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Specific Features of Deformation of the Elements of Metal Beam-To Column Flange Connections

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Abstract. Flange connections are structural elements used for joining different members of metal structures, as they determine the rigidity and strength of the structures as a whole. The difficulty of estimating the stress-strain state in the elements of the flanged joints is associated with the following factors: the three-dimensional geometry of the mated parts; the contact interaction between the elements of a bolted joint at the stages of its assembling and operation; the need for mathematical modeling of deformation processes in the framework of the theory of inelasticity. In this paper, the results of experimental and theoretical studies on the deformation behavior of the elements of a metal beam-to-column flange connection are presented. Experiments were conducted on large-scale samples subjected to elastic and inelastic deformations required for complete failure of these samples. Displacements at the characteristic points of the samples were recorded during loading. Relative deformations were measured at the points of the greatest concentration of stresses and strains. Such a set of quantities measured on different scales most accurately characterizes the interrelation of the deformation processes in different elements of the sample, especially when the deformation becomes inelastic. Theoretical studies were concerned with the development of a mathematical model capable of providing an adequate description of the distribution of elastic and inelastic zones in the elements of a flange connection.

Introduction

Flange connections are widely used for connecting the bearing elements of different structures. These connections ensure the rigidity and strength of the structure as a whole. A flange joint is composed of a load-bearing beam and a flat-end element joined by welding or in any other fashion. The joint elements are connected together by high-strength bolts. Flange joints are known to be one of the most effective types of bolted joints, since the high bearing capacity of bolts is used directly and almost completely. The advantages of these joints are as follows: simple assembling, possibility of assembling the structure under different climatic conditions, disassembling the structure without damaging its bearing elements, and manufacturing flanges for bolted connections in factory conditions using automated welding lines. Flange connections exhibit high reliability under dynamic loads, and their maintenance or replacement is quick and easy.

There are many investigations devoted to the analysis of features of the strain state of the elements of flange connections in various embodiments [1]. In [2], a series of full-scale tests were performed using the sample composed of a column and an adjacent beam and subjected to a bending moment applied to the beam, until the connection was broken; the size of the plate and the number of connecting bolts varied. The authors of [3] discovered that the strengthening the flange plate with additional stiffeners increases the strength of the connection, but reduces its deformability. The share of plastic deformations in the reinforced connection decreases and, as a consequence, the ability of the connection to dissipate vibrations due to seismic loads decreases. In [4], one of the approaches aimed at increasing the structural stability to seismic loads is considered. This approach consists in local reduction of the shelves of the beam near the connection with the column. This increases the deformation of the beam and reduces loads applied to the column. In [5], the work of a node with a non-orthogonal adjunction of a beam to a column under conditions of seismic loads is analyzed.

In the experimental and theoretical study of the “column-to-column” bolted joint [6], a detailed mathematical modeling of the node was performed, taking into account the three-dimensional geometry of the columns, flanges and bolts. On the flanges, a contact condition is set, realizing dry friction; the bolt pretension is taken into consideration. Analysis of the structure, consisting of a large number of beams connected by bolted connections, is presented in [7]. A nonlinear calculation of the construction using the method of subconstructions has been performed, which makes it possible to significantly save the calculation time. The behavior of the structure is modeled when one of the flange connection bolts is removed. In experimental-theoretical work [8], the influence of the characteristics of the bolted flange connection "column-beam" on progressing breakdown of the structure is investigated. In [9,10], data are presented on experimental and numerical studies of welded and bolted flange joints under constant and cyclic loads.

Each version of the flange connection has its own peculiarities of deformation behavior, and they become especially significant under inelastic deformation. In the engineering environment, the development and implementation of verified mathematical models that allow analyzing the deformation processes in the elements of flange connections from the elastic state to the complete loss of bearing capacity is an urgent issue.

This paper presents a series of experimental and theoretical studies to analyze the mechanisms governing the quasistatic deformation processes in bolted flange connections. The complexity of assessing the stress-strain state in the elements of such connections is determined by the following factors: the three-dimensional geometry of the coupling parts; the contact interaction in bolted connections at the stages of installation and operation of the joint; the need for mathematical modeling of the deformation process within the framework of the theory of large elastoplastic deformations. If the first factor is easily overcome with the use of software based on the finite element method, then the next two ones require experimental and theoretical studies that could provide a reliable mathematical modeling of the stress-strain state in the elements of the flange connection.

Experiment description

The diagram of a flange connection sample is shown in Fig. 1. The sample consists of a vertical column and two symmetrically located horizontal beams of I-Beam shape. Horizontal beams are connected to vertical column by eight bolts.

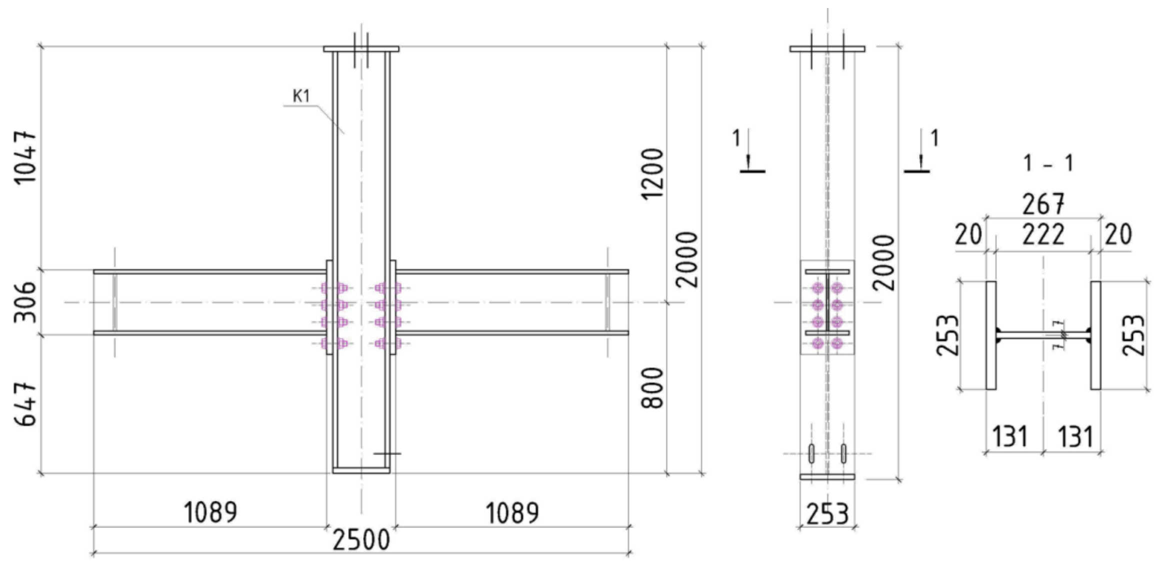


Fig. 1. Flange connections of the sample (dimensions are given in millimeters).

For the experimental study of the deformation processes in the connection elements, a test stand has been developed. The structural diagram of the stand, loading scheme and registration system location are shown in Fig. 2. The sample consisting of vertical column 3 and horizontal beams 4 is loaded in power frame 1 using hydraulic jacks 5 connected to the common hydraulic line, which ensures symmetrical loading of the sample throughout the experiment.

The figure shows: F, 2F – reaction forces arising, respectively, in the horizontal beams and the column from the action of the jacks; U1, U2, U3 – location of vertical displacement sensors; E1, E2 – location of sensors for measuring deformation in a horizontal direction, EF – location of sensor for measuring deformation along the vertical beam axis.

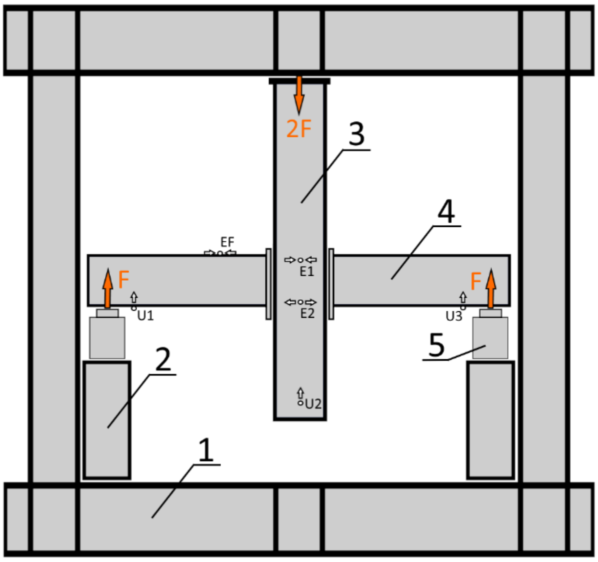


Fig. 2. The structural diagram of the test stand with the sample having flange joints

The registration system includes three displacement sensors and three deformation ones. Vertical displacements of the horizontal beams and of the lower end of the vertical column with respect to the independent reference base were measured. Measurement points U1, U2 are located in the vicinity of the places of force application. Such a scheme for measuring vertical displacements made it possible to control the symmetry of the deformation relative to the vertical column, and also to determine the value of the vertical displacement of the column only due to the entire set of the deformations in the flange connection.

The positions of sensors E1-E4 and EF are determined according to the results of mathematical modeling of the quasistatic elasto-plastic deformation process in bolted connections. The E1-E4 sensors record the dominant strain along the horizontal axis on the shelf of the vertical column. The EF sensor is fixed on the upper shelf of the horizontal beam at a distance of 33 cm from the flange. This position ensures the absence of plastic deformations at this point and allows one to control the effort from the jacks.

Fig. 3 shows a graph of the external force *F*, given by the jacks, versus time *t*. This force has a periodic character with increasing maximum value and unloading to zero on each cycle. Such a character of the external force makes it possible to determine the force at which inelastic components appear in the recorded deformations and also to estimate the measure of accumulated inelastic deformations caused by an external force. These results are used to verify the mathematical model.

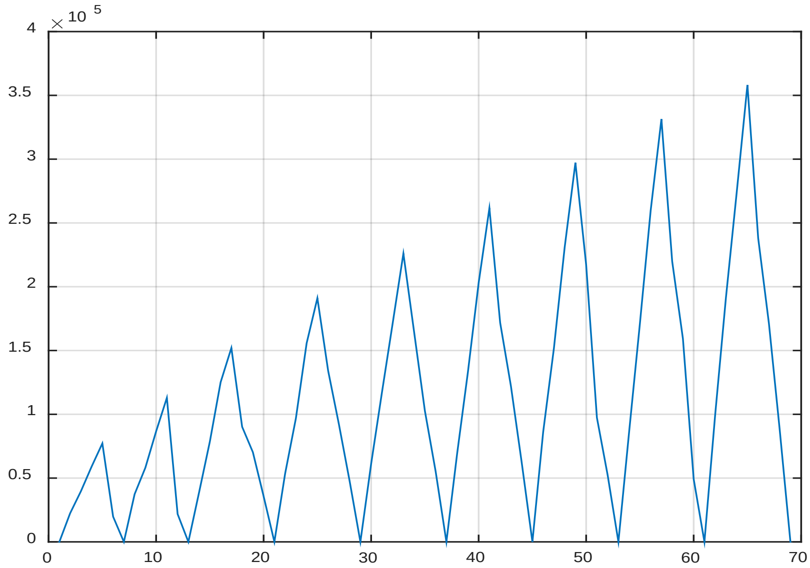


Fig. 3. The dependence of external force *F*(N) on time *t* (min)

Mathematical model

The computational model consists of 19 parts: a column, 2 beams, 16 bolts. To describe the mathematical model of the group of these bodies, we introduce the superscript ^{k}, which indicates that the variable belongs to the corresponding body. The initial position of the points of each body is given by the radius vectors $\mathbf{X}$, and the deformed position by the vectors $\mathbf{x}$. The radius vectors, determining the initial state and deformed one, are calculated in the initial coordinate system $\mathbf{E}_j$. The relationship between the initial and deformed states is determined by the deformation gradient tensor $\mathbf{F}$ with components $F_{ij} = \dfrac{\partial x_i}{\partial X_j}$.

Indices i, j take the values 1, 2 and 3. The moving coordinate system associated with the body $\mathbf{e}_i$ is obtained as follow

$$\mathbf{e}_1 = \frac{\mathbf{e}'_1}{|\mathbf{e}'_1|},\ \mathbf{e}_2 = \frac{\mathbf{e}'_1 \times \mathbf{e}'_2}{|\mathbf{e}'_1 \times \mathbf{e}'_2|},\ \ \mathbf{e}_3 = \mathbf{e}_1 \times \mathbf{e}_2, \tag{1}$$

where $\mathbf{e}'_i = \mathbf{F} \cdot \mathbf{E}_i$ are the auxiliary vectors. The rotation tensor, connecting the original coordinate system with the moving one, has the form of $\mathbf{R} = \mathbf{e}_i \otimes \mathbf{E}_j$.

The mechanical behavior of each body is determined by a set of equations.

- *Equilibrium equations*

$$\frac{\partial \sigma_{ij}^k}{\partial x_j} = 0, \tag{2}$$

where: σ_{ij}^k is the stress tensor; x_j is the Cartesian coordinates in the reference configuration.

– *Geometric relationships*

$$\boldsymbol{\varepsilon}^k = \mathbf{R}^k \cdot \mathbf{L}^k \cdot \left(\mathbf{R}^k\right)^T, \tag{3}$$

where $\boldsymbol{\varepsilon}^k$ is the deformation tensor in the moving coordinate system; $\mathbf{L}^k = \frac{1}{2}\left(\left(\mathbf{F}^k\right)^T \cdot \mathbf{F}^k - \mathbf{I}\right)$ is the deformation tensor in the original coordinate system; $\mathbf{I}$ is the unit tensor.

– *Physical equations*, which take into account plastic deformations and are given in increments, are

$$d\boldsymbol{\sigma}^k = \mathbf{D}^k \left(d\boldsymbol{\varepsilon}^k - d\boldsymbol{\varepsilon}^{k,pl} \right), \tag{4}$$

where $d\boldsymbol{\sigma}^k$ is the stress tensor increment; $\mathbf{D}^k$ is the tensor of elastic constants; $d\boldsymbol{\varepsilon}^k$ is the deformation tensor increment; $d\boldsymbol{\varepsilon}^{k,pl} = \lambda \dfrac{\partial Q(\boldsymbol{\sigma}, w)}{\partial \boldsymbol{\sigma}}$ is the plastic deformation tensor increment; (this form corresponds to the associated plastic flow law); w is the work of plastic deformations.

– *Contact conditions* are set on the surfaces of the abutment: a beam-column, a bolt-beam and a bolt-column. They correspond to the dry friction model and are given as inequalities. The first inequality sets the condition of non-penetration of surfaces

$$(\mathbf{U}^{k2} - \mathbf{U}^{k1}) \cdot \mathbf{n}^{k1-k2} \ge 0\,, \tag{5}$$

the second one limits the tangential force on the contact area

$$\tau \le K^{fr} \cdot P\,, \tag{6}$$

where: $\mathbf{U}^{k1}$ and $\mathbf{U}^{k2}$ are the displacement vectors at the contact points of the contacting bodies numbers $k1$ and $k2$, respectively; $\mathbf{n}^{k1-k2}$ is the normal vector to the contact surface, which is calculated with respect to body $k1$ in the contact area of bodies $k1$ and $k2$; $\boldsymbol{\sigma}^{k1}$ is the stress tensor on the contact surface of the body $k1$; $P = \boldsymbol{\sigma}^{k1} \cdot \mathbf{n}^{k1-k2} \cdot \mathbf{n}^{k1-k2}$ is the normal stress at the contact point; $\tau = \left| \boldsymbol{\sigma}^{k1} \cdot \mathbf{n}^{k1-k2} - P \cdot \mathbf{n}^{k1-k2} \right|$ is the tangential stress at the contact point; K^{fr} is the friction coefficient.

- *Boundary conditions:*

$$\mathbf{U}^k \Big|_{\mathbf{X} \in S_u^k} = f_u^k\,, \tag{7}$$

$$\sigma^k \Big|_{\mathbf{X} \in S_\sigma^k} = f_\sigma^k\,, \tag{8}$$

where f_u^k is the displacement distribution function on the contact surface (for the body number k); f_σ^k is the stress vector distribution function on the surface where external forces are applied (for the body number k).

The described mathematical model is solved numerically by the finite element method. Fig. 4 shows the finite element mesh. The elements use the quadratic approximation of displacements. The number of nodes in the design scheme is 52491. The size of the element in the contact area is 2 centimeters.

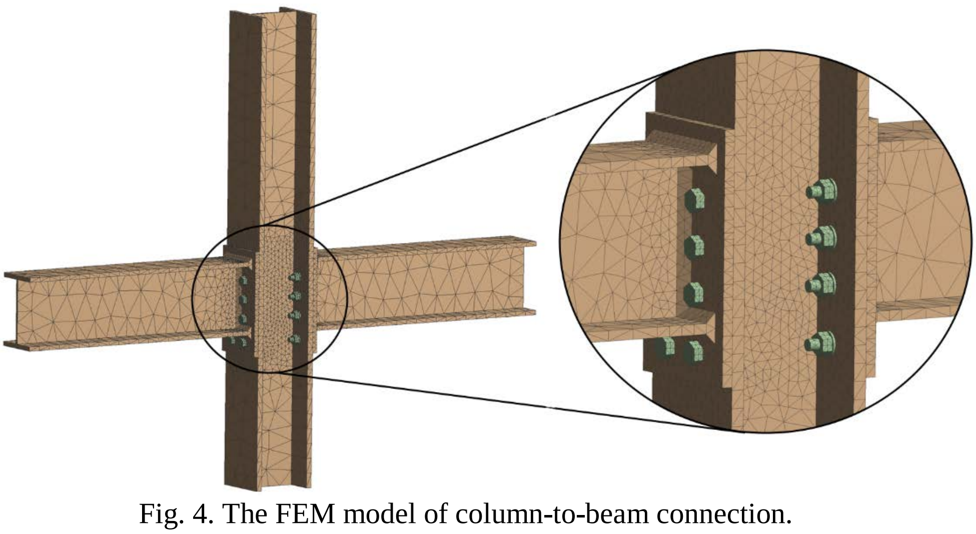


Fig. 4. The FEM model of column-to-beam connection.

Results and Discussion

Five samples of flange connections were used to realize the experimental study. Based on the results of the first experiments, the mathematical model was corrected. In particular, the conditions for contact interaction in bolted connections were determined and the corrections were made to the values of the parameters of the physical equations for the elastic-plastic flow of metal.

Below one can find the results of experimental studies, in which the deformation parameters were measured, and the results of mathematical simulations. These data were obtained for the external force *F(t)* applied to the jacks and varying according to the law shown in Fig. 3.

Fig. 5 shows the time dependence of the averaged value of vertical displacements at points *U1* and *U3* of the horizontal beams on the displacement of the vertical column at point *U2* (Fig. 2):

$$U(t) = \left[U_1(t) + U_3(t)\right]/2 - U_2(t) \tag{9}$$

Here, $U_1(t), U_2(t), U_3(t)$ are the vertical displacements relative to the reference base at the corresponding point of the structure. The red line indicates simulation results, and the blue one - experimental data. The value *U(t)* can be regarded as a macro parameter that integrally reflects all the deformation processes occurring in the vicinity of the bolted connection, including inelastic and contact interactions. Therefore, *U(t)* can be used as an informative parameter in the monitoring of the deformation processes in the flange connection. From the obtained results it follows that when we apply the load exceeding 150kN to the jacks and then unload the sample, no "elastic" return occurs, i.e. the value *U(t)* does not return to zero, and thus no inelastic deformation develops in this case.

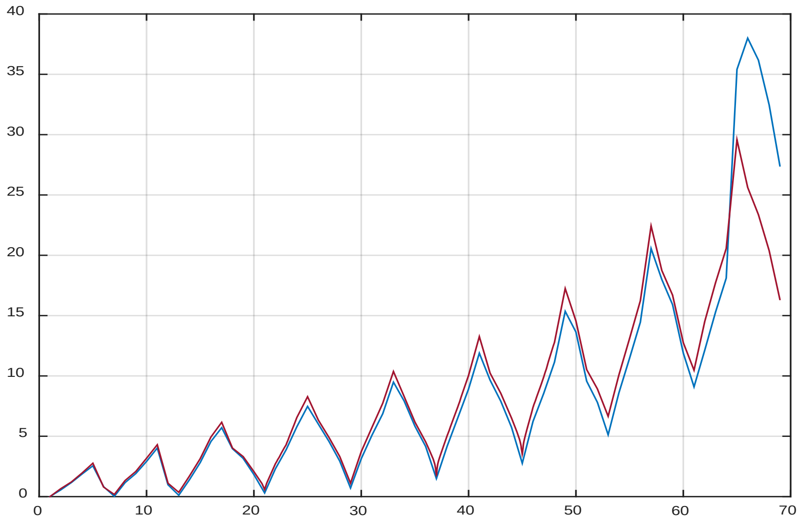
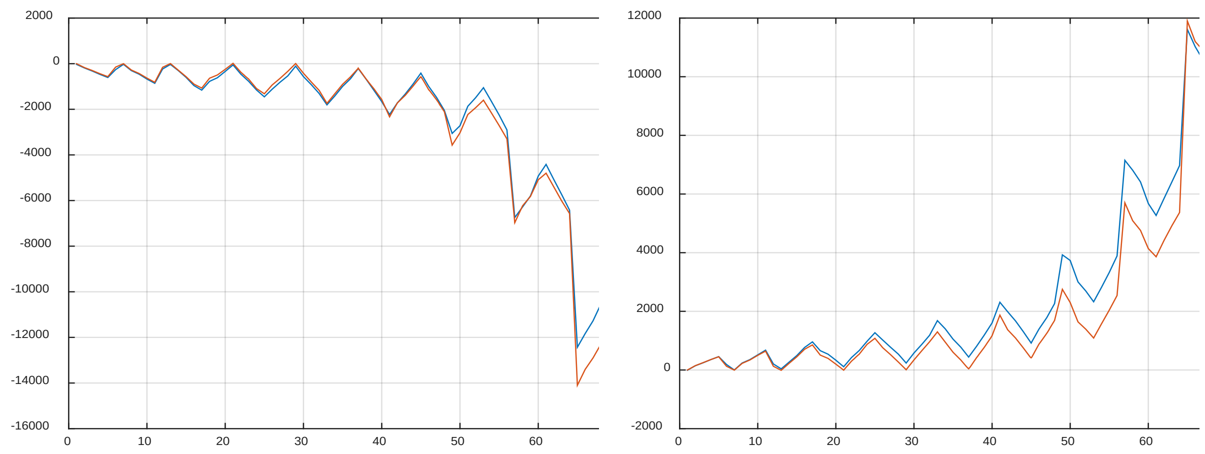


Fig. 5. Vertical displacement *U(t)* (mm) versus time *t* (min)
(red line - simulation, blue one - experiment)

Fig. 6 shows the local deformations ε_1 and ε_2 (in the horizontal direction) of the vertical column in the vicinity of the bolted connection depending on time *t*. These deformations correspond to points E1 and E2 (Fig. 2) where strain gauges are installed.



a) b)

Fig. 6. Deformations ε_1 (μm / m) at point E1 (a) and ε_2 (μm / m) at point E2 (b) versus time *t* (min): (red line - simulation, blue one - experiment)

Based on the results, it can be concluded that $\varepsilon_1 < 0$ (compression) is realized at point E1 and $\varepsilon_1 > 0$ (tension) is realized at point E2. It is interesting that the inelastic behavior of the metal in the compressed zone begins at higher loads than in the extended zone (at jack forces of 225kN and 190kN, respectively). At the same time, the beginning of the inelastic zone with respect to the vertical displacement parameter *U(t)* (Fig. 5) corresponds to the jack force of ~ 150 kN, which can be caused by the inelastic contact deformation in the bolted joint.

Conclusion

We have performed a number of experimental and theoretical studies to investigate the deformation behavior of a metal bolted flange connection under quasistatic deformation.

The experimental measurements of the deformation parameters on the samples representing full-scale flange joints made it possible to verify the mathematical model of deformation processes within the framework of the theory of elasticity.

Analysis of simulation results and experimental measurements allowed us to determine the deformation parameters reflecting mechanisms that govern the strain state in the vicinity of bolted joints. These parameters are essential in monitoring bolted flange connections.

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