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STRESS-STRAIN STATE OF STEAM TURBINE LOCK JOINT UNDER PLASTIC DEFORMATION

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The stress-strain state problem for the lock joint of the rotor blades of the first stage of the medium-pressure cylinder under plastic deformation is solved. When solving the problem, the theory of elastic-plastic deformations is used. The problem is solved using two different approaches to specifying plastic deformation curves. The applicability of using a simpler bilinear approximation instead of the classical multilinear one is estimated. Based on the example of solving this problem, the time required to perform the calculation with the use of the bilinear and multilinear approximations is shown. Comparison of the results obtained in the form of the distribution of plastic deformations, equivalent stresses, and contact stresses over support pads made it possible to assess the difference when the two types of approximation are used. The obtained result error value when using the bilinear approximation made it possible to draw conclusions about the applicability of this approach to the processing of plastic deformation curves for solving problems of this kind. The problem is solved using the finite element method. To objectively assess the effect of plastic deformation on the redistribution of loads in the lock joint, a finite element model is used, obtained when solving the problem of the thermally stressed state of the rotor blade lock joint. The distribution of contact stresses in the lock joint is shown. The results are compared with those obtained earlier when solving the problem of thermoelasticity. Significant differences in the level of contact stresses are noted. Results of the computational assessment of the stress-strain state of the lock joint of the rotor blades of the first stage of the medium-pressure cylinder of a steam turbine are presented, which allow characterizing the degree of relaxation and redistribution of stresses in the structure in comparison with the results obtained earlier when solving the problem of thermoelasticity. Conclusions are made about the economic viability of using the calculation methods presented.

Keywords*: turbine, lock joint, rotor blade, stress state, deformation curve, yield point.*

Introduction

In unsteady operating modes, individual elements of the flow path of powerful steam turbines can be subject to plastic deformation, as a result of which stress redistribution occurs in them. When under plastic deformation, the material undergoes structural transformations which lead to a violation of the conditions of normal operation of assemblies. These changes must be taken into account in the calculations of the operability and load-bearing capacity of structures.

Currently, JSC Turboatom is concerned with the development of a new generation of 500–750 MW steam turbines with steam parameters in front of the turbine of about 29 MPa / 600 °C. The prototype for the creation of such a series of turbines is the existing serial K-500-240 turbine, during the long-term operation of which there were violations of the integrity of the rotor blade lock joint (Fig. 1) [1].

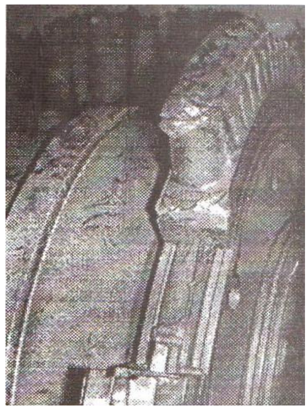


Fig. 1. The state of the disk of the first stage rotor blades in the area of the lock joint after a breakdown

A photograph of the damaged disk (Fig. 1) gives us an idea of the nature of the damage: there is a separation of a part of the disk in the area of the rotor blade lock joint. A preliminary analysis of the damaged surface makes it possible to speak of insufficient load-bearing capacity of this unit under the influence of certain power loads. This circumstance is primarily due to the imperfection of the calculation base and difficulty of taking into account the maximum number of factors. Among them are complex geometric design, high operating temperatures (about 535 °C), existence of a temperature gradient along the disk width, spatial loading from centrifugal forces due to steam loading, contact interaction of elements in the lock joint, work outside the elastic region.

To identify the causes of such breakdowns and develop recommendations for their prevention, more accurate computational studies of the stress-strain state (SSS) of the rotor blade lock joint were required. Consistent consideration of these factors, when solving the problem of determining and analyzing the stress state of the lock joint, made it possible to determine the degree of influence of one or another factor on its strength [2–5]. Thus, carrying out the computational studies of the stress state of the three-support mushroom-shaped lock joint [2–4] made it possible to assess the applicability of the technique chosen. The stress state of the lock joint was determined using the finite element (FE) method [6, 7]. The solution to the problem was carried out taking into account the contact interaction of lock joint elements [6–9]. The calculation results were compared with the test data of the experimental model of this lock joint [10]. Further clarification of the picture, associated with the distribution of stresses over the lock joint structure, required that the temperature field effect on the stress state of lock joint elements be assessed [5]. The thermal contact problem was solved taking into account the effect of heat transfer on the transfer of forces in the lock joint [11, 12]. Based on the results of solving the problem, it was noted that in the place of the cutout in the rotor disk for the locking blade there are zones of maximum stresses, the magnitude of which significantly exceeds the yield point of the disk material at operating temperature (Fig. 2) [13]. It is natural to assume that the high level of stresses is due to the occurrence of additional temperature stresses in the lock joint structure, which, in turn, is associated with the presence of structural elements with different coefficients of thermal linear expansion [13]. Thus, the KhN70VMYuT alloy (pins) has the largest thermal expansion coefficient, and the EI-415 steel (disk) has the smallest one. During heating, the thermal expansion of some lock joint elements exceeds the expansion of others in magnitude, which ultimately causes the appearance of additional temperature stresses.

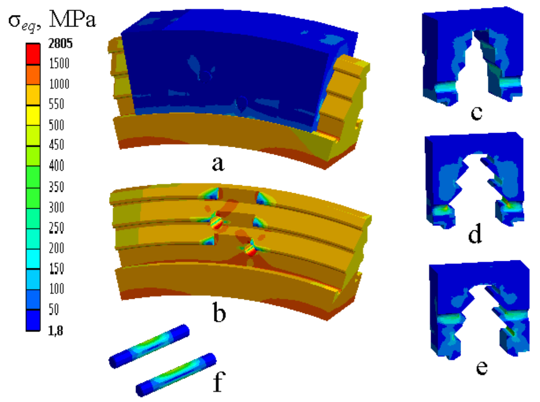


Fig. 2. Distribution of equivalent stresses, MPa:
a – lock joint; b – disk; c – locking blade;
d – adjacent blade (with the lower pin);
e – adjacent blade (with the upper pin);
f – locking pins

Problem Formulation

The purpose of this paper is to determine the SSS of the lock joint of the rotor blades of the first stage of the medium-pressure cylinder (MPC), taking into account the influence of the plastic deformation of lock joint elements.

To describe the SSS of the lock joint of the rotor blades of the first stage of the MPC, taking into account the influence of plastic deformation of elements in the joint, this paper uses the theory of elastic-plastic deformations.

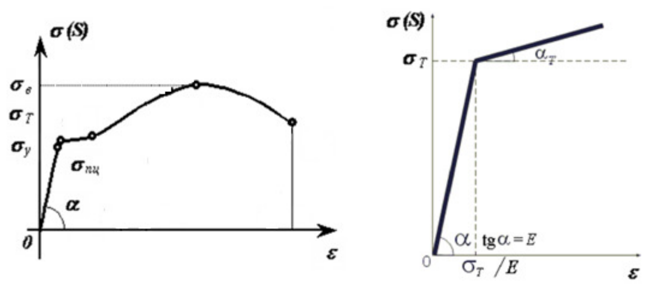
In the case of the rotor blade lock joint, there exists a simple type of loading in which the theory of elastic-plastic deformations is in good agreement with the experimental data in [14–17]. In this case, the total deformation of materials in the lock joint is the sum of elastic, plastic, and temperature deformations [17]

$$\varepsilon = \varepsilon_e + \varepsilon_p + \varepsilon_t ,$$

where ε_e is the elastic component of total deformation; ε_p is the plastic component of total deformation; ε_t is the temperature component of total deformation.

When describing the deformation curves of materials in the lock joint, this paper uses two types of approximation (Fig. 3): multilinear (Fig. 3, a) and bilinear (Fig. 3, b) [13].

The multilinear approximation (Fig. 3, a) makes it possible to most accurately set, as initial data, the plastic deformation characteristic – the deformation curve of the material. However, the issue of free access to the available deformation curves of materials of interest is often problematic. In such cases, a more simplified technique for specifying the characteristics of plasticity can be used with the use of the bilinear approximation (Fig. 3, a).



a b

Fig. 3. Approximation of the material deformation curve:
a – multilinear; b – bilinear

When the bilinear approximation is used, the gradient of the first section of the deformation curve is determined based on the elastic characteristics of materials [13].

$$tg\,\alpha = E ,$$

where E is Young's modulus.

The gradient of the second section is determined by using the material's yield point σ_T and the tangent modulus E_T .

$$E_T = tg\,\alpha_T = 0{,}35 \cdot m \cdot E$$

where m is the strain hardening index

$$m = 0.75 \frac{\ln(S_k / \sigma_T)}{\ln\left(\dfrac{1}{0.2 \cdot 10^{-2} + \sigma_T / E} \ln \dfrac{100}{100 - \psi}\right)},$$

where S_k is the true tensile strength

$$S_k = \sigma_в (1 + 1.4(\psi / 100)),$$

where ψ is the relative contraction; $\sigma_в$ is the material ultimate strength.

Table 1 shows the mechanical properties of the materials used in the lock joint [14].

As the load that determines the SSS in the lock joint were taken the centrifugal forces occurring during the rotation of the rotor around the axis with an angular velocity of 314.16 rad/s. In connection with the symmetry of the system, not the entire bladed disk was considered, but only its sector with the corner angle φ=20°, at the ends of which the symmetry conditions were set.

To assess the effect of plastic deformation on the redistribution of stresses in the lock joint, a finite element model was built, consisting of 371,498 finite elements (FE) (Fig. 4).

Table 1. Physical and mechanical characteristics of the materials

Material	E, MPa		σ_T, MPa	$\sigma_в$, MPa	Ψ, %	S_k, MPa	m	E_T, MPa
15Kh12VNMF	T=500 °C	1.840×10^5	470	520	57.0	934.96	0.0988	6,360
	T=600 °C	1.750×10^5	350	370	48.5	621.23	0.0844	5,020
20Kh3MFA	T=500 °C	1.800×10^5	520	540	68.3	1007.44	0.0962	5,860
	T=550 °C	1.740×10^5	500	515	58.1	976.24	0.0916	5,770
KhN70BMYuT	T=500 °C	1.965×10^5	640	1020	29.0	1434.12	0.1449	9,960
	T=600 °C	1.900×10^5	600	985	23.0	1302.17	0.1480	9,850

The FE mesh was created using the twenty-node *Solid226*. This element has degrees of freedom in displacement and temperature, allowing one to obtain a solution to a simultaneous thermal contact problem taking into account the influence of plastic deformation (Fig. 5).

By calculating the stress state of a number of FE models of the lock joint, the optimal FE size was determined, equal to 3 mm, from the condition that with a further decrease in its size, the calculation results change by no more than 3% (see Fig. 6). In this case, a further decrease in size leads to a rapid increase in the number of FEs and an increase in calculation time.

The FE model under consideration has several zones of contact interaction: contact of the pins with the disk, with the locking blade, with the adjacent blades; support pads of adjacent blade roots, and the disk shaft end. In the contact zones, which mainly affect the transfer of forces between interacting elements, there is a thickening of the mesh with a decrease in the FE size to 1 mm, which increases the calculation accuracy.

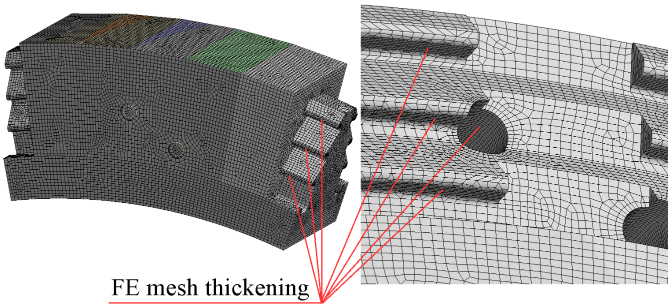


Fig. 4. Breakdown of the rotor blade lock joint model into FEs

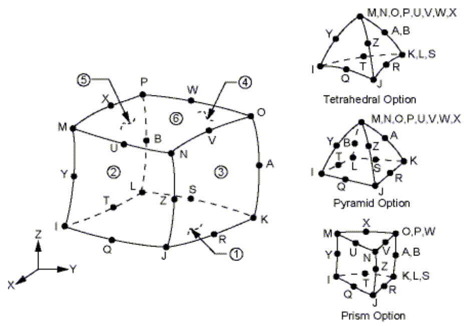
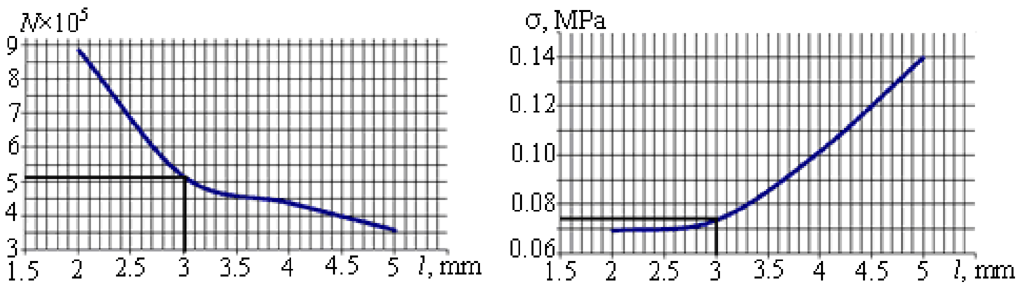


Fig. 5. FE Solid226



a b

Fig. 6. Determination of the optimal FE size:
a – by quantity; b – by equivalent stresses

Iterative Problem Solution

The total calculation time was 16 h 3 min for the variant with the use of the multilinear approximation (Fig. 7). In this case, the time for calculating the variant of solving the problem with the use of the bilinear approximation was 5h 4m. To get the convergence of the problem required 35 iterations. In both cases, an i7 processor computer with 24 GB RAM was used.

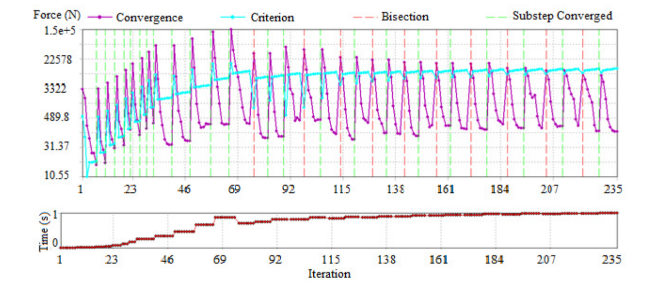
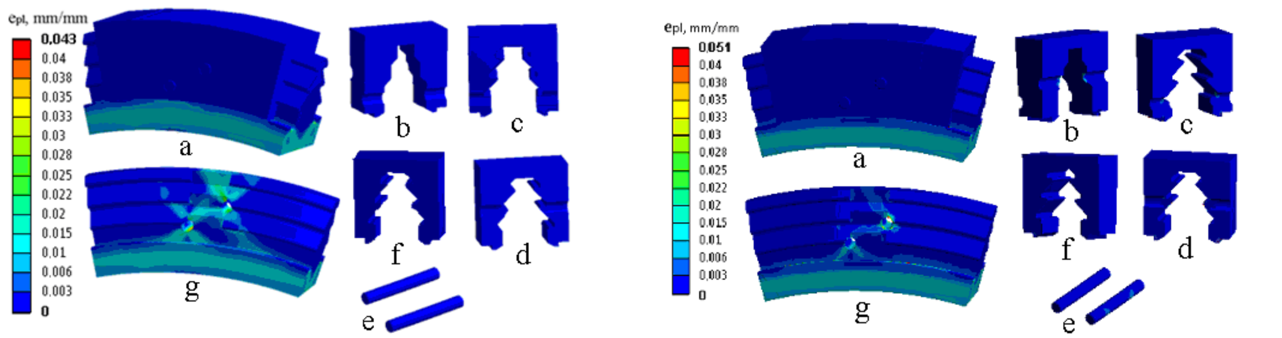


Fig. 7. Iterative process of solving the problem with the use of the multilinear approximation

Numerical Analysis of the SSS of the Lock Joint Under Plastic Deformation

To assess the effect of plasticity on the SSS of the rotor blade lock joint, one should, first of all, analyze the distribution of equivalent plastic deformations (Fig. 8). These results, together with those obtained earlier, when solving the thermoelasticity problem (Fig. 2) [5], make it possible to identify the zones subject to plastic deformation.

Fig. 8 shows the calculation results in the form of distributing equivalent plastic deformations, using the bilinear and multilinear approximations. To carry out a qualitative assessment of the nature of the distribution of equivalent plastic deformations over the lock joint, the same color level scale was used. Analyzing the results obtained, we can see that the nature of the distribution of equivalent plastic deformations, both in the first and second cases, are very close, and equally represent the zones with the maximum level of deformations. Moreover, the upper level of deformations themselves is somewhat different. When using the multilinear approximation, the resulting upper limit is 0.051 mm/mm, which is higher than the upper value obtained using a bilinear approximation of 0.043 mm/mm. In both cases, the maximum level of residual plastic deformations is observed at the holes in the disk for the installation of the pins that fix the locking blade (Fig. 8, g). Let us recall that the level of equivalent stresses, when solving the problem of thermoelasticity in this zone, reached 2,800 MPa. We can see that with increasing distance from the holes, the level of plastic deformations decreases unevenly, clearly demonstrating the tension of the part of the disk under the locking blade. So, the most deformed areas are the areas between the holes, the area of the upper part of the disk under the locking blade, as well as the fillet transitions at the base of the disk and flanges. In the rest of the disk and the entire lock joint, the level of plastic deformations is low, not exceeding 0.002 mm/mm.



With the use of the bilinear approximation

With the use of the multilinear approximation

Fig. 8. Distribution of equivalent plastic deformations, mm/mm:
a – lock joint; b – locking blade; c – adjacent blade with the lower pin; d – adjacent blade with the upper pin; e – locking pins; f – rotor blade; g – disk

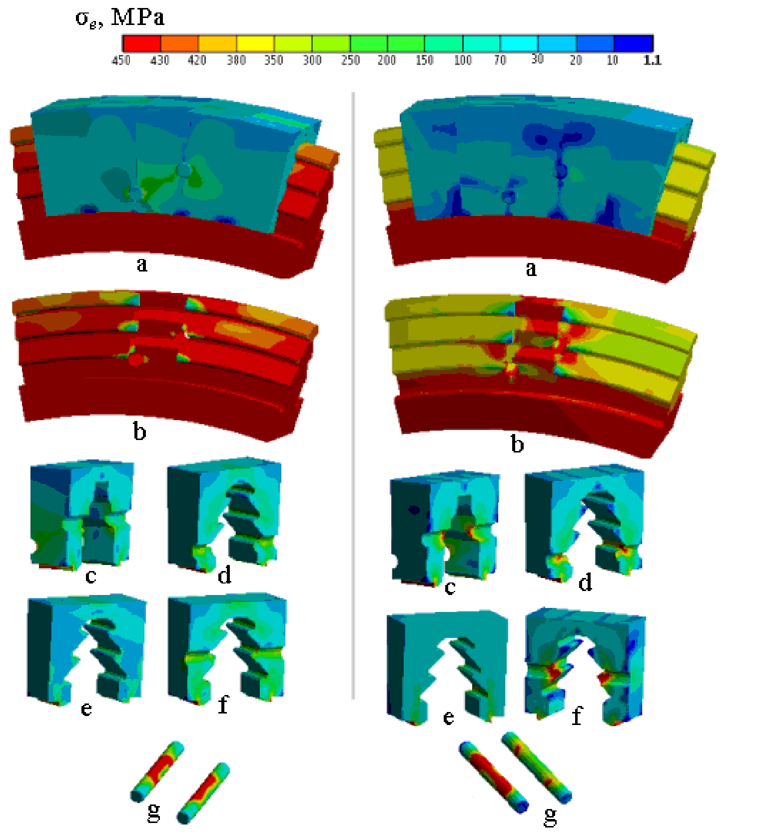
As a result of the computational studies, the distribution of equivalent stresses over the lock joint was obtained (Fig. 9).

As in the case of plastic deformations, the results are presented for two calculation variants: using the bilinear and multilinear approximations.

Obtained as a result of solving the problem, the distribution of equivalent stresses in the rotor blade lock joint has a complex spatial nature. The presented picture is the result of stress redistribution due to the plastic deformation of the 20Kh3MFA steel as the disc material. We can see that despite a significant decrease in the level of equivalent stresses in the rotor blade lock joint, there are zones with the stress level close to the value of the yield point at the operating temperature σ_T=450 MPa (Fig. 10). In both solution variants, this is the area around and above the pin installation holes, as well as the area of fillet transitions of the flanges and base of the disc. The maximum level of equivalent stresses for the variant using the bilinear approximation reaches 448 MPa, and the variant using the multilinear one reaches 443 MPa. We can see that the numerical values of the maximum equivalent stresses for the two calculation variants are quite close, the difference being less than 5 MPa. At the same time, attention should be paid to the difference in the nature of the distribution of equivalent stresses over the lock joint. Thus, comparing the results obtained, we can see that for the case with the use of the bilinear approximation, a less pronounced gradient of the level of equivalent stresses is observed. This is most clearly seen when comparing the results of the distribution of equivalent stresses over the disk. At the same time, in the case with the use of the multilinear approximation, a distinct boundary between the most stressed and less stressed zones in the disk is noticeable. The resulting discrepancy in the nature of the distribution of equivalent stresses of the two calculation variants is associated with the existing differences in the behavior of lock joint materials under loading and deformation. The latter, in turn, is associated with errors in defining the plastic deformation curves, using the bilinear and multilinear approximations. Analyzing the results obtained, we can assume that for this particular case, the greatest errors are associated with the difference in the deformation curves in the average load zone, namely, around values close to the yield point on the deformation curve.

The proximity of the level of residual stresses in the disk to the specified value of the yield point is apparently associated with the impossibility of further deformation and constraint of deformations due to the design features of the rotor blade lock joint.

Fig. 11 shows the distribution of contact stresses over the rotor blade support pads in the lock joint for the case of using the multilinear approximation of deformation curves. When considering the results obtained, the



With the use of the bilinear approximation | With the use of the multilinear approximation

Fig. 9. Distribution of equivalent stresses in the lock joint, MPa:
a – lock joint; b – disk; c – locking blade; d – adjacent blade with the lower pin; e – rotor blade; f – adjacent blade with the upper pin; g – locking pins

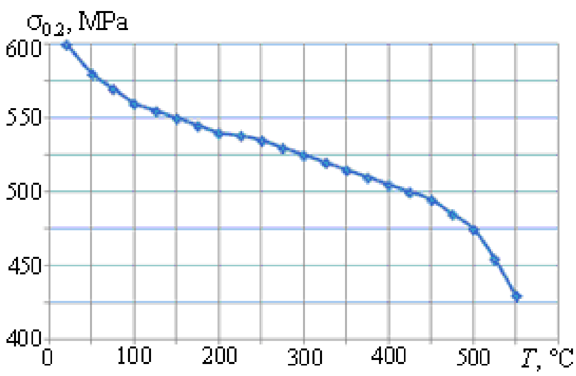


Fig. 10. Dependence of the level of the EI-415 steel yield point from temperature

support pads are numbered as follows. The upper pair of support pads is the first pair, the middle pair is the second pair, the lower pair is the third pair, and the lateral support surfaces of the root are shoulders.

We can see that, as in the case of solving the problem of thermoelasticity, the nature of the distribution of contact stresses over the support pads is of a complex spatial nature and depends on the position of the support pads in the lock joint with respect to the locking blade.

The presented results of the distribution of contact stresses over the support pads of blade roots (Fig. 11) make it possible to evaluate the change in the nature of the contact interaction of these blades with the disk in the lock joint in comparison with the results obtained earlier [5]. As expected, the highest level of contact stresses is observed on the third pair of the rotor blade support pads. As in the case of solving the problem of thermoelasticity, the maximum value of contact stresses is achieved from the side of the holes for additional pins and mainly depends on the position of the pins in height.

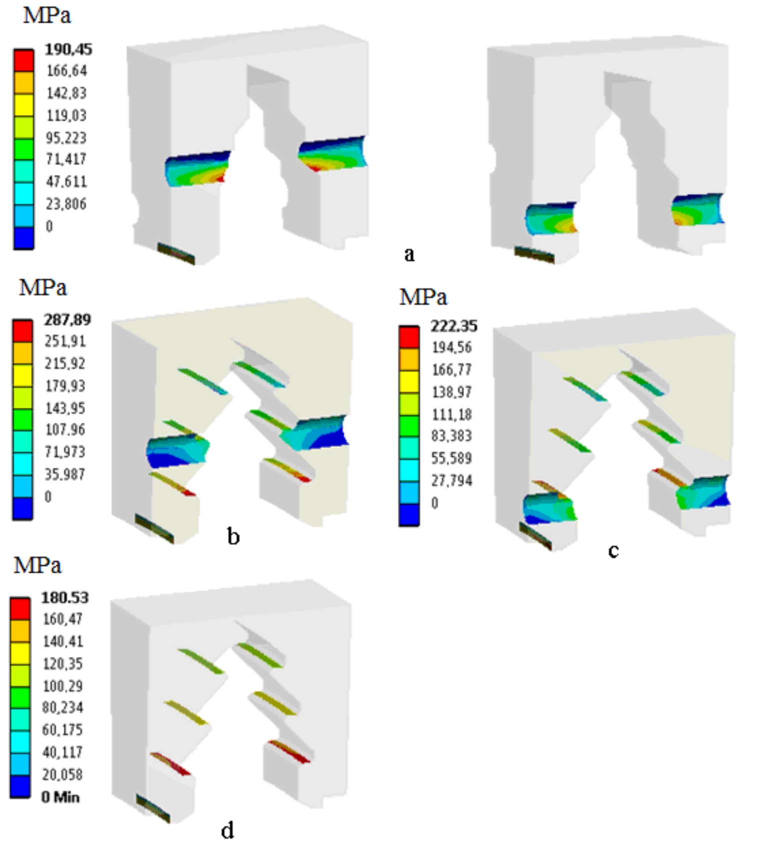


Fig. 11. Distribution of contact stresses over the rotor blade support pads in the lock joint:
a – locking blade; b – adjacent blade with the upper pin;
c – adjacent blade with the lower pin; d – rotor blade

The change in contact stresses on the adjacent blades is characterized by a pronounced gradient along all the support pads. In this case, the most significant difference between the results obtained is the level of contact stresses over the rotor blade support pads. We can see that the maximum value of contact stresses at the edge of the third support pad reaches about 200 MPa, which is almost four times higher than the maximum values of contact stresses obtained earlier when solving the thermoelasticity problem [5]. The average level of contact stresses over the support pads also increased significantly and is about 80 MPa at 35 MPa in the case of solving the problem of thermoelasticity.

Table 2 shows the results of the distribution of contact stresses over the rotor blade support pads in the lock joint for various calculation variants.

Table 2. Distribution of the level of contact stresses

Blade	Approximation	First pair		Second pair		Third pair	
		MPa	%	MPa	%	MPa	%
Adjacent (with the lower pin)	Bilinear	79	23	110	32	155	45
	Multilinear	85	24	98	28	170	48
Adjacent (with the upper pin)	Bilinear	80	18	175	39	190	43
	Multilinear	85	18	190	39	210	43
Rotor blade	Bilinear	100	28	110	31	150	41
	Multilinear	110	28	130	33	160	39

The numerical values given in table 2, together with the results in Fig. 11, make it possible to present a picture of the distribution of contact stresses over the rotor blade support pads in the lock joint during plastic deformation. In addition, the presented results make it possible to perform a comparative analysis of the calculation variants when different approaches to the approximation of deformation curves are used. We see that the results obtained differ slightly. Comparing the absolute values of contact stresses over the support pads, we have a maximum difference of 30 MPa for the third pair of support pads of the adjacent blade with the upper pin. On average, over the support pads, the difference does not exceed 10 MPa. At the same time, the percentage distribution of stresses differs by less than 5%. In both cases, the third pair of support pads is the most stressed, and the first pair is the least stressed.

Conclusions

The results presented in this article made it possible to characterize the degree of relaxation and redistribution of stresses in the structure in comparison with the results obtained earlier, when solving the problem of thermoelasticity [5]. It is shown that the maximum level of residual plastic deformations, as expected, is observed at the holes in the disk for the installation of the pins fixing the locking blade, and reaches about 0.05 mm/mm.

Solving the problem of the SSS of the lock joint in the considered formulation made it possible to assess the change in the nature of the distribution of contact stresses in the lock joint. The results obtained showed a significant difference in the level of contact stresses over the rotor blade support pads. Thus, the maximum value of contact stresses at the edge of the third support pad reaches about 200 MPa, which is almost four times higher than the maximum values of contact stresses obtained earlier, when solving the problem of thermoelasticity. In this case, the average level of contact stresses over the support pads also increased significantly, and is about 80 MPa at 35 MPa in the case of solving the problem of thermoelasticity. The increase in contact stresses is probably associated with the redistribution of forces in the lock joint due to the plastic deformation of its elements.

A significant decrease in the equivalent stresses obtained when solving the thermoelastic problem is observed, from 2800 to 448 MPa. The proximity of the level of equivalent stresses of the deformed part of the disk in the lock joint with respect to the yield point is associated with the impossibility of further deformation of the considered structure of the rotor blade lock joint. This, probably, later became the reason for the destruction of the indicated area of the disk.

The results of solving the problem of the SSS presented in this article, with account taken of plastic deformations, using the example of the lock joint, also allowed us to consider the applicability of the calculation method using the bilinear approximation. It was shown that the time required to perform the calculation when using a more accurate multilinear approximation of plastic deformation curves is about 16 hours, while when using a simpler bilinear approximation, it is about 5 hours. Comparison of the results obtained in the form of the distribution of plastic deformations, equivalent stresses, and contact stresses over the support pads showed that there is a slight difference when using two types of approximation. In this case, the error of the results when using the bilinear approximation does not exceed 5%. This confirms the applicability of this approach to the processing of plastic deformation curves for solving problems of this kind.

Using the presented methodology for calculating rotor blade lock joints in the creation of new designs of steam turbine rotors operating in the zone of high thermal and power loads, taking into account the contact interaction of elements in the lock joint, taking into account the various mechanical and physical properties of materials, as well as their changes depending on the operating temperature, already at this stage of software development, it allows detecting problem areas in the design and preventing further breakdowns in the turbine. This calculation method by detecting problem areas and strengthening them can significantly reduce the economic costs caused by the downtime of the turbine unit during repair work.

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Напружено-деформований стан замкового з'єднання парової турбіни в умовах пластичного деформування

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Розв'язується задача про напружено-деформований стан замкового з'єднання робочих лопаток 1-го ступеня циліндра середнього тиску в умовах пластичного деформування. Під час розв'язання задачі використовується теорія пружно-пластичних деформацій. Розв'язання задачі здійснюється з використанням двох різних підходів до задання кривих пластичного деформування. Оцінюється можливість застосування більш простої білінійної апроксимації взамін класичної мультилінійної. На прикладі розв'язання даної задачі показано час, необхідний для виконання розрахунку при використанні білінійної та мультилінійної апроксимацій. Порівняння отриманих результатів у вигляді розподілу пластичних деформацій, еквівалентних напружень і контактних напружень по опорних площадках дало можливість оцінити відмінність під час використання двох типів апроксимації. Отримане значення похибки результатів під час використання білінійної апроксимації дозволило зробити висновки про можливість застосування такого підходу до обробки кривих пластичного деформування для розв'язання подібного роду задач. Розв'язання задачі здійснюється за допомогою методу скінченних елементів. Щоб об'єктивно оцінити вплив пластичного деформування на перерозподіл навантажень в замковому з'єднанні, використовується модель, отримана під час розв'язання задачі про термонапружений стан замкового з'єднання робочих лопаток. Показано розподіл контактних напружень в замковому з'єднанні. Проведено порівняння результатів з отриманими раніше під час розв'язання задачі термопружності. Відзначено суттєві відмінності рівня контактних зусиль. Наводяться результати розрахункової оцінки напружено-деформованого стану замкового з'єднання робочих лопаток першого ступеня циліндра середнього тиску парової турбіни, що дозволяють охарактеризувати ступінь релаксації і перерозподілу напружень в конструкції порівняно з результатами, отриманими раніше під час розв'язання задачі термопружності. Зроблено висновки щодо економічної доцільності використання поданої методики розрахунку.

***Ключові слова**: турбіна, замкове з'єднання, робоча лопатка, напружений стан, крива деформування, границя текучості.*

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