The consideration of compliance of structural joints in the numerical calculation of large-panel buildings

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Abstract. The article considers the determination of compliance of vertical joints of wall panels of large-panel buildings made on embedded parts. The simulation of these joints in the calculation model of the structural system of a large-panel building is shown. The algorithm for determining the compliance of vertical joints of wall panels of large-panel buildings is described using the «New displacement program» developed by the authors of this article. The service opportunities of the program for the presentation of calculation results are shown. The comparative results of determining the compliance of wall panels vertical joints using two types of connecting parts are presented, which demonstrates the capabilities of the program to investigate the operation of vertical joints in large-panel buildings with different structural solutions of joints.

Large-panel buildings in the mass housing development of recent years successfully compete with monolithic buildings, restoring to themselves the positions lost by them in the nineties of the last century after the total rejection of prefabricated house construction in favor of monolithic ones.

A special feature of calculation of large-panel buildings is the need to take into account compliance (stiffness) of joints between assembled elements of large-panel buildings.

In this case, the stiffness $C$ of joint elements is characterized by the force arising in them at a unit displacement in the direction of action of this force, and its compliance $\lambda$ - by the displacement of the joint elements in the direction of action of the unit force.

The stiffness of the connection and its compliance is related by: $C = \frac{1}{\lambda}$.

In 2017 a set of rules for the design of large-panel structural systems [1] was developed and published, which provides algorithms for determining the compliance coefficient of different types of vertical and horizontal joints.

Currently, research and development of new structural solutions for joints of load-bearing elements of large-panel buildings are ongoing [2, 3, 4, 5].

When performing numerical calculations of large-panel buildings, in particular, using the LIRA-SAPR software package, starting with the 2017 version of the software package, it became possible to construct a calculation scheme for the structural system of a large-panel building with simulation of operation of the joints between the load-bearing elements of the building. One of the parameters of the simulated joint is its compliance (stiffness) coefficient.

As an example, we can consider the determination of the compliance coefficient of the vertical joint of wall panels made on embedded parts.
Figure 1 shows a design solution and a calculation model of a vertical joint between wall panels. Connection panels of mutually perpendicular walls is carried out in two levels on the height of the floor with four ties at each level. Each of the connections is simulated in the calculation scheme of the structural system of a large-panel building with a discrete connection in the form of a bar finite element (KE55).

![Figure 1. Structural solution (a) and calculation model of the vertical joint (b) between the wall panels, made on embedded parts: 1 - wall panels mating in a vertical joint, 1a - plate elements of wall panels in the calculation scheme; 2 - discrete communication KE55 for simulation the joint in the calculation scheme; 3 and 4 - structural elements of the joint (connecting angle piece-cover plate and embedded parts of wall panels mated for welding)](image)

The compliance of vertical joints of wall panels on embedded parts is determined by compliance of structural elements of joint, namely, compliance of embedded parts of mating wall panels, compliance of connecting elements and compliance of welded joints.

Compliance of embedded parts of mating wall panels is connected with compliance of anchor rods of embedded parts.

It depends on the location of the rods relative to the direction of shear of the embedded part, the deformation modulus of the concrete of the wall panel $E_b$, the diameter of the anchor rods $d_s$, as well as the number $n_s$ of the anchor rods in the embedded part.

It should be noted that when the embedded part is shifted, all its anchor rods operate in parallel. The compliance of embedded part at arrangement of anchor rods parallel to shift is determined by formula:

$$\lambda_i = 1 / \sum_{i=0}^{n_s} (1 / \lambda_i) = \frac{1}{n_s / \lambda_i} = \frac{6}{n_s \cdot d_s \cdot E_b},$$

The compliance of embedded part at arrangement of rods along direction of shear is determined by formula:

$$\lambda_i = \frac{1.5}{n_s \cdot d_s \cdot E_b}.$$

Shear forces $Q$ act on the connecting elements of the vertical joint (connecting cover plates, connecting angle piece-cover plate). If we consider the relationship between stress and deformation at the shear of connecting angle piece-cover plate and designate the length of the angle as $b$, its thickness as $t$, then compliance the connecting element of the vertical joint will be determined by the formula:
\[ \lambda = \frac{b}{G \cdot A}, \] 

where

\( A = b \cdot t \) - the cross-sectional area,

\( G = 0.4 \cdot E_b \) - shear modulus.

It should be noted that the connecting elements of the vertical joint can experience the action of shear forces in the direction of the global axes. The embedded part may be bent.

The compliance of welds is considerably less than compliance of embedded part and connecting elements.

It is practically not investigated and is not taken into account in calculating the compliance of joints of large-panel buildings, although a lot of attention has been paid to the study of welds for metal structures [6]. The uneven distribution of stresses in the weld can determine the nature of the destruction of the structural elements of the vertical joint: the embedded part or the weld.

Thus, to perform numerical calculations of the structural system of a large-panel building at the initial stage of design, it is necessary to develop a constructive solution of the joint, to determine the constructive parameters of the joint elements, including compliance.

To determine the compliance coefficient of vertical joints on embedded parts for large-panel buildings, the authors of the article developed a computer program «New displacement», made in the JavaScript programming language. This program also allows you to conduct investigation of structural solutions of joints of various types to find the optimal joint solution taking account the parameter of compliance.

JavaScript programming language allows you to open the program in any Internet browser, which greatly facilitates the user’s work.

The program «New displacement» finds the compliance values \( \lambda \) of the vertical joint on embedded parts when entering the following parameters into it:

- \( N_x \) - horizontal effort;
- \( E_p \) - modulus of elasticity of concrete;
- \( E_s \) - modulus of elasticity of steel;
- \( d \) - anchor diameter;
- \( n_{an1}, n_{an2} \) - The number of anchors, respectively, in the 1st part, in the 2nd part;
- \( l_{ce} \) - connecting element length;
- \( h_{ce} \) - connecting element height;
- \( t_{ce} \) - connecting element thickness;
- \( \varphi \) - coefficient;
- \( A_{ce} \) - cross-sectional area of the connecting elements in the direction in question.

Thus, the initial data for determining compliance are the structural parameters of the vertical joints of the bearing structures of panel buildings, the initial and final value of the vertical shear load, the stages of application of this load, the value of the horizontal load.

When using the program, it is possible to correct the compliance with the obtained experimental data by entering a refinement coefficient.
Figure 2. "New displacement" program block diagram

The output of the calculation results is provided in graphical form. In this case, the dependence of the compliance of the vertical joint on embedded parts from the load is displayed (see Fig. 3).

The developed program «New displacement» is based on the formulas given in the recommendations for the design of steel embedded parts for reinforced concrete structures [7].

Figure 3. Graphical and tabular presentation in the «New displacement» program the results of calculating the compliance of vertical joints on embedded parts:

a) with a profile angle piece-cover plate;
b) with a bent angle piece-cover plate
Figure 4 shows a constructive solution of a vertical joint using a profile unequal connecting angle piece-cover plate 150x75x9 according to DSTU ISO 657.2-2001 (1st option) and a bent corner 154x74x8 L = 100mm (2nd option) as a connecting element.

Figure 4. Scheme of constructive solutions of the vertical joint of wall panels (a); experimental model of the joint of wall panels with embedded parts (b); connecting element - bent angle piece-cover (c):
1. 2 - wall panels; 3 - embedded parts of wall panels; 4 - connecting element - bent angle piece-cover; 5 - cement-sand mortar

A comparative calculation of the connecting elements compliance of the vertical joint was performed using the "New displacement" program for two types of connecting angle piece-cover plate. According to the calculation results, graphs were automatically built, which significantly accelerated the calculation.

The use of a bent metal angle piece becomes necessary in case of violation of the accuracy of panel mounting and deviation of the angle of their mating in vertical joints from 90°, as a result of which bent angle pieces are used more often by builders than angle pieces made of profile steel. However, the insufficient accuracy of panel mounting negatively affects the quality of joints and the appearance of buildings.

Besides, the constructive solution of vertical joints on embedded parts using bent metal connecting angle piece-covers is characterized by an increased coefficient of compliance of the joint as compared to the use of profile connecting angle piece-covers as connecting elements, which was shown by the undertaken investigations using the «New displacement» program.

Table 1 shows initial data for calculation.

| Table 1. | Input data for a comparative calculation of the compliance of the profile and bent angle piece-cover |
|-----------|--------------------------------------------------------------------------------------------------|
| Input data | Bent angle piece-cover 154x74x8 L = 100mm | Profile angle piece-cover unequal 150x75x9 ISO 657.2-2001 |
| Vertical Load, Horizontal Compression | $N_1 = 60kN$, $N_2 = 25kN$ | |
| Modulus of elasticity of concrete | $E_b = 3 \times 10^7$ | |
Modulus of elasticity of steel $E_s = 1.74 \times 10^7$ $E_y = 2.06 \times 10^8$

| Diameter of an anchor | $d = 0.010 m$ |
|-----------------------|----------------|
| The number of anchors in the first and second embedded part, respectively | $n_{an1} = 2$, $n_{an2} = 6$ |
| Length of a connecting element | $l_{ce} = 0.065 m$ |
| Height of a connecting element | $h_{ce} = 0.1 m$ |
| Depth of a connecting element | $t_{ce} = 0.008 m$, $t_{ce} = 0.009 m$ |
| Coefficient depending on the duration of the load | $\varphi = 1$ |
| Cross sectional area of the connecting element | $A_{ce} = 0.0157$, $A_{ce} = 0.016$ |

Below is the algorithm according to which the profile angle piece-cover calculation was performed in the «New displacement» program.

1. The displacement of the embedded part 1 from the shear force (directed perpendicular to the normal anchor rods):

   $$ u_{e1}^{sh} = \varphi_1 \cdot (1000 \cdot \frac{N^2}{n_{an1} \cdot d \cdot E_s} + \frac{N}{n_{an1} \cdot d \cdot E_s} \cdot (1 + 0.8 \cdot \frac{N}{N_s}) \cdot 1 \cdot (1000 \cdot \frac{60^2}{2 \cdot 0.010 \cdot 3 \cdot 10^3} \cdot (3 \cdot 10^{-7})^2 + \\
   + \frac{60}{2 \cdot 0.010 \cdot 3 \cdot 10^3} \cdot (1 + 0.8 \cdot \frac{25}{60}) = 0.00167 m$$

2. The displacement of the embedded part 2 from the shear force (directed perpendicular to the normal anchor rods):

   $$ u_{e2}^{sh} = \varphi_2 \cdot (1000 \cdot \frac{N^2}{n_{an2} \cdot d \cdot E_s} + \frac{N}{n_{an2} \cdot d \cdot E_s} \cdot (1 + 0.8 \cdot \frac{N}{N_s}) \cdot 1 \cdot (1000 \cdot \frac{60^2}{6 \cdot 0.010 \cdot 3 \cdot 10^3} \cdot (3 \cdot 10^{-7})^2 + \\
   + \frac{60}{6 \cdot 0.010 \cdot 3 \cdot 10^3} \cdot (1 + 0.8 \cdot \frac{25}{60}) = 2.996 \cdot 10^{-4} = 0.00022 m$$

3. The displacement of the connecting part (angle piece-cover) from the shear force (directed perpendicular to the normal anchor rods):

   $$ u_{ce,z} = l_{ce} \cdot \tan \left[ \frac{2.6 \cdot N_s}{h_{ce} \cdot t_{ce} \cdot E_s} \right] = 0.065 \cdot \tan \left[ \frac{2.6 \cdot 60}{0.1 \cdot 0.008 \cdot 2.06 \cdot 10^3} \right] = 0.09 m$$

4. General displacement:

   $$ \sum u = u_{e1}^{sh} + u_{e2}^{sh} + u_{ce,z} = 0.00167 + 0.000219 + 0.09 = 0.09 m$$

5. Joint compliance from vertical shear:

   $$ \lambda = \frac{\sum u}{N} = \frac{0.09}{60} = 0.0015 m / kN$$

6. The displacement of the embedded part 1 from the horizontal force:
7. The displacement of embedded part 2 from tensile force:

\[ u_{t2}^N = \frac{1.2 \cdot \varphi \cdot N_s}{n_{a2} \cdot d \cdot E_s \cdot \frac{d}{0.016}} = \frac{1.2 \cdot 1 \cdot 25}{6 \cdot 0.010 - 3 \cdot 10^7 \cdot 0.016} = 2.1 \cdot 10^{-5} m \]

8. The displacement of the connecting part (angle piece-cover) from tensile force from Hooke's law:

\[ u_{c,x} = \frac{N_{c,x} \cdot l_{c,x}}{A_{c,x} \cdot E_s} = \frac{25 \cdot 0.065}{0.016 \cdot 206000} = 0.00049 m \]

9. Full displacement in the direction of horizontal effort:

\[ \sum u_2 = u_{t1}^N + u_{t2}^N + u_{c,x} = 0.0005 m \]

10. The compliance of a connecting element:

\[ \lambda_s = \frac{\sum u_2}{N_s} = \frac{0.0005}{25} = 0.00002 m/kN \]

The results of the comparative calculation are shown in table 2.

| Angle piece-cover type                | Value of compliance |
|---------------------------------------|---------------------|
| Bent corner 154x74x8 L=100mm          | 0.00227             |
| 150x75x9 ISO 657.2-2001               | 0.00153             |

The calculation results show that the compliance of the bent angle piece-cover is higher than the compliance of the angle piece-cover of profile steel at a vertical load of 60 kN and a horizontal load of 25 kN (0.00227 > 0.00153).

During the investigation using «New displacement» program, the vertical load was set from 10 to 100 kN with steps of Appendix 10. The results of a comparative calculation of the compliance at these loads are shown in Figure 3.

An analysis of the results showed that the compliance will vary linearly, the compliance of the vertical joints with the use of a bent angle piece-cover in welding is higher than the compliance of the vertical joints with a profile angle piece-cover at all stages of load application.

Thus, the constructive solution of the vertical joint of the bearing structures of a large-panel building with a connecting element in the form of bent angle piece-cover is characterized by high compliance, therefore, it is necessary to introduce the limits of applicability of this constructive solution. The criterion of applicability may be the coefficient of compliance of the joint.
It should be noted that the developed program «New displacement» is original, convenient, affordable and can be used when performing calculations of vertical joints on embedded parts at the design stage.

References

[1] Joint venture 335.1325800.2017. Large-panel structural systems. Design rules.
[2] Granovsky A V, Dottuev A I, Blajko V P 2014 Experimental studies of shear strength and tension of vertical joints of panels with research of connections from steel locks *BT-Spansschloss Industrial and civil construction*, No. 1, pp. 17-20
[3] Zenin S A 2016 Analysis of existing methods of evaluation of compliance of large-panel buildings *Concrete and reinforced concrete*, No. 3, pp. 27-29
[4] Chistyakov E A, Zenin S A, Sharipov R S, Kudinov O V 2017 Taking into account the compliance of discrete type joints in calculations of structural systems of large-scale buildings *Academy. Architecture and construction*, No.2, pp. 123-127
[5] Malakhova A N, Davletbaeva D A 2019 The consideration of compliance of structural joints in calculation of large panel buildings *XXII International Scientific Conference "Construction the Formation of Living Environment" (FORM-2019), Tashkent, Uzbekistan. E3S Web of Conferences*, Vol. 97
[6] Nikolayev G A 1962 Welded structures *Mashgiz*, p. 552
[7] Yakushin B F, Bakulo A V 2017 The mechanism of formation of structure of metal of a seam at pulse and arc welding *Welding production*, No. 9, pp. 29-35
[8] Recommendations for the design of steel embedded parts for reinforced concrete structures 1984 *NIIJB, Stroyizdat*, p. 87