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The features of fatigue resistance of critical members steels under high stress ratio

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Abstract

From the standpoint of risk analysis and the concept of safety, the authors propose a new interpretation of critical members. Their performance determines the level of losses during the operation of mechanical systems. Therefore, it is advantageous to make critical members from high-strength steels that are sensitive to most influencing factors. Elements made of high-strength steels suffer from cyclic load with high stress ratio. In this aspect, cylindrical samples of heat-treated 09Cr16Ni4Nb and 13Cr15Ni4Mo3 steels were tested for tensile fatigue. The test results were presented in the form of a lifetime equation. Smith diagrams in coordinates were obtained by simple transformations from lifetime equation. These graphs showed a slightly anomalous concave shape instead of the expected convex shape. This indicates a loss of sensitivity to mean stress at high stress ratio. The authors explain this phenomenon from the standpoint of the merging of fatigue and fracture mechanics concept. Interestingly, a similar form was obtained for the graph of the dependence of the critical cyclical SIF on stress ratio. That is, the sensitivity of cyclic toughness to the value of the stress ratio decreases as it increases.

Keywords: critical members, high-strength steels, stress ratio, fatigue lifetime

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1. Introduction

The cycle asymmetry factor was one of the first to be studied in fatigue methodology. Many models have been developed to take into account its influence. The current surge in the influence of the cycle asymmetry factor research, in the authors' opinion, is due to several reasons. Gomes et al. (2025) point out that after the sensitivity of fatigue

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deformation criteria to mean stress was discovered, the need to check the invariance of other universal criteria to this factor has arisen. Gomes et al. (2025), Liu et al. (2024), Abasolo et al. (2024) emphasize that this is especially true for multiaxial fatigue conditions, where the variety of combinations of the action of individual cyclic processes dictates the development of new durability models. It is also necessary to take into account the active introduction of composite and additively manufactured parts in mechanical engineering and construction. This also requires checking their behaviour under extreme loading conditions, which can include modes with high asymmetry. Also, the motivation for studying the influence of asymmetry is the attention to non-design loading modes with overloads and underloads. In fact, the study of modes with underload corresponds to the study of the influence of the cycle asymmetry factor. Finally, increasing the requirements for the safety of structures requires a more accurate assessment of the influence of operational loading, which is characterized by the variation in the average stress.

Another reason for the attention to the asymmetry factor may be due to the widespread use of high-strength steels (HSS). They are used to manufacture crucial (important) or critical members of mechanical systems. They are the cornerstone for solving problems of mechanical engineering, which are in a state of technical contradiction. Against the background of the trend of increasing the functional efficiency of mechanical systems, such requirements are imposed on the latter as increasing reliability and safety along with reducing their weight and dimensions. This contributes to reducing fuel and energy consumption for operation. In addition, as noted by Krejsa et al. (2024), the problem of reducing maintenance costs is particularly highlighted.

Critical members are made from high-quality materials, which include high-strength steels. Critical members made of HSS have reduced dimensions, and therefore increased overall stress marks. Such parts receive, along with cyclic, static loads from the weight of the machine (springs), from internal pressure in the shells of units of the metallurgical and chemical industries, from tightening forces (threaded joints), and there are also residual stresses (welded joints). This leads to an increase in the asymmetry of the cycle due to an increase in the average stress. For example, as indicated by Jiao et al. (2024), high-strength bolts operate at stress ratio R=0.8.

From the point of view of structural and functional analysis, critical members (CM) are understood by most experts as those parts of the machine that perform its main functions. Failure of the CM leads to the loss of operability of the object. From the standpoint of risk analysis and the concept of safety, the authors propose a new interpretation of CM. By critical members, Belodedenko et al. (2025) understand the parts of machines, the value of which is tens and hundreds of times less than the losses to which their refusal leads. The severity of the failure is used to calculate the criticality level, which is used to measure the risk. At the operation stage, the durability of critical members is predicted mainly by probabilistic physical models or based on physics-of-failure. This approach is the basis of the theory of individual structural reliability, which ensures operational safety. As accident analysis shows, not only basic designs and main mechanisms, but also fastening, connection and sealing nodes can be attributed to CM. And as indicated by Belodedenko et al. (2020, 2025), they can lead to initiated failure.

The purpose of the paper is to analyze and evaluate the influence of the stress ratio on the durability under uniaxial loading of high-strength steels based on the results of fatigue tests that were conducted in the process of developing a manufacturing technology for critical aerospace parts and members.

2. Materials and methods

2.1. Statement of the research problem

The cycle asymmetry factor is characterized by the average cycle stress or stress ratio $R= \sigma_{min} / \sigma_{max}$, where the numerator contains the minimum stress and the denominator contains the maximum stress of the cycle. Now this is considered, for the most part, with the help of models in the form of Smith or Haigh diagrams. When using S-N curves as basic fatigue resistance models (master curve), it becomes necessary to reduce the operating cycles of arbitrary asymmetry to the equivalent one, which is usually determined for R=-1 or for σ_m=0. This equivalence is carried out using Smith charts (LAD), which connect the amplitude σ_a and average σ_m of the cycle stresses for a certain endurance N. In Fig.1, such a diagram is made for the relative values of $\sigma_{ar} = \sigma_a/\sigma_y$ and $\sigma_{mr}=\sigma_m/\sigma_y$.. The boundary for Smith charts is a straight line connecting the σ_{ar}=1 and σ_{mr}=1 points. Its equation corresponds to the conditions of static failure, when $\sigma_m + \sigma_a = \sigma_y$. This line separates the zone of sudden and gradual failures (Fig.1). Below the line between the points $\sigma_{ar} = \sigma_{-1r}$ (endurance limit at R=-1) and σ_{mr}=1 is the zone of limited endurance. The shape of this line can be varied, based on the equation of the limiting amplitude diagrams (LAD). As a matter of fact, finding out the shape of the LAD is the purpose of studying the influence of cycle asymmetry on durability. Below the LAD line is the non-destructive zone up to durability *N*.

The most common form of LAD, which connects σ_{-1r} and σ_{mr}=1 points, is the linear or Goodman model (Fig.1). Sometimes the line that connects σ_{-1r} and σ_{mr}=1 points, is described by using a piecewise function (not shown in Fig.1). Their slope characterizes the sensitivity of the material to the asymmetry of the cycle ψ_R. The smaller the value of ψ_R, the smaller the slope to the horizontal axis of the LAD segment. In addition, there are convex, concave and mixed convex-concave shaped LAD (Fig.1).

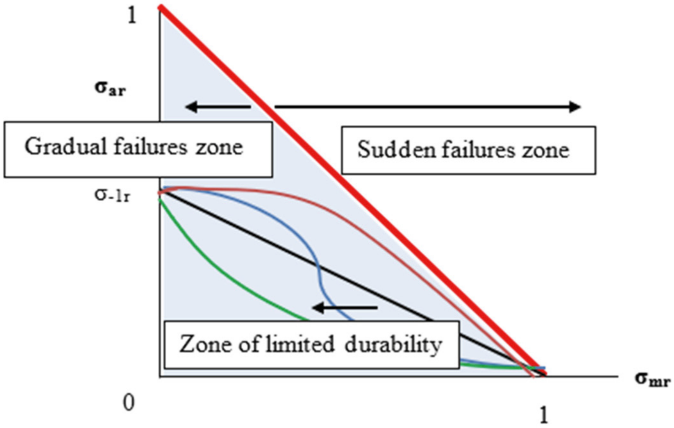

Fig.1. Using Smith’s diagrams to assess reliability and safety.

Practice shows that in a wide range of durability, asymmetry of cycles and material properties LAD have convex shape, and their concave shape is rather perceived as an anomaly. Despite the variety of LAD shapes, in the canonical interpretation they should all intersect the points σ_{-1r} and σ_{mr}=1. The latter point coincides with the LAD limit and corresponds to the principles of continuum mechanics.

The position of LAD is mostly influenced by the factors of the ultimate endurance *N*, for which the diagram is constructed, as well as the stress concentration K_σ. The boundary of the Smith chart can be perceived as LAD for *N*=1 and K_σ=1. The lowest position is occupied by LAD for unlimited durability N_G. For a smaller number of cycles, LAD have a more convex shape. The increase in each factor leads to a decrease in the sensitivity ψ_R, and the shape of LAD goes from convex to concave. This is due to the fact that the effective concentration coefficient for average cycle stresses is much lower than the similar characteristic for amplitude stresses. At the same time, the zone of limited durability narrows, and hence the range of safe load modes narrows. This is also facilitated by an increase in the stress coefficient *R*.

In the zone of high asymmetries, safe operation is possible only for small amplitudes. An unusual situation is created when the material undergoes elastoplastic deformations that are characteristic for low-cycle fatigue, and the durability corresponds to the region of multi-cycle fatigue. The behaviour of the material under such conditions is not determined. The increase in the static strength of the material under the conditions of localization σ_{yk} gives rise to the existence of LAD outside the line from σ_{ar}=1 to σ_{mr}=1. The same effect is observed in the presence of cracks. This cannot be explained in terms of classical mechanics. There was a need to study the fatigue resistance of HSS with significant positive cycle asymmetry in more detail when stress ratio *R*=0.5 – 0.8.

2.2. Testing

Fatigue tests were performed on samples of two steels. They are used in aerospace engineering for the manufacture of critical parts. In particular, 13Cr15Ni4Mo3 steel (tensile strength, σ_U=1552 MPa, yield strength $\sigma_{0.2}$=1373 MPa) is used for the manufacture of bolts for fastening aircraft wheels. 09Cr16Ni4Nb steel (σ_U=1147 MPa, $\sigma_{0.2}$=935 MPa) is used in missile systems.

According to all classifications, both steels can be classified as HSS. The heat treatment of the samples corresponded to the heat treatment of steels, which is specified in the drawings of the parts. The blank for the samples of 13Cr15Ni4Mo3 electroslag remelting steel was a hot-rolled bar with a diameter of 22 mm. Unnotched specimens had sand watch shape, diameter 8 mm and stress concentration factor K_σ=1. The groove of the notched samples with an outer diameter of 14 mm imitated the cavity of a metric thread with a pitch of 1.5 mm. It was applied after the heat treatment and K_σ=4 was adopted for such samples. Bolts with a knurled thread M18 and a pitch of 1.5 mm were also made from 13Cr15Ni4Mo3 steel. Their test modes corresponded to the test modes of the samples. Samples from 09Cr16Ni4Nb steel were made only unnotched with a diameter of 9 mm. The workpiece in this case was a bar with a diameter of 80 mm.

Tests under stationary axial loading were carried out at a frequency of 5-15 Hz. The tests were carried out until the samples were completely destroyed, when the durability *N* was determined. After the tests, the fractures of the samples were analysed with the measurement of the Final fracture area. Depending on the value of *N*, the shape of the crack front, which affects the geometric factor in determining the stress intensity factor (SIF), changed. The most common pattern for changing the crack front: 1 semicircle → 2 semiellipse → 3 segment.

After determining the critical crack size ε_c, the critical cyclic toughness ΔK_{fc} was determined for fracture mode I. For this purpose, the previously obtained dependences of Toribio et al. (2022) for round rods, which are approximated under the research conditions, were used.

2.3. Processing test results

At the first stage, unnotched samples of 09Cr16Ni4Nb steel were tested in a wide range of changes in the asymmetries of the *R* cycle. The conditions of the test regimes were designed so that it was possible to obtain the multiple regression equation:

$$lg\,N = b_{0r} - m \cdot lg\,\Delta\sigma_r - b_R \cdot R + b_{RR} \cdot R^2, \tag{1}$$

where b_0, m, b_R, b_{RR} – model coefficients that determine the sensitivity of durability to the influence of a certain factor; $\Delta\sigma = 2\sigma_a / \sigma_U$ – relative double amplitude of cycle stresses.

According to the research of Belodedenko S. et al. (2020), such a model is called the longevity equation, from which both S-N curves and Smith charts can be obtained. In this case, the longevity equation takes the meaning of the master model instead of the common master S-N curve.

LAD obtained from the durability equations have a concave shape and can be approximated by exponential equations over a wide range of cycle asymmetries Fig.2:

$$\sigma_{ar} = \sigma_{-1r} exp\left(-\gamma_m \sigma_{mr}\right), \tag{2}$$

$$\sigma_{ar} = \sigma_{0r} exp\left(-\gamma_{m0} \sigma_{mr}\right), \tag{3}$$

where σ_{-1r} and σ_{0r} - respectively, fatigue limits in symmetric and pulsating modes, γ_m, γ_{m0} – LAD parameters. For the studied objects, the parameter γ_{m0} varied from 0.27 to 0.70.

The dependence of the critical cyclic fracture toughness ΔK_{fc} on the value of *R* can be approximated by the exponential dependence Fig.3:

$$\Delta K_{fc} = \Delta K_{fc0} exp\left(-\chi_R R\right), \tag{4}$$

where ΔK_{fc0} – critical cyclic fracture toughness in pulsating mode; χ_R– model parameter. For the studied steels, this parameter is 2.50 (09Cr16Ni4Nb steel) and 1.78 (13Cr15Ni4Mo3 steel). At the same time, the average destruction rates are ΔK_{fc0}=159 MPa·m$^{1/2}$ (09Cr16Ni4Nb steel), ΔK_{fc0}=193 MPa·m$^{1/2}$ (13Cr15Ni4Mo3 steel).

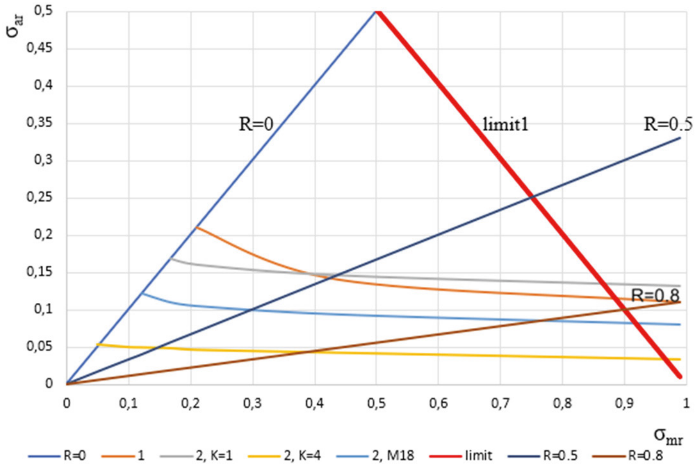

Fig.2. Comparative LAD of the 09Cr16Ni4Nb steel when K_σ=1 (1), 13Cr15Ni4Mo3 steel when K_σ=1 (2), when K_σ=4 (2, K=4), M18 bolts made of this steel with knurled thread (M18) in the cycle asymmetries positive.

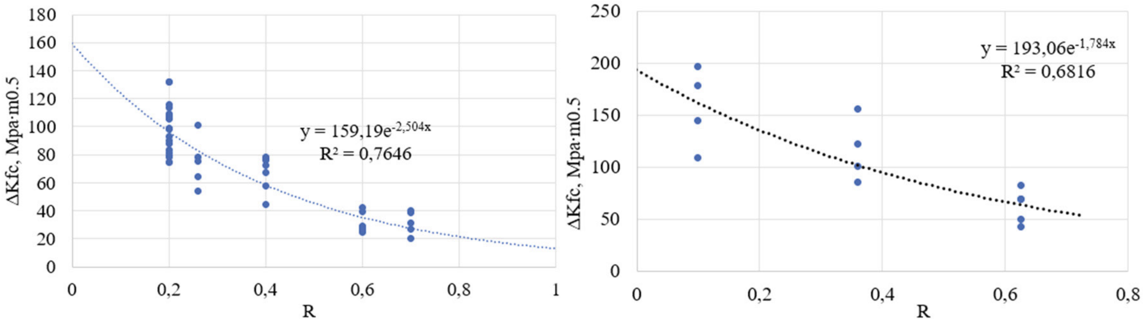

Fig.3. Experimental models of the relationship between cyclic fracture toughness and cycle asymmetry of steels 09Cr16Ni4Nb steel (left), 13Cr15Ni4Mo3 steel (right).

3. Results and discussion

The authors explain the investigated phenomena from the standpoint of the merging of fatigue and fracture mechanics concept. The main connections between the two theories were formulated by J.C. Newman (1998). The loss of sensitivity to cycle asymmetry for high-strength steels can be explained by a similar phenomenon for the parameters of the Paris diagrams. With an increase in cycle asymmetry after a certain *R*, the values of the threshold ΔK_{th} and critical ΔK_{fc} cease to decrease Fig.4. Moreover, the ranges of change of ΔK_{fc} are less than the range of ΔK_{th}. This feature is associated with the phenomenon of crack closure.

The relationship between the values of ΔK_{th} and the amplitude of the endurance limit σ_a is carried out through the $\sigma_a(\Delta K_{th}, K_\sigma)$ function, the form of which depends on the loading method, the level of stress concentration or the sharpness of the notch Fig.4. Therefore, according to Petr Lukáš and Ludvík Kunz (1981), this relationship can have a different form. As can be seen from the LAD formation diagram Fig.4, the form of the functions $\Delta K_{fc}(R)$, $\Delta K_{th}(R)$, $\sigma_a(\sigma_m)$ are similar to each other.

The concave nature of the LAD is explained by the existence of some minimum possible endurance limit σ_{ath}, which corresponds to the value of ΔK_{th}. Therefore, the LAD line cannot reach the $\sigma_m=\sigma_y$ or $\sigma_{mr}=1$ points. In fact, the limit of existence of the LAD from the straight line between the points $\sigma_{ar}=1$ to $\sigma_{mr}=1$ (limit 1, Fig.2) goes into the limit $\sigma_a=\sigma_{ath}$ (limit 2, Fig.4). Below this line, the mechanism of material failure changes. The material can enter the zone of so-called static fatigue with failure from plasticity exhaustion. There emerges a transition from creep-fatigue to creep-ratcheting. Or the material fails from the internal crack in the zone of very high-cycle fatigue. For example, for all tested titanium alloy samples at $R > 0.5$, fatigue failure began from a subsurface crack. According to the authors, the first case is typical for materials that undergo cyclic softening. The second case is typical for materials that undergo cyclic hardening.

Assuming that the value of l_c is a material constant, Petr Lukáš and Ludvík Kunz (1981) proposed a power model of the threshold SIF ΔK_{th} (R).

Hence, the amplitude of the fatigue limit under asymmetric loading σ_R is determined by a similar dependence:

$$\sigma_R = \sigma_{-1} \cdot \left(\frac{\sigma_{max}}{\sigma_a}\right)^{-\gamma}, \tag{5}$$

where $\gamma = 0 \ldots 1$ – material constant that characterizes the sensitivity of threshold values to cycle asymmetry; σ_{max} – maximum operating cycle stress.

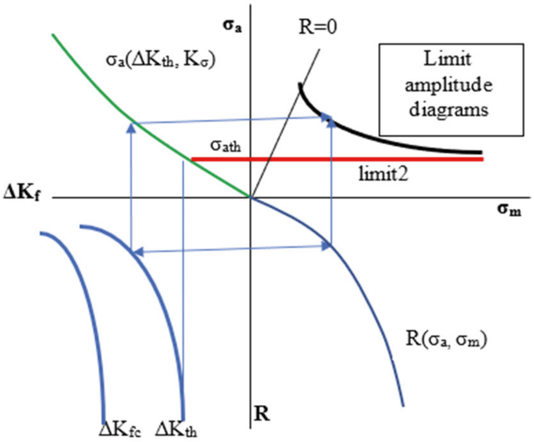

Fig.4. Diagram of formation of LAD for unlimited endurance N_G according to threshold SIF ΔK_{th}.

Using the value R to characterize the asymmetry, we obtain:

$$\sigma_R = 2^{-\gamma} \cdot \sigma_{-1} \cdot (1-R)^{\gamma}. \tag{6}$$

The last two equations represent LAD. Their graphs have a concave appearance. Such forms of LAD are most closely matched by the well-known hyperbolic Oding equation (1962): $\sigma_R^2 + \sigma_R \cdot \sigma_m = \sigma_{-1}^2$.

The disadvantage of this dependence is associated with a fixed ratio of amplitudes for symmetric (R=-1) σ_{-1} and pulsating (R=0) σ_0 cycles: $\sigma_{-1} = \sigma_0 \sqrt{2}$. This is not always done.

Oding equation can be represented in terms of the value R:

$$\sigma_R = 2^{-0.5} \cdot \sigma_{-1} \cdot (1-R)^{0.5} = \sigma_0 \cdot (1-R)^{0.5}. \tag{7}$$

When $\gamma = 0.5$, equations (5) and (7) are identical. For the observed range of asymmetries, the fatigue limits determined by these equations with a tolerance of 10% correspond to the durability equation (1). Thus, the dependencies (5) and (7) are a theoretical confirmation of the experimental model (1). Expressing the amplitude σ_0 at $R = 0$ from the equation of the S-N curve, after logarithmization, we finally obtain:

$$lg\,N = b_0 - m \cdot lg\,\sigma_R + 0.5 \cdot m \cdot lg(1-R). \tag{8}$$

Structurally, this dependence corresponds to the durability equation and allows to avoid the experimental determination of the $ϐ_R$ and $ϐ_{RR}$ coefficients.

Recommendations of the FKM-guideline Rennert et al (2024) are in favour of concave LAD models. They propose a Haibach model, where the LAD consists of 4 sections of piecewise linear functions. The slope in the last sections in the sign-invariant region of the regimes (R>0) is three times smaller than the slope of the LAD for sign-changing regimes (σ_m<0). The decrease in the slope is proportional to the decrease in sensitivity to cycle asymmetry.

4. Conclusions

1. Two models of the exponential type were obtained for LAD in a wide range of stress ratio R. To construct them, it is enough to have one master *S-N*-curve found at values R=-1 or R=0. In the latter case, the correlation between the cycle parameters is higher. For the R>0 region, a model of LAD analogues has been obtained, which has a linear shape. Analogues of the DPA are built in the coordinates of the amplitude stress σ_a – stress ratio R. All these models are developed based on experimentally obtained lifetime (durability) equations. Their presence relieves researchers of the need to use LAD at all.

2. The loss of sensitivity of high-strength steels to the medium stress factor was revealed, as evidenced by the form of Smith diagrams (LAD). This phenomenon is explained by the presence of the lowest possible endurance limit σ_{ath} in materials, which forms the limit 2 of the existence of LAD. In turn, the presence of such a limit is due to the behavior of critical ΔK_{fc} and threshold ΔK_{th} SIF with an increase in the stress ratio R. The function $\Delta K_{fc}(R)$ was experimentally obtained, which also has an exponential form. It can be assumed that the functions $\Delta K_{th}(R)$ have the same shape. A relationship between threshold SIF ΔK_{th} and fatigue limits σ_R was found.

3. A model of the equation of durability based on the concept of merging fracture mechanics and fatigue methodology is proposed. Its application in practice is a priority and requires the assignment of only one parameter in the form of an indicator of slope S-N curve.

4. The authors associate further studies of the influence of the cycle asymmetry factor with finding out the reasons for the absence of a threshold fatigue limit σ_{ath} in a certain group of metals. After all, considerations about the presence of limit 2 of the existence of the LAD seem to be valid for most materials.

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