

Bearing capacity and life time of multielement structures exposed to corrosive wear

V K Chernykh¹, I I Ovchinnikov²

¹Building Constructions Department, Penza State University of Architecture and Construction, 28, Herman Titov st., Penza 440028, Russia

²Transport Construction Department, Yuri Gagarin State Technical University of Saratov, 77, Politechnicheskaya street, Saratov 410054, Russia

E-mail: mtt91@yandex.ru

Abstract. When in operation, a significant part of metal structures is exposed to aggressive media, causing the damage and failure of construction sites. This paper reviewed the well-known mathematical models and calculation methods of multielement metal structures, exposed to corrosive wear. Also, this paper described the solution approaches of stress-strain state and a life time evaluation of multielement rod structures. The finite element method is used for the solution of stress-strain state evaluation; the advantages of this method are also described. This paper proposes the statements of problems and solution algorithms of life time calculation of multielement rod structures, such as statically indeterminate trusses operating in the aggressive medium. This paper considered the most common corrosion wear case, where the corrosion rate is a stress function. The proposed solution methods involve the use of mathematical models and analytical formulas.

1. Introduction

Currently, the corrosion damage of metal structures caused by the aggressive media impact is one of the most pressing challenges. The cost-reduction along with the bringing down the high incidence-rate at the facilities are vital problems of construction, in particular, of transport facilities. To the full extent, the tasks of improving quality, reliability, and safety are related to the design problems of structures operating in aggressive medias [1,2].

The flat and space multielement metal structures with different configurations are popular in various construction areas. While in operation, such structures are exposed to combined actions of loads, temperatures and aggressive media. In this regard, the problem of developing effective models focused on the calculation of the bearing capacity of structural elements exposed to corrosive wear is of topical interest [3].

Over the past three decades, the progress in this area has been made in a lot of profiles: in statements of problems and their practical applications, in the development of solution methods, new approaches to the corrosion modeling, etc.

The research papers of following domestic and foreign scientists occupies a prominent place in this direction: V.V. Petrov, I.G. Ovchinnikov, F.F. Azhohin, H.V. Akimov, Yu.I. Archakov, L.A. Hlikman, E.M. Hutman, H.V. Karpenko, V.P. Korolev, V.V. Romanov et al. The basis of numerous reference materials is formed by working results of large number of researchers [4-7].



The papers concerned with the selection of certain cumulative damage models and the determination of coefficients by measured data are particularly noteworthy. This problem is bound up with the main task and the problem solution of strain-stress computation and the life time of the corroding structures largely depends on its solution. [8-11].

The calculation methodology of the stress-strain state of complex rod metal structures (trusses), taking into account the effect of a number of factors (load, aggressive medium) was developed throughout this study.

2. The Solution Approaches

The approach based on the joint use of any numerical calculation method of the stress-strain state and the numerical solution of the Cauchy problem for a differential equation system describing the process of damage accumulation is traditionally applied to solve stress-strain state and the life-time evaluation problem of multielement rod structures. The finite element method will be used to solve the stress-strain state analysis problem [12-15]. The advantages of this method include the following:

- the possibility to solve the stress-strain state and the life time evaluation problem of structures with unrestricted loading conditions and boundary conditions;
- the possibility to consider damage accumulation law for each finite element (or group of finite elements) and to research the most common cases of aggressive medium effect including the simultaneous effect of several different media;
- the application of certain parameters of finite elements (or groups of finite elements) as variable parameters for solution the optimal design problem.

Along with the obvious advantages, the application of the finite element method in solving of stress-strain state and the life time evaluation problems of structures taking into account the corrosion involves solving a number of problems [16].

3. The lifetime of a statically indeterminate space truss with the simultaneous effect of several aggressive medias

A lot of multielement metal structures are operated outdoors and exposed to atmospheric corrosion. This type of corrosion is characterized by two stages. On the first stage, the intensive corrosion process is observed. On the second one, the corrosion process damps out due to accumulation of corrosion products on the metal surface decelerating its destruction. The process speed is independent of the mechanical stress level based on the wide range of papers concerned with the study of atmospheric corrosion. The most reasonable mathematical description of this process is reduced to the use of a logistic equation of the following form:

$$\frac{d\delta}{dt} = k\delta(b - \delta) \quad (1)$$

where δ — the corrosion damage depth; t — the time; k — a certain coefficient, taking into account the medium effect on the corrosion rate.

The solution of life time evaluation problem involves the series of design calculations with resized elements at different points in time and creates no problems.

The problem becomes significantly more complicated if the structure, in addition to atmospheric corrosion, is also exposed to corrosion of a different class, for example, electrochemical corrosion. This situation is possible during the operation of structure under "factory atmosphere" conditions, i. e. the saturated atmosphere with oxides of acid-forming elements and water vapors at high temperature.

These cases will be characterized by partial or complete destruction of the field-oxide films due to chemical reactions on the metal surface and, to some extent, deformation of the structural elements. We propose to use the mathematical model as a set of models describing processes of a different nature to study the structures under such operating conditions. Let us suppose for definiteness that the electrochemical corrosion is described by the equation:

$$\frac{d\delta}{dt} = v_0 [1 + k \sigma_{eq}] \quad (2)$$

where v_0 — the corrosion rate without stresses (the chemical component of the corrosion process); σ_{eq} — the absolute value of the equivalent stress.

Let us present the model as follows:

$$\frac{d\bar{\delta}}{dt} = n_1 v_0 [1 + k_1 \sigma(\bar{\delta})] + n_2 k_2 \bar{\delta} (\delta^* - \bar{\delta}) \quad (3)$$

$\bar{\delta}$ — the vector of corrosion depths in the structural elements; δ^* — the maximum depth of corrosion damage with oxide films; n_1 and n_2 — weighting coefficients ($n_1 + n_2 = 1$); k_1 and k_2 — constants.

Since the aggressive medias act independently, the damage parameter value in the structural element can be found as the sum of two components:

$$\delta = n_1 \delta_1 + n_2 \delta_2 \quad (4)$$

The solution of equation (1) entering into the right side as addend (3) is known, and the expression for δ_2 has the form:

$$\delta_2 = \frac{\delta^*}{1 + \frac{a}{\exp(k_2 \delta^* t)}} \quad (5)$$

where a — constant.

Thus, the analytical expressions for various components of corrosion damage are known, and the algorithm considered in [17,18] can be applied for solution. However, in this case, an analytical solution of the life time evaluation problem of an individual element is impossible. Indeed, the damage parameter value, corresponding to the element failure moment, will include both components. We obtain an life time equation t being solved only numerically by expressing δ_1 from (4) and substituting its value with regard for (5).

For instance, let us consider the life time determination problem of a translation tower constituting the 25-element statically indeterminate space truss (Fig. 1). The structure is operated in conditions of simultaneous effect of two different aggressive media. The calculation scheme of the translation tower is borrowed from [19].

For illustrative purposes, we considered a truss, in which the elements (1) - (12) are made of the channel No 12, the rest — from the angle bar No. 10. The dimensions in the figure are in centimeters. The aggressive media parameters: $v_0 = 0.15$ centimeters per year; $k_1 = 0.005$ MPa⁻¹; $k_2 = 16.49$ (cm×yr)⁻¹; $\delta^* = 0.3$ cm; $a = 34$. The weight coefficients for the elements (1) - (12): $n_1 = n_2 = 0.5$; for the elements (13) - (25): $n_1 = 0.3$ and $n_2 = 0.7$.

The structure's life time firstly was determined from the nonlinear equation obtained with regard for (4) and (5). In this case, the changeability of the internal forces in the elements [20] was ignored. In this instance, the active constraints were cross-section solidity constraints, i. e., the truss life time was determined by the thickness reduction moment of the element's stand (5) to the critical value: $D_5(t) = 0,1 D_0$. The life time value determined under this constraint was $t^* = 11.21$ years. The problem of the finite element method was solved only once — for the structure at the initial instant.

By contrast, the life time problem was solved taking into account changes of internal forces in the rods with a time step $\Delta t = 1.0$ year and $\Delta t = 0.5$ years. The FEM (Finite Element Method) problem was solved 12 and 23 times, respectively. The obtained results: $t^* = 11.12$ years and $t^* = 11.07$ years.

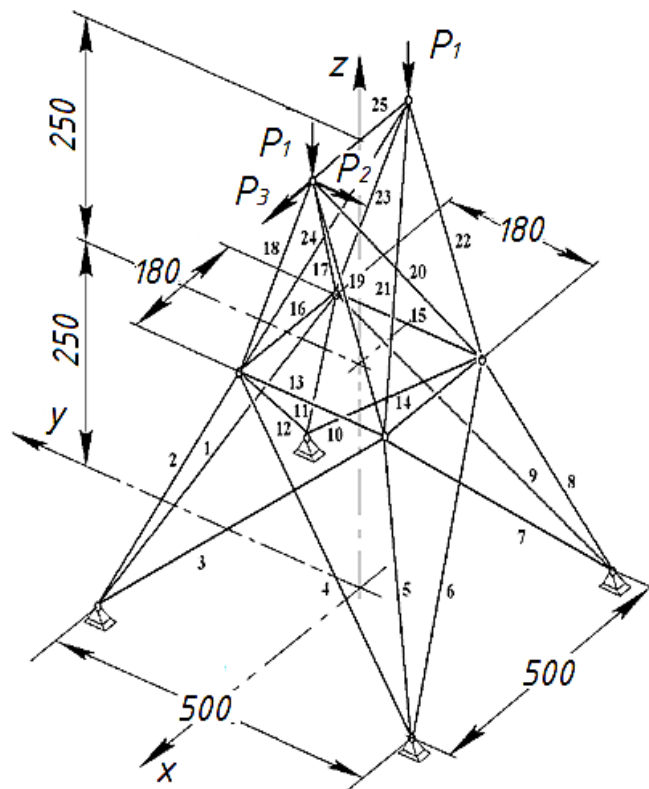


Figure 1. The Statically Indeterminate Space Truss.

The time step value was determined by the specified accuracy of the numerical solution of the Cauchy problem for the differential equation system (3) using traditional algorithms. The value selection Δt in this case was $\Delta t = 0.075$ years. For Δt value, the number of finite element method reference was 148. The result was improved by the parabola method. The life time calculated value was $t^* = 11.26$ years. Some imprecision can be explained by the calculation error accumulation in the FEM procedure implementation and the parabola method error in the result improvement.

4. Conclusions

The study covered a statically indeterminate truss, exposed to a high-aggressive environment. For the purposes of solution the stress-strain state and the life time evaluation problem, the modified finite elements with induced variable rigidity were developed. The effectiveness of the developed algorithms based on the use of analytical formulas is confirmed by the practical coincidence of the obtained results and incommensurable, in this respect, computational costs, even in considering rather complex cases of corrosive effects.

The obtained results can be used to predict the life time of building metal structures operating under real operating conditions.

References

- [1] Ovchinnikov I G, Likverman A I, Rasporov O N et al 2014 *The Corrosion Protection of Metal and Reinforced Concrete Bridge Structures by the Color-Coating Method* (Saratov: "Kubik" Publ.) p 504

- [2] Ovchinnikov I I, Mironov M Y, Ovchinnikov I H, Snegiryov H V, Chernykh V K, Moiseev O Yu 2013 The Preservation of Small and Medium-Sized Bridges with Metal Spans *Naukovedenie* (Moscow: Naukovedenie Publ.) **5** (18)
- [3] Zelentsov D H 2006 *The Structural Calculations with Changing Geometry in Aggressive Media. Rod systems* (Dnepropetrovsk: USUCT) p 168
- [4] Archakov Yu I 1985 *The Hydrogen Corrosion of Steel* (Moscow: Metallurgy Publ.) p 112
- [5] Berezhnoy K P 1986 The Corrosive Effect on the Reliability of Steel Building Structures at Low Temperatures *Industrial Technical Solutions for the Reconstruction of Buildings and Structures: The Abstracts of All-Soviet Union Seminar* pp 49–51
- [6] *The Protection against Corrosion, Aging and Biodeterioration of Machines, Equipment and Structures: a handbook in 2 vol, 1987, ed. A A Gerasimenko, vol. 1* (Moscow: Mechanical Engineering Publ.) p 688
- [7] Steklov O I 1990 *The Resistance of Materials and Structures to Stress Corrosion* (Moscow: Mechanical Engineering Publ.) p 384
- [8] Ovchinnikov I H, Kudaiberhenov N B and Shein A A 1999 *The Operational Reliability and State Assessment of Tank Structures* (Saratov: STUS) p 316
- [9] Petrov V V, Ovchinnikov I H and Shikhov Yu M 1987 *The Calculation of Structural Elements Interacting with an Aggressive Media* (Saratov: STUS) p 288
- [10] Filatov H V 2001 To Issue about the Determination of Mathematical Model Coefficients of Corrosion Destruction by the Polynomial Approximation Method under Optimal Design of Structures Interacting with an Aggressive Medium *The Issues of Chemistry and Chemical Technology* **3** pp 114–117
- [11] Filatov H V 2000 The Method of Multiple Identification of the Mathematical Model of Corrosion Damage in the Optimal Design of Shells Exposed to the Aggressive Medium Effect *The Issues of Chemistry and Chemical Technology* **1** pp 330–333
- [12] Alexandrov A V, Lashchenikov V Ya and Shaposhnikov N N 1983 *The Structural Mechanics. Thin-walled three-dimensional system* (Moscow: Stroizdat Publ.) p 488
- [13] *The Finite Element Method in Mechanics of Solids*, 1982, eds. A S Sakharov and I Altenbach (Kiev: Higher School Publ.) p 480
- [14] Bazhenov V A, Gulyar A I, Sakharov A S, Topor A H 1993 *The Semianalytic Finite Element Method in the Deformable Solid Body Mechanics* (Kiev: Machine-Building Scientific Research Institute) p 376
- [15] Khazanov Kh S, Saveliev L M 1975 *The Finite Element Method in Application to the Structural Analysis Problem and the Elastic Theory* (Kuibyshev: KAI) p 127
- [16] Zelentsov D H, Radul A A, Lyashenko O A, Ovchinnikov I I and Ovchinnikov I H 2012 The Connectionist Calculation Model of Corroding Notched Plate *Naukovedenie* **4** p 15 <http://naukovedenie.ru/PDF/7tvn412.pdf>
- [17] Zelentsov D H, Naumenko N Yu, Novikova L V, Ovchinnikov I H and Ovchinnikov I I 2012 The Precision Control of the Numerical Solution of Certain Classes of Differential Equation System of Structural Mechanics *Naukovedenie* **4** p 18 <http://naukovedenie.ru/PDF/11tvn412.pdf>
- [18] Zelentsov D H and Uskova T Yu 2004 The Study of the Perimeter Effect on the Optimal Parameters of the Cross Sections of Corroding Incurvated Rod Elements *The Issues of Chemistry and Chemical Technology: Collection of Research Papers* **6** pp 119–122
- [19] Hog E, Arora Ya 1983 *The Applied Optimal Design* (Moscow: Mir Publ.) p 478
- [20] Zelentsov D H and Filatov G V 2002 The Review of Researches on the Application of Nonlinear Mathematical Programming Methods to the Optimal Design of Structures Interacting with an Aggressive Medium *The Issues of Chemistry and Chemical Technology* **4** pp 108–115