The deformability of shear bonds in the load-bearing systems of panel buildings

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Abstract. Civil buildings, like construction objects, have a certain life cycle; building structures subjected to power influences lose their design bearing capacity and operational suitability over time. The service life of prefabricated buildings was oriented to 50 years. Nevertheless, most of these buildings are still in operation in Russia. The service life of the mass typical series of prefabricated panel buildings is coming to an end, which necessitates a reliable assessment of the stress-strain state of building structures. Analyzes the stress-strain state of the load-bearing systems of mass buildings with linear and nonlinear deformation of shear bond materials. A 9-story large-panel residential building, consisting of one section, was taken as the object of study. Introduction to the algorithm of nonlinear deformation of only one type of shear bond allows us to fix a noticeable difference in the stress-strain state of the vertical load-bearing structures of the building. The discrete-continuous mathematical model creates a methodological basis for researching other basic elements of the spatial bearing system of a multi-storey building and assessing their contribution to the redistribution of efforts.

1. Introduction

The service life of prefabricated buildings was determined to be 50 years. Nevertheless, most of these buildings are still in operation in Russia. In most small towns and remote regions, the existing panel building stock will be the foundation of urban housing for decades to come. The service life of typical series of prefabricated buildings is coming to an end, which necessitates a reliable assessment of the stress-strain state of building structures.

As a mathematical model of the load-bearing systems of multi-storey buildings, a discrete-continuous model was adopted [1-3]. A multi-storey building is modeled by a beam of cantilever vertical elements and connected in space by shear bonds - shear bonds. The discrete arrangement of vertical load-bearing elements is determined by the geometry of the building, and the connections connecting the entire building into the spatial system are replaced by continuum. Overlaps are considered absolutely flexible from the plane and absolutely rigid in their plane (figure 1).

Existing models of load-bearing systems of multi-storey buildings, in most cases, are guided by the elastic work of load-bearing elements and their connections. In the classical analysis of a building, in order to simplify the problem, the relationships between stresses and strains are specified by the Hooke elastic-linear law. However, they do not allow sufficient use of the safety margins of the entire load-bearing system or can distort the assessment of the real state of this load-bearing system of the building. An important feature of the real work of materials is the nonlinear nature of the relationship...
between stress and deformation of both vertical load-bearing structures and the elements connecting them.

Figure 1. The discrete-continuous model of the bearing system of a multi-storey building.

In panel buildings, shear ties are the most stressed elements of the load-bearing system of a multi-story building and are a regulator in the redistribution of efforts, taking into account the nonlinear work of materials. Structurally, shear bonds may include: a platform joint or a horizontal seam, a concrete key, vertical joints, welding of embedded parts and jumpers.

Various studies are devoted to the analysis of the operation of such shear bonds as jumpers [4-6], vertical joints [4-9], [16], horizontal joints [10-13] and plate ties [14], [15]. Experimental studies of other shear bonds are very limited.

The aim of this work is to conduct a comparative analysis of the stress-strain state of the load-bearing systems of mass buildings with linear and nonlinear deformation of shear bonds.

The main task of the work is to establish changes in the stress-strain state of the building's spatial support system, taking into account the linear and nonlinear work of some shear bonds, namely tight bonds in the form of embedded parts welding.

2. Method of solution for nonlinear formulation of the problem

To solve this problem, it was necessary to analyze the resistance of the spatial load-bearing system of the building, presented in the form of a mathematical model - discrete-continuous [1], [17], under the influence of vertical load.

As a result of deformation of the carrier system under the influence of an external load, the bonds resist bending and shear. Shearing forces \( Q_{ij} \) arise in them, which are balanced by the normal forces of \( N_i \) arising in the columns (Figure 2).

For an arbitrary \( i \)-th column of some spatial construction, we can write:

\[
N_i(x) = \sum_{j=1}^{n} \int_0^x Q_{ij}(x) dx
\]

The building's resistance to external load is described by a system of differential equations [17]:

\[
N'' - RN = F
\]

where
- \( N \) - matrix of unknowns, size \((m+1) \times n\);
- \( m \) - number of vertical load-bearing elements;
- \( n \) - the number of design sections for the height of the supporting system;
- \( R \) - square matrix of stiffness coefficients, size \((m+1) \times (m+1)\);
- \( F \) - external load matrix, size \((m+1) \times n\).
The algorithm for calculating the spatial bearing systems of multi-storey buildings in a linear formulation was taken as the basis [17-19]. At which the following assumptions are made:
- the material of all elements of the supporting system works elastically, obeys the linear law of deformation;
- the columns do not take into account the influence of shear deformations;
- the calculation is carried out according to the non-deformable scheme;
- in horizontal elements (connections) the influence of axial (longitudinal) deformations is neglected.

In this work, the object of study was a 9-story large-panel residential building of the 125th series, consisting of one section. The supporting structures in this house are internal reinforced concrete panels (poles) with a thickness of 160 mm from concrete of class B25. Exterior wall panels having a thickness of 400 mm are self-supporting. Depending on the location of the load-bearing elements, the cargo areas of each column were determined. Through cargo areas, a load is transferred to each pole. Only a vertical load was applied to the carrier system. The design scheme of the building is shown in figures 3 and 4.
Figure 4. The design scheme of the building (communication).

The change in the stiffness (compliance) of tight shear bonds and shear bonds of the jumper type is described by nonlinear dependences obtained experimentally. For shear bonds, a piecewise linear diagram is adopted according to [20]. For dense steel shear bonds, a deformation diagram was adopted for testing real joints of panel buildings [21]. For other shear bonds, including overlap, the experimental Q-Δ dependencies or fixed values can be used [1].

A system of nonlinear equations is not explicitly formed, and the solution is found by the step method with subsequent recalculation of the stiffnesses of each series of shear bonds.

The mathematical model of bearing systems, taking into account the physical nonlinear properties of shear bonds, includes the main system of the discrete-continuous model (2) and a nonlinear system that describes the change in the compliance of shear bonds:

\[ S = f(N) \]

where

- \( S \) - shear bond deformability matrix, size \( l \times k \);
- \( l \) - number of vertical shear bonds;
- \( k \) - the number of intervals along the height of the building, within which deformability is constant

System (2-3) describes a nonlinear boundary-value problem, at the boundary of two adjacent intervals \( i \) and \( j \), the conditions of equal forces (strains) are observed:

\[ N_i = N_j \]

\[ N_i' = N_j' \]  \hspace{1cm} (4)

The values of the deformability of the shear bonds vary along the height of the building in view of the variability of the shear forces, therefore, when modeling, the building is conditionally divided in height into a number of sections. Efforts and deformability on them rely on constant. The number of intervals in height can be taken equal to 4-6, focusing on changing the percentage of reinforcement of reinforced concrete structures along the height of the building and changing the size of the cross section of the vertical load-bearing elements.

Systems (2) and (3) are solved jointly by the sweep method and the iteration method.

Since the system of nonlinear equations is not formulated explicitly, it is impossible to explicitly formulate the conditions for convergence. This is also due to the fact that the equilibrium condition of the building's building system is described by a system of second-order differential equations, and the
“force – displacement” dependencies can be represented by absolutely any, mathematically, dependencies, tabular data on the results of experiments.

Nevertheless, the accuracy of the numerical solution in this approach was compared on simply connected building systems with one row of vertical shear bonds, for which there is analytical dependence (1) and the exact solution [1]. The error in the numerical solution did not exceed 5%.

To improve the convergence process in the non-linear approach, the iteration method was modified: the deformability value $S$, adopted in the new calculation cycle, is defined as the half-sum of the $S_i$ deformability of the previous stage and the $S_{i+1}$ deformability, again determined from the force – displacement diagrams, the half division method is used together with method of successive approximations. Thanks to this, the possibility of the convergence of the proposed iterative process is eliminated. When calculating the proposed model, there were no cases of slow convergence or non-convergence of the iterative process.

The use of a nonlinear diagram of the deformation of shear bonds obtained on the basis of experimental data made it possible to record changes in the stress-strain state of vertical structures and the bonds connecting them (figures 5 and 6).

**Figure 5.** Plots of normal forces in columns 10, 5 (continuous line - linear calculation, dashed line - calculation with a change in the deformation of the bridges).

**Figure 6.** Plots of shearing forces in bonds 18, 20 (continuous line - linear calculation, dashed line - calculation with a change in the deformation of the jumpers).
3. Results

In bonds №1 and №3, compliance increased by 9% and 11%, respectively; in connection №5, compliance decreased by 26%.

An increase in compliance leads to a decrease in the stiffness of the bonds; accordingly, normal forces in the columns of the diaphragms decrease. In pillars №10 and №21, normal forces decreased by 9% and 8%, respectively (figures 5).

It is noteworthy that the changes affected all the shear links, for example, in №9 and №18, the cutting forces increased by 18% and 17%, respectively (figures 6).

Introduction to the calculation of the algorithm of nonlinear deformation of only shear bonds allows us to fix a noticeable difference (more than 10%) in the level of stress state of some vertical load-bearing structures of the building. This proves that all the elements in the spatial load-bearing system of the building are interconnected and when the strength of one element changes, the redistribution of forces occurs in all load-bearing structures of the building [19-21].

4. Conclusion

The use of nonlinear diagrams of deformation of shear bonds in a discrete-continuous mathematical model introduces significant changes in the stress-strain state of the building's bearing system. This condition is different from the elastic approach.

Studies of the deformability of shear bonds performed earlier are simplified and incomplete. In this regard, there is a need for the accumulation of experimental data with the use of modern loading devices in research to obtain complete strain diagrams of all types of shear bonds. The point values of stiffness do not make it possible to obtain a complete and reliable picture of the stress-strain state of structures, since they are a function of the forces and stresses along the height of a multi-story building.

Information about the experimental data of other shear bonds (for example, fictitious and planar) is very limited. This creates a platform for research and evaluation of their contribution to the redistribution of efforts in the spatial load-bearing system of the building and to determine the state and residual life of panel systems.

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