

Parallel experiments of numerical and full-scale models of flange joints of the beam-column type

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Abstract. The paper discusses a multi-factor experiment method for determining the strength and stiffness of flanged beam-to-column connections. The method suggests two identical models – full-scale and numerical development. Models are matched by geometry and initial imperfections, physical properties of materials, boundary conditions and full loading history. They are matched by displacement and deformation at each loading stage of the models. When the results match, the conducted experiments can be stated and obtained mathematical models are correct and valid, hence using expensive full-scale models in further research can be avoided.

1. Introduction (problem description)

The main objective of structural design and analysis is to ensure reliability and cost efficiency through introduction of effective design methods. This can be achieved through matching analytical models and actual physical behavior of structures, determined by way of full-scale experiments.

In Russia, testing of full-scale models (FSM) of beam-to-column flange connections (FC) has not been conducted, that fact was resulted in current absence of national engineering standards in this field. Joints of this type are designed in Russia based on an old practice for joint series 2.440-2 dd. 1989, which results in physical installation of many unnecessary structural elements, such as support bracket, stiffeners, backing plates, haunch etc.

Since FC is one of the most technologically effective and economical types of rigid connection between elements, the problem arouses intensive scientific and practical interest. Many instances of FC research use mathematical modeling [1, 2], however every model requires verification by experiment.

The most frequently reproduced experiment in flange behavior research is elementary T-shaped flanges test [3]. It only gives a relative understanding of certain bolts and flanges behavior, and it does not provide a full picture of the entire joint's behavior. Separation of FC into individual T-shaped elements is the basis of Eurocode-based design of such joints.

Full-scale experiments are extremely rare due to their high cost. Among the experimental research of flange connections, Emmet A. Sumner's study is worth special notice. The experiment was conducted in Virginia Polytechnic University [4]. A. Sumner tested 11 FSMs of flange connections with bilateral and unilateral abutment of beams for cyclic loading effects (approximately 30 loading cycles). In Sumner's research there are some inconsistencies. Firstly, stress-strain state of column in the test rigs of his design does not correspond to their real behavior, as the experiment with bilateral abutment of beams was based on a skew symmetric scheme and axial force in the column was equal to



zero. In case of unilateral abutment, the occurring axial forces are both negative and positive, as one section of the column was extended and the other compressed. Secondly, strain measurement was not performed during the test.

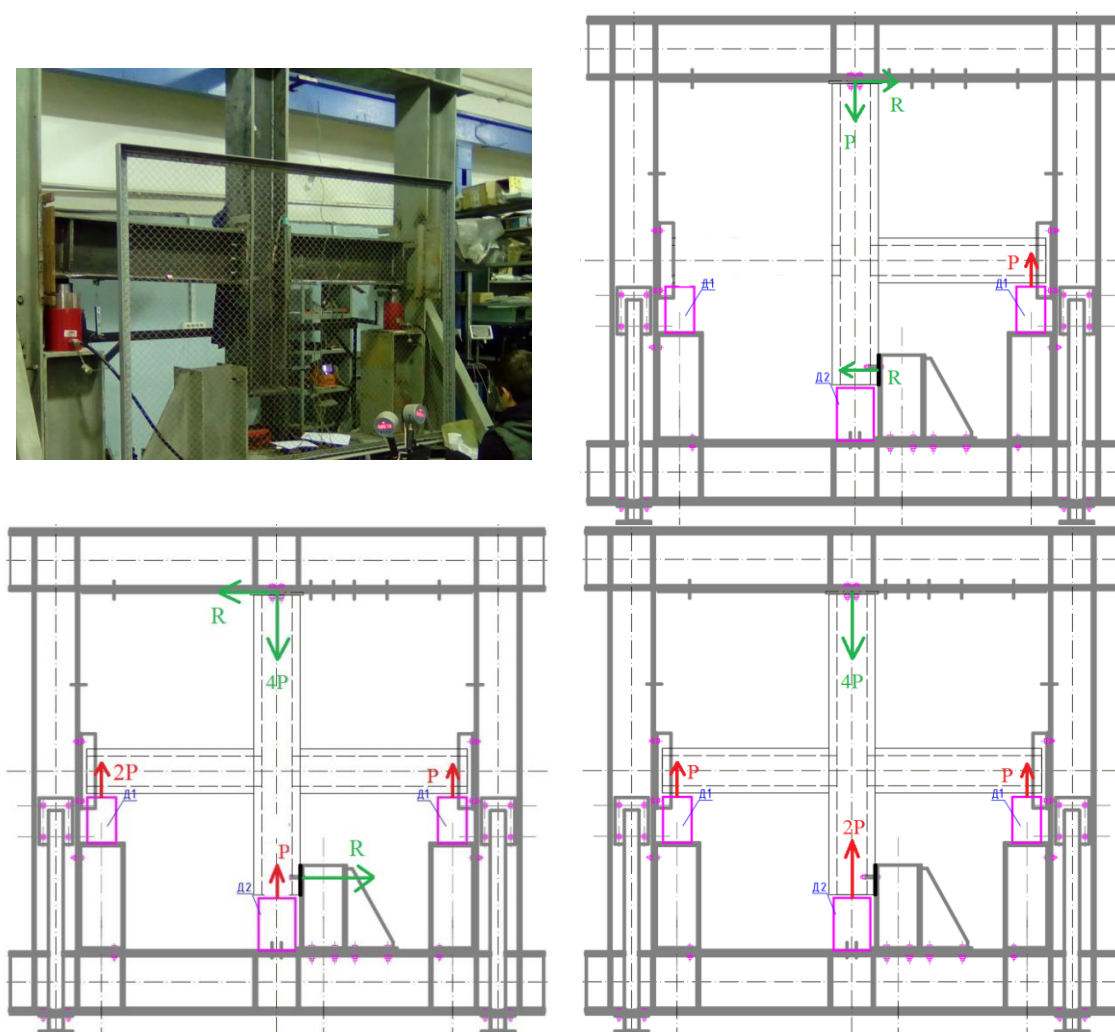


Figure 1. Full-scale model. Loading system scheme.

2. Research objectives and tasks

In 2016-2018, the laboratory of Perm National Research Polytechnic University (PNRPU) with participation of Steel Construction Development Association (SCDA) performed tests of flange connection full-scale models (Figure 1). The objective of the experiments was the research of behavior and load carrying capability of beam-to-column flange connections in elastic and elastoplastic stages under static load. Experiments were conducted according to multi-factor plan, up to destruction of the models.

The research tasks were: 1) FC full-scale tests in stress-strain state approximating real operating conditions. Compressing axial force should occur in the column, while moments and transverse forces have to occur in beams. 2) Strain measurement during tests and connection stress-strain state evaluation. 3) Development of a mathematical finite element model which matches the real stress-strain state of the connection at all loading stages.

Phenomena and facts discovered during the experiment may be merely local in nature, or simply wrong. Therefore, experiment reproduction crisis is observed [5]. If a research is accompanied by

thorough mathematical modeling of the object, than in case of high correlation of the obtained results it is possible to state that the experiments were correct. By achievement of full physical equivalence of FSM tests and numerical model (NM), it is possible to entirely avoid further expensive full scale tests and limit the research to numerical tests.

3. General description of full-scale models

FSMs consist of supports and beams – welded I beams corresponding to sections 25K6 and 30III3 of the new GOST R 57837-2017 “Hot rolled steel I beams with parallel flange edges”. Models with plan size 2x2.5m made of S345 steel are manufactured in two types: with unilateral and bilateral abutment of beam. Support-to-beam connection is made by tightening the connection between stand end-plate and beam flange using high strength bolts with regulated torque. FSM loading is performed using 50 and 100 ton-force hydraulic jacks. Variable parameters: flange thickness 16 to 30 mm, bolt resistance class 8.8 and 10.9, FSM loading scheme (Figure 1). Over all quantity of tested models is 12.

4. General description of finite element models

Mathematical model geometry is developed in *Design Modeler* graphic editor and consists of multiple solid elements: bolts, welded seams, two beams, a column, and flanges. FC mathematical model is designed in *ANSYS Workbench 16.2* software. The joint is modeled using 10-node solid finite elements. Grid step is 2 to 50 mm. In abutment places between flange and column, contact zone condensation was applied. Abutment of individual bodies is described by contact types *Bonded* and *Frictional*. *Bonded* represents full bond of surfaces and is used for welded connections. *Frictional* represents contacts with friction, are given 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 determined as inequalities (1,2). The first inequality sets the condition of non-penetration of surfaces

$$(U^{k2} - U^{k1}) \cdot n^{k1-k2} \geq 0 \quad (1)$$

The second one limits the tangential force on the contact area

$$\tau \leq \mu \cdot P \quad (2)$$

where U^{k1} and U^{k2} are the displacement vectors at the contact points of the contacting bodies with numbers $k1$ and $k2$, respectively; n^{k1-k2} is the normal vector of the contact surface is calculated relative to body $k1$, in the contact area with body $k2$; σ^{k1} is the stress tensor on the contact surface for a body with number $k1$; $P = \sigma^{k1} \cdot n^{k1-k2} \cdot n^{k1-k2}$ is the normal stress at the contact point; $\tau = |\sigma^{k1} \cdot n^{k1-k2} - P \cdot n^{k1-k2}|$ is the tangential stress at the contact point; μ is the coefficient of friction, calculated 0.3. Physical (described through *Multilinear Isotropic Hardening* parameter) and geometrically nonlinear analysis is performed using step-by-step increment of external forces. The first step is tightening of bolts up to the design level. This loading is captured, and followed by loading with forces according to the loading scheme. Overall representation of the numerical model strain-stress state is provided in Figure 2.

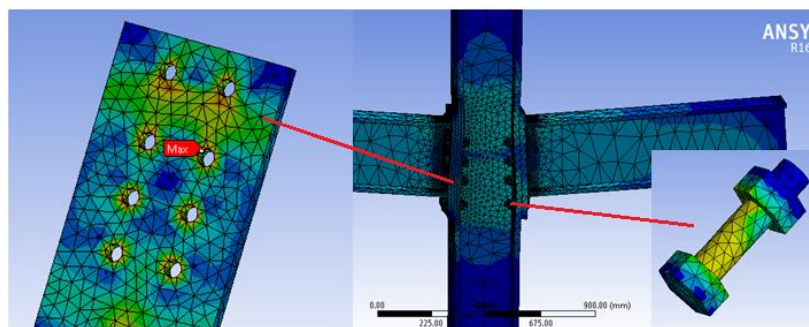


Figure 2. Finite element grid of numerical model. Overall strain-stress state of the joint.

Unified Belsky-Odessky diagrams were used as behavior diagrams. Knowledge of bolt steel deformation diagram is not sufficient for bolts modeling. Bolt yield consists of bolt body yield without thread, yield of the bolt threaded part, yield of head, but the highest yield occurs in the contact between the washer thread and the bolt. It is also known that contact deformations upon its working surfaces exert a significant influence on the thread compliance, because of this fact, the own ductility of the threads can increase by 2-4 times. Therefore, bolts require separate experiments to determine their strength and stiffness. Bolt M24 is modelled by a cylindrical body with the reduced diameter $d = 21.2$ mm and the reduced elastic modulus $E = 30\text{-}40$ GPa (depending on the thickness of the flanges), and bolt head and screw-nut are made absolutely rigid.

5. Correlation between full-scale and numerical models

Prior to FSM mounting, its actual size and initial imperfections are being clarified. Measurements are performed using 30 cm metal rulers with 0.1 mm size tolerance and 1m ruler with 0.2 mm size tolerance. Thickness of plates is determined using electronic calipers with 150 mm measurement range and 0.01 mm tolerance. A small bore is made in sheets welded from all sides to perform thickness measurement using a retractable rod. Flanges and column end plates have more control measurement points as thickness in these areas is more uneven because surfaces are milled to achieve the required contact density (over 0.1 mm gap is unacceptable).

Next is the mounting of flange connections in succession by torque-regulated tensioning of bolts from the middle to the edges. Tensioning of bolts and its regulation is performed using a torque wrench. Density of contact between the flange and the column end plate is controlled by 0.1 mm feeler.

After FSM installation in design position, overall flatness deviations of model points are captured by measurement of distances from a stretched string. Besides, 3D scanning method was used to determine all initial deviations and real sizes. Leica scanner was installed in six points of the laboratory. Scanning step for FSM and test rig was 2 mm.

Next, NM was developed based on real geometrical sizes, deviations, boundary conditions and physical properties of materials. Initial structural analysis for effect of increasing forces is performed according to the loading scheme. Purpose of the analysis is to receive apriority information about behavior of the structure – to determine possible displacement of FSM points and destructive loads. During full-scale tests, the loading system has to ensure the possibility to apply forces exceeding design loads. Linear displacement sensors must have sufficient range to register displacement of points identified during analysis. The main purpose of the initial analysis is to assess deformation of the model. Adhesion areas of resistance strain sensors (RSS) must match with characteristic NM points with high deformation but low deformation gradients. Figure 2 shows a strain diagram in section 1-2, located along the column symmetry axis. The points with extreme deformation values are determined. Resistance strain sensors are glued to the extremum points and adjacent points (in short distance) along the line 1-2. RSSs are glued to the column wall in pairs: one to the front side of the wall, the other on the rear side with the same coordinates.

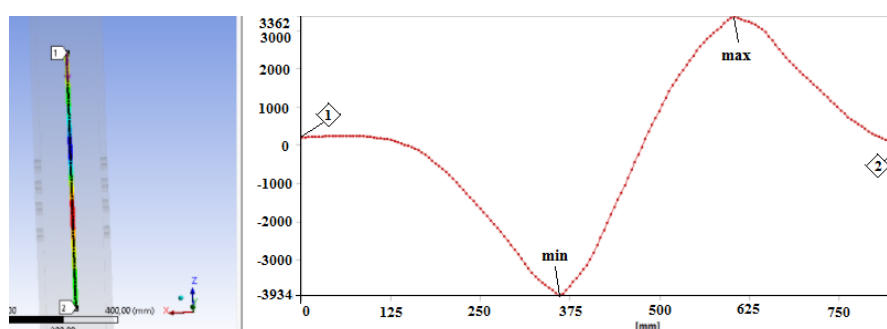


Figure 3. Strain diagram ϵ_x ($\mu\text{m}/\text{m}$) in section 1-2 based on analysis results obtained using ANSYS.

After gluing of all RSSs and mounting of all displacement sensors, the full-scale trial begins. Loading is applied by “loading-unloading” steps using a system of hydraulic jacks. Increment constitutes 2–4 ton-force at each step. Every 2 seconds, indications of all devices and sensors are captured, recorded and stored in the universal multichannel measurement recorder. Strength tests continue for several hours and end in FSM destruction. This period is sufficient to generate bulk data containing several thousand lines.

A dedicated check resistance strain sensor is used to correlate the numerical and full-scale models. It is mounted in the compressed area of the beam (for gluing convenience), in the section, which exhibits elastic behavior throughout the entire experiment path. Based on the measured deformation values, it is possible to determine the level of applied forces (formula 3). Correctness of measurement and calculation of forces is controlled by pressure meters in the loading system.

$$P = \frac{\varepsilon \cdot E \cdot W}{l} \quad (3)$$

where ε is deformations registered by check RSS, E is steel modulus of elasticity, W is beam sectional modulus, P is hydraulic jack force.

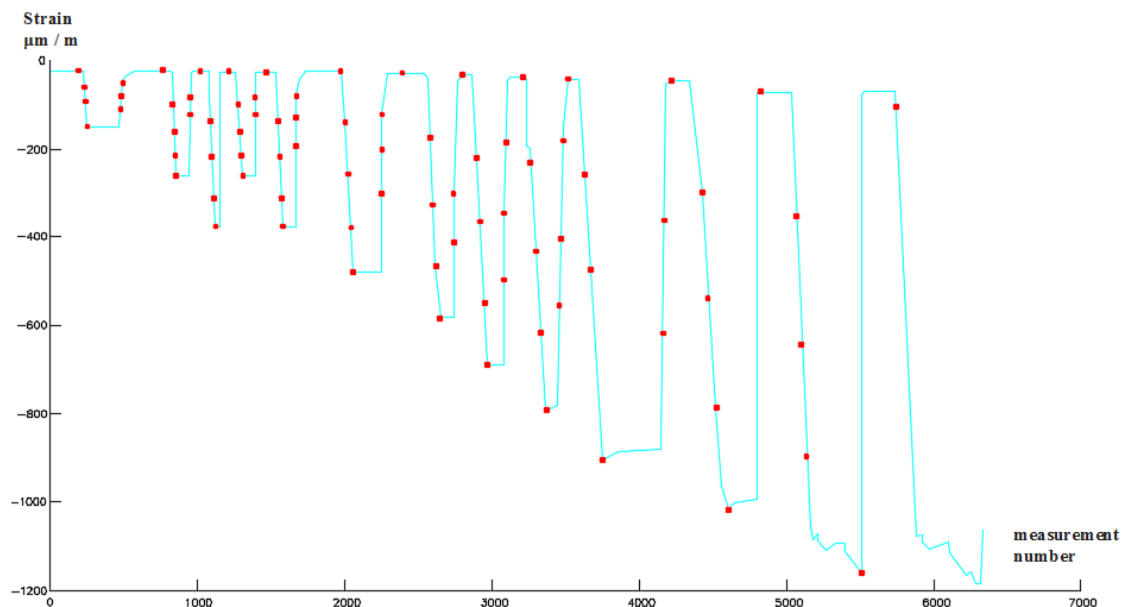


Figure 4. Dynamics of deformations based on check RSS readings over time.

The next task is to reproduce the entire loading trajectory of FSM in NM. Figure 4 shows the course of the test, over ≈ 6500 measurements performed by one sensor. It is not reasonable to perform calculation and compare models for several thousand points. Therefore, the data is pre-processed in *MatLab* software using specifically designed procedures. From thousands of measurements, only a specified number of the most relevant measurements remains (marked points in Figure 4). Out of the entire bulk of data, local extremum points (peaks) of the curve and 2-3 intermediate points of each loading-unloading line are taken. Using formula 3, values of forces are calculated for these points. Forces corresponding to the obtained points are transferred to the mathematical model in the same sequence, preserving the loading history of the model. After the analysis, results of numerical and full-scale experiments are compared by all measured parameters: displacements, deformations, and with the help of destruction scenario.

Figures 5,6 show comparison of the load points and calculation and experiment results for a symmetrically loaded model (Figure 1). The thickness of the flanges is 20 mm. The vertical deflection

in Figure 5 is defined for the point of the beam located at a distance of 85 cm from the flange. The strain in Figure 6 corresponds to the min / max points of Figure 3.

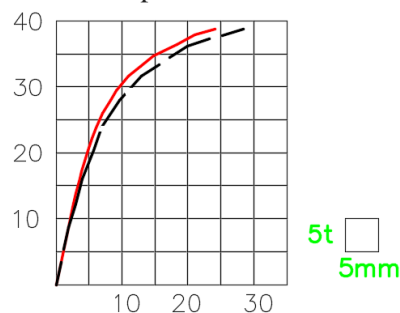


Figure 5. Force-displacement graph. — the full-scale model, - - - the numerical model.

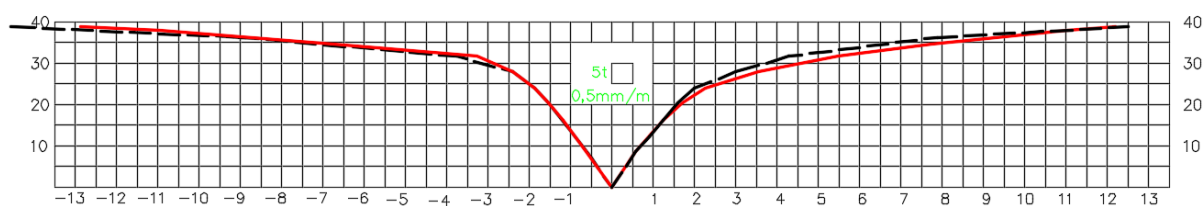


Figure 6. Force-strain graph. — the full-scale model, - - -the numerical model.

Twelve full-scale models were studied based on the test method described herein. Destructive loads, displacement and deformation values were obtained, new phenomena and facts were discovered [7].

6. Conclusion

A series of experimental and theoretical studies of the deformation behavior features 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 tests were performed by method of full matching between the full-scale and the numerical model. Their equivalence, manifested in matching geometrical parameters, boundary conditions and initial imperfections, material diagrams from standalone tests, one-to-one correlation of loads, deformations and displacements in both models, confirms correctness of the performed tests and validity of the developed numerical models. Consequently, further research can be performed using only numerical models obtained in the course of the multi-factor experiment described above.

References

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