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NUMERICAL INVESTING OF TRUSS FLANGE JOINTS WITH TRIMMED FLANGES

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Summary. In modern construction, steel trusses remain one of the most common types of load-bearing structures used in the construction of industrial, civil, and public buildings. Their use is driven by high load-carrying capacity, relatively easy installation, and economic feasibility in long-span structures.
One of the most critical elements of such structures is the flange joint, through which the main internal forces are transferred from one part of the truss to another. The reliability and durability of the entire system largely depend on the accuracy of its calculation and design.
Special attention must be paid to situations where the joint is subjected not only to axial loads but also to bending moments and torsion, which create a complex stress–strain state. In such cases, traditional calculation methods, based on simplified models and assumptions of uniform stress distribution, do not always allow for the identification of local concentrations that may lead to premature structural failure. In this context, improving numerical analysis methods that consider the real spatial geometry of the elements, the specifics of the connections, and the nature of the loading becomes especially relevant.
The proposed approach is based on constructing an analytical model of the joint, enabling the calculation of internal forces in critical zones without the need to model the entire truss. This not only reduces the time required for calculations but also improves their accuracy. Such an approach contributes to the early detection of potentially hazardous zones where stress levels may exceed permissible limits, thereby reducing the risk of loss of serviceability.

Keywords. equivalent stress, flange, component-based finite element method, numerical modeling, joint stiffness, steel truss, local stress.

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PROBLEM STATEMENT

Flanged joints of steel trusses are critical components of spatial structures, as they serve as the primary means of transferring forces between the frame's bar elements. These joints often exhibit complex stress–strain states caused by the combination of axial, bending, and transverse forces. The geometric configuration of the joint—particularly the flanges, stiffening ribs, and bolts—leads to a non-uniform distribution of stresses within the elements.

Traditional analytical and code-based design methods often rely on simplified assumptions, such as uniform force distribution or conventional load transfer areas. However, numerical modeling, especially using the component-based finite element method, reveals the presence of local stress concentration zones that are not accounted for in standard calculations. This is particularly evident in areas remote from the load application center, such as those affected by edge effects or contact zones between elements.

The lack of universal engineering methods for accurately determining stresses at these points limits the ability to make informed decisions about joint design. This poses risks of underestimating or overestimating structural load capacity and complicates the assessment and diagnostics of existing buildings or structures during technical inspections.

Moreover, the use of circular or rectangular steel tubes in truss structures complicates the situation, as these elements are prone to local buckling. In the presence of rigid flanged joints with stiffening ribs, highly stressed zones may develop, often exceeding permissible stress limits—especially in areas of rib insertion or welded joints. These zones are difficult to accurately calculate due to the complex geometry and interaction between elements.

Existing standards provide general principles for joint design but do not always allow for precise assessment of the actual stress distribution in specific cases, such as eccentric loading, force eccentricity, or combinations of forces and moments. This highlights the need to improve design approaches that integrate both numerical methods (FEM) and practical criteria for evaluating the strength and stiffness of joints. Developing a more reliable methodology will enhance structural safety and reduce the risk of premature failures during the operational phase of structures.

ANALYSIS OF PREVIOUS RESEARCH

It is important to acknowledge the contributions of the "pioneers" in the study of flanged joints in trusses made of tubular and closed cold-formed welded sections, particularly in developing analytical models for determining boundary conditions and evaluating the strength of such joints [11, 12].

In addition to the regulatory documents [2, 3], significant progress has been made in improving the calculation methodology for welds in flanged joints [1].

Structural solutions for steel structures and forms and domes have been investigated[5, 13, 14, 15, 16, 24, 25].

Of particular importance is the advancement of research on the analysis of bolt behavior in flanged joints under complex stress–strain conditions using the finite element method, as well as the mechanics of flanged joints in steel tubes under axial tension [4, 6, 7, 8, 9, 17, 18, 19, 20, 21, 22, 23].

Studies have also addressed the stability of elastic members with initial imperfections in steel trusses with rigid joints [10].

Moreover, experimental methods are used in the research to verify the results of numerical modeling, including full-scale tests, which allow for a more accurate assessment of joint behavior under real loading conditions. These approaches provide a foundation for the development of new design recommendations for flanged joints in steel tubular structures, taking into account both strength and stability, as well as technological aspects of fabrication and welding.

PRINCIPAL RESEARCH

In the classical definition of normal stresses in a cross-section:

$$\sigma = \frac{N}{A} \qquad (1)$$

The classical definition of normal stresses in a cross-section lacks a specification for the distribution of forces over the surface of an element. It assumes only a uniform stress distribution, which accounts for idealized working conditions and does not consider areas of localized stress concentrations.

In the complex stress–strain state typical of flange joint connections and structural elements, it should be understood that stresses across the cross-section are often non-uniform. This is due to the presence of stiffening ribs, welds, and bolt holes, which affect the stiffness characteristics of the section.

langed joints require particular attention when subjected to combined loading—axial compression or tension in combination with bending and torsional moments. Under such conditions, a complex interaction occurs between bolts, welds, and stiffening ribs, which do not engage uniformly. In real structures, some ribs may begin to transfer loads earlier than others due to initial geometric imperfections or stiffness variations.

Additionally, it is essential to consider the impact of assembly and manufacturing inaccuracies, which can lead to asymmetric loading of joints. In the spatial behavior of a truss, even minor misalignments can cause changes in the direction of internal forces and overstressing of individual areas.

Forces in flange connections are transmitted through the flanges themselves, the bolts, and the stiffeners. To accurately determine the internal equivalent stresses, numerical modeling using the finite element method should be employed. This approach allows consideration of all specific features of the joints, namely the geometric configurations and force effects in the design model 1 (Fig. 1).

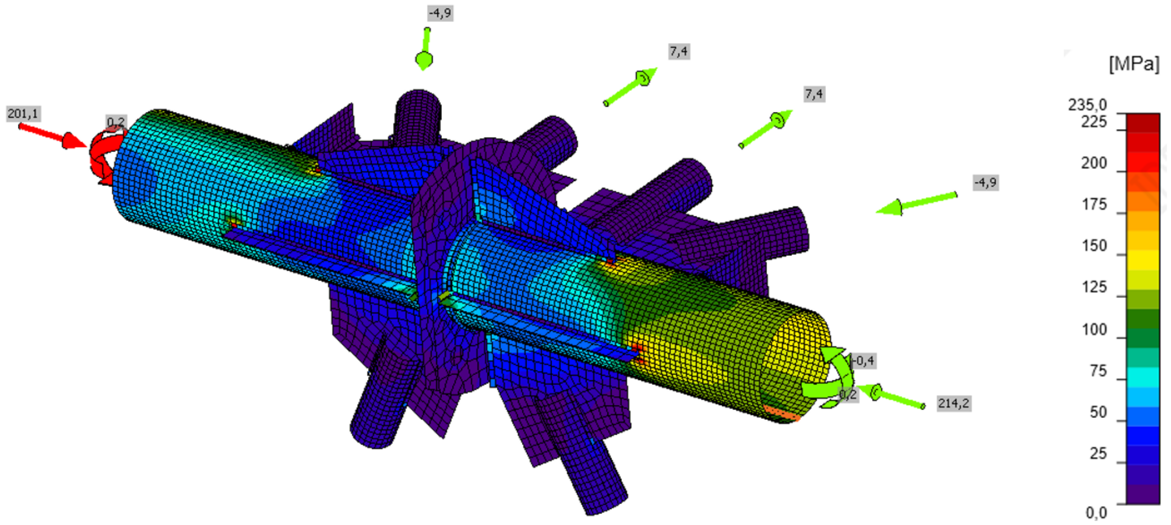
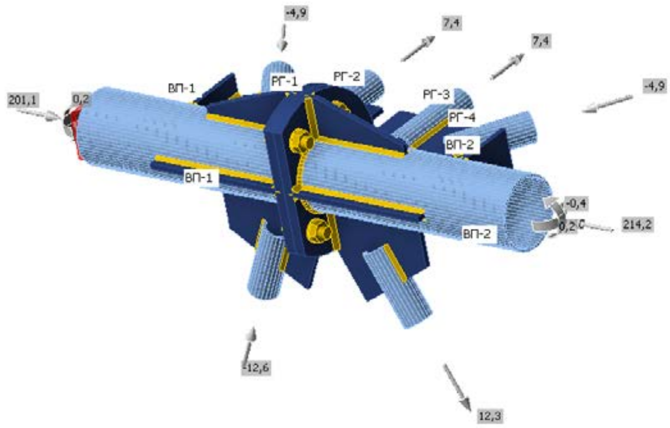
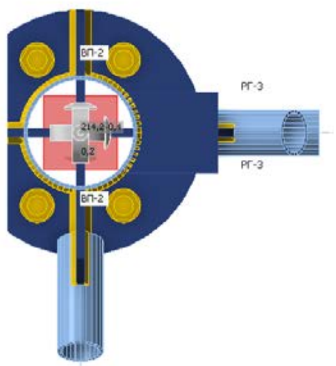


Fig. 1. Distribution of internal equivalent stresses in the top chord of truss Model 1.
Рис. 1. Розподіл внутрішніх еквівалентних напружень верхнього поясу ферми моделі 1.

This particular feature of the joint connection is characterized by end-plate flanges welded to the upper chord and through stiffeners (Fig. 2).



a



b

Fig. 2. General view of Model 1 of the analysed joint with bolted connection and welds (a). Cross-section of the flange connection (b).
Рис. 2. Загальний вид моделі 1 розрахункового вузла з болтовим з’єднання та зварними швами (a). Переріз фланцевого з’єднання (b).

The areas located farther from the load application point experience greater forces; in such cases, the local force at point i should be determined as follows:

$$N_i = N_{ed} \cdot \frac{a_i}{\int_0^{\alpha_m} a(\alpha) d\alpha} \quad (2)$$

де

a_i- the distance from the load application point to point i (mm);

α_m- the boundary of the investigated area (rad).

Thus, the area of the investigated section region is determined as:

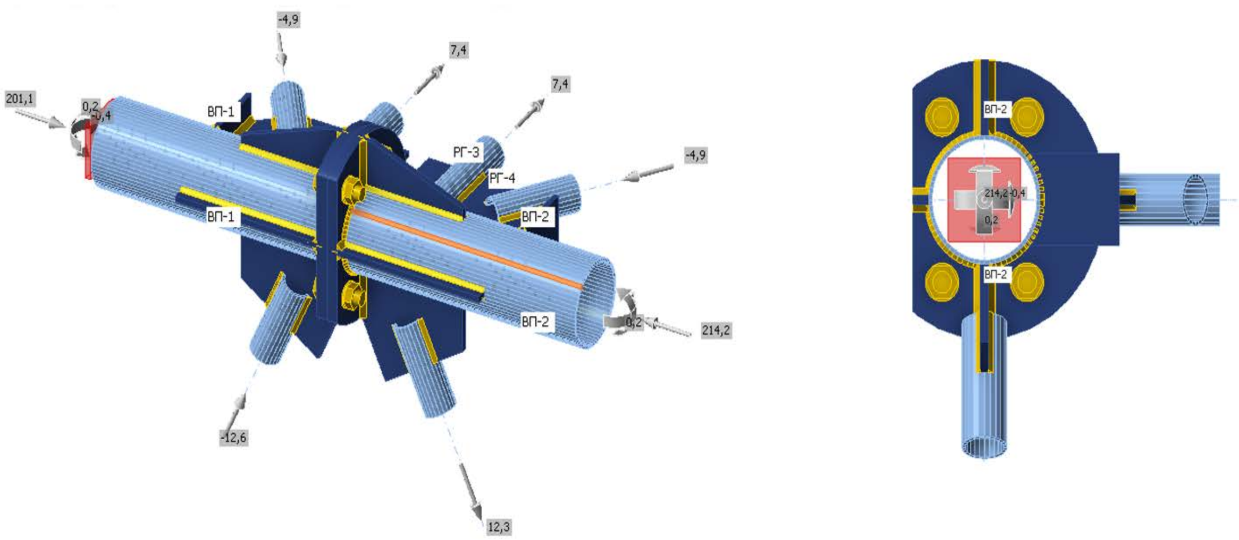
$$A_i = t \cdot l_i \quad (3)$$

де

t – wall thickness of the pipe cross-section;

l_i – length of the section subjected to force.

In the investigated Model 2, if the stiffening ribs are not continuous, this will significantly affect the stiffness characteristics of the joint and will change it from a more rigid connection to one that is closer to a hinged (pinned) joint (Fig. 3).



a *b*

Fig. 3. General view of Model 2 of the analysed joint with bolted connection and welds (a). Cross-section of the flange connection (b).

Рис. 3. Загальний вид моделі 2 розрахункового вузла з болтовим з'єднання та зварними швами (a). Переріз фланцевого з'єднання (b).

The distribution of internal equivalent stresses in the joint shows that when the stiffness characteristics of the joint change, the critical stress zone shifts from the edge areas of the pipe near the flange to the central zone of the flange. However, a more uniform stress transition along the length of the pipe is observed (Fig. 4).

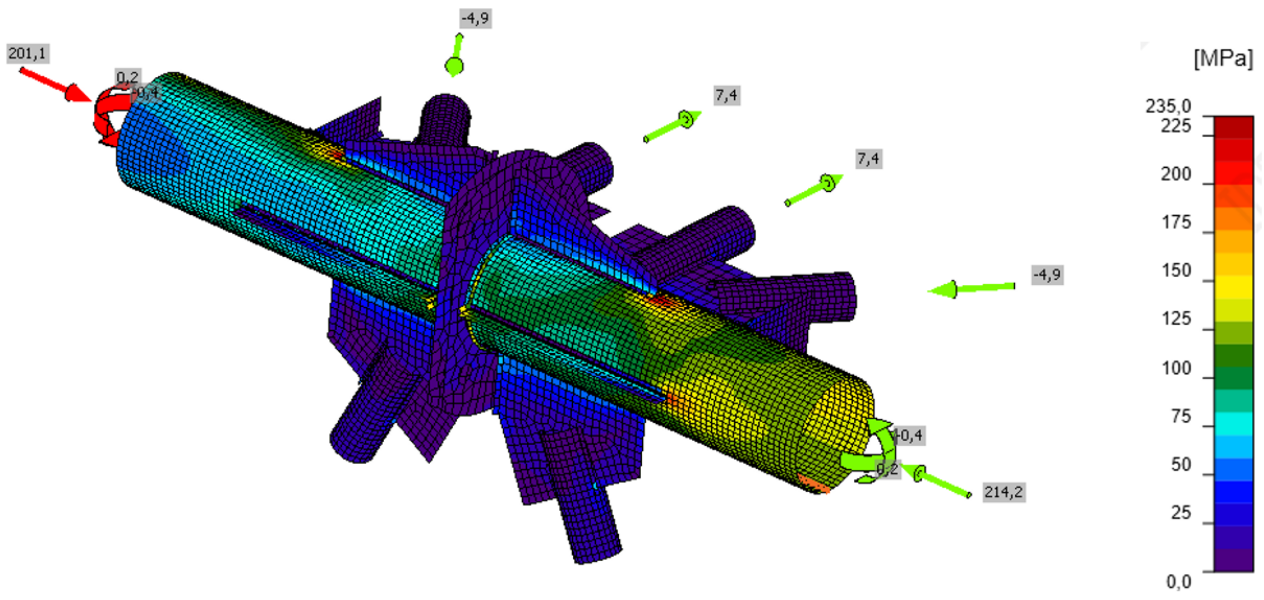
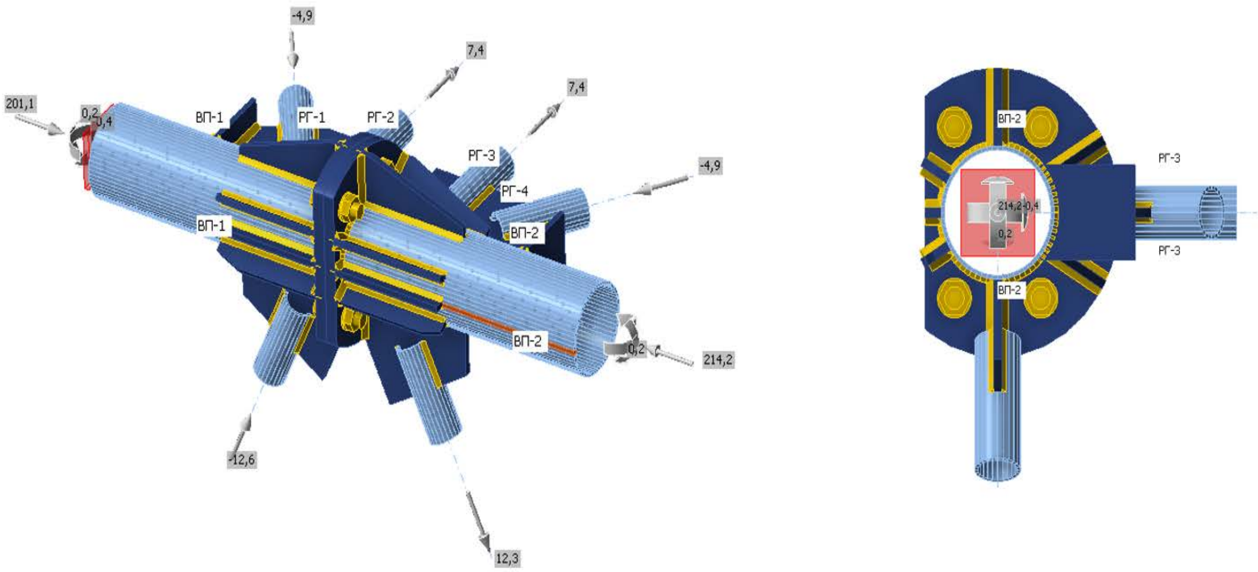


Fig. 4. Distribution of internal equivalent stresses in the top chord of truss Model 2.
Рис. 4. Розподіл внутрішніх еквівалентних напружень верхнього поясу ферми моделі 2.

The next stage of calculation Model 3 involves the introduction of additional stiffening ribs with a 30˚ inclination angle to understand the influence and distribution of internal equivalent stresses in the flange connection (Fig. 5).



a *b*

Fig. 5. General view of Model 3 of the analysed joint with bolted connection and welds (a). Cross-section of the flange connection (b).
Рис. 5. Загальний вид моделі 3 розрахункового вузла з болтовим з’єднання та зварними швами (a). Переріз фланцевого з’єднання (b).

The numerical analysis using the component finite element method with the introduction of additional stiffening ribs indicates that the uniformity of the distribution of internal equivalent stresses occurring in the cross-sections has further improved along the length from the attachment point to the flange (Fig. 6).

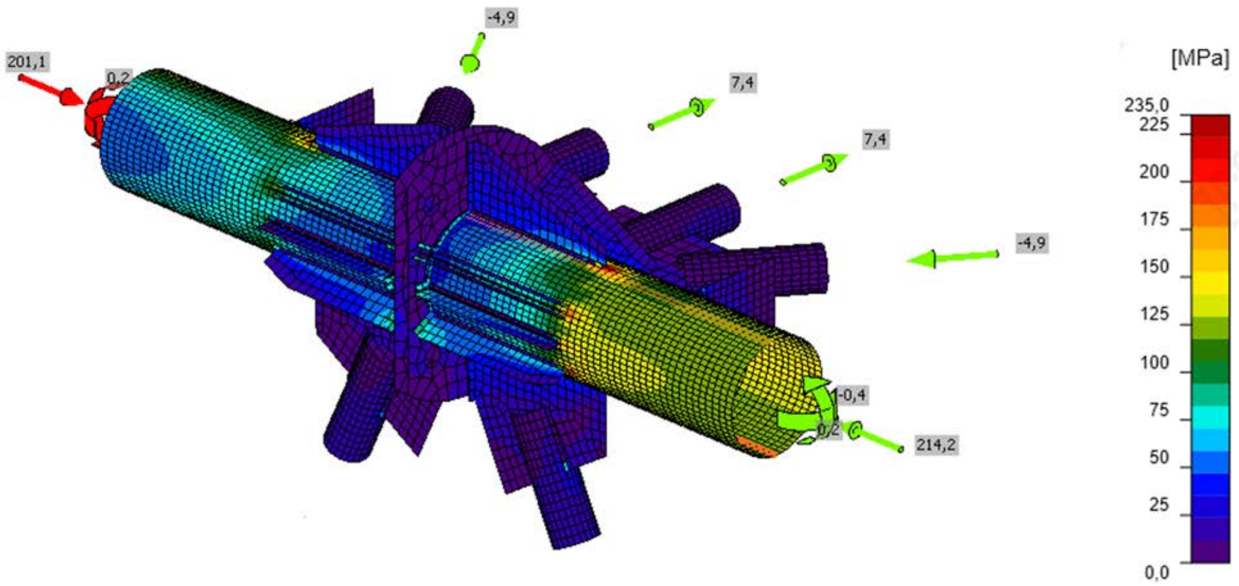
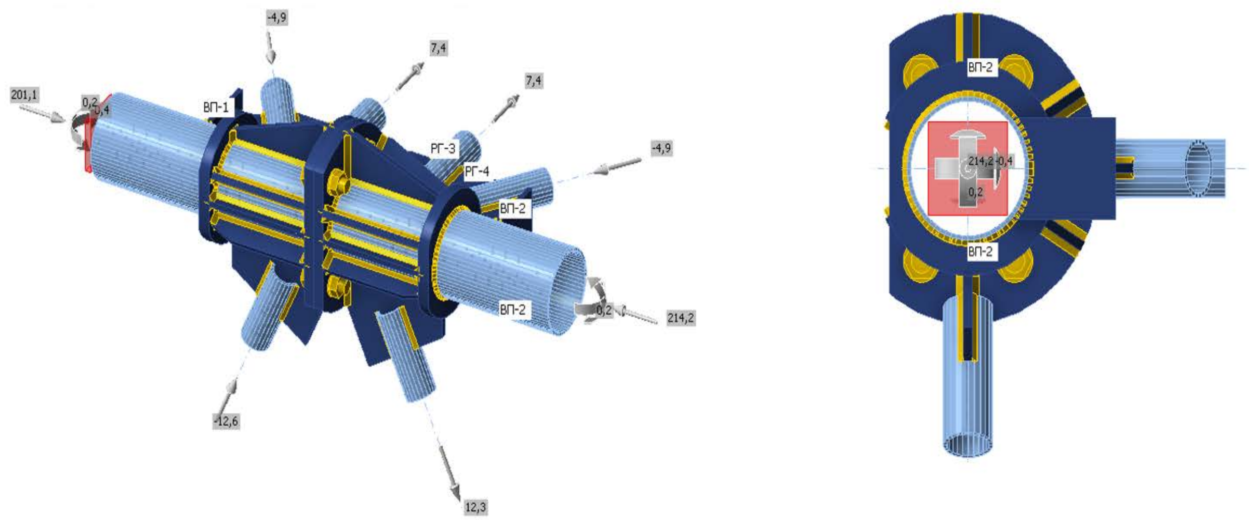


Fig. 6. Distribution of internal equivalent stresses in the top chord of truss Model 3.
Рис. 6. Розподіл внутрішніх еквівалентних напружень верхнього поясу ферми моделі 3.

In Model 4, a variant with additional non-continuous stiffening ribs is also considered, while a stiffness ring is introduced along the outer perimeter of the pipe. An important condition for this addition must be that $t_f \leq t_r$ (Fig. 7).



a *b*

Fig. 7. General view of Model 4 of the analysed joint with bolted connection and welds (a). Cross-section of the flange connection (b).
Рис. 7. Загальний вид моделі 4 розрахункового вузла з болтовим з'єднання та зварними швами (a). Переріз фланцевого з'єднання (b).

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The most optimal joint stiffness has been determined, transitioning from the semi-hinged form of connection observed in Models 2 and 3 with non-continuous ribs to a rigid connection. This is accompanied by the most uniform distribution of internal equivalent stresses, which provides an advantage in the even performance of the joint. The maximum stresses that occur are within the range of 125 MPa (Fig. 8).

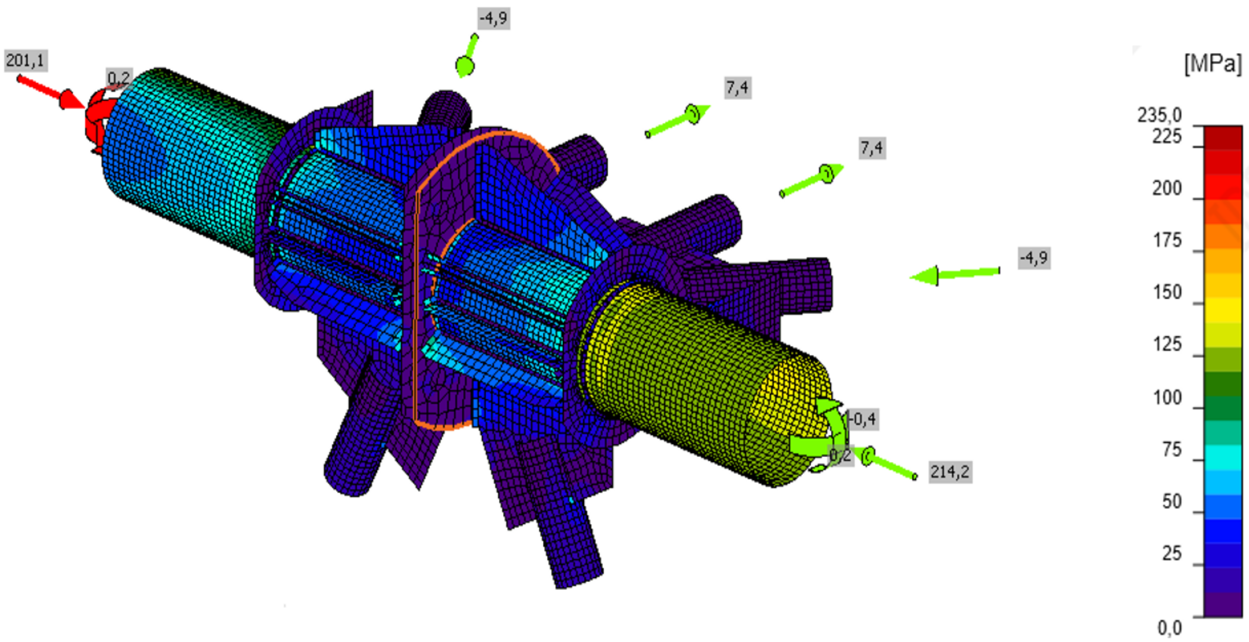

Fig. 8. Distribution of internal equivalent stresses in the top chord of truss Model 4.
Рис. 8. Розподіл внутрішніх еквівалентних напружень верхнього поясу ферми моделі 4.

A consolidated comparison of the finite element numerical analysis and the resulting stresses in the investigated Models 1, 2, 3, and 4 is presented as unfolded views of the upper chords of the truss (Fig. 9) and as the stress distribution in the flange plane caused by the weld seam (Fig. 10).

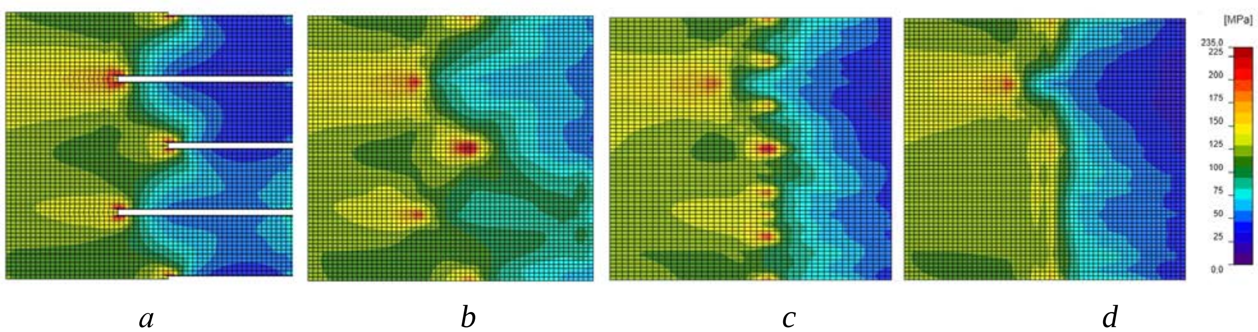

Fig. 9. Unfolded equivalent stress distribution on the upper face of the top chord for Model 1 (a), Model 2 (b), Model 3 (c), and Model 4 (d).
Рис. 9. Розгортка еквівалентних напружень верхнього поясу верху моделі 1 (a), моделі 2 (b), моделі 3 (c), моделі 4 (d).

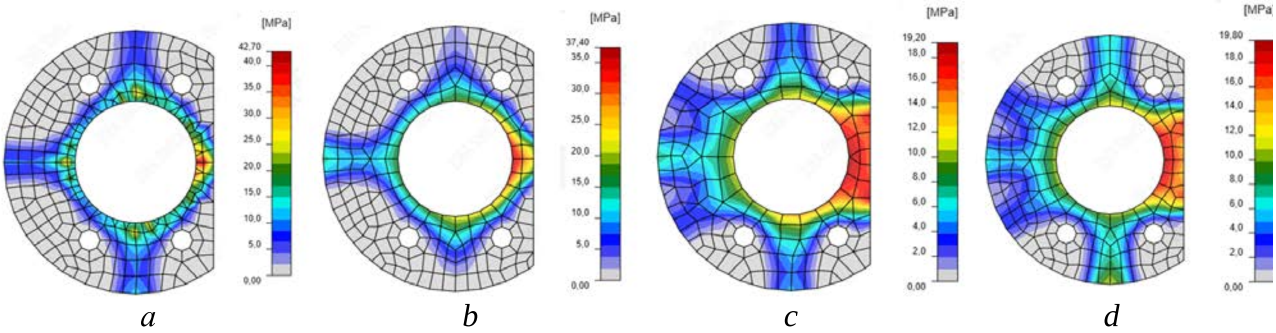

Fig. 10. Stress distribution in the flange plane due to welds: Model 1 (a), Model 2 (b), Model 3 (c), and Model 4 (d).

Рис. 10. Розподіл напружень в площині фланця від дії зварних швів моделі 1 (a), моделі 2 (b), моделі 3 (c), моделі 4 (d).

For analytical calculation, the determination of equivalent stresses at any point of the elements should be improved as follows:

$$\sigma_{Ed,i} = \frac{N_{Ed} \cdot a_i}{A_i \cdot \int_0^{\alpha_m} a(\alpha) d\alpha} \quad (4)$$

$\sigma_{Ed,i}$–equivalent stress at the investigated point i;

α – angular coordinate along the perimeter of the flange or pipe;

$a(\alpha)$ – radial distance from the center of the load in the direction of angle α;

$\int_0^{\alpha_m} a(\alpha) d\alpha$ – integral value accounting for the distribution of forces along the angular perimeter of the element.

CONCLUSIONS AND PERSPECTIVES FURTHER RESEARCH

In Models 1 through 4, a trend is observed toward the reduction of peak concentrations of equivalent stresses and an improvement in the uniformity of their distribution.

This study makes it possible to move away from the classical approach of analyzing the overall stiffness of the joint and allows not only for the analysis of stresses in the joints but also for influencing and structuring the stress distribution—without changing the cross-section of the main load-bearing element.

An improved analytical method for determining equivalent stresses is proposed as an alternative to the numerical finite element method for identifying critical local stress concentrations.

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ЧИСЛОВІ ДОСЛІДЖЕННЯ ФЛАНЦЕВИХ ВУЗЛІВ ФЕРМ З ОБРІЗАНИМИ ФЛАНЦЯМИ

Євген ЦЮПИН

Анотація. У сучасному будівництві сталеві ферми залишаються одним із найпоширеніших типів несучих конструкцій, що застосовуються при зведенні будівель промислових, цивільних та громадських будівель. Їх використання обумовлене високою несучою здатністю, відносною легкістю монтажу та економічною доцільністю використання у великопрогонових спорудах.

Одним із найвідповідальніших елементів таких конструкцій є фланцеві вузли, через які передаються основні зусилля від однієї частини ферми до іншої. Надійність і довговічність усієї системи в значній мірі залежить саме від якості виконання розрахунку.

Особливої уваги потребують ситуації, коли на вузол діють не тільки осьові навантаження, а й згинальні моменти та кручення, що спричиняють складний напружено-деформований стан. У таких випадках традиційні методи розрахунку, які ґрунтуються на спрощених моделях та припущеннях про рівномірний розподіл напружень, не завжди дозволяють виявити локальні концентрації, які можуть призводити до передчасного руйнування конструкції. З огляду на це, особливо актуальним є удосконалення методик чисельного аналізу з урахуванням реальної просторової геометрії елементів, особливостей з’єднання та характеру навантаження.

Запропонований підхід базується на побудові аналітичної моделі вузла з можливістю розрахунку внутрішніх зусиль у критичних зонах без потреби повного моделювання всієї ферми. Це дозволяє не лише скоротити час, необхідний для виконання розрахунків, а й підвищити їх точність. Такий підхід сприяє ранньому виявленню потенційно небезпечних зон, де можливе перевищення граничного рівня напружень, що, своєю чергою, знижує ризики втрати експлуатаційної придатності.

Ключові слова:. еквіваленті напруження; фланець, компонентний метод скінченних елементів; чисельне моделювання; жорсткість вузла; сталева ферма; локальне напруження.

Стаття надійшла до редакції 10.05.2025 р.