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The consideration of compliance of structural joints in calculation of large panel buildings

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Abstract. The article presents and analyzes the design solutions of horizontal and vertical joints, as well as methods for determining the coefficient of compliance joints. It also presents the numerical determination of the coefficients of compliance of the horizontal mortar joint in accordance with the standards for the design of large-panel buildings. It is shown that the compliance of the joint on the embedded parts consists of the compliance of the connecting element, embedded parts of the wall panels, namely the metal plate and reinforcing bars of the anchors, as well as the compliance of the welds. In this case, the joint operates in a complex stress-strain state. It is noted that the most difficult is to determine the compliance of embedded parts. Three calculation methods have been developed for the numerical determination of the compliance coefficients of anchor bars under the action of tension (compression), bending moment and shear forces on the embedded part. The deformation of the welds was defined in MGSU in the framework of the experimental research of the work of the vertical seam with embedded parts. The article presents a graph of the deformation in the weld on the applied vertical load on the test piece.

Large-panel housing construction by the nineties of the last century becomes the main type of domestic housing construction, which was facilitated by the General orientation of the construction industry to the use of precast concrete structures with their subsequent unification and standardization, with the creation of construction catalogs and design of standard series of large-panel residential buildings, as well as public buildings, such as hotels, camp sites, preschool institutions, schools, etc.

The main regulatory document on the design of large-panel buildings of those years [1] provides a comparative assessment of the effectiveness of the construction of large-panel, monolithic and brick buildings. So, in the manual on design of residential buildings it is specified that construction of large-panel buildings allows in comparison with brick buildings to reduce cost on average by 10%, total labor costs-by 25...30%, the duration of construction is 1.5...2.0 times. The construction of monolithic buildings requires significantly lower capital costs than the construction of large-panel buildings, the steel consumption reduced 10...15%, but at the same time increased construction costs.

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The reduction of construction costs for the construction of monolithic buildings in the last two decades, the active use of advanced domestic and foreign technologies, a significant reduction in the production of precast concrete in the country has led to an increase in the volume of monolithic construction.

Monolithic reinforced concrete is used for buildings whose structures are characterized by low repeatability, non-standard, whose structures are difficult to be divided (slabs with holes on a complex plan, foundation slabs) or for buildings under construction in seismic areas. Thus, for modern large-panel buildings, the underground part is usually designed in monolithic reinforced concrete.

However, even now the use of precast concrete in world construction continues to develop: in countries of Europe, Asia and America precast concrete occupies up to 40% of the construction volume. There is an annual increase in the production of reinforced concrete in the Russian Federation.

In any case, the choice of materials and technology for the construction of the building should take a balanced, informed decision. In the Russian Federation the volume of introduction of new technologies of construction of large-panel buildings grows simultaneously with wide application of modern construction materials, new technological and constructive decisions.

So, distinctive features of design of concrete and reinforced concrete designs of large-panel buildings at the present stage are:

- wide application of numerical methods of calculation;
- increase in number of storeys and increase in span of floor slabs of buildings;
- change of strength and deformation characteristics of materials of structural elements;
- search and development of rational structural solutions of buildings, including new types of horizontal and vertical joints of prefabricated elements [5, 6].

In 2017, a set of rules for the design of large-panel structural systems was developed [2]. Currently, the construction industry employs large construction companies that perform a full cycle of construction: design, manufacturing and construction of large-panel buildings.

One of the scientific directions of work of employees of the Department GBK of National Research University Moscow State University of Civil Engineering (MGSU) is research and participation in the design of multi-storey buildings of various structural systems. For large-panel buildings, scientific developments are aimed at improving design solutions, including joints of prefabricated elements of buildings. The head of this scientific direction is Professor of the Department Kabantsev O. V. [7, 8, 9, 10, 11].

In the 60-80 years of the last century at the Department GBK the scientific school headed by Professor P. Drozdov was formed. Professor P. Drozdov made a great contribution to the study of the stress-strain state of large-panel, frame, trunk structural systems and load-bearing elements of multi-storey buildings. Methods and algorithms of calculation were formulated, as well as a progressive for that time software package "Avtoriad", in which a discrete-continuum computational model of the constructive system of a large-panel building was applied. The compliance of the horizontal mortar joints and of shear ties in the vertical joints between the panels was took into account in the formation of the calculation model [12, 13].

And at present, a lot of attention is paid to the reliability of joints of precast concrete elements, because operational qualities of the panel house largely depend on the design solutions of these joints. The compliance of joints of different designs traditionally is related to the problems of calculation of structural joints of large-panel buildings. The special importance of the reliability of joints, the knowledge of their actual work acquire in the process of calculations on the progressive destruction, of the calculations for the seismic loads, the impact of the blast load. The compliance of joints of different designs traditionally is related to the problems of calculation of structural joints of large-panel buildings.

There are many structural solutions for horizontal and vertical joints of reinforced concrete elements of large-panel buildings. But features of work of joints of various constructive decisions are considered in the scientific literature and in the construction norms with different degree of completeness. For example, the compliance of vertical and horizontal joints made using embedded parts is not fully considered. A feature of the calculation of this type of joints is the need to take into account the multifactorial nature, manifested in the work of the material of the seam (concrete), the work of the steel embedded parts, the work of the connecting welds of embedded parts, the work of the anchorage unit of the embedded part in the precast concrete element.

The determination of compliance (stiffness) of joints of precast reinforced concrete panels is one of the steps of determining the parameters for the calculation schemes. The reliability of the results of the calculations, ensuring the safety of people living in the projected buildings depends on it.

The construction of a calculation model of a large-panel building is a long process due to the large number of finite elements of the wall panels and the connections connecting them. The finite-element approach to static and dynamic calculations of a large-panel building requires the introduction of deformative characteristics of vertical and horizontal inter-panel joints, including consideration of their compliance.

Modern software systems, including PC LIRA- CAD [14] when performing calculations of structural systems of large-panel multi-storey buildings allow to simulate volumetric calculation schemes, as well as to simulate the connection of structural system elements and their operation taking into account the parameters of compliance (stiffness) of inter-panel seams. It is possible to take into account their non-linear nature of deformation, as it directly affects the distribution of stresses and strains in the structures of the building.

PC LIRA- CAD enables you to perform the entire list of calculations that are regulated by norms [2]. These calculations include: the calculation of forces and displacements in the bearing elements of the structural system and the nodes of their mates, the calculation of the skew of the upper floor cells, the calculation of the stability of the position (rollover) and others. Construction of the design scheme of the building with the simulation of joints is performed in the "Panel building" PC LIRA-CAD.

Simulation of joints in the calculation of large-panel buildings is based on the description of the constructive parameters of the distributed and concentrated connections of horizontal and vertical joints between the bearing elements of the calculated building. The compliance of joints is determined by the calculation algorithms given in [2].

The main design solution of horizontal joints of large-panel buildings is a platform joint. As shown in figure 1A, the compressive load N is transferred from the overlying to the underlying wall panel (thickness t=140 mm) through the support sections of the slab thickness h_{pl}=120 mm of heavy concrete class B20 with an initial modulus of elasticity E_{pl}=27500 MPa and two mortar joints thickness t_m=20 mm with a class of strength and mobility of fine-grained concrete mixture BSM B15 P2 GOST 7473-2010 (cubic strength of the solution R_m=15 MPa= 15 N / mm^2).

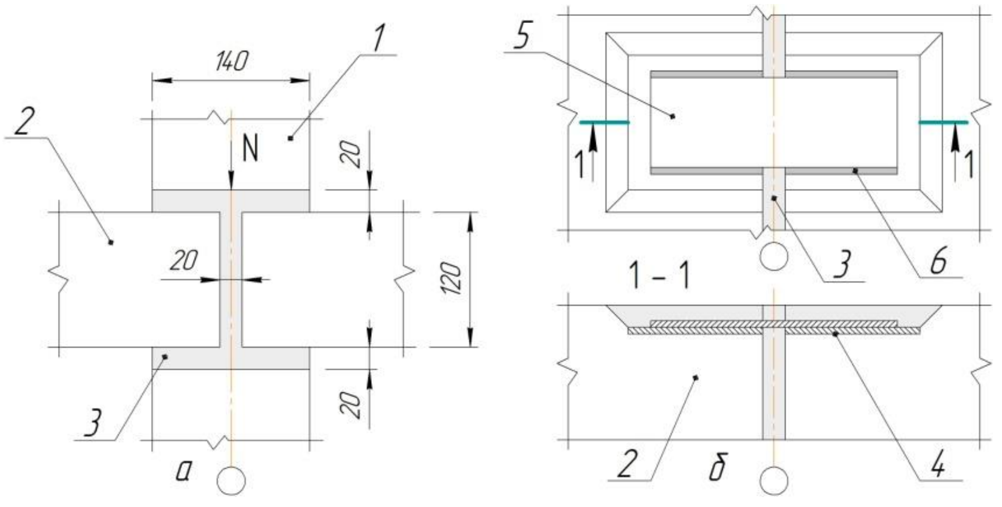

Fig. 1. Horizontal platform joint (a), connection on embedded parts in horizontal joint (b): 1 - wall panel, 2 - floor slab, 3-mortar joint, 4 - embedded part, 5 - connecting strip

Table 1. Determination of the coefficient of compliance

№	The average value of compressive stresses in the mortar seam σ_m, MPa	Coefficient of compliance λ_m of the mortar joint at t_m=20 mm and short-term compression at cubic strength of concrete R_m, MPa				
		1	**2,5**	**5**	**10**	**20**
1	$\sigma_m \leq 1{,}15 R_m^{2/3}$	0,030	0,016	0,010	0,0065	0,0040
2	$2R_m^{2/3} \geq \sigma_m > 1{,}15 R_m^{2/3}$	0,10	0,054	0,034	0,021	0,013

The coefficient of compliance in the compression of a horizontal mortar joint λ_m is determined depending on the geometric characteristics of the seam, the strength of the mortar and the average value of compressive stresses in the mortar joint σm.

At short-term compression of a mortar seam in an operational stage (thickness of a seam t_m=20 mm, cubic durability of a mortar R_m=1...20 MPa) coefficient of compliance of the mortar seam λ_m was adopted for table 1. The coefficient of compressibility of the working seam λ_m in line 1 of table was calculated by the formula $\lambda_{m\leq} 1{,}5 \cdot 10^{-3} R_m^{-2/3} \cdot t_m$, and in row 2 – by the formula $\lambda_{m\leq} 5 \cdot 10^{-3} R_m^{-2/3} \cdot t_m$.

The coefficient of compliance of the horizontal platform joint is determined by the formula:

$$\lambda_{c,pl} = (\lambda_m^{'} + \lambda_m^{''} + \frac{h_{pl}}{E_{pl}}) \frac{A}{A_{pl}},$$

where A/A_{pl} =140/(140-20)=1,167 is the ratio of the wall area from which the load is transferred to the platform area of the joint (one linear meter of the wall and plate is considered).

At $\sigma_m \leq 1{,}15 R_m^{2/3}$:

$$\lambda_{c,pl} = (\lambda_m^{'} + \lambda_m^{"} + \frac{h_{pl}}{E_{pl}})\frac{A}{A_{pl}} = (0,00525 + 0,00525 + \frac{120}{27500})\cdot 1,167 = 0,0173 mm^3/m$$

At $2R_m^{2/3} \geq \sigma_m > 1,15R_m^{2/3}$

$$\lambda_{c,pl} = (\lambda_m^{'} + \lambda_m^{"} + \frac{h_{pl}}{E_{pl}})\frac{A}{A_{pl}} = (0,017 + 0,017 + \frac{120}{27500})\cdot 1,167 = 0,0447 mm^3/m$$

To determine the compliance of the platform joint under compression with a given continuous action of the load must be recalculated modulus $Ep_{l,l}$, and the coefficient of compressibility horizontal mortar seam $\lambda_{m,t}$ (φ_t=1):

$$E_{pl,l} = \frac{E_{pl}}{1+\varphi_{b,cr}} = \frac{27500}{1+2,8} = 7237 МПа .$$

At $\sigma_{m} \leq 1,15R_m^{2/3}$: $\lambda_{m,t} = \lambda_m (1+\varphi_t) = 0,00525 \cdot 2 = 0,0105$,

$$\lambda_{c,pl} = (\lambda_m^{'} + \lambda_m^{"} + \frac{h_{pl}}{E_{pl}})\frac{A}{A_{pl}} = (0,0105 + 0,0105 + \frac{120}{7237})\cdot 1,167 = 0,054 mm^3/m$$

At $2R_m^{2/3} \geq \sigma_m > 1,15R_m^{2/3}$: $\lambda_{m,t} = \lambda_m (1+\varphi_t) = 0,017 \cdot 2 = 0,034$,

$$\lambda_{c,pl} = (\lambda_m^{'} + \lambda_m^{"} + \frac{h_{pl}}{E_{pl}})\frac{A}{A_{pl}} = (0,034 + 0,034 + \frac{120}{7237})\cdot 1,167 = 0,0987 mm^3/m$$

The floor slabs supported on a contour at a platform joint of wall panels can be considered as connections of shift between walls of the perpendicular direction. For this connection, if the brand of a mortar in seams not less M100 and shear deformations not larger than 0.5 mm, the coefficient of compressibility shear $\lambda_{\tau,pl} = 5 \cdot 10\text{-}6$ mm /N.

In accordance with the recommendations given in [2], in order to perceive the efforts in the floor plane of the building, the prefabricated floor slabs must be combined with each other by at least two horizontal bonds arranged along each face, with a distance between the bonds of not more than 3.6 m.

Precast concrete slabs are designed with embedded parts and mounting loops. These elements are used to organize horizontal bonds. Figure 1B shows an example of a constructive solution to the junctions of slabs by welding of embedded parts using joining plates and with subsequent embedment of the node of interface.

For connections located in the floor slabs along the long side of the building, the minimum force value is 15 kN/p.m width of the building; for connections along the short side of the building (its width), the minimum force value is 10 kN/p.m length of the building.

Figure 2 shows the distribution of stresses in the floor slab with a continuous connection along the contour of the slab (platform joint) and with discrete connections using steel embedded parts (8 PCs.).

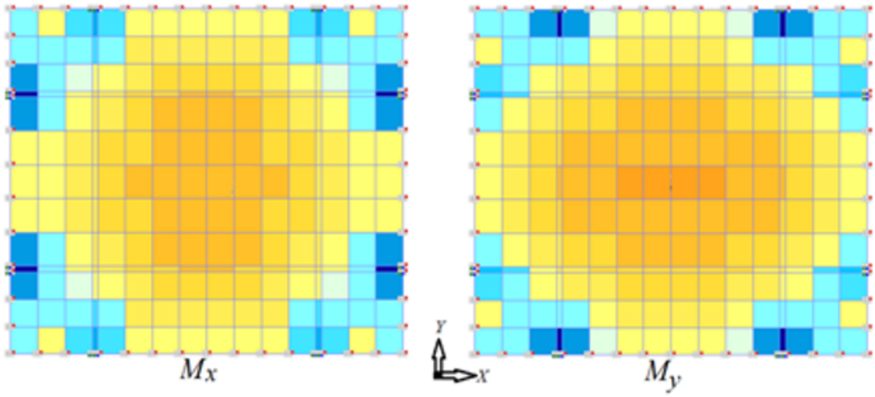

Fig. 2. The stress distribution in the floor slab at the platform joint using connections with steel embedded parts

Despite the presence of a significant number of proposals to determine the compliance of joints, work to improve the assessment of compliance of joints continues [15, 16, 17].

Figure 3 shows various structural solutions of vertical joints between the inner walls of large-panel buildings: keyed connection, connection using steel embedded parts and monolithic connection [15]. Keyed connection wall panels may be supplemented by welding the reinforcing editions of the wall panels.

For connections on embedded parts under the action of forces in the joints: stretching (compression), bending and shear – there is a need to replace the connecting plate on the steel angle. Taking into account the relatively large tolerances in the installation of prefabricated wall panels in practice used steel angles, made in building conditions of metal plates.

It should be noted that the popularity of mating wall panels on embedded parts in comparison with the keyed connection is associated with the absence of the need for installation temporary connections, as well as to make breaks in the work to ensure the achievement of concrete (mortar) joints of the required strength.

For concrete keyed connection of n_k of the same type of keys coefficient of compliance at the mutual shift of the precast element and the concrete grouting of the joint is determined by the formula:

$$\lambda_{\tau,b} = \frac{l_{loc}(\frac{1}{E_b} + \frac{1}{E_{mon}})}{A_{loc} \cdot n_k},$$

where l_{loc} - the conditional height of the key, taken in determining its compliance with the shear equal to 250 mm; A_{loc} - the compression area of the key, through which the compressive force is transmitted in the connection, mm^2; E_b - the deformation module of the precast concrete, MPa; E_{mon} - the same, concrete grouting of the vertical joint, MPa.

If a constructive solution to the vertical joint provides a keyed connection and further connection with the use of free length of reinforcement bars, before the formation of inclined cracks keyed connection works in the conditions of shear with coefficient of compliance $\lambda_{\tau,b}$, and after formation of inclined cracks, it is need to take in account the yielding connection of the free length of reinforcement bars.

$$\lambda_{\tau,m} = \frac{6}{d_s n_s}\left(\frac{1}{E_b} + \frac{1}{E_{mon}}\right), \text{ where}$$

d_s - diameter of reinforcement bars connecting precast elements, mm; ns -number of reinforcement bars connecting precast elements.

It should be noted that the coefficient of compliance at shift λ_τ (mm/N) of connection of two precast elements is accepted equal to the sum of coefficients of compliance for the sections adjoining to each of the connected elements.

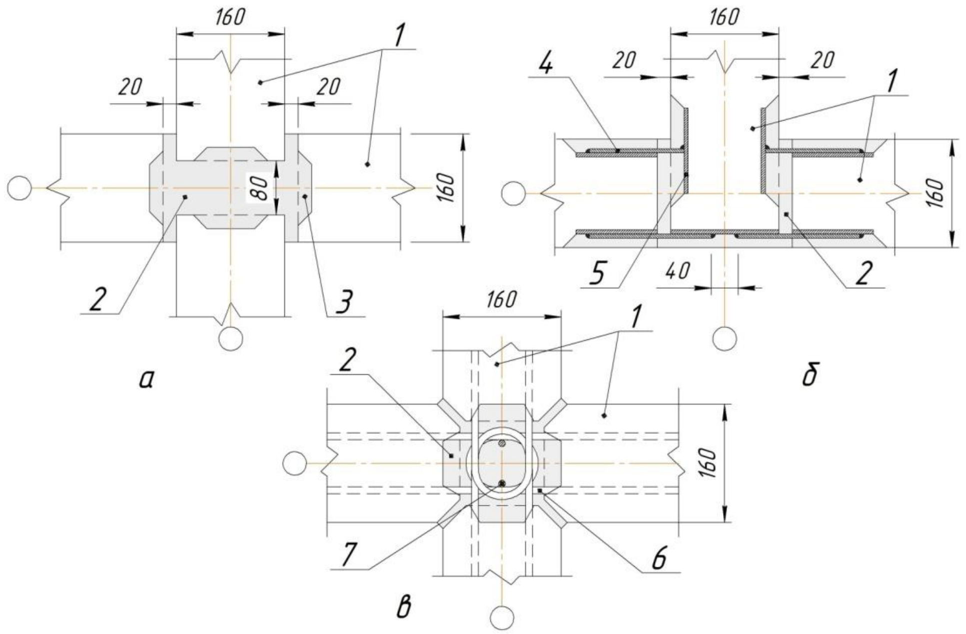

Fig. 3. Keyed connection of wall panels (a), connection on the embedded parts (b), monolithic connection of wall panels (b): 1-wall panel, 2 - filling with a mortar, 3-key, 4-connecting plate, 5-embedded part detail, 6- free length of reinforcement bars, 7-vertical free length of reinforcement bars

The normative documents for the design of large-panel buildings [2] do not provide calculation algorithms for determining the compliance of connections on embedded parts. Meanwhile, the compliance of the connection on the embedded parts is determined by the compliance of the connecting plate, the compliance of the connected embedded parts, or rather the compliance of the anchors – reinforcing bars welded to the embedded parts and embedded in the concrete, as well as the compliance of the welded joints of the coupling plate and embedded parts.

The coefficient of compliance of the connecting element in tension with the cross-sectional area of the plate *A*, the deformation module of the metal *E* and the length of the area of the connecting element between the welds on the embedded parts of the mating walls *l* is determined by the formula:

$$\lambda_t = \frac{l}{E \cdot A}.$$

In MGSU the experimental studies of vertical t-joints of walls of large-panel buildings on embedded parts with connecting elements in the form of bent steel angles were conducted. The strain gauges were installed to determine the deformations in the welds of such joints in the field of welding of bent steel angle and embedded parts and in order to decide other tasks. Figure 4 shows the graphs of deformation in welds on the vertical load applied to the test fragment. The study of the work of welds in building structures is a traditional area of research of the University [19].

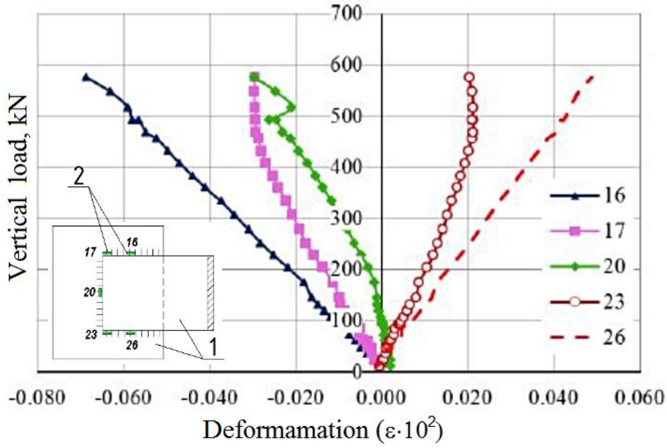

Fig. 4. The graph of weld deformation dependence on the applied vertical load:
1-mating elements, 2-locations of strain gauges on the weld

The most difficult is to determine the compliance of embedded parts of mating wall panels. In [20], three calculation methods are given for determining the compliance coefficients of anchor bars of embedded parts, respectively, under the action of tension, bending moment and shear force on the embedded part. The methods were developed as part of the research work carried out at NIIZHB in Moscow.

The coefficient of compliance of anchor bars in tension (the first calculation method) depending on the strength and deformation characteristics of concrete and reinforcement R_{bt}, R_s, E_s, geometric characteristics of anchor bars d_s and A_s, and taking into account the coefficient ω=0,7, taking into account the unevenness of the stress distribution in the bar along the length of the anchorage, is determined by the formula:

$$\lambda_t = \frac{\omega \cdot R_s \cdot d_s}{10 \cdot R_{bt} \cdot E_s \cdot A_s}.$$

According to the second calculation method, the coefficient of compliance of anchor rods under the action of bending moment taking into account the moment of inertia of the cross-sectional area of the entire armature relative to the axis of the joined structures $I_s = \frac{A_s \cdot z_s^2}{2}$ is determined by the formula:

$$\lambda_\alpha = \frac{R_s \cdot d_s}{10 \cdot R_{bt} \cdot E_s \cdot I_s}.$$

When determining the coefficient of compliance of anchor bars from the action of shear forces (the third calculation method), it is assumed that the maximum displacement of the anchor rod from the initial position $\Delta_{max} = 0,05d_s$ corresponds to the maximum shear force $Q_{max} = 1,5 \cdot d_s^2 \sqrt{R_b \cdot R_s}$, and the coefficient of compliance is determined by the formula:

$$\lambda_r = \frac{\Delta_{\max}}{Q_{\max}} = \frac{1}{30 \cdot d_s \sqrt{R_b \cdot R_s}}.$$

It should be noted that these methods describe the deformation of the classical embedded part, which is a steel plate with normal anchor bars. Embedded parts of the wall panels have a different design solution. They are designed with bent anchor bars and can be closed type.

An important point for improving the design solutions of joints is the assessment of their operational reliability, analysis of joint failure in emergency situations [21]

In view of the above, there is a wide variety of design solutions for horizontal and vertical joints of load-bearing elements of multi-storey buildings of large-panel structural system.

The difficulty in assessing the actual work of joints in a complex stress state is that different types of bonds (distributed and discrete) can be applied in one joint with the variety of their design solutions.

This complicates the development of methods for determining compliance joints. Meanwhile, the description of the structural parameters of the joints should correspond to the level of the design model of the structural system of large-panel buildings in the volumetric setting, taking into account the work of the base, as well as taking into account the physical and geometric nonlinearity in the work of materials and structural system. Only in this case it is possible to fully estimate a number of important deformation and strength parameters of a large-panel building.

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