The simulation of compliance of structural joints in the calculation of multi-story frame buildings

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Abstract. Multi-story frame buildings in precast concrete are one of the main types of buildings being built in the country. The article considers and analyzes the results of the numerical calculation of the structural system of a multi-story frame building, made using the LIRA-SAPR software package. It has been shown that with a semi-rigid assembly of the crossbars with columns it is necessary and possible to simulate the compliance of the joints. The ratio of bending moments in spans and on supports in the crossbars of the calculation scheme depends on the coefficient of compliance (rigidity) of the joints. In its turn, the compliance of semi-rigid joints is a complex quantity, determined by the compliance of the structural elements of the joints, namely: the compliance of the embedded parts in the joined elements of the frame, the compliance of the connecting cover plate, the compliance of the welds for the connecting cover plate, as well as the compliance of the seam between the crossbar and a column filled with cement-sand mortar. An algorithm for determining the compliance of structural elements of a semi-rigid joint is given.
it becomes necessary to simulate the joints of structural elements, including the joints of crossbars with columns in the calculation model of the structural system. The joints in the calculation model of the building are simulated by assignment of characteristics of the degree of deformation of the joints — the stiffness (compliance) of the connections between the structural elements of the calculation scheme. Moreover, the stiffness of tie $C$ is characterized by the force arising in the tie in connection with a single displacement in the direction of this force, and its compliance $\lambda$ - by the displacement of the tie in the direction of the unit force.

Modern software systems, in particular, LIRA-SAPR software [8], allow to simulate the joints of the crossbars with columns in the design scheme of the structural system of a multi-story frame building, taking into account the stiffness of the joint. One of the mechanisms for taking into account the stiffness of the connection of elements of the design scheme is the use of the command «hinges». You can set in the general case the linear and angular stiffness of the simulated joint in the dialog box of this command «hinges». There are other methods for simulating the compliance of joints when calculating the structural system of multi-story frame buildings in precast concrete, for example, those given in [5, 9].

Initially, when creating a calculation scheme for a multi-story frame of bar elements in the LIRA-CAD software package, the joints between horizontal and vertical frame elements are simulated as rigid. Meanwhile, for multi-story frame buildings in precast concrete, three types of joints between the crossbar and the column are used: rigid, articulated and semi-rigid with partial pinching of the support section of the crossbar. It should also be noted that the type of joints of horizontal and vertical frame elements defines the assignment of a multi-storey building frame to one of three structural schemes: tied, tied-frame and frame [3].

When creating a design scheme with articulated coupling of the bearing elements in the support joints between the crossbar and the column, the possibility of free rotation of the support cross section of the crossbar is simulated. When creating a design scheme with rigid conjugation of the frame elements, there is no possibility of free rotation of the support section of the crossbar.

![Figure 1](attachment:image1.png)

**Figure 1.** Results of the static calculation: bending moment diagrams $M_y$ for a flat multi-story frame with rigid (a), articulated (b), semi-rigid (c) conjugation of the supporting elements of the frame in the joint between the elements and the dialog box of the command «hinges» (d)
Figure 1 shows the results of calculating a flat multi-story frame with three types of joints of crossbars with columns: rigid (a), articulated (b), semi-rigid (c). Diagrams of bending moments $M_y$ (kNm) are given.

Figure 1d shows the dialog box of command «hinges», in which the direction of the angular bond (UY) is indicated. The coefficient of angular stiffness $C_\phi$ of the joint of frame elements for a semi-rigid joint ($C_\phi = 11000$ kNm) is also indicated.

Based on the results of the calculation, the graph shown in Figure 2 is constructed for the joint of the upper crossbar with the middle column of a flat multi-story frame (Fig. 1c). This graph shows the connection between the stiffness of the joint in the direction of the angular tie UY and between the bending moment $M_y$ in the support cross-section of the crossbar for the semi-rigid junction of the crossbar and the column.

It can be seen from the graph that if in the direction UY the coefficient of angular stiffness $C_\phi = 0$, then in the flat calculation scheme of the structural system of the frame building the «hinge» joint is simulated. And at $C_\phi = 190,000$ kNm, the junction of the crossbar with the column can be considered practically rigid.

![Figure 2. The graph of relationship of the stiffness of the connection $C_\phi$ in the direction of the angular tie UY and the bending moment $M_y$ in the support cross-section of the crossbar with a semi-rigid junction of the crossbar and the column](image)

Thus, to simulate a semi-rigid joint, it is necessary to have a quantitative estimate of the joint stiffness.

Figure 3a shows a constructive solution of a semi-rigid joint used for a frame of a multi-story building in precast concrete.

To simulate a semi-rigid joint when performing a numerical calculation of the structural system of a multi-story frame building, it is necessary to calculate the coefficient of angular stiffness $C_\phi$, and write the coefficient value in the dialog box of command «hinge» as the value UY.
The coefficient of angular stiffness $C_\phi$ is determined by the formula given in [5]:

$$C_\phi = \frac{M}{\phi},$$

where

- $M$ - bending moment in the reference section of the crossbar,
- $\phi$ - the angle of rotation of the support section of the crossbar.

**Figure 3.** The constructive solution of the semi-rigid junction of the crossbar and the column (a) with a scheme for determining the angle of rotation of the support cross section of the crossbar (b):

1 - embedded parts of the crossbar, 2 - embedded parts of the column, 3 - connecting cover plate, 4 - welds, 5 - seam between the crossbar and the column, filled with cement-sand mortar

Figure 3b shows a diagram for determining the angle of rotation of the support cross section of the crossbar. The angle of rotation of the support cross section of the crossbar is associated with the deformation of the embedded parts of the joined reinforced concrete elements, as well as the deformation of the connecting cover plate, the deformation of the weld joints, the deformation of the mortar seam between the crossbar and the column and it is determined by the formula:

$$\phi = \frac{\Delta_1 + \Delta_2}{l},$$

where

- $\Delta_1$ - the displacement of bonds along the upper edge of the crossbar,
- $\Delta_2$ - the displacement of bonds along the lower edge of the crossbar,
- $l$ - the length of the displacement diagram.

In accordance with the current regulatory documents, the joints of structural elements of a multi-story frame building should be calculated by strength (the first group of limit states), by limiting the deformation of the joint elements, and by limiting the opening of cracks in the mortar seam between the crossbar and the column (second group of limit states).

It should be noted that the stress-strain state of the elements of the joint depends on compliance with the technology of filling the cement-sand mortar between the crossbar and the column when the joint is installed. So, when the vertical seam is filled with a mortar, the force $N_1$ for the strength
calculation of the connecting cover plate and welds is determined taking into account the compressed concrete zone of the normal cross-section of the crossbar [5, 10].

In [10], an algorithm for the strength calculation of a semi-rigid joint is presented. The initial data for the calculation includes the moment in the support section of the crossbar \( M_y \), which determines the horizontal force \( N_1 \) acting on the connecting cover plate. The calculation of cross-sectional area of the connecting cover plate and calculation the welds are performed taking into account the force \( N_1 \). Thus, this algorithm provides only the strength calculation of the joint.

However, when performing numerical calculations of the structural system of multi-story frame buildings using software systems with a semi-rigid joint of the crossbar to the column, the ratio of the reference and span moments in the crossbar is determined on the basis of the joint stiffness (flexibility). Therefore, the calculation should be carried out taking into account deformations arising in the joint.

Thus, the coefficient of compliance of the connecting cover plate \( \lambda_c \), when loading it with a tensile force \( N \) acting along the connecting cover plate can be determined as follows:

\[
\sigma = E \cdot \varepsilon, \quad \frac{N}{A} = E \cdot \frac{\Delta l}{l}, \quad \Delta l = \frac{N \cdot l}{E \cdot A}, \quad \lambda_c = \frac{\Delta l}{N} = \frac{l}{E \cdot A}, \quad \text{where}
\]

\( l \) – the length of the connecting cover plate between the welds,
\( A \) – cross-sectional area of the connecting cover plate,
\( E \) - steel deformation modulus.

Recommendations for determining the coefficients of compliance of embedded parts are given in [11] as applied to the vertical joints of wall panels of large-panel buildings made on embedded parts.

The compliance of the embedded part is determined by the compliance of the anchor rods and the deformation modulus of the concrete \( E_b \) of the structural element into which the embedded part is installed. This takes into account the number of anchor rods \( n \) in the considered embedment, the diameter of the anchor rods \( d_s \), as well as the direction of the location of the anchor rods relative to the direction of shift of the embedded part.

The coefficient of compliance \( \lambda_c \), when shearing one anchor rod of the embedded part located perpendicular to the direction of shear is determined by the formula:

\[
\lambda_{c} = \frac{6}{d_s \cdot E_b}.
\]

The coefficient of compliance of one anchor rod of the embedded part, located along the direction of shear, is determined by the formula:

\[
\lambda_{c} = \frac{1.5}{d_s \cdot E_b}.
\]

The embedded part of the column shown in Figure 3a (joint A) has four anchor rods located along the shear direction. With the simultaneous operation of \( n \), of the same anchor rods parallel to each other, the compliance coefficient of the embedded part of the column is calculated as follows:

\[
\lambda = \frac{1}{n} \sum_{i=1}^{n} \left(1/\lambda_{c_i}\right) = \frac{1}{n \cdot \lambda_c} = \frac{1.5}{4 \cdot d_s \cdot E_b}.
\]
The embedded part of the crossbar, connected by the connecting cover plate with the embedded part of the column, also has four identical anchor rods, but they are located perpendicular to the direction of shear and the compliance coefficient of the embedded part of the crossbar is determined by the formula:

$$
\lambda = 1 / \sum_{i=0}^{n} (1/\lambda_i) = \frac{1}{n/\lambda_i} = \frac{6}{4 \cdot d_i \cdot E_s}.
$$

Since the coefficient of compliance $\lambda$ can be determined at various stages of the stress state both under short-term and long-term loading, both the initial and reduced modulus of elasticity of concrete can be substituted in the above formulas for determining the coefficient of compliance.

A quantitative assessment of the flexibility of the welds between the embedded parts of the crossbar junction and the column has a certain difficulty since it is largely determined by the welding technology and depends on many factors. The mechanism of the appearance and development of residual transverse, longitudinal and bending strains in connecting cover plates during welding is described in [12].

The welded connecting cover plates have residual stresses and deformations. Figure 4 shows diagrams explaining the mechanism of appearance and development of residual stresses and strains in plates during welding.

![Figure 4](image.png)

**Figure 4.** The mechanism of appearance and development of residual transverse, longitudinal and bending deformations in the connecting cover plates during welding: transverse and longitudinal deformations with symmetrical suturing (a), bending deformation during heating and after cooling (b); transverse shrinkage of joints (c)

In the operational stage, the residual stresses in the connecting cover plates add up to the stresses arising from external loads. As a result of this, additional plastic deformations can form, due to which the dimensions of the cross section of the embedded part must be increased.
To determine the forces and deformations in the structural elements of the joint after performing welds, you can use the methods described in [12]. These methods were developed based on the results of experimental studies of the strength and deformability of welds.

An approximate method for determining the deformations caused by the longitudinal reduction of the zone of welded joints can be used to determine the displacements of the welds of the parts to be joined. Plastic deformations and tensile stresses arise here, approaching the yield strength of $R_y$ for steel.

So, the connecting cover plate in figure 3 (position 3) experiences longitudinal deformation (shortening) along the weld. As a first approximation, we consider only one weld of welding the connecting cover plate of the crossbar to the embedded part of the column.

The shrink force in the plate is determined by the formula:

$$N = R_y \Omega_t$$

where $R_y$ - the yield strength of steel,
$\Omega_t$ – the part of the cross-sectional area of the connecting part in which plastic deformations occur.

In this case, the compliance of the welds is an integral part of the overall compliance of the connecting cover plate and it is taken into account through the value of the shrinkage force $N$.

Thus, when performing numerical calculations of the structural system of a multi-story frame building with semi-rigid conjugation of the vertical and horizontal bar elements of the calculation scheme, it is necessary and possible to simulate the compliance (stiffness) of the joint, which is the sum of the compliance of its structural elements. The value of the coefficient of angular stiffness $C_\phi$ for a semi-rigid joint determines the ratio of the support and span moments in the crossbars of the design scheme.

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