Experimental determination of yield in beam-to-column flange connections

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Abstract. The paper describes a universal test bench, designed to conduct full-scale studies of the strength and stiffness of joints of building structures. The paper present the results of full-scale tests of the joints of beam flanged connections with columns in the elastic and elastoplastic stage with the determination of the dependence of their yield on the value of static loads. The study was conducted on 12 models with both one-sided joining of the beam to the column, and with two-sided, for which the flange thickness, resistance class and the controlled tension of the bolts, loading scheme were varied. The experiments were carried out according to a multifactorial plan until the destruction of the models. According to test results, 4 characteristic trilinear diagrams were obtained for dependence of the angles of rotation versus bending moments. The obtained results can be used in the design of flange connections and during the verification of their design models.

1. Introduction
Metal frame is one of the main structural schemes of a building, especially of a high-rise one. In the Russian practice of designing such systems, joints of cross-bars with columns are considered to be either absolutely rigid or ideal hinges. In reality, these joints have a certain yield, confirmed by numerous researches. In study [1], a calculation was made of a flange joint, reinforced by different variants of stiffeners and plates on the web panel of columns. Introduced additional structural elements decreased the yield of the joint, however the joint could not be made rigid according to the Eurocode classification [2]. Paper [3] considers a “hinged” connection joint of an I-beam through angular bolted plates. The paper points out that such a joint has certain rigidity and sustains a certain moment. Not taking into account the joints yield may result in significant errors when performing a frame static calculation, namely: redistribution of internal forces incorrectly calculated deflections and rolls.

Currently, there is an ongoing bulk of research aimed a calculation, construction, and design of construction joints [4]. The highest priority is the joints of crossbars with columns as they have the most complicated stress-strain state.

To a large extent, the research is driven by the major catastrophes of the late last century: earthquakes in Northridge (USA) and Kobe (Japan). In Kobe, more than 200 thousand structures have been destroyed, making apparent the deficiencies in their construction. In Northridge, over 150 metal frames had been damaged in the area of joint between cross-bar and column [5]. This damage was a fragile fracture caused by high rigidity of joints and use of welding connection between beams and columns.
The analysis of damage resulted in the conclusion that the rules for design of metal frame joints have to be revised [2,6]. For instance, instead of welding, bolted connections might be used due to their higher yield and elasticity. Paper [7] discusses options of state-of-the-art bolted connection joints. One of the key characteristics of a joint is its yield, especially in view of plastic deformation. Yield of the joint is discussed in terms of its dependence on stiffeners and their absence in [8,9], on the number of bolts in a series of flange connections in [10], on flange thickness in [11].

2. Normative approach to the calculation and design of flange connection joints

When designing rigid joint design, the aim is to eliminate any slightest turn of the support section of the beam. In 1989 series 2.440-2, flange connections of frame joints are designed with multiple structural elements: stiffeners, haunches, backing plates etc. Sequences of numerical [12,13] and full-scale tests [4,11,14] show that connection reinforcement results in higher strength but lower deformability of the connection. The extent of plastic deformation in a reinforced connection decreases, which entails reduction of the connection’s ability to dissipate oscillations caused by seismic load.

According to Eurocode 8, seismic design of buildings should include diffusion areas which should be designed either at the beam-to-column joint or at the beam, e.g. local reduction of beam flanges adjacent to the column connection – the so-called ‘dog-bone connection’ [6]. EN (1993-1-8-2009) is based on component method of calculating joints which focuses on the fact that the joint is a combination of basic components [2]. The basic components of the joint are presented in table 6.1 EN. The load-carrying capacity of a joint as a whole is determined on the basis of load-carrying capacities of its basic components. When design the nodes, you can apply a linear-elastic or elastic-plastic calculation. The calculated dependence “bending moment – rotation angle (M-ϕ) of the flange connection joint” is a function of the following properties of its basic components: column web panel in shear (1), column web in transverse compression (2), column web in transverse tension (3), column flange in bending (4), end-plate (flange) in bending (5), bolts in tension (10). According to EN beam or column flange and web in compression (7) and beam web in tension (8) have infinite rigidity. Yield of a joint is a total of yields of sequentially connected and paralleled connected “springs” (Fig.1.[1]).

![Figure 1. Components of a joint under Eurocode.](image)

On the basis of the component method and the finite element method, Component Based Finite Element Method (CBFEM) has been developed, where a number of main components are modeled with finite elements, for example, webs and flanges of beams, whereas for other components, stiffnesses are calculated using EN formulas. Study [1] offers a comparison between analyses of numerical models using CBFEM and results of full-scale models testing. The basic criteria for comparison were the limiting perceived moment and the angle of rotation of the support section of the beam. Verification of the carrying capacity has shown high reliability of results, the calculated values
of the moments were 5-14% lower than the experimental ones. The check on displacements revealed insufficient compliance of numerical models, the rotation angles turned out to be 25–90% lower than those obtained during the experiment.

The most important EN postulate, which appears in p.2.5, 5.2.2.1, 6.4, etc., can be summarized as follows, the design characteristics can be obtained either on the basis of experimental data or on the basis of the corresponding computation model, verified by test results.

3. Research objective
To perform full-scale tests of joints of beam-to-column flange connections in elastic and elastoplastic stage in order to determine the true dependence of their yield on the static load value.

To test the connections, a load frame (universal test bench) was developed, representing a closed loop (Fig. 2), the connection of the racks and frame beams is rigid. Inside the load frame, unilateral and bilateral beam-to-column connections can be tested.

![Test bench with full-scale model](image_url)

**Figure 2.** Test bench with full-scale model: 1 – force loop of the test bench; 2 – hydraulic jacks (lifting capacity: 2.1- 56t, 2.2-109t, 2.3- place of installation of the third jack to create additional longitudinal force in the column of the full-scale model); 3 – linear displacement sensors (3.1 - for measuring the deflections of beams, 3.2 – for measuring column vertical displacement, the sensor is positioned on the rear side of the full-scale model); 4 – linear displacement sensor to measure horizontal displacements; 5 – deformation measuring sensors (resistance strain sensors are glued to the frontal and rear side of the full-scale model column web); 6- manometers fixing pressure inside the hydraulic line; 7 – protective shield; 8 – multi-channel universal meter-recorder; 9 – jack support; 10 – arrester perceiving horizontal pressure and transmitting it to the force loop.
Testing can be performed with various loading patterns of full-scale models: symmetric, when installing jacks of equal load-bearing capacity under the ends of beams, asymmetric, it is created by jacks of different carrying capacity.

A 3rd jack can be installed under the column of the full-scale model to create additional longitudinal force in it.

4. Description of full-scale models
The cross sections of full-scale models are designed as per GOST R 57837-2017 “Hot rolled steel I-beams with parallel flange edges” and are made of welded S345 steel sheets. Loading of samples is carried out by jacks. Jacks, creating a moment in the connection, are installed at a distance of 1m from the outer surface of the flange. The experiment comprised the following independent variables: flange thickness (16, 20, 24, 30 mm), bolt resistance class (8.8, 10.9), loading scheme (one-sided, symmetrical, asymmetrical, with an additional jack under the column). Tolerance of structural elements corresponds to the Code of Practice SP 53-101-98 ‘Production and quality control of steel structures”. The samples were mounted according to SP 70.13330.2012 “Load-bearing and separating constructions”. The tension of the bolts was controlled by tightening torque 900 Nm and 1100 Nm for 8.8 and 10.9 bolts, respectively. The quantity of tested models is 12 (Fig.3.).

Figure 3. Full-scale model drawing (dimensions in millimeters).

5. Results of the experiments
In 2016-2018, the laboratory of the Construction Department of the Perm National Research Polytechnic University performed tests of flange connection full-scale models (Fig.3.). The experiments followed a multi-factor plan until to the destruction of models in the amount of 12. Based on the obtained measurements and calculations of moments and rotation angles, 4 characteristic trilinear M-ϕ graphs have been built (Fig. 4.). Graph 2 has been obtained for models with one-sided beams junction, flange thickness in the experiment was 20 mm. Graphs 1,3,4 have been obtained for models with two-sided joining of beams, for flanges with thicknesses 16, 20–24, and 30 mm. respectively.
The loading of the models was carried out by loading-unloading cycles with the increment of the applied bending moment in the joint of the beam with a column of 2.5 tons per each new cycle [15]. Such loading history was used to determine the load causing plastic deformation in the model.

After removal of the applied forces, i.e. at the unloading stage, if the displacements and deformations of controlled points returned to their original state at the initial moment of time, then the full-scale model still works elastically. Otherwise, if the strain gages and displacement sensors recorded an increment of indications, then the model contains plastic deformations.

Experiments revealed that residual deformations in the transverse direction in the web panel begin to appear earlier in the stretched zone. For instance, during symmetric testing of samples with a flange of 16 mm after removing the moment of 10 tm, residual deformations in the transverse direction of the web panel at points on the symmetry axis of the model can be up to 100 µm / m. A similar level of residual deformations in the compressed zone is achieved by applying the load of 15 tons. Despite the relatively early appearance of plastic behavior, it does not significantly impact the yield of the joint until the load reaches of 15-20 ton.

The graphs show that regardless of various parameters (flange thickness, bolts) and loading configurations, the initial rigidity (c) of all models was the same and amounted to c=4800 tm/rad. Flange thickness increase results in later manifestation of plastic behavior, which leads to the continuation of the initial straight line M=сф line. For two-sided beam-to-column joining for flange thicknesses 16, 20-24, 30 the end points of the initial line correspond to moment values 22.5, 25, 28.3 tm and, in the case of linear calculations, the bearing capacity of the node should be limited by these values.

In one-sided beam-to-column joining, the decrease in stiffness begins earlier, with a flange thickness of 20 mm it occurs at a load of 15 tm. This phenomenon is caused by shear deformations in the column web.

6. Conclusion
A series of experimental and theoretical studies of the features of deformation behaviour under quasistatic deformation of a metal bolted flange connection has been carried out. Testing of full-scale models of beam-to-column flange connections was performed according to the loading schemes corresponding to real behavior of joints in frame type buildings.

The obtained results can be directly used in the design and construction of joints similar to full-scale models. Since using numerical models without experimental verification under EN is
unacceptable, the obtained results should form the basis for confirming the correctness and adequacy of the design models, including finite element ones, intended for calculating the joints of flanged connections.

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