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# EVALUATION OF STEEL 09G2S DAMAGE UNDER STATIC AND CYCLIC LOADING WITH CONSIDERING THE LEVEL OF RESIDUAL STRESSES IN METAL

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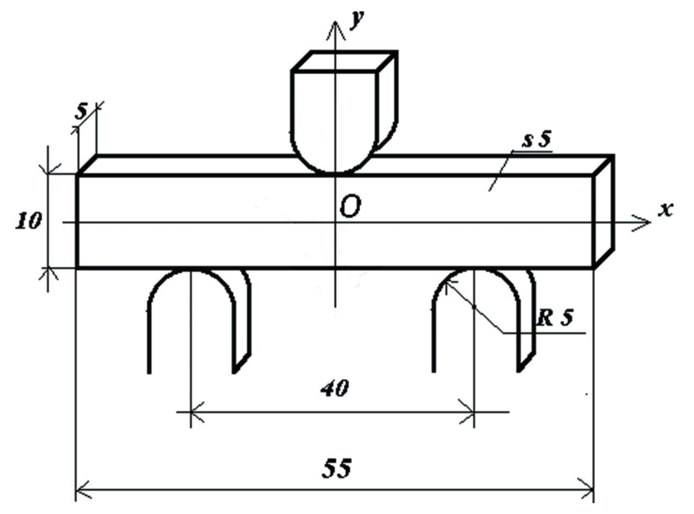
## INTRODUCTION:

Structures, in particular gas and oil pipelines, during operation are subject to both short-term static loads, capable of causing local plastic deformation, and small variables, but at the same time long-acting cyclic loads. At present the calculating of the resource of structural elements subject to the described effects is carried out by exhausting the plasticity of the material (i.e. the dependence of the main mechanical characteristics on the operating time), impact strength, corrosion damage and the determination of the critical length of fatigue origin. However, due to the construction elements features (residual stresses, environmental effects, structural heterogeneity, etc.) as well as operation duration increase, high cost and environmental hazard in the event of major accidents, the development of adequate models for calculating the structural elements resource under complex mechanical influences is an urgent task. The aim of the work was the development of a model for estimating the durability of steel structure elements, taking into account their initial stressed state, and experimental verification of its adequacy based on the results of the experiment on 09G2C steel samples, approximate to the work of real structural elements, taking into account residual compressive stresses.

## MATERIALS AND METHODS

The object of research was a prismatic sample made of structural steel 09G2S. Cyclic loading was carried out on a high-frequency resonance testing machine Mikrotron in a three-point bending scheme.




Prismatic sample loading scheme

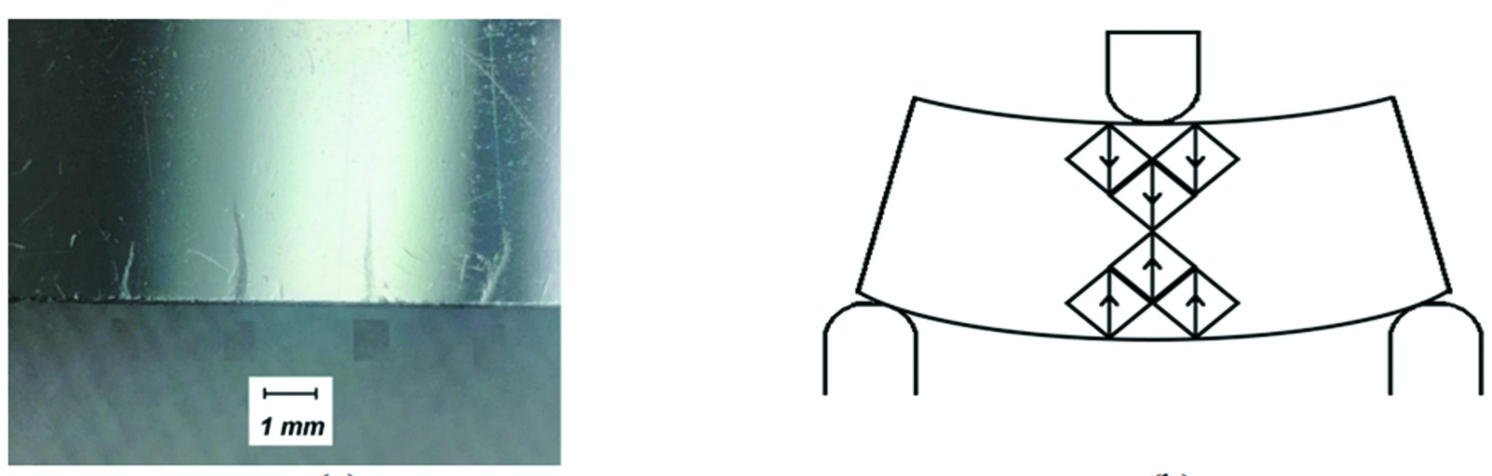
The experimental procedure consisted of cyclic loading with a consistently raised level of the applied maximum cycle forces from 2.78 kN to 6.67 kN. The load was increased after not less than 100,000 loading cycles with the exception of the first stage of loading, the number of accumulated cycles for which was 3500. In the course of the experiment, cyclic loading parameters were monitored - force, displacement, loading frequency as well as the state of the sample surface to detect the onset of plastic deformation.The appearance of macro changes on the polished surface was confirmed by the results of profilometry.

In contrast to the known cyclic loading scheme with uniaxial tension, a three-point bend allows testing the object in the range corresponding to the multi-cycle fatigue with the subsequent achievement of loads causing the initial stage of local plastic deformations in the zone of maximum stress intensity. The design of such experiment will allow to evaluate the results of numerical simulation and to reveal the patterns of resource exhaustion for constructing a reliable model for calculating the durability of structural elements subject to mixed loading. One of the features in the model construction is its multifactority, which consists both in the complexity of the valuation of the stress-strain state caused by the absence of a clearly expressed concentrator, and in the presence of residual stresses, depending on the manufacturing technology and the history of mechanical action during operation.

To determine the residual stresses, X-ray diffraction analysis of the samples was carried out using a SHIMADZU XRD 7000 diffractometer using a monochromatized $K_{\alpha}$-emission of a chromium anode. The microstresses were determined by the moment method from the analysis of the line profile (211) of the $\alpha$-phase. The double angle of line (211) diffraction in chromium radiation is approximately 156 °. The thickness of the layer giving 90% of the intensity of the x-ray reflex (211) is approximately 15 μm. It should be noted that the method of moments makes it possible to determine only the range of variation of residual stresses, that is, their maximum and minimum values in the irradiated volume of the test sample. The calculated values of the residual microstresses range from -50MPa to + 50MPa. For a material with a yield strength in the range of 460 MPa, the set value of the residual stresses can have a significant effect on fatigue failure resistance.

## RESULTS AND DISCUSSION

During the sample cyclic loading experiment with a gradual increase of the applied loads level, when the 417000 cycles (corresponding to the level of the maximum cycle load) were reached, shear bands were visually observe. Samples surface profile analysis carried out after stopping the loading, unambiguously showed the presence of shear bands, which allows one to judge of the samples plastic deformation onset. The direction of the shear bends fixed in the experiment on the sample surface coincides with the loading axis. The direction of the shear bands, which are the direction of the shear strain under uniaxial loading should be oriented at an angle of 45 ° to the axis of the load application. In the case of three-point loading scheme their direction can be explained by a reorientation of the principal stress directions. The schematic construction of the principal stresses fields gives an explanation in the orientation of the shear bands.




(a) (b)

Surface defects (a) and schematic interpretation of principal stresses (b)

Analyzed the existing calculation methods, for determining the structural elements durability an approach based on the V.L. Kolmogorov phenomenological model consisting in determining the parameters of the kinetic equation of damage accumulation was chosen. The calculated value of the damage parameter allows to estimate the material damage at any point and at any time of loading

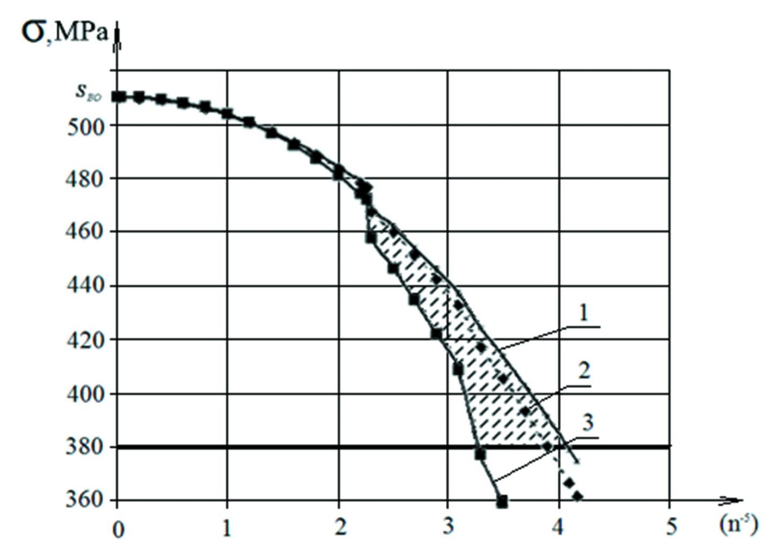
$$\psi = \sum_{i=1}^{n} \psi_i^a .$$

Calculation of exponent a was determined from the mechanical loading history data, changes in the level of mechanical characteristics and internal stresses of the object under study. Accumulated damage, calculated in this way, will allow to estimate the durability of structural elements subject to both periodic static loading and cyclic, i.e. with a complex stress state until the appearance of defects in it, which can lead to the failure of the structure.

Calculation of the durability of a cyclically loaded sample from steel 09G2S according to the proposed method consists of constructing a mathematical model that determines the durability region, when we getting into which we go from elastic deformation to plastic and also to determine the residual stresses using the X-ray method to take them into account in the model.

Results of numerical simulation

| Maximum cycle load, kN | $\sigma_{max}$, MPa | $\sigma_a$, MPa | $\sigma_m$, MPa | $\sigma_{rp}$, MPa | $N_B$ |
|---|---|---|---|---|---|
| 2,78 | 158 | 142,2 | 142,2 | 99,84667 | 1198048 |
| 4,67 | 262 | 235,8 | 235,8 | 121,6867 | 647149 |
| 5,55 | 317 | 285,3 | 285,3 | 133,2367 | 529968 |
| 6,67 | 380 | 342 | 342 | 146,4667 | 445688 |




Graphical interpretation of the numerical calculation results of residual durability for various values of the exponent 1) m = 2.1, 2) m = 2, 3) m = 1.9.

The obtained results of numerical calculation compared with experimental data allow us to say that in order to evaluate the residual durability it is necessary to take into account the state of the material as well as the history of its loading. In the graph, damage accumulation curves are constructed, where the exponent parameter m characterizes the mechanical properties of the material in the initial state. The proposed approach is confirmed by experimental data. In the course of the experiment shear bands were recorded on the lateral surface of the sample, which are inherent of shear deformation. This fact was recorded at 417000 cycles of loading, which coincides with the calculated region of durability.

## CONCLUSION

Based on the studies results the possibility of calculating the residual durability of structural elements with using the numerical modeling taking into account the residual stresses in the material is shown. The adequacy of the model is shown by the example of a cyclically loaded prismatic sample from steel 09G2C without a concentrator with a stepwise increase the stress level to values that cause local plastic deformation in the initial stage. Using the methods of mathematical modeling it is established that it is possible to determine the region of material transition into the stage of plastic deformation, taking into account residual stresses. The proposed methods of setting the experiment as well as approaches to the numerical determination of the residual durability will make it possible to develop a model for estimating the durability of a real structural element subjected to random and mixed loading during operation taking into account the magnitude and distribution nature of the emerging stress intensity values in the region of maximum tensile stresses, as the most dangerous, and taking into account the material properties degradation during its life cycle.

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