МОСТИ ТА ТУНЕЛІ: ТЕОРІЯ, ДОСЛІДЖЕННЯ, ПРАКТИКА

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ASSESSING THE INFLUENCE OF LOCAL CORROSION IN THE JOINTS OF COMPONENTS ON THE LIFE OF MULTIELEMENT ROD STRUCTURES

Purpose. The paper analyzes the reasons resulting in destruction of multielement metal structures. Attention is paid to the impact of deformation types on the corrosion of components of such structures as well as to their potential safe operation. Influence of local corrosion in the joints of rod structure members of rod on the terms of its bearing capacity exhaust has been studied**. Methodology.** To solve the life problem, a 16-rod flat frame has been considered as a simulation structure with design parameters, material characteristics, geometric outline, boundary conditions, and loading conditions. **Results.** A frame life problem has been considered taking into consideration local corrosion in the joints of rods. The problem involves two calculation schemes with common formulation but having proper peculiarities. Its common is in the availability of inverse association within the calculation models. The difference is as follows. If the number of parameters describing a corrosion process within the frame components is finite during the simulation process in the rod section, where it is fixed, it can be considered as a fragment of flatly stressed plate (FSP) where corrosion velocity depends upon stresses. Since stress-strain state is nonuniform in terms of its area, the number of such parameters tends to infinity. It is the peculiarity defining difference of the research from the majority of the known studies. **Scientific novelty.** Certain reasons of origination of typical defects and damages of rod metal structures have been considered inclusive of simulation of processes of damage formation as well as defect location. The tendency potential is to expand opportunities while forecasting the structure life with regard to its operational conditions. **Practical value.** Local corrosion neglecting in the rod joints gives rise to the substantial overestimation of analytical life value. In such a way, structural destruction does not result from bearing capacity exhaust of its component. It results from the broken ties between its separate components despite the fact that a reserve of their bearing capacity is still sufficient.

Keywords: deformation; local corrosion; trouble-free operation; metal structure defects; load-bearing capacity; finite element; plane stressed plate

Introduction

Over time, bearing capacity of structures goes down due to accumulation of damages or origination and development of defects. Hence, determination of bearing capacity reserve becomes an important practical problem. Failure (destruction) of one or several system components cannot be considered as termination of its operation. Consequently, such an idea as 'vitality' (Перельмутер, 2007; Вострое, 2009) is popular today. The term is a property of the structure to maintain its overall bearing capacity under local destructions.

To test strength of metal structures, Building Design Standards and Standards for organizations use elasticity condition for nominal stresses (condition of plastic deformation non-achievement according to von Mises or Saint-Venant) as well as strength criterion limiting absolute values of the principal stresses with the help of a flow stress. Impact of the defects and stress concentrators on

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the strength and life of structures is not considered; moreover, decrease in bearing capacity due to progress of macrocracks, resulting from defects, is not taken into consideration. Consequently, the Standards involve implicitly a 'damage-free operation' concept (ДБН В.2.6-198:2014, 2014; ДБН В.1.2-14:2018, 2018). However, requirement for complete defectlessness of metal and welded joints is not supported by the current means of nondestructive control. They operate with cracks and corrosion. Moreover, there are defects with marginal dimensions which cannot decrease strength components of metal structures (Ivanova, Hapieiev, Shapoval, Zhabchyk, & Zhylinska, 2021). Calculation techniques, involved by the building codes, complicate determination of life, structural safety, and vitality of metal structures since they do not include definitely consideration of a time factor as the basic calculation parameter on the limiting states.

Rod metal structures have a special place among construction structures; they are widely used by different industry sectors. Such structures are influenced by quazistatic, cyclic, dynamic, and random loads. They operate in corrosion environments and experience temperature drops. The factors results in the decreased bearing capacity as well as in the reduced analytical life of the structure.

The main reasons, giving rise to destruction of rod metal structures, are defects of installation or manufacturing defects; use of metal which characteristics are lower than the design values. Nevertheless, the most important factors are incomplete consideration of possible loads and insufficient system of structural bonds. Almost 60 % of failures take place during building process when not all structural components are assembled, and fixed in joints and nodes.

Destruction reasons of rod metal structures are as follows:

– stability loss – 41 %;

– destruction of nodes – 46 %;

– other reasons – 13 %.

Failure analysis of steel structures with fragile and quazi-fragile destruction of their members supports the idea of influence of operational period of structures on the potential of fragile crack initiation and development. For example, 50 % of all failures happen during the first operational winter; 14 % happen during the second winter; 8 % – during the third one etc. Up to 80 % of all the failures fall on the first five years of operation.

Depending upon the nature of influence on bearing capacity, structure damages can be divided into following types:

– varying cross-section geometrics;

– varying nature of stress-strain state of structural components;

– damages varying a structural scheme due to the broken connectivity between constructive members.

With regard to metal structures, just corrosion is among the most important factors causing their destruction. In contrast to problems, formulated classically, numerous constants, characterizing features of any element in neutral medium, are functions if the element operates in an aggressive environment. In this context, a degree of their variations is dissimilar for different structural points. Hence, the aggressive environment impact results in the induced (i.e. time-dependent) nonuniformity of geometrical and in some cases mechanical characteristics in terms of the structure (Зеленцов, 2002).

Processing of results of engineering survey of metal structures in Kryvyi Rih mines has shown a dependence of type of deformation, experienced by a structure component, upon its corrosion damage (Fig. 1).

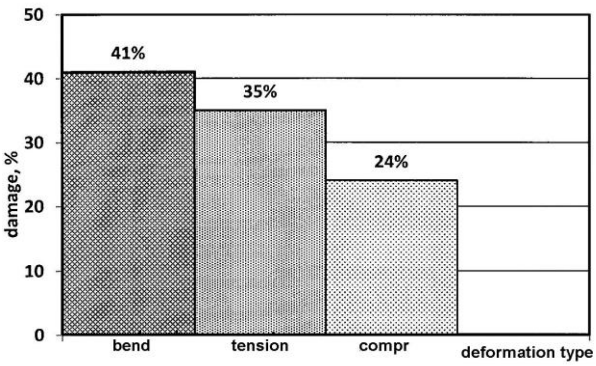

Fig. 1. Dependence of corrosion damages upon a deformation type

Bending rods have demonstrated maximum amount of corrosion damages. The abovementioned is explained by the fact that bending decreases a cross section of element in the compressed area; increase is typical for a tension area. That also concerns tension rods. It is possible to assume the following: increase in the rod length results in the increased area contacting aggressive

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environment, i.e. 'scale effect' takes place (Иванова, 2013).

Recently, the building sector has demonstrated a tendency to structural complication of buildings and facilities, i.e. spans become longer; heights increase; new materials are applied etc. accumulation of damages as well as initiation and progress of defects reduce bearing capacity of structures. Consequently, large size and multielement system run the risk of their bearing capacity failure in addition to the reduction of the lifetime.

As applied to metal structures, the idea of material defectiveness depends directly upon corrosive wear resulting in failure of certain structural components. In particular, local damages sometimes involve failures of bearing capacity of the whole structure; if the component is the primary and load-carrying then the structure may ruin.

Purpose

The research purpose is to analyze influence of local corrosion, arising in the joints of rod structure, on life of both the structure, consisting of rods under tension or compression, and certain rod sections as fragments of flatly stressed plate (FSP) where stress field is of the non-uniform nature.

Methods

Various techniques are applied to joint rod members. Regardless of engineering solutions, the section where rod is connected with another rod or joint member may be considered as a FSP fragment weakened by holes for fasteners. Then, the structure destruction can take place not in any rod on the whole but within the joint due to breaking of bonds between members. Since designing generally uses sample profiles with the specified sizes, thickening with no additional production steps is possible if only profiles having larger cross section thickness are applied as well as those having larger size and a running meter area. It is obvious that such a solution cannot be rational.

It seems expedient to define life of the whole construction, consisting of rods under tension and compression, and life of certain rod sections as FSP fragments where stress field is of non-uniform nature. In the latter case, the solution is implemented as a part of a flat stress problem (Зеленцов, & Радуль, 2005).

Results

To solve the life problem, 16-member frame has been considered as a model structure. Fig. 2 demonstrates its boundary and loading conditions.

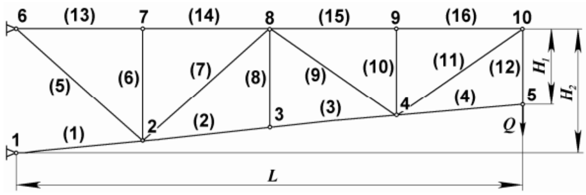

Fig. 2. 16-member rod structure

Design parameters and material characteristics are as follows: L=600 cm; H_1=150 cm; H_2= 250 cm; E= 2.1×10^5 MPa; and [σ]=240 MPa. The applied load is Q=15 kN. Corrosion velocity is v_0=0.1 cm/year; and k= 0.005 MPa^{-1} is coefficient of the model equation of corrosive wear (Наумова, & Овчинников, 2000).

Table 1

Shows member parameters for the analytical model (Fig. 3)

Section of lower boom members	Section of diagonal components and top boom members	Section of fixed members
Unequal angle #14	Equal angle #11	Equal angle #9

In this context, the frame life is 3.02 years. The problem solving has assumed that corrosive wear within the rod joints is similar to those one taking place within the whole structure. Below, you can find local corrosion consideration in the joints.

To analyze corrosion processes within the rod member joints consider frame rod fastening to a gusset plate by bolts (Fig. 3).

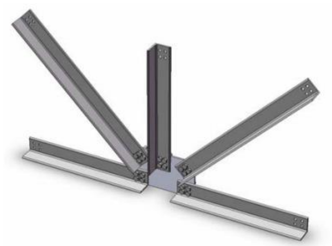

Fig. 3. Member joints within the frame nodes

A frame life problem taking into consideration local corrosion within the areas of rod joint involves two analytical models with the same formulation. However, each of them has its own features.

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Their common characteristic is inverse association. Again, they differ in the following. If the number of parameters, describing corrosion process within the frame members, is finite then the process simulation in the section where rod is fixed may be considered as a FSP fragment where corrosion velocity depends upon stresses. Since stress-strain state is nonuniform significantly in terms of its area then the number of such parameters tends to infinity. This is the feature determining the research difference from the majority of the known studies.

Irrespective of structural concepts, the case demonstrates the necessity to use FSP analytical model. The availability of holes for members to be connected stipulates the necessity to take into consideration stress concentrators which may influence heavily the problem solving.

Algorithm to solve the problem of FSP life. A finite element method (FEM) is applied traditionally to solve a problem of corrosive structure life. For its implementation, computation algorithm to calculate FSP relies upon following hypotheses:

1. A corrosion mechanism is similar for each construction point. If it is not specifically mentioned, the process nonuniformity depends only on the stress field nonuniformity;
2. There is some equivalent stress in terms of which the corrosion process velocity under complex stress conditions coincides with its velocity under simple one;
3. Influence of changes in geometry on the stress increase surpasses by far the influence of changes in the internal power factors.

The paper proposes to use a triangular finite element (FE) with the graduated thickness and twelve degrees of freedom described in detail by paper (Зеленцов, & Радуль, 2005). It gives the opportunity to develop more accurate model of a corrosion process using the second approximation order of a thickness function.

The model of corrosive wear assuming member thickness in the node points as the varying geometrical parameters is

$$\frac{d[H]}{dt} = -v_0(1+k\cdot(t)),\ [H]_{t=0} = [H]_0, \qquad (1)$$

where $[H]$ is $N\times n$ matrix of geometrical parameters of the structure members; N is FE number in the structure model; n is number of the parameters determining the member geometrics (being n=6 for the proposed FE); and σ_{eq} is absolute value of the equivalent stress.

For model (6), paper (ДБН.2.6-198:2014, 2014) has developed analytical formula of life of a flat stress element subjecting to corrosive wear

$$t = \frac{h_0}{v_0}\cdot\sigma_{eq}\cdot\left[k\cdot\ln\frac{\sigma_{eq0}(1+k\cdot\sigma_{eq})}{\sigma_{eq}(1+k\cdot\sigma_{eq0})} + \frac{\sigma_{eq}-\sigma_{eq0}}{\sigma_{eq}\cdot\sigma_{eq0})}\right]. \qquad (2)$$

Equivalent stress is maximum prime stress σ_1 – stress intensity σ_{int} combination. They are efficient stresses according to von Mises. Hence,

$$\sigma_{eq} = \sigma_{int} + \omega\cdot(\sigma_1 - \sigma_{int}), \qquad (3)$$

where ω is constant $\omega \in [1;0]$. In this context,

$$\sigma_1 = \frac{\sigma_x+\sigma_y}{2} + \sqrt{\left(\frac{\sigma_x-\sigma_y}{2}\right)^2 + \tau_{xy}^2}, \qquad (4)$$

$$\sigma_{int} = \sqrt{\sigma_x^2 + \sigma_y^2 - \sigma\sigma_x^2 + 3\tau_{xy}^2}. \qquad (5)$$

For a case of analytical FSP model, life calculation also involves semianalytical algorithm of DES solution applying formula (2).

Consider a fragment of a rod angle in the neighborhood of joint as a FSP weakened by circular cutouts for the connecting elements (Fig. 4).

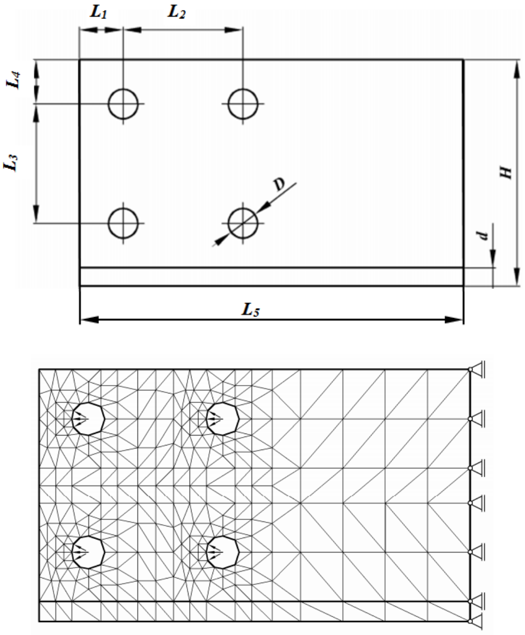

Fig. 4. Analytical model and finite element FSP model (299 nodes; 513 FEs)

Geometrical dimensions for a fragment of angle #11 are: L_1 =L_4 = 1.95 cm; L_2 =L_4 = 6.3 cm; L_5=18 cm; H=11cm; D=1.3 cm; and d=0.8 cm. Maximum permissible stress value is [σ]=240 MPa.

Calculation of joints of rod members should involve knowledge of internal efforts arising within the frame members. For numerical illustration, rods where internal forces (in terms of absolute value) were maximal were selected from each of four groups of rod members (Fig. 3): $P_{н.п.}$=3.65 kN; $P_{в.п.}$ = 3.65 kN; and $P_{c.}$ = 3.65 kN.

Table 2

Demonstrates calculation results of rod member fragments within their joint areas.

Rod member number	Section type	Life, years
Lower boom (member 1)	Unequal angle #14/9 (h=1.0 cm)	2.104
Top boom (member13)	Equal angle #11 (h=0.8 cm)	1.178
Vertical beams (member12)	Equal angle #9 (h=0.8 cm)	1.722
Struts (member11)	Equal angle #11 (h=0.8 cm)	1.870

Scientific novelty

The tendency potential is to expand opportunities while forecasting the structure life with regard to its operational conditions. The results help conclude that local corrosion neglecting within the areas of rod joints results in substantial overestimation of the analytical life value obtained from the previous problem solution (i.e. 3.02 years).

Consequently, structural damage takes place not because of exhaustion of bearing capacity by some member but because of breaking of bonds between certain rods whereas their bearing capacity reserves are still significant.

Conclusions

1. Operational conditions and local damages have a destructive effect on the rod metal structures. In this context, the current normative base takes into consideration only some share of the actions resulting in destruction. In this connection, the task to study more profoundly the behaviour of metal structures under the conditions nonscheduled by standard influence becomes topical. Among other things, it concerns partial damage and destruction of certain members.

2. The research findings have helped conclude that calculation of corrosive rod metal structure life, required to obtain reliable assessment of the life, should involve analytical FSP model simulating a corrosion process within the joints in addition to analytical model of the system. Use of analytical model alone results in substantial overestimation of its life.

3. One of the ways improving the efficiency to calculate rod structures is the possibility to identify dependence between the operational period, loading parameters, aggressive environment, and current state of any structural component. The tendency potential is the expanded opportunities to forecast life of the structure as applied to its operation.

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ОЦІНКА ВПЛИВУ ЛОКАЛЬНОЇ КОРОЗІЇ В МІСЦЯХ З'ЄДНАННЯ ЕЛЕМЕНТІВ НА ДОВГОВІЧНІСТЬ БАГАТОЕЛЕМЕНТНИХ СТРИЖНЕВИХ КОНСТРУКЦІЙ

Мета. В статті аналізуються причини, що призводять до руйнування багатоелементних металевих конструкцій. Увагу приділено впливу виду деформації на корозійний знос елементів таких конструкцій і можливість їх безаварійної експлуатації. Досліджено вплив локальної корозії в місцях з'єднання елементів стрижневої конструкції на терміни вичерпання її несучої здатності. **Методика.** Для вирішення завдання довговічності в якості модельної конструкції розглянута стержньова плоска ферма, яка складається з 16 елементів. Для неї наведені параметри конструкції, характеристики матеріалу, геометрична схема, граничні умови і умови навантаження. **Результати.** Розглянуто задачу довговічності ферми з урахуванням локальної корозії в місцях з'єднання стрижнів, яка включає в себе дві розрахункові схеми, пов'язані єдиною постановкою, але зі своїми особливостями. Загальне для обох схем – наявність зворотного зв'язку в моделях розрахунку. Відмінність полягає в тому, якщо число параметрів, що описують процес корозії в елементах ферми конечно, то при моделюванні цього процесу на ділянці стрижня в місці його кріплення, він може розглядатися як фрагмент ПНП (плосконапруженої пластини), де швидкість корозії залежить від напружень. Оскільки напружено-деформований стан істотно неоднорідний по його області, число таких параметрів прагне до нескінченності. Саме ця особливість і визначає відмінність даного дослідження від більшості відомих робіт. **Наукова новизна.** Визначено причини виникнення характерних дефектів і пошкоджень стрижневих металоконструкцій під час моделювання процесів формування пошкоджень і розташування дефектів. Перспективність цього напрямку полягає в розширенні можливостей прогнозування довговічності конструкції стосовно умов її експлуатації. **Практична значимість.** Ігнорування локальної корозії в місцях з'єднань стрижнів призводить до істотного завищення розрахункового значення довговічності. Таким чином, руйнування конструкції відбувається не внаслідок вичерпання несучої здатності будь-яким її елементом, а при розриві зв'язків між окремими елементами, в той час як їх запас несучої здатності ще значний.

Ключові слова: деформація; локальна корозія; безвідмовність експлуатації; дефекти металоконструкції; несуча здатність; кінцевий елемент; плоско напружена пластина

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