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ENDURANCE CALCULATION OF WELDED JOINTS IN TUBBING ERECTOR MECHANISM USING DIGITAL METHODS

Purpose. To develop and scientifically substantiate a methodology for determining the welded joint endurance during the operation of tubbing erector mechanisms, taking into account the unique conditions of their operation, in particular, under the influence of various types of loads.

Methodology. The research uses both theoretical approaches to determining the influence of loads and experimental methods. In particular, the finite element method (FEM) is used when modeling the stress-strain state in welded joints to identify stress concentration points. To assess the endurance of the joints, semi-empirical calculation methods are used, in particular, Hot Spot Stress and Effective Notch Stress, followed by a comparative analysis of the results obtained.

Findings. It has been determined that the traditional recommendations for selecting parameters for calculating stresses in technical objects using the Hot Spot Stress method are not always adequate for all scenarios of loading. A modified approach to assessing the endurance of welded joints is proposed, which integrates the Hot Spot Stress and Effective Notch Stress methods and takes into account the specifics of singular stress concentrators. Based on the analysis of the assessment results, greater accuracy in predicting the endurance of welded constructions is ensured. Experimental studies have revealed that the stress values occurring in welds depend on their geometric parameters, which made it possible to specify the criteria for assessing the strength of joints using the modified Hot Spot Stress and the Effective Notch Stress methods.

Originality. Since traditional methods for selecting parameters necessary for determining stresses in welded joints using the Hot Spot Stress method are not always appropriate for different types of loads, there is a need to develop a modified combination of the two methods, Hot Spot Stress and Effective Notch Stress. This makes it possible to adapt calculations to the specifics of singular stress concentrators in welded joints, which is the novelty of the research.

Practical value. The research results can be used in mechanical engineering to optimize projects for creating welded constructions, increasing their endurance and reliability. The proposed calculation methods make it possible to determine more precisely the values of equivalent stresses in hot spots of welded joints and predict their endurance, taking into account the real production conditions of the equipment operation.

Keywords: *singular stress concentrators, welded joints, Hot Spot Stress method, Effective Notch Stress method, endurance of welded joints, tubbing erector mechanism*

Introduction. The scientific community of Ukraine demonstrates a high level of activity in the field of development and improvement of technical means, initiating revolutionary ideas and opening new horizons in fundamental and applied research. At the National Technical University Dnipro Polytechnic, the scientific school of mining mechanical engineers consistently demonstrates positive results. Its contribution to the development of the industrial sector is the creation of advanced scientific concepts to solve insufficiently studied technical problems. The development of market relations in the state economy forces domestic manufacturers of technical objects to take into account the challenges associated with the need to improve the quality, reliability and economic efficiency of products that could successfully compete with foreign analogues of products. In this context, scientists of the National Technical University Dnipro Polytechnic and M. S. Polyakov Institute of Geotechnical Mechanics are actively developing the latest methods for mathematical and computer modeling, the use of which will contribute to the improvement of designing technical systems of different complexity.

Under the guidance of Professor I. A. Taran, for the first time, the parameters of new designs of hydro-mechanical transmissions of mine diesel locomotives [1] and the principles of modeling transport routes have been determined and substantiated [2, 3]. Research results of the scientific school representatives Professor V. P. Naduty [4] and his doctoral student V. V. Sukharyev, who studied the stress-strain state of vibrating feeders influenced by impact loads, open new perspectives for the development of knowledge about the behavior of materials under extreme conditions. Complex of studies initiated by Academician H. G. Pivniak and Professor V. I. Samusya [5, 6], is aimed at introducing heat pumps into the production processes of mining enterprises, which provides new opportunities to increase the energy efficiency of industrial technologies.

A significant contribution to the development of the field is also made by the studies by scientists K. A. Ziborov, S. O. Fedoriachenko [7, 8], aimed at substantiating the parameters of new designs of mine locomotives, as well as the activity of Professor K. S. Zabolotnyi. Under supervision of K. S. Zabolotnyi, the analysis of dynamic and static parameters of tubbing erectors [9] as a key means of constructing tunnels, hoisting machines [10, 11] and the theory of laying hoisting ropes on a drum [12] is conducted. Consequently, intensive scientific research of Ukrainian scientists in the development of innovative technologies and methods contributes to the improvement of technical level of domestic industry, opens new opportunities for its development and gains a strong position in the international market.

In the previously performed calculation [13], the position of the tubbing erector mechanism was determined when its nodes reach the maximum equivalent stresses during the cycle of tubing erector delivery to the desired location.

Fig. 1 shows a computer model of the tubbing erector mechanism, developed using the SOLIDWORKS Simulation software. The equivalent stress field according to von Mises criterion for 19.5 s is shown here.

From the data analysis of Fig. 2 it follows that stress concentrators appear in the construction, which is caused by the presence of round-shaped holes *1*, and there are also concentrators caused by the action of welded joints *2*, *3*.

In case of change in the final element mesh sizes, the equivalent stress values in the mentioned concentrators are different (Fig. 3). Thus, a decrease in these mesh sizes to 16, 8 and 4 mm in the first concentrator study (Fig. 3, line *1*) reflects a stress σ_{max1}, which tends to acquire an asymptotic value. Let

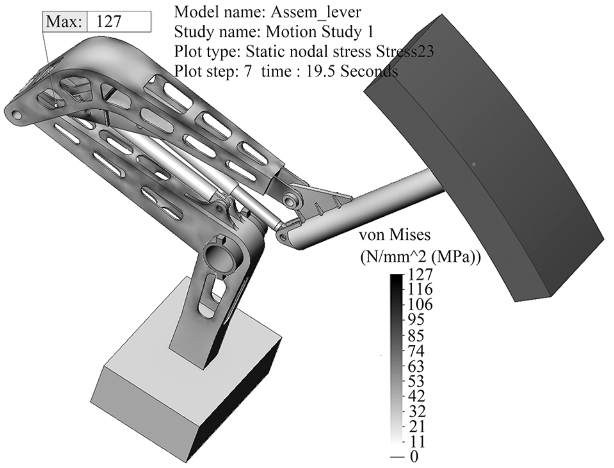


Fig. 1. Changes in the stress field of the tubbing erector mechanism details

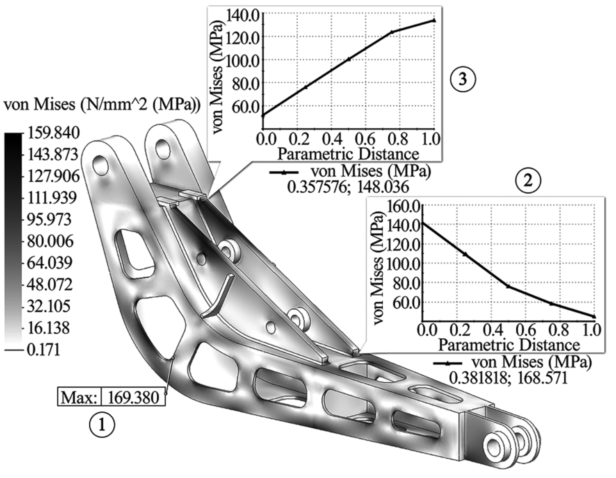


Fig. 2. Regular concentrator in the oval hole area (equivalent stress σ_{max1} = 169.380 *MPa)*

us call such a concentrator a regular concentrator. In concentrators placed on the weld edges (Fig. 3, lines *2* and *3*), the stresses σ_{max2}, σ_{max3} increase indefinitely. Let such concentrators be called singular concentrators.

It should be noted that the automated computational procedures of the SOLIDWORKS Simulation program do not provide tools for assessing the endurance of constructions having singular concentrators. Instead, semi-empirical methods should be used, in particular, calculation by nominal stress parameter, methods for determining stresses in the hot spots of the welded joint [14], namely Hot Spot Stress and Effective Notch Stress.

Literature review. To substantiate the relevance of the studied problem and determine its place in the general context of scientific search, we will perform an analysis of traditional methods and approaches for assessing the fatigue strength of welded constructions, identify the main achievements, and trends in the

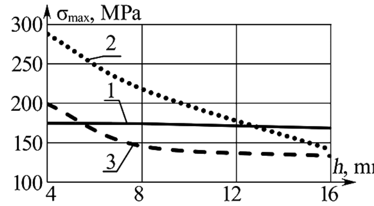


Fig. 3. Dependence of equivalent stresses in concentrators (regular – 1, singular – 2 and 3) on mesh size h

development of knowledge acquired in this area. It is known that the nominal stress method (Nominal stress – NS), the hot spot stress method (Hot Spot Stress – HSS) and the effective notch stress method (Effective notch stress – ENS) are the most common in assessing the stress state of welded constructions [15, 16]. The use of the above methods is enshrined in several international standards and recommendations of the International Institute of Welding (IIW) [16]. These methods are classified as concepts of global stress, structural stress and notch stress, respectively. In addition to the traditional approaches mentioned above, other methods for assessing the fatigue strength of welded constructions are also developed.

Calculation oriented to nominal stresses is recommended to be performed by analyzing welded products of simple shape. Thus, consider the results reported by scientific works in the field of assessing the fatigue strength of welded constructions, emphasizing the use of HSS and ENS methods.

One of the papers [17] compares the ENS and HSS methods in the context of the accuracy of predicting fatigue strength of welded joints, which is a significant contribution to the field of engineering research, especially given the influence of geometric heterogeneity and welding defects. Confirmation of the advantage of the ENS method over HSS in the accuracy of predicting the mentioned parameter allows a more appropriate approach to choosing a method depending on the specifics of the problem. At the same time, quite significant modeling and calculation costs associated with the application of the ENS method may reduce its applicability due to resource constraints.

The performed study of fatigue processes in root cracks of welded joints on cross beams of orthotropic bridges [18] is relevant for increasing the endurance and improving the safety of bridge structures. The HSS and ENS methods used for fatigue strength assessment in the context of exploiting a new generation of orthotropic bridges with increased deck plate thickness broaden understanding of the influence of various factors on fatigue strength. The scientific results described in the mentioned paper testify to the importance of considering local stresses and geometric peculiarities of welded joints when the fatigue life of bridges is to be improved. By limiting the research to orthotropic bridges only, it is impossible to fully envisage the potential applications of the results in other industries.

Assessing the fatigue response of welded joints in pipe constructions to multiaxial loads [19] can be considered crucial for various engineering needs. Here, a new perspective is proposed on the applicability of standard assessment methods, in particular HSS and ENS, under multiaxial stress conditions as typical for tubular structures. The conclusion about the potential or actual excess efforts in the development of models when using HSS and ENS methods, given certain multiaxial loading conditions, may be key to the choice of analysis methods. However, insufficient opportunities to compare the results of study with experimental data and limited information about alternative assessment methods have a negative impact on the completeness of the analysis.

Studying the influence of axial misalignment of construction elements on the fatigue strength of welded joints is very important when it comes to the reliability of welded constructions [20]. The study of cases of macrogeometric imperfection of joints and the relationship of such phenomenon to the fatigue strength of these objects after their processing by HFMI method represents a significant contribution to this field of research. The ability to compensate for the decrease in fatigue strength through processing by HFMI method has been confirmed, which increases the understanding of the mechanisms for improving this parameter. The use of a single type of steel during the research, as well as the failure to consider the long-term impact of operational loads on the construction, which limits the generality of the results, has been identified as a disadvantage of the research.

Another study [21] has proven the importance of the method of structural stress occurring in the so-called hot spots for assessing the strength of welded elements, especially when the nominal stress is difficult to determine due to the complexity of the geometric structure of the joints. This method is relevant when calculating the fatigue strength of complex constructions. The study provides new data on the effectiveness of using the hot-spot structural stress method, compared to other assessment methods, and also provides evidence-based recommendations for various cases of using the proposed method. The disadvantage of the study is the limited data on the results of specific tests, making it difficult to assess the effectiveness of the method in a wide range of applications.

One of the studies on the selected topic [22] analyzes the influence of axial misalignment of construction elements on the fatigue strength of welded joints. The results of such an analysis are very important to increase the reliability and operating life of the devices. The assessment methodology proposed by the authors includes the use of empirical calibration functions and local stress analysis. This methodology can be considered an important step in solving this problem. The research results may be useful for the development of safer and more cost-effective designs, especially for welded joints made of AH36 steel. At the same time, as in previous study, the limited analysis of objects made of one type of steel, as well as the ambiguity in assessing the axial misalignment factors, all this can reduce the universality of the proposed methodology.

Fatigue strength assessment of thick-walled cross welded joints after TIG-Dressing treatment represents an important area of research when it comes to the endurance and reliability of constructions [23]. In this case, the system analysis of the mentioned treatment method influence on the fatigue strength of such joints expands the existing knowledge; moreover, there is a new perspective on the application of this technology. In this study, an original approach to assess the fatigue strength of the joint has been developed, which is based on a combination of ENS and HSS methods. The disadvantage of the study is the insufficient amount of experimental data and the focus on the analysis of products made of a single type of steel, which may reduce the consistency of the results.

In the framework of a scientific study presented in another paper [24], a detailed testing of a methodology, based on the use of maximum principal stress values to analyze the fatigue strength of welded joints under the influence of multicomponent forces, has been conducted. The subject matter of this study is quite relevant in the context of improving available methodologies for assessing the fatigue strength of objects. As an alternative approach, it is proposed to use the equivalent stress values according to the von Mises yield criterion in the analysis, which indicates an innovative way of studying the phenomenology of multicomponent stress states. As can be seen, the research results convince us of the need to give special importance to the use of methods based on the maximum principal stress parameters in the object, as such studies acquire important practical significance.

Problem formulation. The available literature and scientific publications do not fully cover the theoretical basis and practical aspects of using the Hot Spot Stress and Effective Notch Stress methods. Perhaps the reason is their complexity, the need to take into account many factors influencing fatigue processes in metal, or the novelty of the subject matter. The algorithms for implementing the methods were developed based on empirical data, which are not capable of representing all possible operating conditions. The diversity of welded joint geometric structures and loading conditions creates certain difficulties in standardizing methods and generalizing results.

It follows from all said that development and substantiation of the methodology for calculating the endurance of singular stress concentrators in welded joints of the tubbing erector mechanism is an *actual scientific task*.

The **research purpose** is to develop and substantiate methodologies for assessing the welded joint endurance in tubbing erector mechanisms based on digitally modified Hot Spot Stress and Effective Notch Stress methods, which may contribute to improving the accuracy and reliability of calculations in modern engineering applications.

As shown by the data in Fig. 2, singular concentrators occur in the transverse and longitudinal stiffening ribs of the construction, respectively.

The welded joints in the tubbing erector mechanism (Fig. 2) correspond to the reference constructions (Structural Detail) described in [16] under numbers 521 (Fig. 4, *a*) and 511 (Fig. 4, *b*), respectively, with FAT_N numeric codes, where *N* is the maximum permissible stress, caused by influence of two million symmetric load cycles.

Fig. 4, a shows a scheme of a welded joint with a longitudinal rib and a connecting weld around its end.

When making welded joint No. 511 (Fig. 4, *b*), it is recommended for FAT100 class steel that the edges be finished, and for FAT80 – not finished.

It is necessary to perform a comparative assessment of three methods for calculating the endurance of welded joints – taking into account the nominal stresses, as well as Hot Spot Stress and Effective Notch Stress. As an example, reference welded constructions Nos. 511, 521 have been studied [16].

The task set is to determine the advantages and limitations in the use of each of the mentioned methods, as well as to develop their possible upgrades. The key research purpose is to formulate generalized recommendations for the effective integrated use of the developed methodologies in the process of optimizing the performance of designed tubbing erector mechanisms.

Endurance calculation of welded joints based on nominal stress values. Let us calculate the endurance of T-formed welded joint No. 511 (Fig. 4, *b*), using the methodology for determining metal fatigue in welded joints and nominal stress values [16].

Input data for calculation are: plate height is $h = 30$ mm, thickness is $B = 60$ mm, tension force is $F = 250$ kN. The nominal stress is determined by the following formula, MPa

$$\sigma_{nom} = \frac{F}{h \cdot B} = 138.9. \quad (1)$$

The calculation of material fatigue strength using permissible safety factor includes the following values: stress concentration efficiency factor in T-formed joints ($K_\sigma = 2.5$); a coefficient indicating the influence of heterogeneity of welded parts in rolled products ($K_1 = 1.1$); a coefficient indicating the influence of the overall sizes of the parts ($K_2 = 1$); a coefficient reflecting the influence of the T-formed weld length ($K_d = 1$); coefficient for taking into account the welded joint surface quality after rough machine processing ($K_F = 0.8$).

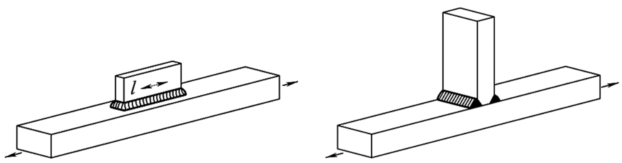
The coefficient for fatigue degree reduction in the welded joint material, which reflects the main factors influencing the process, is determined as follows

$$KCB = K_\sigma K_1 K_2/(K_d K_F) = 3.438.$$

Now let us consider the fatigue degree index in the equation to plot the curve of change in this parameter, provided that the number of load cycles on the weld is less than two million, is $m = 3$.

According to [16], select the ultimate strength σ_B equal to 450 MPa.

The endurance limit of the base metal (steel) for a symmetrical load cycle is determined by the formula [16], MPa



a *b*

Fig. 4. T-formed welded joint No. 521 (a) and No. 511 (b)

$$\sigma_{-1} = 0.43\sigma_B = 193.5.$$

Next, the endurance limit of welded parts, MPa is

$$\sigma_{-1CB} = \sigma_{-1}/KCB = 56.29.$$

In welded parts influenced by load cycle asymmetry, the endurance limit corresponds to this dependence, MPa

$$\sigma_R = 2\sigma_{-1CB} = 112.6.$$

The permissible safety factor value in the zone surrounding the weld of the base metal of machine-building constructions $[S_\sigma]$ is set in the range of 1.40–2.50.

Now calculate the welded joint endurance based on the nominal stresses using this empirical dependence [12]

$$N_Z = N_G \left(\frac{\sigma_R}{\sigma_{nom}\left[S_\sigma\right]} \right)^m,$$

where N_G is the base cycle number ($N_G = 2.7 \cdot 10^5$).

Fig. 5 shows the dependence curve of the welded joint endurance N_z determined on the basis of nominal stresses on the safety factor value in the weld zone $[S_\sigma]$. When calculating the joint endurance, we assume that $[S_\sigma]$ is 1.40; 1.95 and 2.50.

Using regression analysis, it is possible to determine a relationship between the welded joint endurance Nz and the permissible safety factor $[S\sigma]$, which has the following form

$$N_z([S_\sigma]) = (2.13 - 1.659 \cdot [S_\sigma] + 0.3357 \cdot [S_\sigma]^2) \cdot 10^6,$$

where $[S_\sigma]$ is the permissible safety factor of machine-building constructions ($[S_\sigma] = 1.4–2.5$).

Conclusions. From the analysis of the results of calculating the welded joint endurance, performed on the basis of nominal stresses, it follows that the parameter N_z value is independent of the design of the T-formed joint and the geometric parameters of the weld. The method does not reflect local stresses near the welds, the geometric shape and heterogeneity of the welded joint.

These disadvantages indicate the necessity for more comprehensive methods for calculating this parameter, capable of taking into account the influence of local stresses, joint configuration, stress concentration effects, microstructural peculiarities of materials, as well as complex operating modes of the construction to improve the accuracy and reliability of the research results.

Welded joint endurance calculation using the Hot Spot Stress method [16]. Here it is proposed to determine the equivalent stresses using reference lines drawn at a distance of 0.5 and 1.5t from the hot spot, where t is the rib thickness. It has been determined that the computational mesh size is equal to t. Using the found values of these stresses, a linear extrapolation can be used to calculate the stress in the welded joint hot spot as follows: $\sigma_{HSS} = 1.5\sigma_{0.5} - 0.5\sigma_{1.5}$.

The Hot Spot Stress method is used to calculate the endurance of the T-formed welded joint No. 511. For this purpose, we focus on a model of T-formed welded joints in a plate, which has sizes of 30, 60 and 400 mm and a transverse rib attached to it (Fig. 4, *b*), as well as on a model of a plate with a longitudinal rib (Fig. 4, *a*). Assume that the rib height is taken to be 100 mm. The following boundary conditions are added to the calculations: on the left plate end there is a ban on normal movements towards it, on the right – a tension force of 250 kN.

Perform several computational experiments.

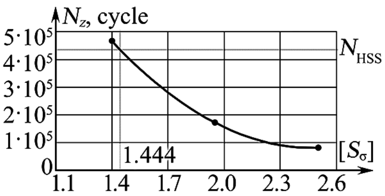


Fig. 5. Dependence curve between N_z and $[S_\sigma]$ parameters

Computational experiment No. 2. Fig. 6 shows the results of calculating equivalent stresses in a T-formed welded joint with a transverse rib. The calculation is performed according to [16]. As can be seen, along the plate, the zone of influence of hot stresses does not exceed 5 mm. At a distance of 0.5t, the stresses will be equal to nominal (139 MPa). This means that recommendations for choosing the parameter t and the computational mesh size are not correct.

On the other hand, it can be seen that the zone of hot spot influence is comparable to the weld leg size. Moreover, the larger this size is, the larger the zone of the hot spot influence. When determining stresses using linear extrapolation, it is necessary to comply with the condition that at least one of the reference lines is located in the zone of the hot spot influence.

Computational experiment No. 2.2. Modify the Hot Spot Stress method. For this purpose, by performing a calculation using finite element applied to the weld edge, the mesh size is found to be 0.05b, where b is the weld leg size. The maximum equivalent stresses $\sigma_{0.5}$and $\sigma_{1.5}$ are determined using reference lines (Fig. 7) drawn at a distance of 0.5b and 1.5b from the hot spot.

Equivalent stresses in the welded joint hot spot should be calculated using linear extrapolation, namely

$$\sigma_{HSS} = 1.5\sigma_{0.5} - 0.5\sigma_{1.5}. \quad (2)$$

The endurance of a welded joint with a transverse rib (Fig. 5) is calculated using the equivalent stress values in the hot spot, found on the $S–N$ curves with the FAT100 numeric code [16], that is, cycle

$$N_{HSS} = 2 \cdot 10^6 \cdot \left(\frac{100\ \text{MPa}}{\sigma_{HSS}} \right)^3. \quad (3)$$

Computational experiment No. 2.3. Determine the dependence of the parameter N_{HSS} on the parameter b. To do this, in the model with a transverse rib (Fig. 4), its thickness is successively changed as follows: 30, 20, 15, 4 mm (DSTU-NBA31-16), and the weld leg height – 8, 7, 6, 5, 4 mm. Equivalent stresses in the hot spot are calculated by formula (2), and welded joint endurance by formula (3). The calculation results are presented in Table 1.

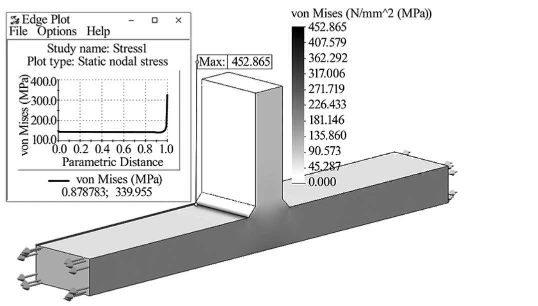


Fig. 6. Stress field in a welded joint when the rib thickness is 30 mm and the weld leg is 8 mm

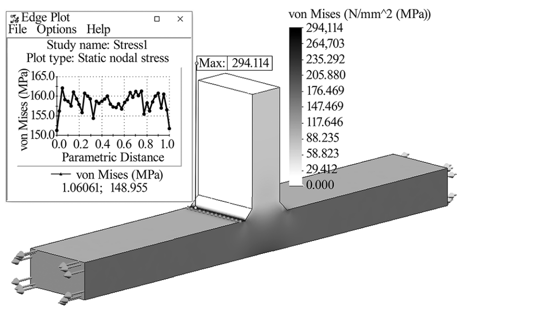


Fig. 7. Stress field in a T-formed joint:

a – equivalent stress distribution; b – reference line

Table 1

Dependence of the T-formed welded joint endurance with a transverse rib N_{HSS} on the weld leg height b

Calculation No.	b, mm	N_{HSS}, cycles
1	4	$4.538 \cdot 10^5$
2	5	$4.353 \cdot 10^5$
3	6	$4.605 \cdot 10^5$
4	7	$4.929 \cdot 10^5$
5	8	$4.448 \cdot 10^5$

From the data analysis in Table 1, it can be seen that the N_{HSS} welded joint endurance is practically independent of the weld leg height b and is on average $4.575 \cdot 10^5$ cycles.

Fig. 5 compares data on the average welded joint endurance, determined by the modified Hot Spot Stress method, as well as those obtained using the calculation method, where nominal stresses are introduced. A comparison shows that both types of results are almost in the same range, which confirms the correctness of the developed Hot Spot Stress method modification.

Computational experiment No. 2.4. In literary sources [16], it is determined that in steel T-formed welded joint No. 521, depending on the longitudinal rib length l, the following numeric code values should be taken: $l < 50$ mm – FAT80; $l < 150$ mm – FAT71; $l < 300$ mm – FAT63; $l > 300$ mm – FAT50. To test this recommendation, perform a computational experiment by determining the maximum equivalent stresses in a welded joint with a longitudinal rib, and the weld leg height is 7 mm (Fig. 8). In the calculation, different longitudinal rib length values l are taken (Table 2).

Fig. 8 shows that the maximum stresses occur in the transverse welded joints, the stresses are even lower in different zones of the longitudinal weld.

Table 2 data analysis shows that the maximum equivalent stress value is independent of the welded joint longitudinal rib size. Consequently, its endurance is independent of the mentioned rib parameter.

Computational experiment No. 2.5. Compare the results of calculating the endurance of welded joints having a transverse and longitudinal rib, making them dependent on the weld leg height b (Fig. 9).

Fig. 9 data analysis shows that the endurance of a welded joint with a transverse rib (curve *1*) is practically not affected by the weld leg size b, and in relation to the longitudinal rib (curve *2*) this parameter increases according to a parabolic dependence. The following regression models can be used to model and analyze the ratios between variables describing this relationship:

- endurance of welded joint with transverse rib, cycle

$$N_{HSS,\,1} = -6.32 \cdot 10^6 + 4.68 \cdot 10^6 \cdot \beta - 1.19 \cdot 10^6 \cdot \beta^2 + 1.30 \cdot 10^5 \cdot \beta^3 - 5.25 \cdot 10^3 \cdot \beta^4; \quad (4)$$

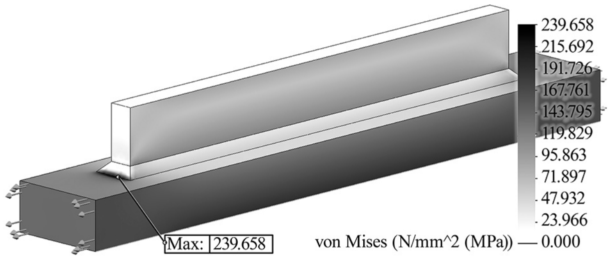


Fig. 8. Equivalent stress field of the transverse weld, when the longitudinal rib length is l = 400 mm, in T-formed welded joint No. 521

Table 2

Dependence of the maximum equivalent stresses in the transverse weld hot spot on the longitudinal rib length

Calculation No.	l, mm	σ_{max}, MPa
1	40	233.5
2	100	239.1
3	200	239.6
4	400	239.7

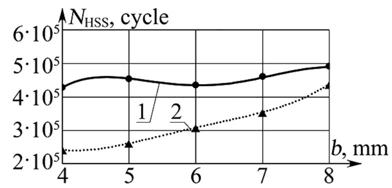


Fig. 9. Curves of changes in endurance of N_{HSS} welded joints depending on the weld leg size b, mm:

1 – transverse rib; 2 – longitudinal rib

- endurance of welded joint with longitudinal rib, cycle

$$N_{HSS,\,2} = 3.35 \cdot 10^6 - 2.24 \cdot 10^6 \cdot \beta + 5.85 \cdot 10^5 \cdot \beta^2 - 6.56 \cdot 10^4 \cdot \beta^3 + 2.82 \cdot 10^6 \cdot \beta^4, \quad (5)$$

where β is dimensionless weld leg ($\beta = b/1$ mm).

Conclusions. Based on the analysis of the results of computational experiments 2.1–2.5, performed using the Hot Spot Stress method, the key factors influencing the accuracy of calculating the weld endurance have been identified.

For the first time, it has been found that recommendations on the choice of the rib thickness parameter t and the finite-element mesh size are not correct.

The calculation of the mentioned parameter using FEM should be performed in application to the weld edge, and the finite element mesh size should be $0.05 \cdot b$, where b is the weld leg height. The maximum equivalent stresses $\sigma_{0.5}$ and $\sigma_{1.5}$ should be determined using reference lines drawn at a distance of $0.5b$ and $1.5b$ from the welded joint hot spot.

It has been confirmed that the results of calculations of the stress-strain state occurring in the joints, performed using modified Hot Spot Stress method, are well consistent with those obtained by calculating based using nominal stresses (Fig. 5), which confirms the correctness of the developed modification of the method.

It has been found that the endurance of a welded joint with a transverse rib $N_{HSS,1}$ almost does not change at the weld leg height b, and under the influence of a change in the longitudinal rib length, the weld $N_{HSS,2}$ endurance increases according to parabolic dependence on the weld leg size b (Fig. 7).

The value of the maximum equivalent stresses occurring in T-formed welded joint No. 521 does not depend on the longitudinal rib length (Table 2).

Welded joint endurance calculation using the Effective Notch Stress method. Fig. 10, *a* shows a scheme for a stress concentrator in the form of a weld edge with a radius of curvature R_e equal to zero. If such a condition applies, then the stresses in the concentrator tend to infinity.

When calculating endurance using Effective Notch Stress (ENS) method, in [16] it is proposed to select an effective curvature radius R_e value equal to 1 mm (Fig. 10, *b*). To assess the stress fatigue of a material, determined under the proposed conditions, it is necessary to compare it with a single *S*–*N* fatigue curve corresponding to the FAT225 numeric code.

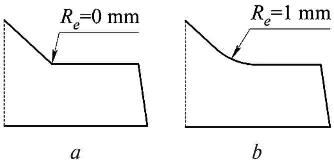


Fig. 10. Effective value of the curvature radius R_{ENS} made on the stress concentrator

Now consider how the recommendations described in [16] are consistent with the computational experiment results.

For this purpose, determine the dependence between the weld endurance value calculated using *ENS* method, *NENS* and the curvature radius *RENS* effective value, the weld leg height *b* and the welded joint type (reference samples 511 and 521).

The conditions for conducting a computational experiment are taken from paragraph 1 of this paper (plate sizes are 30, 60, 400 mm, it can have a transverse rib (Fig. 4, *a*) or a longitudinal rib (Fig. 4, *b*), the height of which is 100 mm. Rib thicknesses of 30, 20, 15, 4 mm and the following weld leg sizes of 8, 7, 6, 5, 4 mm are set according to DSTU-NBA31-16.

Computational experiment No. 3.1. Determine the dependence of the *NENS* weld endurance value, calculated using the *ENS* method, on the curvature radius *Re*. Use the algorithm described below.

1. For comparison, the *HSS* method (Fig. 11) is used to calculate the endurance of the reference welded joint sample No. 511 (with a transverse rib) (Fig. 12).
2. Then, several curvatures of this weld edges are sequentially modeled (Fig. 11), using a finite element mesh, whose cells are equal to 0.2 R_{ENS} of the curvature radius. After that, the maximum equivalent stresses σ_{ENS} are calculated and the endurance of N_{ENS} welds is determined by the *ENS* method, taking into account the FAT225 numeric code. If the N_{HSS} endurance value is in the range between the two N_{ENS} values already calculated by this method, then linear interpolation is used to find the curvature radius [R_{ENS}], which would correspond to the mentioned parameter values calculated using the *HSS* and *ENS* methods.
3. To clarify the curvature radius [R_{ENS}], a verification calculation is performed and the error in the results of using two methods is found in determining the weld endurance. If necessary, additional experiments with varying curvature radius values are conducted.

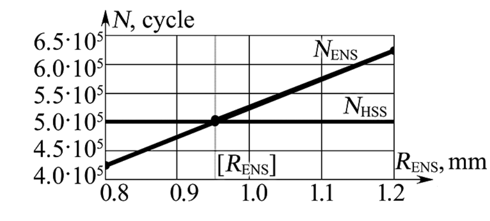


Fig. 11. Dependence of the N_{HSS} and N_{ENS} weld endurance in reference sample No.511, calculated using the HSS and ENS methods, on its curvature radius RENS

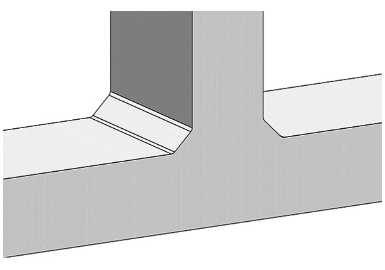


Fig. 12. Rounding the weld edge in a transverse rib

4. Repeat steps 2–3, using the changed values of the weld leg height *b*.
5. Next, a series of computational experiments similar to those described above is conducted with the reference welded joint No.521 (with a plate having a longitudinal rib) (Fig. 13).

The results of computational experiments are shown in Fig. 14. As can be seen, near the legs of welds with a transverse rib, the curvature radius [R_{ENS}], determined from the condition of coincidence of the endurance values calculated by two methods (*ENS* and *HSS*), differs significantly from that accepted in the literature [16]. The dependence of the curvature radius [R_{ENS}] on the weld leg height *b* is close to linear, but examination of the longitudinal plate rib shows that the increase in the curvature radius [R_{ENS}] occurs more intensively.

To model and analyze the relationships between the curvature radius [R_{ENS}] and the weld leg *b,* the following regression models can be used:

- the curvature radius with the welded joint leg of the plate having a transverse rib, mm

$$[R_{ENS}]_1 = (-17.936 + 12.306 \cdot в - 3.046 \cdot в^2 + 0.333 \cdot в^3 - 0.013 \cdot в^4); \quad (6)$$

- the curvature radius with the welded joint leg of the plate having a longitudinal rib, mm

$$[R_{ENS}]_2 = (5.105 - 3.454 \cdot в + 0.983 \cdot в^2 - 0.117 \cdot в^3 + 0.005 \cdot в^4). \quad (7)$$

Test how the external load influences the recommended curvature radius values determined using the *ENS* method, [R_{ENS}], when *b* is the specified weld leg height. Let the relative curvature radius be

$$\rho = [R_{ENS}]\frac{1}{b}.$$

For comparison, take the reference sample No. 511 (Fig. 15). Perform computational experiments with the following conditions: tension force *F* acquires the values of 125; 187.5 and 250 kN. In this case, the value of 250 kN corresponds to the safety factor beyond the yield strength, that is, K_t = 1.5. Weld leg is 8 mm.

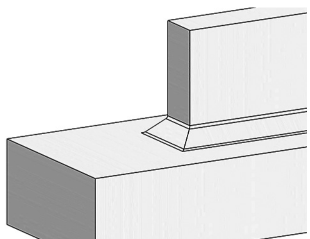


Fig. 13. Rounding the weld edge in a longitudinal rib

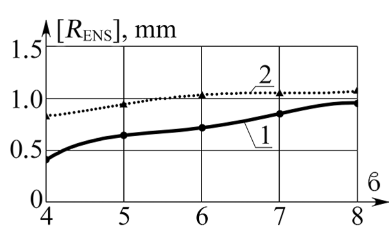


Fig. 14. Change in the curvature radius [R_{ENS}] near the weld leg, in particular, depending on its height:
1 – when a plate edge is transverse; 2 – when longitudinal

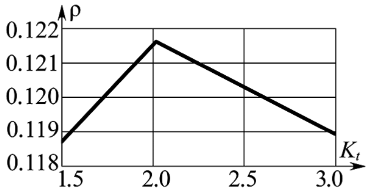


Fig. 15. Dependence of the relative curvature radius ρ on the safety factor taking into account the yield strength of the material K_t

It follows from the analysis of the computational experiment results that when the load changes by 2.5 times according to the theory of elasticity, the ratio of the curvature radius values and the weld leg height changes by no more than 1.5 %, since this is due to a calculation error. Therefore, the relative curvature radius value ρ is practically independent of the applied load value.

Now, we use the proposed methodology for calculating the weld endurance in the tubing erector mechanism.

To do this, consider the weld of one of the parts (Shoulder) of the mentioned mechanism, shown in Fig. 16. When the mechanism operates, a stress-strain state occurs here, similar to that present in reference weld sample No. 511 (Fig. 7). The height value of the weld legs *b*, on the edges of which singular stress concentrators are located, is 8 mm.

The calculation uses a modified Hot Spot Stress method. But first, use the finite element method. To do this, we apply a finite element mesh to the weld edge, the size of which is $0.05 \cdot b$, where *b* is the leg height of this weld. The maximum equivalent stresses $\sigma_{0.5}$ and $\sigma_{1.5}$ should be determined using reference lines drawn at a distance of $0.5b = 4$ mm and $1.5b = 12$ mm from the weld hot spot (Fig. 16).

Fig. 16 data analysis shows that the stress distribution in the tubing erector element (in contrast to the stress-strain state in reference sample No. 511 (Fig. 9)) along the weld edge changes by 2.3 times.

For calculation, we take the maximum stress values determined using the corresponding reference lines, that is: $\sigma_{0.5} = 139.8$ and $\sigma_{1.5} = 127.5$ MPa.

The calculation of the equivalent stresses in the hot spot is determined using linear extrapolation (2), namely $\sigma_{HSS} = 1.5\sigma_{0.5} - 0.5\sigma_{1.5} = 145.95$ MPa.

The endurance of the welded joint, where there is a transverse rib, is determined using the found equivalent stresses in the hot spot and focusing on the *S–N* curves with the FAT100 numeric code value, namely, cycle

$$N_{HSS} = 2 \cdot 10^6 \left(\frac{100\ \text{MPa}}{\sigma_{HSS}} \right)^3 = 6.433 \cdot 10^5.$$

For comparison, it should be noted that the calculated weld endurance of reference sample No. 511 is $5 \cdot 10^5$ cycles (Fig. 7). Consequently, the error of the result obtained, if compared with the above calculated one, is 29 %.

Calculate the weld endurance (Fig. 17) using the *ENS* method. The curvature radius value $[R_{ENS}]$ is taken from the data in Fig. 9 or determined using equation (6). Therefore, $[R_{ENS}] = 0.95$ mm. Assume that the finite element mesh size is 0.19 mm (Fig. 17).

Then the stress value is $\sigma_{ENS} = 300.5$ MPa and the weld endurance, cycle, is

$$N_{ENS} = (a_{225}/\sigma_{ENS})^m = 8.395 \cdot 10^5;$$

$$N_{HSS} = (a_{225}/\sigma_{HSS})^m = 6.433 \cdot 10^5.$$

As can be seen from Fig. 17, if the weld curvature radius along the length of its edge varies in a wide range, then the maximum stress value is $\sigma_{\text{ENS}} = 300$ MPa. Using the *ENS* method and taking into account the FAT225 numeric code, the weld endurance can be determined as follows, cycle

$$N_{ENS} = \left(\frac{FAT225}{\sigma_{ENS}} \right)^3 = 8.4 \cdot 10^5.$$

The endurance value just found is 23.4 % higher than that determined by the *HSS* method. This is because the curvature radius R_e is determined according to the scheme of reference sample No. 511 (Fig. 13), and in it the equivalent stress intensity along the weld does not change, while in the Shoulder link scheme a change in the stress distribution along the weld edge is provided for by 2.3 times (Fig. 12).

Summarizing the results of computational experiments, the following methodology can be proposed for calculating the endurance of singular concentrators in the welded joints of the tubing erector mechanism.

1. The operating life of a construction is calculated using the finite element method, while determining stress concentrators (hot spots).

2. Stress concentrators are divided into two groups, and a reference weld sample is taken from each of them (Fig. 4).

3. A modified Hot Spot Stress method is used. First, using FEM, the equivalent stresses are determined at the locations of the parting lines drawn from the hot spot connection at a distance of 0.5*b* and 1.5*b*, where *b* is the weld leg size, and then the stresses in the hot spot itself are calculated. In this case, the welded joint endurance is determined depending on its scheme and the corresponding FAT_N numeric code given in the literature [16].

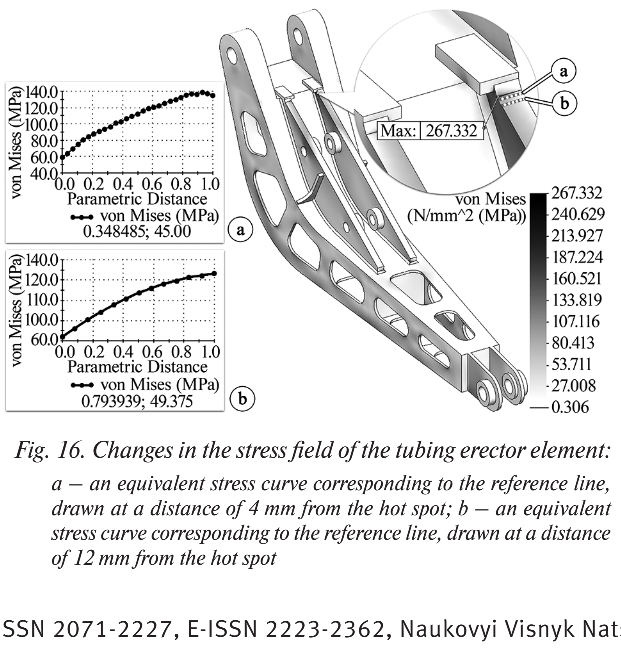


Fig. 16. Changes in the stress field of the tubing erector element:
a — an equivalent stress curve corresponding to the reference line, drawn at a distance of 4 mm from the hot spot; b — an equivalent stress curve corresponding to the reference line, drawn at a distance of 12 mm from the hot spot

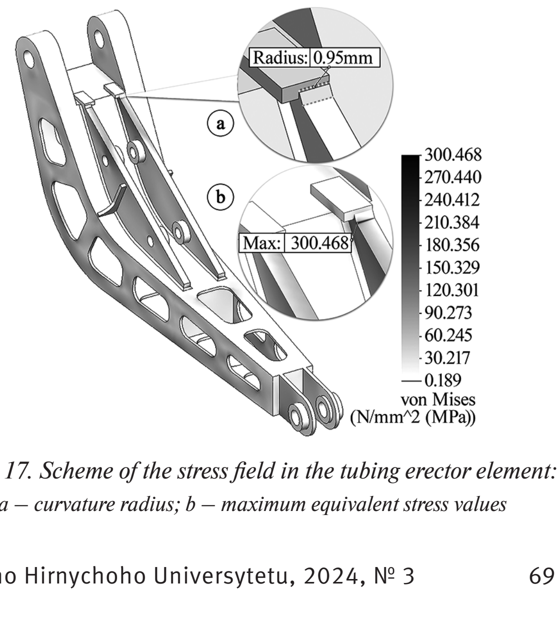


Fig. 17. Scheme of the stress field in the tubing erector element:
a — curvature radius; b — maximum equivalent stress values

4. When calculating the parameters using the Effective Notch Stress method, initially, the FEM is used for the area of rounding in the hot spot. In this case, the curvature radius values [R_{ENS}] are taken according to the weld leg height *b* (Fig. 14), or according to equations (6) or (7), taking into account reference welded joint samples No. 511 or No. 521.

5. Having compared the calculated endurance values, the lowest value is taken as the basis for assessing this parameter in the entire construction.

Welded joints can be specific, so it is not possible to select a standard for them, and then the endurance calculation is performed only using the Effective Notch Stress method. In this case, the curvature radius value is taken from the previously performed concentrator calculation or in the range of values 0.35–1.2 mm.

Conclusions.

1. The relevance of the research conducted here stems from the need to improve the reliability and endurance of welded joints in important constructions of the tubing erector mechanisms. Despite considerable progress in this issue, challenges inevitably arise related to accurate prediction of equipment operating life, in particular, in the context of the occurrence of singular stress concentrators in it. The analysis of stress distribution in welded joints indicates the occurrence of both regular and singular stress concentrators in them. This confirms the need for a detailed study of their impact on the endurance of constructions.

2. A comparative assessment of the endurance calculation results, obtained using the Hot Spot Stress and Effective Notch Stress methods and taking into account nominal stresses, shows that accurate prediction of the endurance of welded joints is possible provided that the specifics of stress concentrators and the influence of external factors on these elements are known.

3. It has been determined that standard recommendations for selecting the rib thickness parameters and the size of computational mesh elements may be insufficient to adequately reflect the influence of singular stress concentrators on the endurance of welded joints.

4. The effectiveness of the modified combination of the Hot Spot Stress and Effective Notch Stress methods has been confirmed by good convergence of the calculated data with the experimental results, which opens the way to optimize the design of technical objects.

5. It has been determined that the endurance of welded joints does not depend on the weld leg height, which indicates the importance of the correct choice of calculation methods to assess this characteristic of the construction.

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Розрахунок довговічності зварних з’єднань у механізмі тюбінгоукладача з використанням цифрових методів

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Мета. Розроблення й наукове обґрунтування методології визначення довговічності зварних з’єднань під час роботи механізмів тюбінгоукладачів, з урахуванням унікальних умов їхньої експлуатації, зокрема під впливом диверсифікованих типів навантажень.

Методика. У дослідженні були використані як теоретичні підходи до визначення впливу навантажень, так і експериментальні методи. Зокрема в моделюванні напружено-деформованого стану у зварних з’єднаннях з виявленням місць концентрації напружень був застосований метод скінченних елементів. Для оцінювання довговічності з’єднань застосували напівемпіричні методи розрахунку, зокрема Hot Spot Stress і Effective Notch Stress, із подальшим порівняльним аналізом отриманих результатів.

Результати. Було визначено, що традиційні рекомендації стосовно вибору параметрів для розрахунку напружень у технічних об’єктах методом Hot Spot Stress не завжди адекватні всім сценаріям навантаження. Запропоновано модифікований підхід до оцінювання довговічності зварних з’єднань, в якому інтегровані методи Hot Spot Stress і Effective Notch Stress і врахована специфіка сингулярних концентраторів напружень. На основі аналізу результатів оцінювання забезпечена більша точність у прогнозуванні довговічності зварних конструкцій. Експериментальні дослідження виявили залежність величин напружень, що виникають у зварних швах, від їхніх геометричних параметрів, що дозволило уточнити критерії оцінювання міцності з’єднань за допомогою модифікованого методу Hot Spot Stress і методом Effective Notch Stress.

Наукова новизна. Оскільки традиційні способи вибору параметрів, потрібних для визначення напружень у зварних з’єднаннях методом Hot Spot Stress, не завжди відповідають різним типам навантажень, то виникає потреба в розроблені модифікованого поєднання двох методів, Hot Spot Stress і Effective Notch Stress, що дає можливість адаптувати обчислення до специфіки сингулярних концентраторів напружень у зварних з’єднаннях. У цьому й полягає новизна дослідження.

Практична значимість. Результати дослідження можуть бути використані в машинобудуванні для оптимізації проєктів створення зварних конструкцій, підвищення їхньої довговічності й надійності. Пропоновані методики розрахунку дозволяють точніше визначати величини еквівалентних напружень у «гарячих» точках зварних з’єднань і прогнозувати їхню довговічність з огляду на реальні виробничі умови експлуатації обладнання.

Ключові слова: *сингулярні концентратори напружень, зварні з’єднання, метод Hot Spot Stress, метод Effective Notch Stress, довговічність зварних з’єднань, механізм тюбінгоукладача*

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