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## COMPARISON OF SEMI-ANALYTICAL FINITE ELEMENT (SFEM) NUMERICAL SIMULATION RESULTS FOR A FLANGE JOINT WITH EXPERIMENTAL DATA

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**Abstrakt.** The study presents numerical modeling of the stress–strain state of a flange connection subjected to a bending moment. Three computational approaches were considered: the Semi-Analytical Finite Element Method (SFEM), the classical Finite Element Method (FEM), and the engineering software Idea StatiCa. The numerical results were verified through comparison with experimental data.

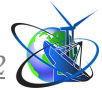
A detailed analysis of the stress–strain state of the connection was conducted, with particular attention given to the stress distribution in the bolts as the most critical structural components. A comparative assessment of the results obtained using the different methods was performed, and the degree of agreement with the experimental data was determined. The study also outlines the specific features and applicability of each method for analyzing flange connections subjected to bending loads.

The obtained results make it possible to evaluate the suitability and effectiveness of various numerical approaches for practical engineering analysis of flange connections.

**Keywords:** Semi-Analytical Finite Element Method (SFEM), bolted joint, flange bolted joint, contact stresses, experiment, uniform heating load, experimental data

### Introduction.

Bolted flange connections are widely used in practice for joining pipes and pipelines in construction and mechanical engineering. Such connections may incorporate either a solid or a ring-type flange, as described in detail in [5]. Due to the critical nature and frequent use of these joints, there is a need for their detailed analysis and accurate assessment of the stress–strain state (SSS). A comprehensive SSS analysis enables the investigation of the influence of initial and service-induced defects in individual components on their residual service life as structural elements.



The range of possible initial and acquired defects is quite extensive, but the most common ones include: cracks in components, mechanical damage, deformations, corrosion effects, thermal loads, and defects accumulated under cyclic loading, among others. Particular attention in flange joints should be given to the analysis of the SSS of bolts, as they are among the most critical structural elements. Additionally, detailed SSS assessment at both the design stage and during operation allows predicting the behavior of joint components under service conditions and estimating their remaining service life. This, in turn, enables the development of inspection and maintenance programs, contributing to improved reliability and operational performance of the structure as a whole.

The Finite Element Method (FEM) [2, 6, 7] is the most commonly used approach for such analyses. However, to optimize and increase the efficiency of the computational process, it is more appropriate to apply the Semi-Analytical Finite Element Method (SAFEM/SFEM) for local analysis. In SFEM, discretization is performed within the cross-sections of the bodies, while a single finite element is considered along the generating direction. The fundamental concepts of SFEM are described in detail in [1].

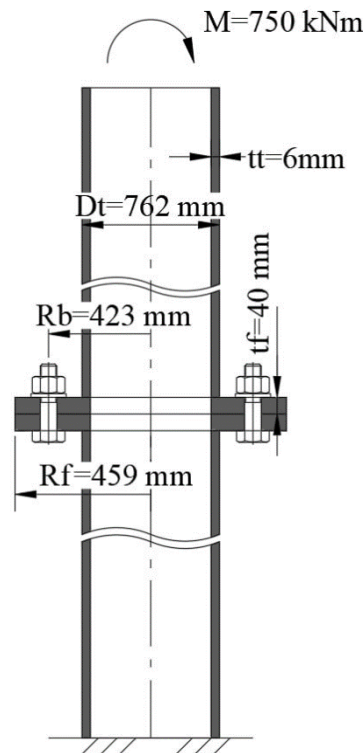
In this work, the stress–strain state of a bolted joint is analyzed using a selected fragment of the flange assembly subjected to a bending moment. The numerical simulation results are compared with experimental data [9] and with the findings of previous studies [4, 5].

### **Literature Review.**

The object of the study is a bolted flange connection of two pipes (Fig. 1). The connection is subjected to a concentrated bending moment  $M = 750kNm$  applied along the central axis of one of the pipes, while the second pipe is rigidly fixed.

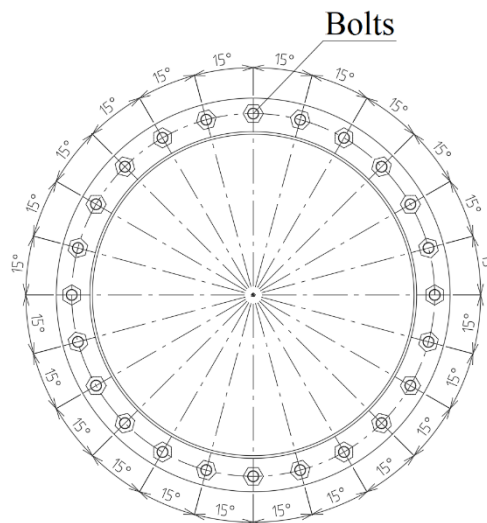
The pipe and flange material is steel with Young's modulus  $E = 2.06 \times 10^5$  and Poisson's ratio  $\nu = 0.3$ .

The bolts are M24 of strength class 10.9, with a total of 24 bolts evenly distributed along the radius (Fig. 2).



**Figure 1 – General view of the joint**

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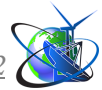
**Figure 2. Bolt arrangement in the flange joint**

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To simulate bolt preload, a load corresponding to uniform heating was applied. The magnitude of this load was chosen to match the force that would produce the same absolute elongation of the bolt as the thermal deformation  $\epsilon_T$

$$\epsilon_T = \alpha \times \Delta T$$

where  $\alpha = 0.000012$  is the coefficient of linear thermal expansion for steel,  $1/^\circ C$  ;



$\Delta T$  – temperature change,  $^{\circ}C$ .

The stresses and the corresponding forces are determined using the following formulas:

$$\sigma = E \times \varepsilon_T, P = \sigma \times A$$

where  $A = 0.00045m^2$  – cross-sectional area of a bolt;

$P$  – the bolt preload force corresponding to

$$B_0 = 0.9R_{bh} \times A_{bn} = 0.9 \times 700 \times 353 = 224.3kN \text{ where, according to DBN V.2.6-198-2014;}$$

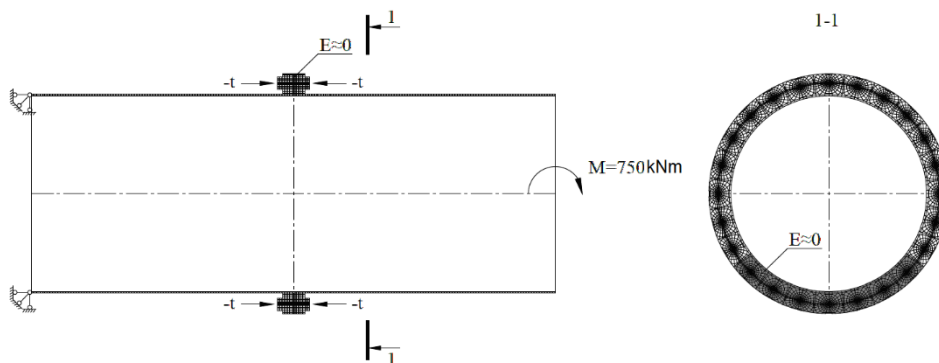
$$R_{bn} = 0.7 \times R_{bh} = 0.7 \times 1000 = 700N/mm^2 \text{ – the design tensile resistance of the bolt;}$$

$A_{bn} = 353mm^2$  – is the tensile stress area of the bolt thread..

Accordingly

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

The design (computational) scheme of the flange joint is presented in Fig. 3.



**Figure 3 – Computational model of the flange joint**

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To refine the stress distribution in the zone of stress concentration, a fragment of the structure containing the most heavily loaded bolted connection was considered. This approach makes it possible to achieve the required accuracy in determining the local stress–strain state (SSS) parameters while maintaining reasonable computational cost.

The modeling of the extracted fragment was performed using a semi-analytical variant of the finite element method, which combines numerical discretization procedures with an analytical representation along one of the spatial coordinates.

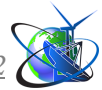
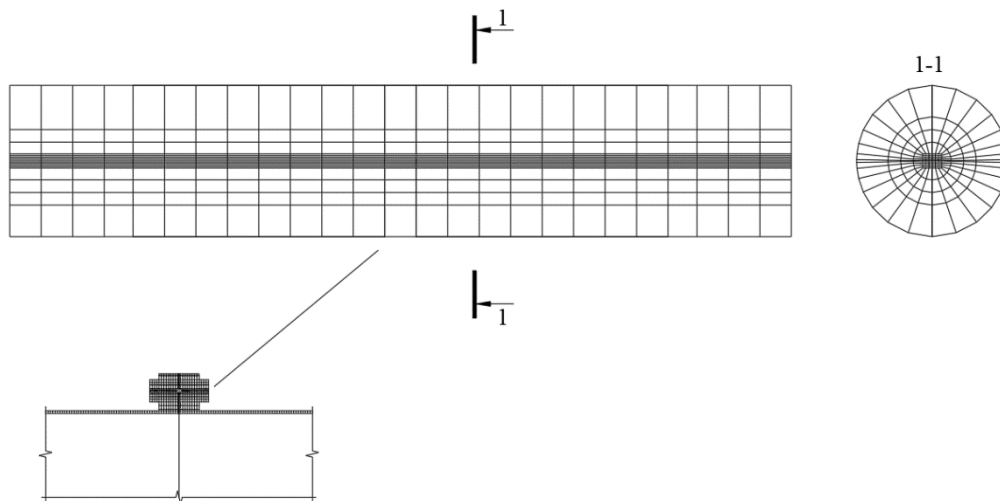


Figure 4 shows the computational model of the bolt, taking into account contact interaction and support conditions.



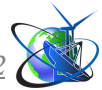
**Figure 4 – General view of the SFEM computational model.**

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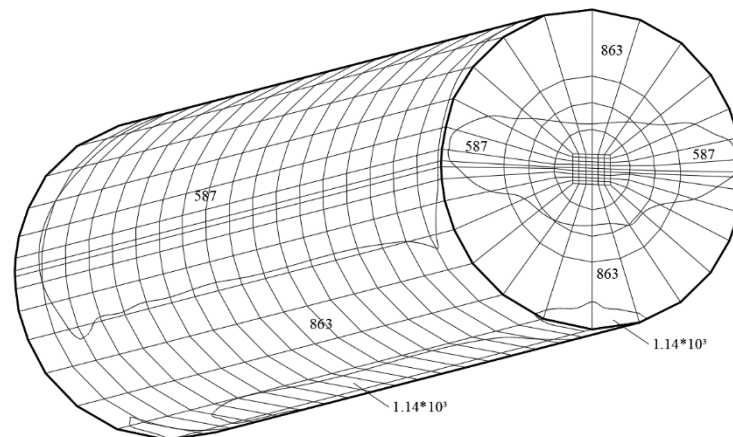
The model reproduces the actual geometry of the bolt shank, the preload force, and the nonuniform distribution of contact reactions. Accounting for these factors ensures an accurate representation of high-stress zones and makes it possible to identify areas where defects are likely to form.

The analysis focuses on the stresses arising in the pipe wall. According to previously obtained finite element results in a 3D formulation using general quadrilateral shell elements, the maximum stresses are 337 MPa and 345 MPa [5]. When using general three-dimensional eight-node isoparametric solid elements, and based on the calculation performed in the IDEA StatiCa software package, the maximum stress reaches 355 MPa [8]. The maximum stresses in the pipe wall according to the calculation of the overall scheme amount to 338 MPa, which indicates a high level of agreement between the results.

The stress distribution within the bolt body is shown in Fig. 5. A nonuniform stress distribution is observed in the direction of the applied bending moment, indicating deformation of the bolt under external loading. At the same time, in the plane perpendicular to the moment direction, the stresses are distributed symmetrically relative to the bolt's central axis. This pattern is characteristic of spatial bending of an



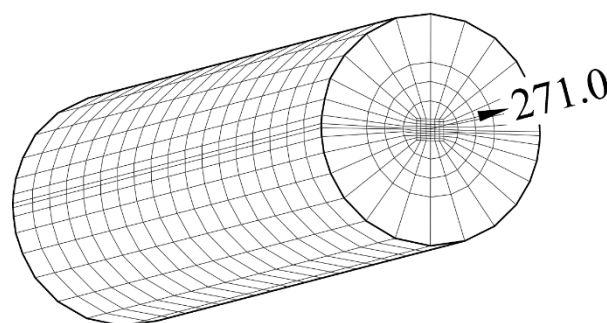
element with a rigid central shank and confirms the adequacy of the adopted computational model.



**Figure 5 – Stress distribution in the bolt body (SFEM)**

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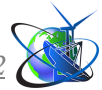
The tensile force values in the most heavily loaded bolt, obtained using different calculation methods, show some divergence. When using the FEM with general quadrilateral shell elements, the maximum force is 217 kN. For the model built with general three-dimensional eight-node isoparametric elements, the tensile force increases to 293.2 kN. The calculation performed in the IDEA StatiCa software package yields an intermediate result — 239.6 kN [8]. According to the experimental data, the reported tensile force value is 285 kN [9]. The calculation performed using the semi-analytical finite element method produced a value of 271 kN (Fig. 6).



**Figure 6 – Tensile force values in the most stressed bolt (SFEM)**

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The calculation results based on the Semi-Analytical Finite Element Method (SFEM) demonstrate a fairly high level of agreement with the experimental data [9].



This approach significantly reduces the time required to obtain the stress–strain state (SSS) results of the joint and optimizes the computational process. The close correlation between the obtained results and the experimental data indicates the applicability of the proposed method for analyzing the SSS of bolts in flange connections.

The summarized comparison results are presented in Table 1.

**Table 1 – Consolidated overall calculation results**

Verification	Experimental Data [9]	SFEM	FEM with eight-node finite elements [3,5]	FEM with quadrilateral finite elements [3,5]	IDEA StatiCa
Maximum tensile force in bolts, kN	285	271	293,2	217	239,6
% compared to experimental data	-	-5,04	2,84	-27,09	-17,31

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The results obtained using the classical Finite Element Method (FEM) show better convergence with the experimental data, but require more computational time. The results from the IDEA StatiCa software package are also quite satisfactory. One of the advantages of this software is the convenience and clarity of creating the computational model; however, it has limitations in the detailed analysis of the obtained results.

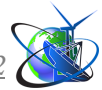
### **Conclusions**

The obtained results based on SFEM demonstrate a high degree of convergence and allow for optimization and acceleration of the SSS evaluation of flange-type connections subjected to bending moments. This approach enables detailed analysis of the SSS of joint components, which, in turn, allows predicting the behavior of the joint elements during operation and estimating their service life. Such predictive capability supports the development of scheduled inspection and maintenance programs, thereby enhancing the reliability and operational performance of the structure as a whole.



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**Abstract.**

*Bolted flange connections are among the most common structural elements in construction and mechanical engineering. The high criticality of these joints necessitates detailed investigation of their stress–strain state (SSS) both at the design stage and during operation.*

*The relevance of this work lies in the need for accurate prediction of flange connection behavior under load and verification of numerical calculation methods based on experimental data. Particular attention is paid to the analysis of the SSS of bolts as critical components determining the overall reliability of the connection.*

*For numerical modeling of the SSS, the Semi-Analytical Finite Element Method (SFEM) was applied, which provides an optimal balance between accuracy and computational efficiency. A key feature of SFEM is discretization only across cross-sections, using a single finite element along the generating direction, which significantly reduces computation time without compromising result accuracy.*

*This study performs numerical modeling of the SSS of a flange connection under bending moment using three approaches: SFEM, classical Finite Element Method (FEM), and the engineering software package IDEA StatiCa. The obtained results were verified by comparison with experimental data.*

*The SFEM-based calculations demonstrate a high degree of agreement with experimental data while significantly reducing computation time compared to classical FEM. Calculations using classical FEM show the best convergence with experiments but require substantially greater computational resources and time. The IDEA StatiCa software package offers convenience in creating computational models and clarity in presenting results but has limitations regarding detailed SSS analysis capabilities.*

*Comparative analysis confirms that SFEM is an effective tool for engineering analysis of flange connections, allowing optimization of the calculation process without significant loss of accuracy. The study results can be used for predicting structural behavior under load and improving calculation methodologies.*

**Key words:** *Semi-Analytical Finite Element Method (SFEM), bolted joint, flange bolted joint, contact stresses, experiment, uniform heating load, experimental data*

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