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COMPREHENSIVE STRESS-STRAIN STATE ANALYSIS OF A FLANGE JOINT BASED ON AN ANALYTICAL APPROACH AND NUMERICAL MODELING WITH EXPERIMENTAL COMPARISON

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Abstrakt. *The article presents a detailed calculation of a flange bolted joint using the finite element method (FEM) in a three-dimensional problem formulation. Several approaches to modeling bolt preload are considered, which made it possible to evaluate the influence of different methods of accounting for initial tension on the stress–strain state of the structure. A comparative analysis of the obtained numerical results with experimental data was carried out, enabling verification of the model's adequacy and determination of its degree of convergence with the actual behavior of the joint. The obtained results confirm the effectiveness of applying FEM for assessing the performance of flange bolted joints and their further optimization.*

Keywords: *finite element method (FEM), bolted joint, flange bolted joint, contact stresses, experiment, thermal loading due to uniform heating*

Introduction.

One of the most common and versatile methods for structural analysis is the finite element method (FEM) [2]. This numerical approach makes it possible to investigate the stress–strain state of a structure in detail, both as a whole and in its individual elements, by employing a three-dimensional problem formulation with eight-node isoparametric finite elements. The application of FEM [1,2,7] ensures high accuracy in reproducing the spatial behavior of the system and enables the identification of critical stress concentration zones.

Local stress–strain state analysis is crucial for improving prediction accuracy, optimizing parameters, and ensuring the reliability of a structure during operation. Particular attention in engineering analysis is devoted to joints, especially bolted flange connections, since they largely determine the stiffness and load-bearing capacity of the entire system.

Flange joints may operate under axial compressive or tensile forces, as well as under bending moments arising both from applied loads and from eccentricities. Such eccentricities may result from initial or developed defects, which significantly affect the performance of the joint and the structure as a whole.

In this study, the primary focus is placed on analyzing the stress–strain state of a pipe flange joint subjected to a bending moment. The final stage of the work involves comparing the FEM results with available experimental data [8].

Literature Review.

The object of investigation is a flange bolted joint of two pipes with the following parameters:

- pipe diameter: $D_p = 762mm$;
- pipe wall thickness: $t_p = 6mm$;
- flange thickness: $t_f = 40mm$ (a ring-type flange is adopted);
- outer flange radius: $R_f = 459mm$;
- inner flange radius corresponds to the inner pipe surface;
- bolt circle radius: $R_b = 423mm$;
- bolts: $M24$, strength class 10.9;
- number of bolts: 24, evenly distributed along the bolt circle (Fig. 2).

The general view of the joint is shown in Fig. 1. A concentrated bending moment $M = 750kNm$ is applied to the joint along the central axes of one pipe, while the other pipe is rigidly fixed. The material of the pipes and flanges is steel $S355$, with an elastic modulus of $E = 2.06 \times 10^5$ and a Poisson's ratio of $\nu = 0.3$.

The joint calculation was carried out using the finite element method (FEM) in the displacement formulation with universal three-dimensional eight-node isoparametric finite elements. Bolt preload was modeled in two different ways: by applying concentrated forces along the bolt axis and as thermal loading due to uniform heating [4,5,6].

The FEM analysis was performed using the Lira-SAPR software package [3]. The general view of the computational model is shown in Fig. 3.

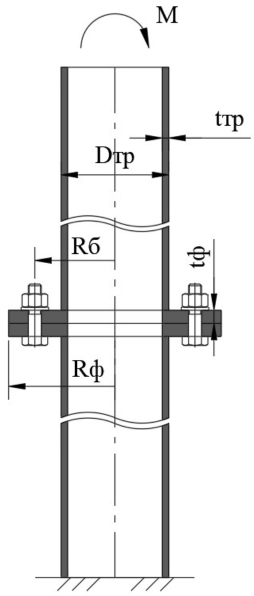

Figure 2 – General view of the joint

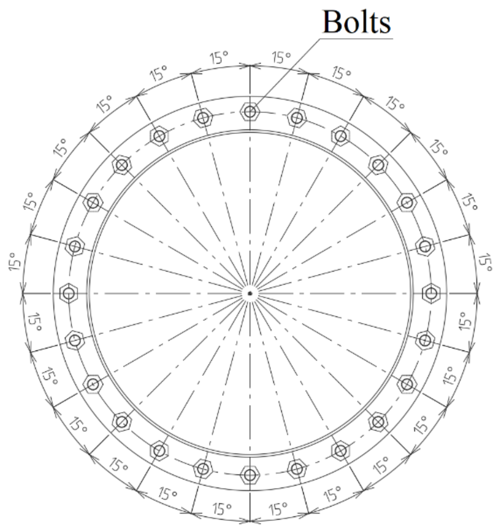

Figure 2. Bolt arrangement in the flange joint

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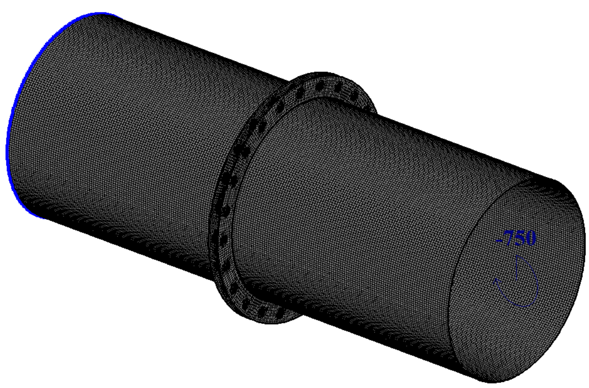

Figure 3. General view of the computational model

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In the finite element model, the elastic modulus of the elements located in the region between the bolt shank and the flange was set to zero (E = 0), following the previously developed approach [4,5]. This technique allows the stiffness transfer in this region to be eliminated where necessary, ensuring a more accurate representation of the stress–strain state of the joint.

As the structure was loaded with a concentrated bending moment, a complex stress–strain state developed in the flange joint region, characterized by the formation of compression and tension zones. The compression zones are localized in the lower part of the cross-section and are predominantly resisted by the flanges, which transfer compressive forces through the contact surfaces. In contrast, the tension zones that emerge in the upper part of the cross-section under the applied moment are resisted by the bolts of the joint, which operate in tension. This force distribution is typical of flange joints subjected to bending and requires careful consideration in numerical modeling.

To determine the boundaries between the compression and tension zones, and to more accurately reproduce the physical and mechanical behavior of the bolted joint in the model, two-node finite elements with unilateral elastic links were employed. These elements make it possible to simulate contact interaction that acts only in one direction (e.g., transferring compressive forces but not tensile ones), thereby enabling a correct representation of flange behavior in the contact zone and preventing an unrealistic overlap of compression and tension regions.

In addition to the bending moment, the bolts were also subjected to preload, which ensured tight contact between the flanges and provided the required joint stiffness. In the model, bolt preload was introduced both as thermal loading due to uniform heating and as concentrated axial forces.

The values of the concentrated forces were taken equal to the bolt preload force,

$$B_0 = 0.9R_{bh} \times A_{bn} = 0.9 \times 700 \times 353 = 224.4kN,$$

where, according to DBN V.2.6-198:2014,

$R_{bn} = 0.7 \times R_{bh} = 0.7 \times 1000 = 700N/mm^2$ – design tensile resistance of the bolt.

$A_{bn} = 353мм^2$ - Cross-sectional area of the bolt at the threaded portion.

The bolt preload was also modeled as thermal loading due to uniform heating. In this case, the load value was assumed equal to the force that produces the same absolute bolt elongation as that calculated from thermal strain ε_T:

$$\Delta T = \frac{P}{E \times \alpha \times A} = \frac{222.4}{2.06 \times 10^6 \times 0.000012 \times 0.00045} = 200^0 C$$

The computational schemes for these two cases are shown in Figs. 4 and 5.

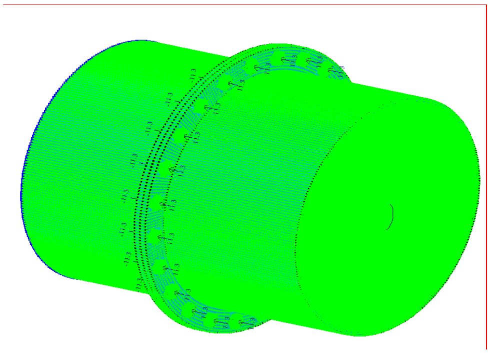

Figure 4. Computational model with bolt preload simulated by concentrated axial forces

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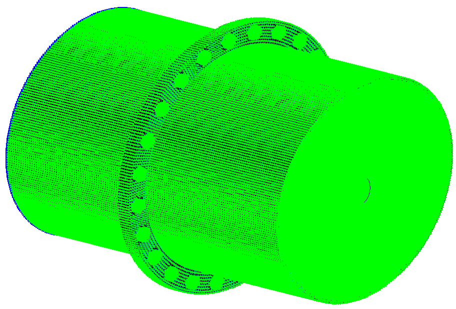

Figure 5. Computational model with bolt preload simulated by uniform thermal loading

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The stress–strain state of the flange joint was analyzed taking into account the equivalent stresses arising in the structural elements of the assembly, as well as the internal forces developed in the bolted joints under the action of applied loads and bolt preload.

The study was based on numerical modeling using the finite element method in a three-dimensional formulation, which allows for a more accurate consideration of the actual geometry of the joint, loading conditions, and interaction between individual elements.

The numerical analysis was performed with the Lira-SAPR software package [3]. During the analysis, particular attention was paid to identifying stress concentration zones, evaluating maximum equivalent stresses, and monitoring the force levels sustained by the bolts.

The simulation results showed that the maximum equivalent stresses in the pipe wall reached:

396 MPa - when the bolt preload was modeled as concentrated forces (Fig. 6);

345 MPa - when the bolt preload was modeled as thermal loading due to uniform heating (Fig. 7).

The observed difference between the obtained results indicates a certain error when simulating the bolt preload with concentrated forces.

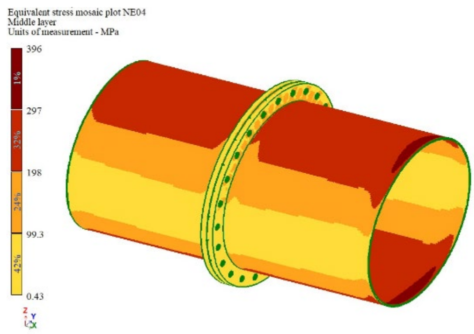

Figure 6. Equivalent stresses (FEM) with bolt preload modeled by concentrated axial forces

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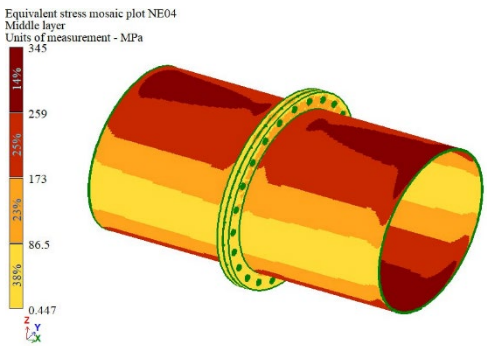

Figure 7. Equivalent stresses (FEM) with bolt preload modeled by uniform thermal loading

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At the same time, it is worth noting the differences in the distribution of forces in the bolts (see Figs. 8–11). The maximum tensile force in the most loaded bolt was 217 kN when calculated using universal quadrilateral shell finite elements, and 293.2 kN when using universal three-dimensional eight-node isoparametric finite elements in Lira-SAPR.

The distribution of forces in the finite elements representing the bolts and the compression zones at the flange contact surfaces is shown in Figs. 8–11.

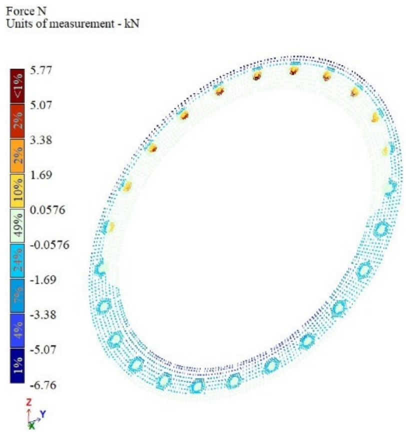

Figure 8. Force distribution in the flange contact zone with bolt preload modeled by concentrated axial forces

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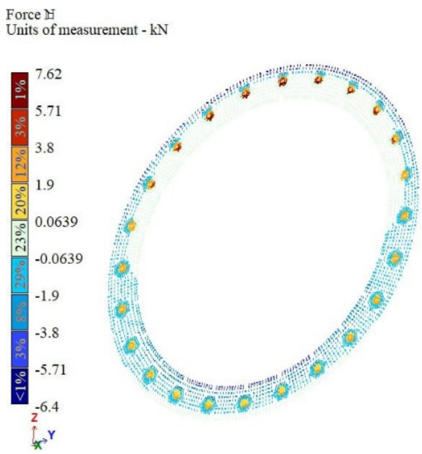

Figure 9. Force distribution in the flange contact zone with bolt preload modeled by uniform thermal loading

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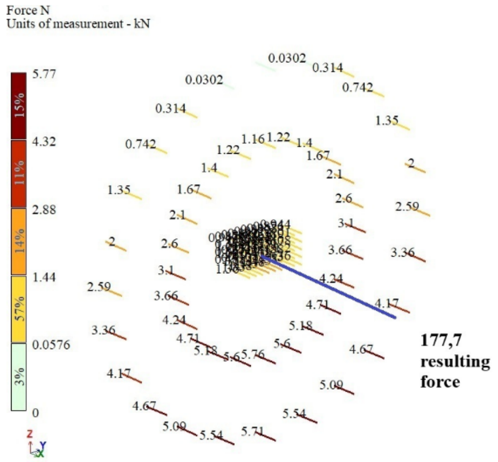

Figure 10. Forces in two-node unilateral elastic link elements of the most loaded bolt and resulting force with bolt preload modeled by concentrated axial forces

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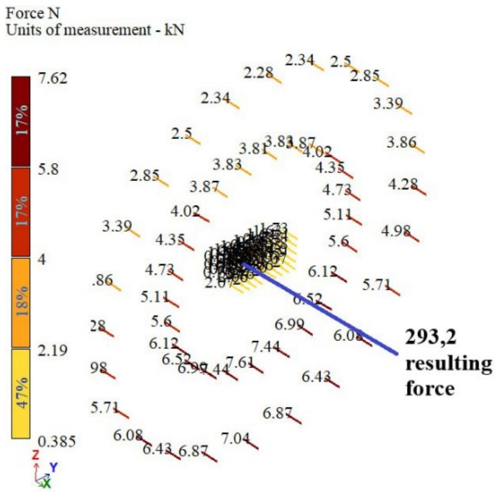

Figure 11. Forces in two-node unilateral elastic link elements of the most loaded bolt and resulting force with bolt preload modeled by uniform thermal loading

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According to the experimental data [8], the maximum bolt force is 285 kN. Based on the FEA results obtained using eight-node isoparametric finite elements, the maximum force in the bolt under preload modeled by concentrated axial forces is 177.7 kN (Fig. 10), while in the case of bolt preload modeled by uniform thermal loading it is 293.2 kN (Fig. 11). The obtained calculation results are summarized in Table 1.

The calculation results were compared with the experimental data reported in [8], as well as with the numerical results obtained using the software package LIRA-SAPR.

Table 1 – Summary of Calculation Results

Verification	Experimental Data [8]	FEA modeling of bolt preload by concentrated forces	FEA modeling of bolt preload by uniform heating load
Maximum tensile force in bolts, kN	285	177,7	293,2
% compared to experimental data	-	-37,65	2,84

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The nature of the local deformation can be seen in Fig. 12, while the local deformation zone from the experiment is shown in Fig. 13. It should be noted that there is a general consistency between the deformation distribution obtained numerically using different bolt preload modeling approaches and the experimental observations, which confirms the adequacy of the applied model and the chosen methods of analysis.

Thus, the results of the finite element analysis of the flange bolted joint using different approaches to bolt preload modeling show varying levels of agreement with the experimental data [8]. The approach based on simulating bolt preload through uniform heating demonstrates a high degree of consistency, whereas modeling the preload with concentrated forces applied along the bolt axis shows a significant discrepancy in the bolt force values (see Fig. 10).

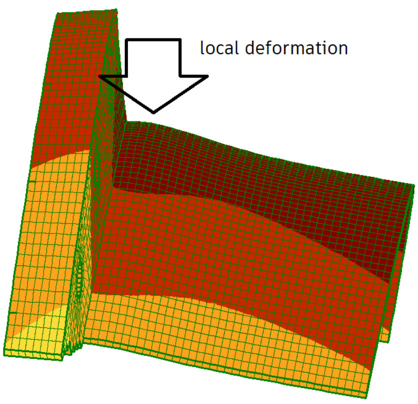

Figure 12 – Local deformation zone of the pipe wall according to the numerical calculation

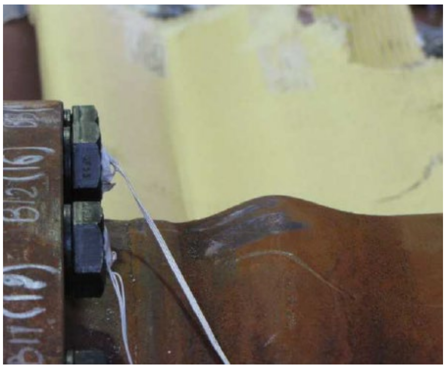

Figure 13 – Local deformation zone of the pipe wall according to experimental data [8]

The obtained data confirm the sufficient accuracy of using three-dimensional eight-node finite elements, as well as the bolt preload modeling approach based on uniform heating, for reliable prediction of the stress–strain state of flange bolted joints.

Conclusions

The obtained calculation and analysis results indicate that finite element modeling of the flange bolted joint, taking into account bolt preload and the load induced by uniform heating, demonstrates a high degree of agreement with the experimental data [8]. In particular, both the character of local pipe wall deformations and the magnitudes of the bolt forces show similar patterns and values. At the same time, further analysis of this type of joint should pay special attention to the pipe-to-flange plate connection zone.

The numerical results correlate well with the observations obtained during physical testing: specifically, the distribution of stresses and deformations in the flange joint area, the local deformations of the pipe wall, and the bolt force magnitudes exhibit close correspondence in both values and trends. This confirms the validity of the applied methodology and the realism of the chosen computational model.

However, the results obtained with bolt preload modeled as concentrated forces show poorer agreement with experimental data. This approach provides a less accurate representation of the actual behavior of the bolted joint compared to preload modeling through uniform heating, which produces a more natural and distributed effect on the element.

Therefore, the application of a thermomechanical preload model allows for a more realistic reproduction of the stress–strain state of the joint and yields results that correlate best with experimental observations. At the same time, in future analyses and refinements of models of similar flange bolted joints, particular attention should be paid to the pipe-to-flange plate attachment zone, since this region experiences the highest stress concentration, which significantly affects the overall strength and durability of the structure. A more detailed study of this area will improve the accuracy of predicting joint behavior and help identify potential risk zones under operational loads.

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Abstract. *In this work, a comprehensive numerical study of the stress–strain state of a flange bolted pipe joint under bending moment was carried out, taking into account the initial bolt preload and employing the finite element method in a three-dimensional formulation. Three-dimensional eight-node isoparametric elements were used for modeling. This approach provides a detailed representation of the spatial behavior of the joint, accounting for the stress and strain distribution in critical zones as well as the influence of bolt preload on the overall structural response.*

Special attention was given to the bolted connections, which largely determine the stiffness and load-bearing capacity of the system. The model considered the effects of initial preload, the compression and tension zones formed in the flange under bending, as well as possible load eccentricities caused by initial or acquired defects. Such considerations make it possible to adequately assess the behavior of the joint under service loads and to identify potential stress concentration zones.

A comparative analysis was performed between the numerical modeling results, experimental data, and calculations obtained using other software environments. The results showed that the use of three-dimensional eight-node isoparametric elements with different approaches to bolt preload modeling yields varying degrees of agreement with the experimental data, explained by increased force concentration in local contact zones, which leads to higher equivalent stresses and changes in the deformation distribution.

The obtained results confirm the feasibility and effectiveness of employing three-dimensional isoparametric models with bolt preload consideration for accurately predicting the stress–strain state of flange bolted joints. This approach not only improves the accuracy of stress evaluation but also enables the optimization of design parameters, ensuring the reliability and durability of such joints under real operating conditions.

Key words: *finite element method (FEM), bolted joint, flange bolted joint, contact stresses, experiment, thermal loading due to uniform heating*

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