced concrete. The author of [21] conducted studies of the fire resistance of prefabricated monolithic structures. Issues of joint deformation under various types of force effects were

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considered in [29, 32]. The issues of the stability of flat plates in the stage of progressive destruction were considered in [30], and the features of the deformation of the nodal joint of the overlap with the column at different frequencies of repetitive load were studied in [31]. In [22], numerical and experimental studies of beam bending elements with external sheet reinforcement were carried out.

The authors of this article in [33] numerically considered the distinctive features of the stress-strain state of a precast-monolithic flat frame, taking into account the phased installation, and in [1, 24] the authors of this article carried out experimental studies, that allowed to determine a sufficiently high stiffness of the nodal junction of the hollow plate and the beam, as well as the precast-monolithic beam with the column, while identifying certain design disadvantages.

In addition to experimental and numerical studies scholars offer various calculation methods of precast-monolithic structures both with the use of automated software, and performing «manual» calculations. The authors of [5, 8, 26] proposed an algorithm for performing the calculation of prefabricated monolithic structures in software packages based on the finite element method. In [5] the method of calculation of precast-monolithic beams with a keyless contact and load transfer to the precast part is given to take into account the influence of dowel effect of transverse reinforcement on the stress-strain state of the contact between the concrete and the design in general. At the same time, focusing on reducing the stiffness of the node junctions of the hollow plate with a composite monolithic beam by the time the connection carrying capacity is exhausted, the following variants of design schemes [7, 26] are proposed: with rigid joint of the plate with the beam – when calculating the 2nd group of limit states, and with a hinged joint – when calculating the 1st group. The author of publication [12] has proposed a method for calculation of normal cracks formation in precast-monolithic reinforced concrete bendable elements on the basis of the deformation model, where the criterion for the formation of cracks is the achievement of stretched zone of ultimate concrete tensile strength by the fiber. In addition, the set of performed calculations identified the necessity to consider positive effect of thrust strength on bearing capacity of disk panels.

In this case, the calculation of the carrying capacity of a normal section “by hand” is proposed to be performed either using the above section parameters (State Standard “Concrete and reinforced concrete structures”) or through fiber deformations of the fibers. The questions of the equations and calculation methods taking into account the nonlinear creep of three-layer plates and shallow shells are considered in [20].

Apart from that, engineers and scientists actively offer new constructive systems or suggestions for improvement of existing systems. For example, a technical solution of overlapping with the use of hollow slabs based on prefabricated monolithic or monolithic beams through keyway interfacing [11, 14] has become quite popular. In addition, solutions are proposed using prestressed reinforcement mounted directly on the construction site [25, 28]. Along with the design solutions, various aspects of the technology of precast-monolithic construction are considered [10], including the features of construction at negative temperatures [18].

As for the topic and motivation for these studies, a number of previously performed experimental and numerical contributions [1, 24] on the study of the features of deformation of individual nodular joints of precast-monolithic elements, has allowed to reveal a rather unpleasant fact – the formation of cracks in the place of the key interface of the hollow-core slab and precast-monolithic or monolithic beam with subsequent destruction of the hollow plate. In particular, the cracks were fixed in the upper non-reinforced zone of the slab both in its longitudinal direction at the transverse bending from the deformation of the beam [24] and in the transverse direction due to the longitudinal bending of the slab and sufficient rigidity of the key joint for the appearance of the bending moment in it. Along with this, a number of techniques [6] for the calculation of precast-monolithic overlap in software systems is suggested based on the finite element method, where the simulation of this coupling is performed by a hinge, which, of course, will not allow to take into account the occurrence of significant tensile stresses on the surface of the slab in reality.

It is the above mentioned results of experimental studies and observations that prompted the authors of this article to perform additional numerical studies prestressed – deformed state (the subject of research) of the key joint with of the hollow plate with precast monolithic beam (object of research), followed by their comparison with the previously obtained experimental data. The aim of performed numerical research was a detailed study features of joint deformation of the hollow slab and the beam at the key joint in the precast-monolithic frame.

On the basis of these and other related studies of different authors one can state the fact that the prefabricated monolithic frame is a quite reliable construction system, providing the requirements of existing building codes. Of course, some studies, particularly aimed at studying the local aspects, such as junctions of structural elements, identify some shortcomings present in various structural systems.

It is the above mentioned results of experimental studies and observations that have prompted the authors of this paper to perform additional numerical studies of the stress-strain state (the subject of the study) of the key joint of the hollow plate with the precast-monolithic beam (the object of study), with their subsequent comparison with the previously obtained experimental data. The aim of numerical studies was a more detailed research of the features of the joint deformation of the hollow plate and the beam at the key joint in the precast-monolithic frame. To achieve this goal, the following tasks were defined: assessment of the stress-strain state of the joint of the hollow slab with the beam in terms of bearing capacity and deformability, as well as verification of the results of experimental studies. In this case, the object of research is the key joint of the hollow slab with precast-monolithic or monolithic beam, and the subject of research is its stress-strain state.

Experimental studies were carried out at the laboratory of testing building structures of Siberian Federal University [1]. In addition to “The Lira” software numerical studies of the stress-strain state of the slab – beam joint were carried out and comparison of the results with experimental data was performed.

2. Methods

Experimental study was carried out on three full-scale models of the joint of the hollow-core slab with the beam (in the laboratory of building construction tests based on Siberian Federal University of Krasnoyarsk). This type of the joint is quite common in the practice of building construction of precast-monolithic reinforced concrete [6, 7, 10]. Samples were divided into two types depending on the type of the beam. In particular, samples of type 1 (T-1 and T-2) included (Figure 1, a):

– fragments of the hollow-core slab with 1200×220(h) mm cross section and a length of 700 mm, reinforced by prestressed 7Ø12K1500 ropes and interfaced with a monolithic part of the beam through the device in the cavities of the slab, simultaneously with a monolithic part of the beam of concrete 1Ø10A400 reinforced dowels, having a variable length of 200...300 mm;

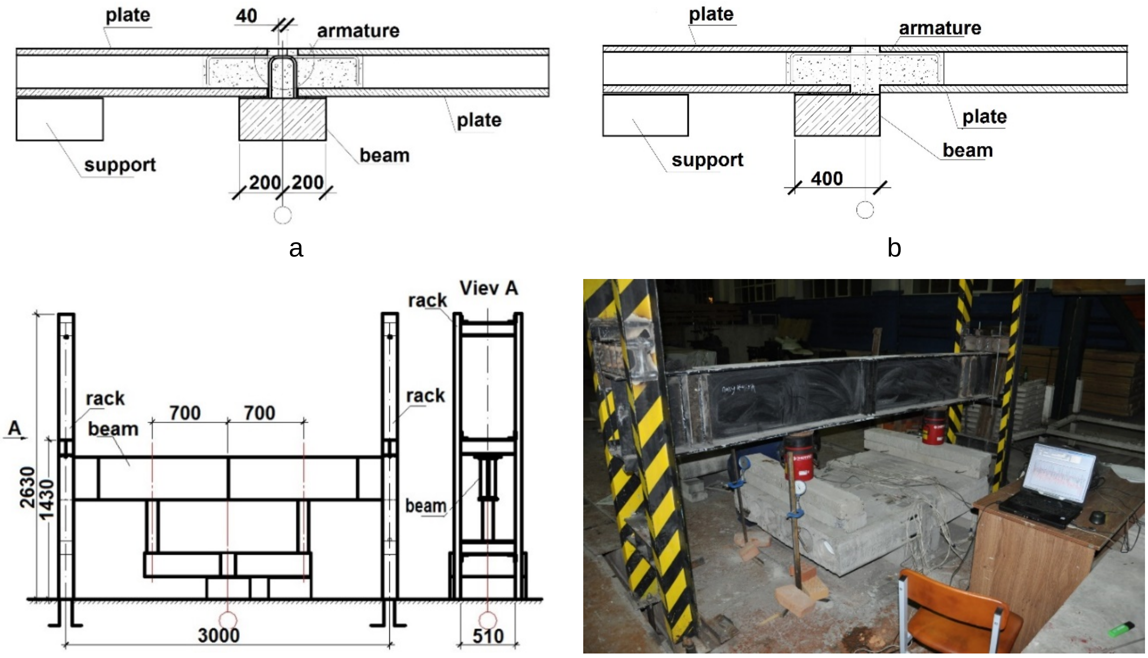
– precast-monolithic beams, including the precast part of 400×200(h) mm cross-section with a length of 1.200 mm, and a stacked on top monolithic part of 140×220(h) mm section performed simultaneously with the dowels in the hollow-core slabs.

Type 2 (T-3) sample was performed similarly to the samples T-1 and T-2, but with the difference that monolithic 140×220(h) mm cross-section beams, 1.200 mm long were used, performed simultaneously with the dowels in hollow slabs (Figure 1,b).

The load on the prototypes was applied top-down on the edges of the consoles with two jacks (Figure 1, c, d).

In conducting numeric research with «Lira» software, based on the method of finite elements, for the simulation of materials operation, physically nonlinear three-dimensional (concrete) and rod (reinforcement) elements were used. The nonlinearity of the work of materials was considered by two – and three-line diagrams of deformation inherent in [State Standard “Concrete and reinforced concrete structures”]. Loading was performed by step load with the step size of 4 kN. Similarly, experimentally calculation of the two type’s calculation of the two types of numerical models of key joint of a hollow – core slab with a precast-monolithic beam (model B-1) and monolithic beam (model B-2) was performed. All models had real scale size, as in previously conducted experiments, at the same time, the P-1 numerical model is structurally consistent with the T-1 and T-2 experimental models, and P-2 is similar to T-3.

For the convenience of modeling the holes of hollow core slabs were converted from round to square, based on the equivalence of flexural rigidity.



a b

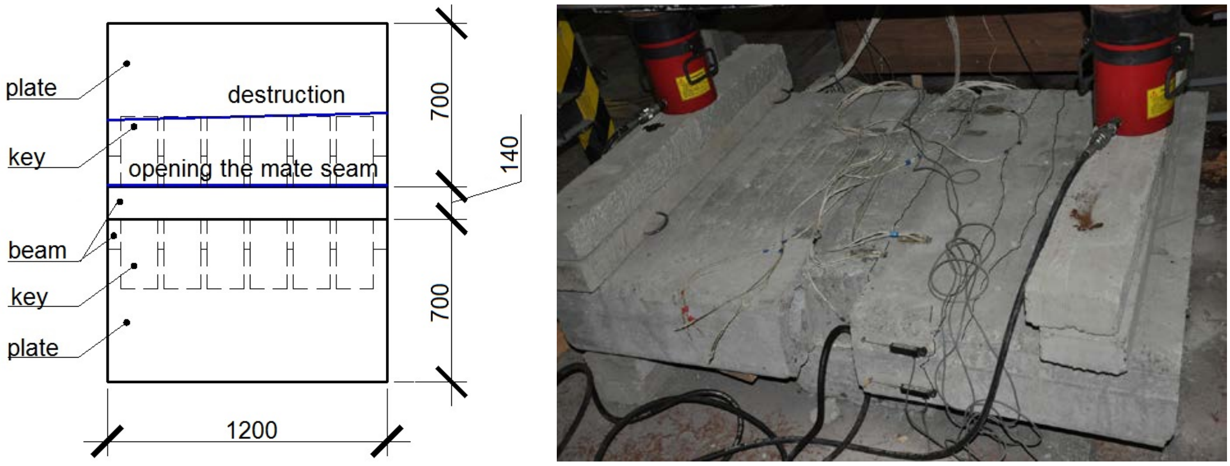
c d

Figure 1. Model of a key joint of the hollow-core slab: a – with precast-monolithic beam; b – with monolithic beam; c – experimental unit scheme; d – experimental unit photo.

3. Results and Discussion

An important factor which has been determined during experimental studies is that in the real joint of the hollow – core slab with precast-monolithic or monolithic beam, arranged through reinforced concrete dowels, there arises a bending moment, which, in the case of improper design of the hollow core slab, leads to its destruction. This fact must be taken into account in the design of reinforced concrete structures. For example, at present, the joint of the slab with the beam is looked at as a hinged one [7], but, as studies have shown, it should be considered as rigid. The same ability of the key joint of the slab with the beam to perceive the bending moment is recorded in the numerical studies as well.

During all the experiments, the formation of cracks on the upper stretched surface of the hollow-core slab was recorded in the place where the monolithic dowel ends. It is at the moment of formation of this crack that the load-bearing capacity of the tested sample was exhausted (load 20...24 kN), which is due to the absence of any reinforcement of the upper zone of the slab. It should be mentioned that the destructive load of all experimental samples is approximately in the same range, namely, the models T-1 and T-3 collapsed at a load of 20 kN, and the model T-2 – at 24 kN. Any other cracks in the test plates were not recorded, except for the minor seam opening in the joint of precast and monolithic concrete occurring at the penultimate stage loading with loads of 12 to 16 kN. The picture of cracking is presented in Figure 2.



a b

Figure 2. Scheme of crack formation in experimental models.

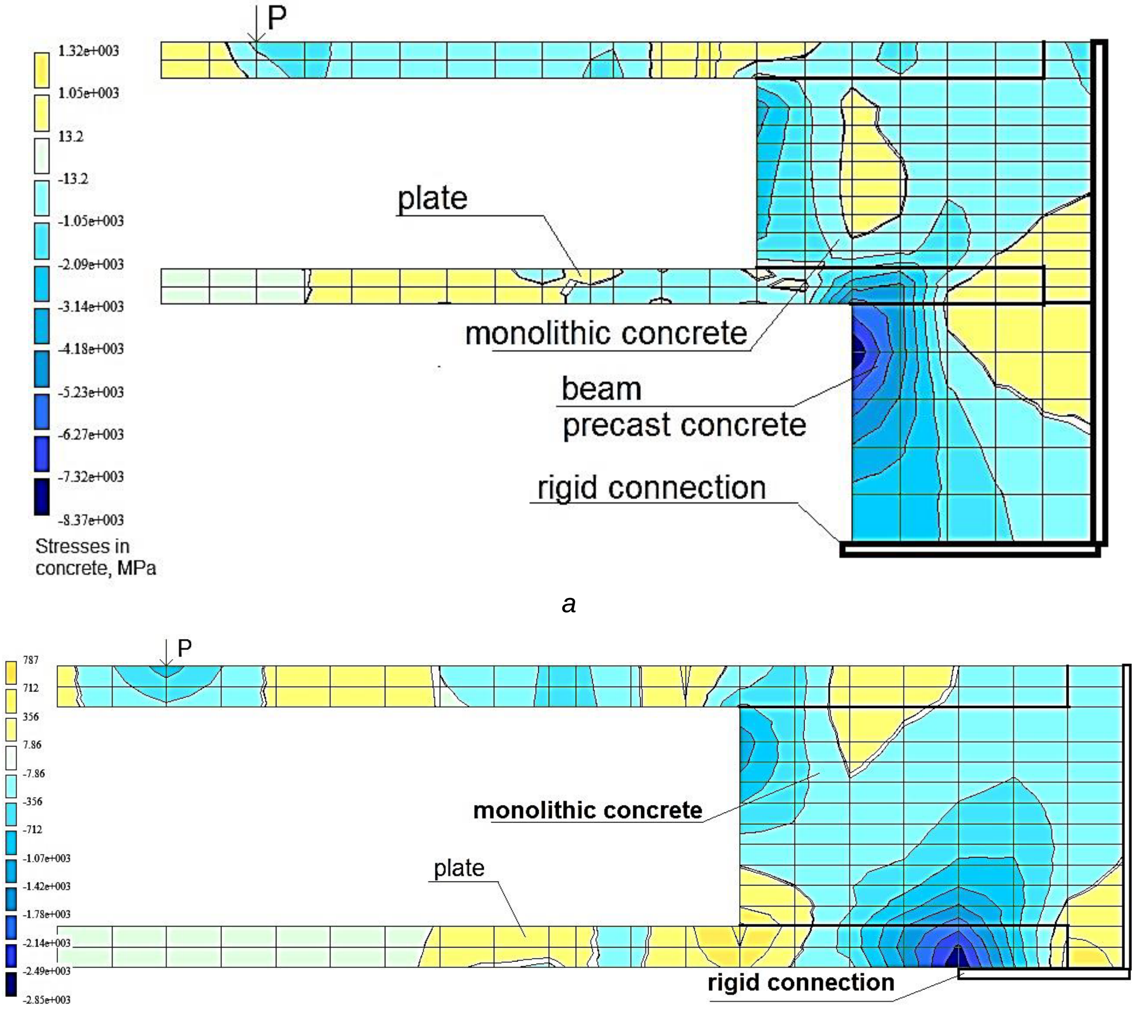
Numerical studies have fully confirmed the results obtained in experimental studies, namely, there is the same picture of structural failure, the formation of a critical crack is also recorded, leading to the rapid subsequent destruction in the hollow slab in the zone of the end of the concrete dowel, i.e., in the place where there is no reinforcement of the upper stretched part. Moreover, such a picture of destruction is observed both in the key joint with a precast monolithic beam (model B-1) and in the joint with a monolithic beam (B-2), which indicates the dependence of the form of destruction of the junction not so much on the type of the beam, but on the length of the dowel and the fact of its reinforcement (Figure 3). The breaking load was 20 kN in both models, which coincides well with the experimental values.

Thus, results of numeric and experimental studies have allowed to draw the conclusion that the junction have been confirmed that the junction of the hollow-core slab with precast-monolithic or monolithic beam, arranged through reinforced concrete dowels, has sufficient rigidity for the occurrence in it of the bending moment. This, in turn, leads to the need of its positioning as hard in the calculation of building structures.

The lack of top reinforcement in hollow-core slabs leads to the fact that the key joint of the hollow slab with the beam being hard, becomes a weak point in the whole structure of the overlap because of the inability of perception of the reference time at the end of monolithic reinforced monolithic dowels.

Thus, the need to implement certain constructive solutions to address this shortcoming is quite obvious. Such measures might possibly include: the device of the corresponding reinforcement of the upper zone of the hollow floor slab, or the refusal to use the reinforced dowel, making the junction of the slab and the beam rigid enough, that is, the implementation of the junction hinged.

The deflections, which were obtained in experimental studies of samples T-1 and T-2, had approximately the same uniform increase with load increasing (Figure 4). At the same time, it is quite expected that the deflections of the slab based on the precast-monolithic beam turned out to be significantly lower than the deflections of the slab joined with the monolithic beam.



a

b

Figure 3. Stress-strain state of the butt joint (MPa): *a* – model B-1; *b* – model – B-2.

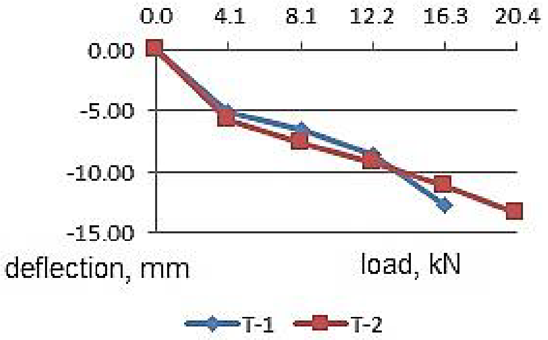


Figure 4. Deflection graphs of experimental models.

The deflections obtained during the numerical research, have turned out to be smaller than previous experimental values; the discrepancy did not exceed 30 %. In particular, with the load of 12 kN the maximum value of the experimental deflection in the joints with precast-monolithic beam amounted to 9.3 mm, while in numerical calculations this value was 12.6 mm.

Numerical and experimental studies have made it possible to clearly and unambiguously note the fact that any destruction of the concrete dowel does not occur. In particular, there is no cut and destruction of the concrete body. In experimental studies no information on deformations and stresses in the concrete dowels was obtained, however, the nature of structural collapse and its subsequent inspection show the integrity of the concrete. Stress values in concrete dowels obtained in numerical studies did not exceed 4 MPa for compression and 0.5 MPa for tension, which confirms the results of the experimental data.

Data from strain gauges, which were obtained in experimental studies have shown that the yield strength in the dowels reinforcement did not exceed 30 MPa, indicating a significant reserve of reinforcement bars safety.

The stresses in the dowel reinforcement in numerical models, as well as in experimental models, have small values (less than 20 MPa), and absolutely cannot be the cause of the exhaustion of the bearing capacity of key joint of the hollow-core slab with the beam because of reaching the reinforcement yield strength.

Similarly to reinforcement, in compressed concrete on the lower surface of the slab, exhaustion of carrying capacity was not recorded both in experimental and numerical studies. In particular, during the experiment this conclusion was made on the basis of the fact that the relative deformations on the compressed (lower) surface of the hollow slab barely reached the value of 0.0003, while their limit values are 0.002.

In particular, during the experiment this conclusion was made on the basis that the limiting relative concrete compression deformations had not been reached. In addition, the data of strain gauges indicate that in the area of the dowels, directly in the place of the joint of the slab with the beam, deformation of the tensile concrete is also less than the ultimate limits of 0.00015 (the maximum value of deformation of concrete stretched in the experiment amounted to about 0.0006) up to the point of structural failure. All the obtained results were confirmed by visual inspection, in which there were no areas of destruction (fragmentation of concrete, cracks and other signs) in the above designated areas.

Thus, there is a significant margin of safety (at least 10x) of the dowel junction on the perception of bending moment in place of the direct dowel device that actually is not used.

In further numeric research compressive stresses of the concrete slab and the beam do not reach the limit values and do not exceed 9 MPa, while the tensile stress in the beam and in the hollow slab at the place of monolithic dowel arrangement also did not exceed the limit tensile stress, which proves the integrity of the structure in these points.

In addition, it should be pointed out that the studies of the joint of the slab key joint with the beam “in its pure form”, i.e. when only the junction of the slab with the beam is considered, rather than the construction of the overlap as a whole, were not found. However, the authors of this article have previously conducted studies of a similar overlap disk and its fragments [1, 24], which did not fix the formation of any cracks in the end of the dowel, but this was due not to the reliability of the nodal coupling, but to a significant (much higher than the normative) reserve of the bearing capacity of the entire overlap disk and carrying out tests not before the destruction (which is quite justified), but only to control values of the load.

In addition, earlier studies [1, 24] of the core coupling of the beam with the column revealed another constructive “trouble”, which is carried by the key joint, namely, the joint deformation of the hollow slab with the precast monolithic beam during its bending (in the reference zone) leads to the appearance of tensile stresses on the upper surface of the slab in the transverse (non-working) direction. Given the absence of horizontal reinforcement in the upper area of the slab in the longitudinal and transverse directions, the hollow-core slab forms normal cracks in the direction parallel to the voids. And this fact also requires the adoption of constructive measures to avoid the formation of cracks in the hollow slab in the transverse direction, for example, by introducing appropriate reinforcement in the hollow slab or excluding rigid joint work of the hollow slab and the beam.

4. Conclusions

Experimental and numerical study of the butt joint of the hollow-core slab with the beam has allowed to draw the following conclusions:

1. butt joint of the hollow- core slab with precast-monolithic and monolithic beam performed through the device of the monolithic dowel is not hinged and has sufficient rigidity for the perception of bending moment, which allowed the experimental model to take the load up to 24 kN during the experiment;

2. “a weak point” of the butt joint is the lack of top reinforcement in hollow-core overlap slabs, leading to brittle fracture of concrete of upper stretched zone of the slab at the end of monolithic reinforced dowels. The discrepancy between the numerical and experimental data for the bearing capacity was not more than 20 %;

3. to avoid the formation of cracks in the hollow slab and the subsequent structure destruction process might be possible, either by the introduction of the reinforcement (top longitudinal reinforcement) of the hollow-core slab, or by eliminating the hard joint work of the hollow plate and the beam (except the key joint);

4. the bearing capacity of the zone of the dowel location has a high bearing capacity both in the perception of the bending moment and in the perception of the transverse force (especially given the rather frequent location of the dowels). At the time of failure of the samples in the elements, determining the bearing capacity of the key joint (compressed concrete and key stretched reinforcement) voltage has not reached 10 % of the limit value;

5. features of deformation of the hollow-core slab with key joint connection in the holding area of the beam require horizontal reinforcement in the slab in the transverse direction.

6. abovementioned constructive decisions can increase significantly the bearing capacity of joint connection towards the perception of the bending moment. However, further investigations (experimental and numerical) focused on detailed study of bearing capacity of key joint for shear are required;

7. according to the analysis of previously performed works, the thrust strengths has a positive effect on strain-stress state of disk panel (increasing the strength of bearing capacity). However, this fact requires additional investigations, primarily, experimental, that will allow to consider thrust strength in calculations definitively.

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Совместность деформирования пустотной плиты с ригелем

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Ключевые слова: строительные конструкции, железобетонные конструкции, сборно-монолитное перекрытие, ригель, шпоночное соединение, несущая способность, жёсткость, трещиностойкость

Аннотация. Рассмотрены особенности деформирования узлового шпоночного сопряжения пустотной плиты перекрытия со сборно-монолитным (монолитным) ригелем каркасной конструктивной системы, применяемой для возведения многих зданий, в том числе зданий серии Saret. Выполнены экспериментальные исследования, а также проведены численные исследования напряжённо-деформированного состояния узла сопряжения плиты и ригеля сборно-монолитного каркаса. На основании полученных данных выполнен сопоставительный анализ результатов численных исследований с экспериментальными данными, который показал удовлетворительную сходимость результатов. В результате проведённых исследований получены новые данные касающиеся конструктивных особенностей стыкового соединения пустотной плиты с ригелем. Даны заключения о несущей способности, жёсткости и трещиностойкости конструктивного решения узла сопряжения. Обозначены «слабые места» связанные с проектированием и эксплуатацией узлового соединения плиты с ригелем. Предложены технические решения по устранению выявленных недостатков, такие как установка в пустотной плите верхней арматуры в продольном и поперечном направлениях или исключение шпоночного жёсткого соединения, позволяющие повысить конструктивную надёжность здания.

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