Contribution of Clearance Holes to Semi-rigid Effects of Bolted Joints

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Abstract. This paper presents an analysis of semi-rigid effects of bolted joints occurring due to clearance holes and manufacturing tolerances at temporary fixing and the exploitation stages. The manufacturing requirements of SP 53-101-98 ‘Production and Quality Control of Steel Structures’ and GOST 23118-2012 ‘Building Steel Structures. General Specifications’ are used for calculations. Friction-grip joints with high-strength bolts are considered as well as joints with ordinary structural bolts. Different permissible assembling technologies are reviewed to account a non-linear behaviour of the joint at temporary fixing and during the operational stage. The recommendations were developed for the scheduling of mounting works which can provide convergence between the design of a whole building and the consequential calculations of mounting schemes.

1. Introduction
The last century saw the evolution of analysis methods of semi-rigid joints: the slope-deflection equation and moment distribution methods, to matrix stiffness methods, iterative methods. Studies agree that in frame analysis, joint rotational behaviour should be considered.

In practice bolted joints are usually assumed either hinged or rigid. This simplification leads to an incorrect estimation of frames behaviour. In fact, the connections are between the two extreme assumptions and possess some rotational stiffness. Existing studies reveal, that accounting of semi-rigid behavior of joints is very important for different problems such as optimum design of steel structures [1-4], seismic-force resisting systems [5,6] and other applications.

There are a lot of different models of semi-rigid joints [7-11] which describe behaviour of structure in operational stage, but semi-rigid effects of temporary fixing is beyond of this studies. Calculation scheme of frames is changing while construction process, hereby total stress-strain state is depends on stiffness's of joints and mounting sequence. Hence, semi-rigid behavior of joints in pre-exploitation stage should be considered.

Modern building industry goes from standard unified solutions to individual projects. Monolithic reinforced concrete is widely used in buildings with metal frames, which leads to decreasing in the degree of industrialization of construction and installation works. The transfer of basic technological processes to the construction site negatively affects both the cost of construction and the quality of the works.
One of the largest part of the direct costs in construction site is the operational cost of machines and mechanisms including the salary of machinists, hence the main objectives of optimizing the organizational and technological solutions for assembling can be formulated as follows:

- the framework assembly must be the leading flow of work schedule;
- all structures should be temporary fixed and released from slings as earlier as possible to obtain minimal downtime of lifting devices (cranes);
- the structures should be enlarged down on the ground for reducing amount of works in height and amount of elements for lifting.

Bolt holes usually have to be 2–3 mm larger than the nominal bolt diameters [12,13]. This allows to increase the collection rate of metal structures and simplify the installation. The joint receives initial deformations under the own weight of structures. These deformations depend on the size of the tolerances and the height of the cross-section. These deformations are usually ignored in calculations.

2. Initial deformations

2.1. Clearance holes and manufacturing tolerances

Using the well-known equations of structural mechanics, we can derive a equation for the angle of rotation \( \phi_p \) of the support section of a beam on two hinged supports at maximum load. For example, for the case of a uniformly distributed load and a symmetrical section:

\[
\phi_p = \frac{qL^2}{2AEI} = \frac{8ML}{24EI} = \frac{WRL}{3EI} = \frac{2RL}{3Eh}
\]

where \( q \) – uniformly distributed load; \( L \) – distance between supports (span); \( E, R \) – respectively the modulus of elasticity and the yield stresses of the beam material; \( h, W, I \) – respectively, height, section modulus and second moment of area of the cross-section of the beam.

We can find equations for other types of loading in the same way. It should be noted that the angle of rotation of the cross-sections depends only on the material and the ratio between the height of the neutral line of the beam and the span.

We use the hypothesis of small deformation. Before the bolts begin to be subjected shear forces in the plate joint we can find the maximum rotation \( \phi_0 \) of the cross-section of the beam as:

\[
\phi_0 = \tan \phi_0 = \frac{s}{h}
\]

where \( s \) – maximum relative horizontal displacement of bolts of different shelves on the different sides of the joint.

Equating the angles of rotation of the cross-section according to equations (1) and (2) it is possible to find minimal length of beam, which start incorporating bolts in the shear resistance of connection. For example, I-beam made of steel C245 with holes clearance of beam-column connection equal to 2 mm, which made without deviations from the project has a minimal length for non-pinned behaviour:

\[
L_{\text{min}} = 1.5 \frac{sE}{R} = 1.5 \frac{0.008 \cdot 206000}{240} = 10.3 \text{ m}
\]

As you can see, the problem of initial deformations of bolted joints is relevant for almost all spans used in steel structures.

The tolerances of diameters of the holes increase the initial deformation of the joint, and at maximum tolerances [13] can reach \( s = 2.4 \) mm for holes with a nominal diameter up to 17 mm and \( s = 4 \) mm for holes with a nominal diameter exceeding 17 mm (for high-strength bolts and ordinary bolts of classes B and C). The relative displacement of the holes can both increase and reduce the
possible rotation of the section. In accordance with \([14]\), the displacement of holes axes is allowed within \(\pm 1\) mm. Otherwise, assembly capability is not guaranteed.

In addition, the tolerances for hole diameters can be compensated by the discrepancy of the length of the beam (\(\pm 3\) mm with the beam length up to 6 m and \(\pm 5\) mm from 6 m) and the deviations of the columns. Because of this, the incorporating bolts in the shear resistance of one flange occurs later than the other, changing the stress-strain state of the support part of joint but not affecting the rigidity of the unit as a whole.

2.2. Clearance holes and manufacturing tolerances

Summarizing the foregoing, it can be concluded that the design stiffness of the temporary fixing with a beam length less than \(L_{\text{min}}\) can't be provided by the work of the bolts on the slice. For connections on bolts of strength class not exceeding 8.8 this means that part of the bending moment (and possibly the whole) will not be carried by the bolted connection, and therefore the corresponding part of the load should be considered throw the hinged scheme.

In friction-grip joints it is assumed that all effort should be carried by frictional forces between elements tightened by high-strength bolts. During installation, this condition may not be provided due to the insufficient tension of the bolts and the reduced number of bolts allowed \([15]\). At the same time, there are currently no additional guidelines for the calculation of temporary connections, taking into account the differences between requirements for design fixing and temporary fixing.

| Table 1. Characteristics of connections. | Ordinary 5.8 | High-strength 10.9 |
|-----------------------------------------|--------------|-------------------|
| M16 | M20 | M24 | M16 | M20 | M24 |
| Maximal tightening with a wrench, kN | 58.5 | 62.4 | 71.5 | 58.5 | 62.4 | 71.5 |
| Friction force for 1 bolt, kN | 14.6 | 15.6 | 17.9 | 33.9 | 36.2 | 41.5 |
| Design shear resistance per 1 bolt, kN | 42.2 | 65.9 | 94.9 | 68.8 | 107.3 | 154.6 |
| Ratio between temporary friction forces and design resistance, % | 34.6 | 23.6 | 18.9 | 49.3 | 33.7 | 26.8 |

The maximum force of worker which can tighten the bolt without using a torque wrench is several times less than the design tension of the bolt for the friction-grip joint. Hence, it follows that in the calculation it is necessary to take into account the decreasing of the bearing capacity of the connection. When using bolts without controlled tension, the frictional force is assumed to be insufficient to carry the weight of the structures (Table 1), so we ignore it in the calculation.

The tension force is found from the equation:

\[ P = \frac{M}{K_d} \]

where \(M\) is the twisting moment with a force of 343 N by proper wrench \([15]\); \(K_d = 0.11\) is the minimum allowable twisting coefficient according to the specifications of high-strength bolts; \(d\) is the nominal diameter of the bolt.

The bearing capacity of the connection in terms of one bolt is determined in accordance with the requirements of \([12]\). The coefficient of friction of the painted elements is less than 0.25. The thickness of the details is considered sufficient to avoid crumple.

3. Scheduling

The design scheme of the building during the construction period doesn't correspond to the design one, hence it's difficult to determine the load-carrying capacity of the frame elements and joints. Sufficient
accordance between the real scheme and the project can only be achieved when concrete works are two levels behind mounting of framework. In this case, more than 4 spans should be built in parallel. For floor-by-step division into work zones this means that the workflow step three times longer than the installation of one storey, which is completely unacceptable from the point of view of optimizing the time schedule.

Reduction of workflow step is possible at the beginning of concreting with a delay in mounting by 1-2 work zones. In this case, it is necessary to take into account the reduction in the rigidity of the loaded level. Depending on the type of structural connections, it may also be necessary to take into account semi-rigid behaviour of bolted joints.

Ordinary bolted joints (without tension control of bolts) should be considered pinned during the mounting stage due relatively large mounting tolerances. In this case flanges are not included in the work until the beam reaches certain deflections, achieved only with loads greater than the mounting ones, hence flange plates can be installed after releasing from slings. For a temporary connection it is sufficient to install the bolts only along the wall in the required amount [15] to carrying the own weight of the element and the loads resulting from the installation.

4. Conclusions
As we can from Table 1, the initial deformations of the joints occur with forces more than two times lower than the design resistance. Temporary fixings with ordinary bolt classes up to 8.8 should be considered as pinned, taking into account the fact that [15] allows temporary fixing of 1/3 of the design number of bolts. Since the shear work of high-strength bolts in friction-grip joints is not allowed, amount of bolts for the temporary fixing should be sufficient to carry mounting loads at a reduced bearing capacity of connection. Otherwise, the design fixing must be done before the slings releasing, which negatively affects the efficiency of the scheduling of lifting machines. This problem can arise when the beams are enlarged in the overly big mounting blocks.

Increasing the rigidity of the framework increases the supporting moments of the beams. Low-deformative temporary connections should be calculated to support this moments. For high-deformative connections it does not matter, since they can't practically carry the moment at the stage of temporary-fixing.

The rigidity of the joints of upper floors is determined only by the underlying part, therefore the beginning of concreting can be made with a minimum time gap from installation in order to reduce the construction time. The time of concreting on one work zone should be reduced so that the beginning of the flow of concreting coincides with the end of the installation of the required number of floors. The works safety in time of intersections of work brigades one under another can be received by replacement two adjacent work zones for concrete workers.

The intensification of the installation of steel frames for multi-storey buildings with monolithic floors may lead to the collapse of buildings under construction because temporary connections, calculating in accordance with the assumptions [15], sometimes don't provide sufficient stiffness. Reducing the workflow step reduces the rigidity of the frame during the installation stage, hence it can be used in a limited number of cases. A safe way to reduce the construction time is a certain departure from the principle of flow, with the separation of a part of the framework in a separate workflow of installation without the first few floors.

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