Force resistance of steel columns of industrial buildings with corrosion damage

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Abstract. It is proposed to use the computer modeling results to assess the degree of operational suitability and the possibility of further safe operation of building metal structures of industrial buildings and structures that have received corrosion damage, and to predict their reliability at various stages. The force resistance of steel eccentrically compressed columns, taking into account corrosion wear, was determined in SCAD PCS using a linear model of universal finite elements for shell calculation, as well as taking into account physical and geometric nonlinearity in ANSYS PCS. The authors obtained isofields and isolines of various components of displacements and stresses for the linear model, isofields of main stresses per Mises-Hencky, and displacements for the model, taking into account changes in the elastic material modulus with increasing stresses beyond the limits of proportionality. Verification of the computer modeling results for compliance with reality was performed through an experiment. To perform the study, it is possible to evaluate the power resistance eccentrically compressed structures subject to corrosion, to determine the influence of corrosion factors and the locations of elements on the bearing capacity, to give recommendations on ensuring the reliability of the operational characteristics of structures when diagnosing the technical condition of buildings.

1. Introduction

The reliability of a building structure is defined as a set of properties that ensure its uninterrupted regular operation under the given conditions (loads, temperature, application severity of the external environment, etc.) [1]. The regular operation of metal structures in industrial buildings is primarily determined by protection from corrosion damage. According to G2MT Labs [2], economic losses in 2016 in the United States from metal corrosion amounted to $1.1 trillion, which corresponds to about 3% of gross domestic product (GDP); similar figures are also registered in the United Kingdom and Germany. In Russia, according to experts, the loss from the destruction of materials under the influence of climate factors is about 4% of GDP. Aggressive influence of the department environment of many industrial enterprises causes corrosion of building structures, which causes their natural wear and tear – a continuous process over time [3].

It is required to set some values range of physico-mechanical properties of building structures and parameters of defects and damages identified in the survey process [4] to assess the degree of usability and the possibility of further safe operation of building structures or buildings [5,6].

The subject of this study is to assess the possibility of further operation of load-bearing steel structures of industrial enterprises, based on the study of computer models, which will ensure the effective use of elements [7] that have received corrosion damage.

The aim of the study is to predict the reliability of steel structures at various stages of the existence of an object. Such an assessment makes it possible to identify specific turnaround times for overhauls taking into account the degree of aggressiveness of the environment of a given enterprise, as well as to
establish the possibility of limited operation of structures before scheduled repair and restoration work 
with reinforcement or the need for immediate termination of operation in an emergency.

2. Methods

Deviations of the actual state of structures are defined as differences from the spatial position, 
geometric dimensions, shape, and continuity of structures and their elements, the presence of 
mechanical damage provided for by the project [8] (a column with corrosion damage is shown in 
Figure 1).

The objective of the study is determine the level of force resistance of metal structures of industrial 
enterprises, taking into account the corrosion wear recorded during the survey [9].

![Figure 1. Corrosion of a steel H-beam column](image)

Modern programming and computing suites (PCSs) make it possible to perform modeling of 
damaged steel structures [10] and take into account all possible impacts on the structure using 
computed tests, if necessary, taking into account the physical and geometric curvilinearity of the 
elements [11-13]. The design model is selected based on identified deviations, defects and damages, 
actual field application and the load direction, the actual values of the element stiffness, and the degree 
of pinching at the nodes [10].

To analyze the reliability of the computer modeling results, they were compared with the results of 
physical model tests. The work [14] presents the results of experimental studies of the authors of the 
force resistance of eccentrically compressed steel columns with damages. H-beam section steel 
columns No. 10 (according to GOST 8239-89) were tested. Corrosion damage was simulated by 
reducing the cross-sectional area of the shelves (with a cutter on each side of the shelf by 4 mm). The 
geometric dimensions of the damaged columns are shown in figure 2. In order to create conditions for 
cramped deplanation during the tests, 16-mm-thick plates were welded to the ends of the columns.

The strength characteristics of the sample material were determined experimentally: the average 
value of the temporary steel resistance was 453.4 MPa, and the average value of the yield strength was
280 MPa. The load application interval was 2.5 kN, and tests were carried out until the load-bearing capacity of the columns was exhausted. The AD/DA converter 16/16 "SigmaUSB" of "Electronic Technologies and Metrological Systems – ZET" (Moscow) was used to record the test results.

![Figure 2. Column with simulated corrosion damage. Geometric dimensions](image)

To determine the force resistance of a steel eccentrically compressed column, taking into account corrosion wear, the test results of which are given in [14], a linear model of universal finite elements for calculating shells was implemented in the SCAD PCS.

Geometrical dimensions, the scheme load application and column support anchors, and eccentricity values are shown in figure 3.

![Figure 3. Load application scheme and column support anchors at a uniaxial eccentricity](image)

At four points of each endplate, some connections prevent horizontal movements but do not prevent vertical movements of the column. The load increment was carried out in increments of 2.5
kN. Corrosion damage was simulated by reducing the estimated cross-sectional area of the shelf, which corresponds to the recommendations of clauses 2.19 and 2.46 [15].

The scheme of splitting the column into end elements in the SCAD PCS is shown in figure 4.

![Figure 4](image1.png)

**Figure 4.** a – scheme of splitting the column into end elements in the SCAD PCS; b – enlarged fragment of the finite element grid

As a result of linear calculation in the SCAD PCS, isofields and isolines of various displacement components are obtained. The total movements are shown in figure 5, the stress isofields are shown in figure 6.

![Figure 5](image2.png)

**Figure 5.** Column model with corrosion damage in the SCAD PCS. Total displacement isofields. Uniaxial eccentricity. 50 kN load
**Figure 6.** Column model with corrosion damage in the SCAD PCS. Isofields of Nx and Ny voltages. Uniaxial eccentricity. 50 kN load

**Figure 7.** Shows the movement of columns without damage (C0) and with corrosion damage (C4) under load, obtained from the calculation in the SCAD PCS.
To identify additional reserves of the load-bearing capacity of the tested element and to assess the adequacy of the design scheme, the calculation of the test column was performed taking into account the physical and geometric nonlinearity in the ANSYS PCS. Using this software allows performing a study of the object model, taking into account the nonlinear properties of the material, plasticity, and contact interactions.

To create the object model, a one-dimensional rod with a given stiffness or a thin-walled profile with a given wall thickness could be used, but the authors used a full-size three-dimensional model [16]. This is since the maximum stresses in the loaded column go beyond the limits of elasticity, structural defects form a complex geometry, so the implementation of the model in the form of a rod or thin-walled element can give incorrect results [17].

Nonlinear model analysis implies an iterative solution in which a decision is made on each new iteration following the results of the previous iteration. Physical nonlinearity is caused by taking into account the nonlinear dependence between the components of generalized stresses and deformations in the calculation and characterizes the work of the construction material in the elastic-plastic area [18]. The change in the elastic modulus of the material with an increase in stresses that go beyond the limits of proportionality is taken into account in the model used following the scheme shown in Figure 8.

![Figure 8. Scheme of elastic-plastic material deformation](image)

Geometric nonlinearity implies a disproportionate change in body deformation with increasing stress, the equilibrium equations, in this case, have to be made taking into account changes in the structure shape and size according to the deformed scheme [19, 20].

Feodosiev noted [21] that the plastic material begins to be damaged in places where the Mises stress becomes equal to the limit stress, which in most cases is used as the yield point.

For the main maximum stresses $\sigma_1$, $\sigma_2$, and $\sigma_3$, the Mises stress based on the Mises-Hencky theory [22] is expressed as

$$\sigma_{\text{Mises}} = \left\{ \frac{[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2]}{2} \right\}^{1/2}. \quad (1)$$
3. Results and Discussion

As a result of nonlinear calculation in the ANSYS PCS, the Mises isofields of the main stresses are obtained, as shown in figure 8, and the movement of the column under load, shown in figure 9.

![Figure 9](https://via.placeholder.com/150)

**Figure 9.** The values of the principal Mises stresses a) reference column (without damage); b) column with simulated corrosion damage

![Figure 10](https://via.placeholder.com/150)

**Figure 10.** Displacement values: C0 – reference column (without damage); C4 – column with simulated corrosion damage
A comparison of the results of computed modeling in linear and nonlinear formulation with the results of physical modeling is shown in the table.

**Table 1.** Results of computed and physical modeling of an eccentrically compressed Column

| Load, kN | Column 0 | Test result | Column 4 | Calculation in the ANSYS PCS | Calculation in the SCAD PCS | Calculation in the ANSYS PCS | Calculation in the SCAD PCS | Test result |
|---------|----------|-------------|----------|-------------------------------|---------------------------|-----------------------------|---------------------------|-------------|
| 10      | 0.3127   | 0.3433      | 0.45     | **0.3583**                    | 0.8023                    | 0.4214                      | 0.4214                    | 0.42        |
| 20      | 0.6251   | 0.6865      | 0.78     | **0.6265**                    | 0.8023                    | 0.8023                      | 0.8023                    | 0.85        |
| 30      | 0.9375   | 1.0299      | 1.13     | **0.9845**                    | 1.2124                    | 1.2124                      | 1.2124                    | 1.25        |
| 40      | 1.2499   | 1.3731      | 1.48     | **1.3425**                    | 1.6097                    | 1.6097                      | 1.6097                    | 1.65        |
| 50      | 1.5635   | 1.7164      | 1.82     | **1.7005**                    | 2.0674                    | 2.0674                      | 2.0674                    | 2.05        |
| 60      | 1.8459   | 2.0597      | 2.20     | 2.0858                        | 2.4874                    | 2.4874                      | 2.4874                    | 2.46        |
| 70      | 2.1583   | 2.4029      | 2.59     | **2.165**                     | 2.8145                    | 2.8145                      | 2.8145                    | 2.86        |
| 80      | 2.4707   | 2.7462      | 2.95     | **2.7745**                    | 3.7309                    | 3.7309                      | 3.7309                    | 3.73        |

4. Conclusions

The rack movements obtained by the results of numerical simulation in the ANSYS PCS taking into account geometric and physical nonlinearity differ from the experimental values by 9.9% for the control rack and 1.6% for the rack with corrosion damage. Linear calculations in SCAD PCS showed displacement values differing from experimental ones by 18.5% and 19.8%, respectively. It is characteristic that the presence of corrosion damage is well modelled by a nonlinear calculation, while the error in the linear calculation is larger than the experimental data. Based on the performed research, we can conclude that the results of design modelling in programming and computing suite are adequate. This makes it possible to estimate the force resistance of eccentrically compressed columns that are subject to corrosion based on numerical models and to ensure the reliability of the metal structures of industrial buildings.

Such an assessment makes it possible to give recommendations to operating organizations for setting specific turnaround times for major repairs, taking into account the degree of corrosion damage to the supporting metal structures.

Force resistance assessment of construction design of buildings and structures, taking into account all the negative impacts during operation, must be included in the complex of diagnostic and planned preventive measures carried out in the existing enterprises. This shall minimize the likelihood of failures and emergencies.

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