UDC 519.6:004.942

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DECOMPOSITION METHOD FOR SOLVING SYSTEMS OF DIFFERENTIAL EQUATIONS FOR THE PROBLEMS OF MODELLING CORROSION DEFORMATION PROCESSES

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The article offers and justifies a method for solving systems of differential equations (SDE) that simulate time changes of stress and strain state due to the influence of corrosive environment (the process of corrosion deformation). The objective of modelling is the determination of the construction durability that is the time of its flawless operation. The finite element model of the object under study determines dimension of SDE modelling the process of corrosion deformation. The right-hand sides of the differential equations contain functions of mechanical stresses. The finite element method is used to calculate stresses. The proposed decomposition method is based on the transformation of the initial differential equations by introducing functions describing the influence of the remaining equations and the subsequent solution of one of these equations. Based on the analysis of the factors influencing the stress change in the area of the given finite element, we propose to introduce into the corresponding differential equation a function approximating the change of internal forces over time. In this case, the discrepancy between the results of the initial SDE solution and an individual equation is determined only by the error in approximating the dependence of the internal force on time. The article shows that this allows a multi-rate reduction of computational costs. In addition, for a numerical solution of SDE, we propose to use a modified algorithm of the Euler method with a variable integration step by argument. The result of the solution is determination of corrosive construction durability, i.e. operating time before exhaustion of bearing capacity. To illustrate the proposed method, we solved the problem of calculating the durability of a flat-plate subjected to corrosive wear. The article provides the results of numerical experiments confirming the accuracy of the proposed numerical solution with minimal computational costs. The decomposition method for solving SDE, modelling the process of corrosion deformation of plane-stressed plates, can be generalized to other classes of constructions.

Keywords: decomposition method, corrosive medium, process of corrosion deformation, system of differential equations, plane-stress corroding plates.

Statement of the problem

When solving practical problems associated with the finite element modelling of the corrosion deformation process and predicting the durability of metal constructions operating in corrosive environments (CE), the problem of accuracy and efficiency of computational methods and algorithms becomes particularly important. In the general case, modelling of changes in stress and strain state of a construction in time due to the physical and chemical processes occurring in its elements assumes a numerical solution of the Cauchy problem for systems of differential equations (SDE) describing the accumulation of geometric damages. The finite element model of the object under study determines the dimension of the SDE. The increase in accuracy due to the increase in the number of nodes of the time grid leads to a sharp increase in computing costs. In this article, we propose and justify the method of solving SDE, based on the decomposition of the system and allowing to achieve high accuracy of the numerical solution with minimal computational costs.

Analysis of recent research and publications

At the initial development stage of Corrosive Structure Mechanics as an independent direction of Construction Mechanics most works practically do not pay attention to analyzing the accuracy of the obtained results. At best, only the method of solving SDE is indicated [1]. Such a disregard for numerical methods, and, especially, for estimation of their accuracy, is probably caused by the fact that authors were interested only in qualitative estimates.

The paper [2] should be considered one of the first works, which gives recommendations for choosing the parameters of the numerical solution for SDE in the study of corroding plates. It was proposed to take the length of the integration step in time not more than 1/200 of the plate thickness ratio to the corrosion rate in the absence of stresses. These recommendations, however, do not take into account such important factors affecting inaccuracy of numerical solution as the value of stress at the initial time and the rate of stress changes. In addition, following these recommendations can lead to excessive computational costs in the study of multi-element constructions, especially for optimization problems.

In later works, the increase in the efficiency and accuracy of computational algorithms was provided due to their modification including the use of analytical dependencies between the parameters of the cross section and the corrosive environment, stress, limiting values of the corrosion depth and time [3]. However, quantitative estimates of the errors in solution were not given in these studies.

Obviously, one of the first papers devoted to improving the efficiency of numerical integration of systems of differential equations is [4]. In this paper, they used the method of dynamic programming for the problem of minimizing the number of arithmetic operations when integrating a system of ordinary differential equations of the nth order by controlling the length of the integration step.

The approach based on the formalization of information about the influence on solution inaccuracy (in addition to the length of the integration step) of such factors as the initial values of stresses in the element, parameters of corrosive environment and, for rod constructions, the characteristics of its cross-sections (shape, area, perimeter) is apparently more promising. This formalization was carried out with the help of artificial neural networks (ANN) [5,6] in the study of hinged-rod structures (HRS). With the obvious advantages of this approach, the question about the effect of the time variation of internal forces in finite elements on the accuracy of the obtained solution remained open.

The problem of the accuracy and efficiency of the numerical solution for SDE describing accumulation of geometric damages becomes especially important in problems of optimal design for corrosive structures [7] where the calculation of the constraint functions involves determining the durability of the construction. It should be noted that methods for solving discrete optimization problems including genetic methods assume higher computational costs in comparison with methods of Mathematical Programming [8].

Research objective

We will consider plane-stressed plates subject to corrosive wear as an object of study. The task of modelling is the determination of the construction durability - the time of its trouble-free operation.

Due to the influence of a corrosive environment, the thickness of the plate decreases that, in turn, leads to an increase in mechanical stresses. If we take the depth of a corrosion damage as a parameter for corrosion action (damage parameter), the system of differential equations modelling the process of corrosion plate deformation can be presented as follows:

$$\frac{d\delta_i}{dt} = v_0 \cdot F\left(\sigma_i\left(\bar{\delta}\right)\right); \quad \delta_i\Big|_{t=0} = 0; \quad i = \overline{1, N}. \qquad (1)$$

Here: t – time; v_0 – corrosion rate in the absence of stress; σ – equivalent of stress; F – function describing the influence of stress over the rate of the corrosion process; N – number of elements in the finite element model.

The right-hand sides of the SDE contain the functions of mechanical stresses F(σ). The following equations of Deformable Solid Mechanics are used to calculate stresses: the system of equations of equilibrium and deformation compatibility, the Cauchy relations and physical relationships (the Hooke's law for elastic bodies). As a system of equations for the finite element method (FEM) they look as follows:

$$\begin{cases} \bar{R} = K^{-1} \cdot \bar{u}; \\ \bar{\varepsilon} = D \cdot \bar{u}; \\ \bar{\sigma} = E \cdot \bar{\varepsilon}, \end{cases} \qquad (2)$$

where K, D, E are the matrices of rigidity, differentiation and elasticity; $\bar{R}, \bar{u}, \bar{\varepsilon}$ and $\bar{\sigma}$ – vectors of nodal loads, displacements, deformations, and stresses.

Since the stress state is complex: $\bar{\sigma} = \left[\sigma_x, \sigma_y, \tau_{xy}\right]^T$, in the right-hand side of the system (1), the stress intensity is taken as the equivalent stress σ_{eq}. Stresses are calculated in the center of finite element (FE) gravity. The structure loses its bearing capacity when the stress in any of its elements reaches the maximum permissible value. The time moment corresponding to this state determines durability of the structure. Thus, the solution of the durability problem reduces to solving the Cauchy problem for a system (1) together with the solution of FEM problem (2). The calculation cycle is repeated until the structural capacity is exhausted.

Obviously, the system (1) can be solved only numerically and the solution of the FEM problem (2) is performed at each node of the time grid. This determines the level of computational costs which increases nonlinearly with FEM problem dimension growth and, as a consequence, the growth of SDE dimension.

Main material of the research

Stress changes in the finite elements are affected by two factors: the change in the thickness of these elements h_i and the change in their internal forces Q_i. The first factor is relatively easy to take into account, since the magnitude of the corrosion damage in the ith element is determined by the stress value only in this element. At a constant value of forces, SDE (1) degenerates into a simple set of unbound differential equations varying only in parameters.

$$\frac{d\delta_i}{dt} = v_0 \cdot F\left[\sigma_i\left(h_i\left(\delta_i\right), Q_i\right)\right]; \qquad \delta_i\Big|_{t=0} = 0; \quad i = \overline{1, N}. \qquad (3)$$

The durability of any element can be determined analytically, i.e. exactly (within the accepted model of corrosion wear). Thus, the solution of the durability prediction problem for statically plane-strained plates reduces to solving independent differential equations.

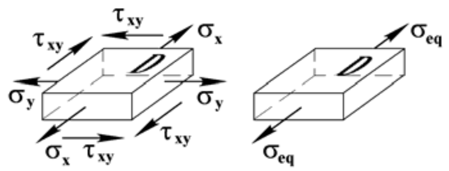
In the proposed algorithm for solving the durability problem, we use analytical formulas that determine the relationship between the thicknesses of FE, the initial and final stresses in them and parameters of corrosion wear.

Suppose that stress values are constant in D surroundings of some point (Fig. 1,a). It follows from the hypothesis of equivalent stress that the corrosion process in its vicinity occurs at the same rate as in the vicinity of the same point under the conditions of simple stressed state at $\sigma=\sigma_{eq}$ (Fig. 1,b).

To obtain a durability formula, we consider a plate fragment as a rod of rectangular cross section under uniaxial loading. As a model for accumulation of geometric damages, we take the following kinetic equation:

$$\frac{d\delta}{dt} = v_0\left(1 + k\sigma\right), \qquad (4)$$

where k – coefficient of stress influence on the rate of corrosion.



ab

Fig. 1. Corrosion process under conditions of complex and simple stress state

Substantiation for the possibility of the equation (4) usage in modelling of processes of corrosion deformation is given in the monograph [3].

For a simple stress state, stresses in the element of h(t) thickness in the area D are determined as follows:

$$\sigma_{eq}\left(t\right) = \frac{q_{eq}}{h\left(t\right)}, \qquad (5)$$

where q_{eq} – intensity of the equivalent force in the plane of the element.

Differentiating (5) with respect to time after simple transformations for the damage accumulation model (4) we obtain a differential equation determining relationship between the initial and final equivalent stresses, the initial thickness of the element, the parameters of the corroding medium over time:

$$\frac{d\sigma_{eq}}{dt} = \frac{\sigma_{eq}^2}{\sigma_{eq\,0}} \cdot \frac{v_0}{h_0}\left(1 + k\sigma_{eq}\right). \qquad (6)$$

By means of integration (6), we finally obtain:

$$t = \frac{h_0}{v_0}\sigma_{eq\,0}\left[k \ln\frac{\sigma_{eq\,0}\left(1 + k\sigma_{eq}\right)}{\sigma_{eq}\left(1 + k\sigma_{eq\,0}\right)} + \frac{\sigma_{eq} - \sigma_{eq\,0}}{\sigma_{eq}\sigma_{eq\,0}}\right]. \qquad (7)$$

This solution can also serve as an approximate estimate for durability of statically indeterminate constructions. Its inaccuracy is determined by the degree of change in forces within the boundaries of the finite elements.

In statically indeterminate constructions, the force in a given element depends on time-varying thicknesses of all the elements. This is what determines relationship between equations of the system (1):

$$\frac{d\delta_i}{dt} = v_0 \cdot F\left[\sigma_i\left(h_i\left(\delta_i\right), Q_i\left(\bar{\delta}\right)\right)\right];$$
$$\delta_i\Big|_{t=0} = 0; \quad i = \overline{1, N}. \tag{8}$$

In addition to parameters of corrosive wear, a large number of factors influence the character of the change in time including topology of the construction, its initial geometric parameters, boundary and loading conditions as well as the number of elements in the finite element model.

The idea of the method proposed by the authors is to create a function for the time variation of the force that allows to consider a separate differential equation instead of SDE (8) since this function allows to take into account influence of the remaining equations 2.

If dependence of force on time in the element which determines durability of the structure as a whole is formalized, then instead of a system of equations (8) it is sufficient to obtain a numerical solution of a single equation with any degree of accuracy since it is no longer necessary to solve the FEM problem to calculate the stresses. This considerably reduces computational costs. Discrepancy between a hypothetical exact solution of SDE (8) and a solution of one equation is determined only by the approximating error of the force and time dependence. On the other hand, a function approximating the dependence of the internal force on time can be created only as a result of solving SDE as mentioned above (8).

Accordingly, we offer to carry out the solution of the problem in two stages.

The first stage involves a numerical solution of SDE with a minimum number of nodal points for determining the number of the element which determines the construction durability and creating for it an approximating function of time variation of the force. As a result of the first stage realization, the approximate value of the structure durability $\tilde{t}$ is determined.

The results of numerical experiments lead to the conclusion that the third-degree polynomial quite accurately approximates the law of internal force variation. Therefore, in the time interval $[0;\tilde{t}]$ four node points are sufficient. Thus, at the first stage the FEM problem is solved only four times.

The second stage includes transformation of a differential equation describing the corrosion process in the element with the shortest durability by means of introducing the resulting approximating function Q=Q(t) into its right-hand part and then its numerical solution with the required accuracy. Its solution is a specified value of the structure durability.

Let us consider the algorithm for the numerical solution of Cauchy problem for the following SDE (8).

In most of the known works, one-step numerical methods of the Runge-Kutta type were used to solve SDE, most often the Euler's method. The disadvantages of these methods, in addition to low efficiency, are amply described in [3].

The main disadvantage of the methods used is that the abscissa of the intersection point of the function graph σ=σ(t) with the line σ*=σ*(t) is unknown; its definition is the result of solving the problem of forecasting durability. The arbitrary assignment of the integration step length (the distance between the nodes of the time grid) not only does not allow to control the accuracy of a numerical solution, but also not always provides the condition of its existence for all possible parameters of SDE.

This article offers to use the modified algorithm of the Euler's method with a variable integration step by the argument for the numerical solution of SDE (8) (Fig. 2). We suggest to specify the increment of the function $\Delta\sigma_S$=const and determine the corresponding value of the argument increment Δt_S by the formula (7). The parameter of the computational procedure is the number of equidistant node points of the interval [σ_0; σ*].

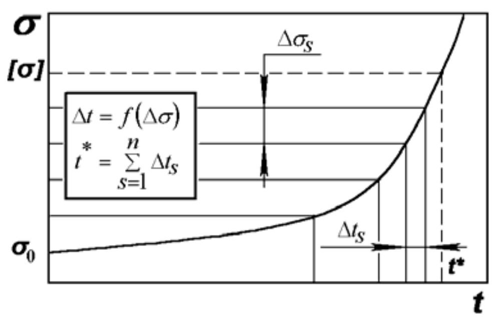
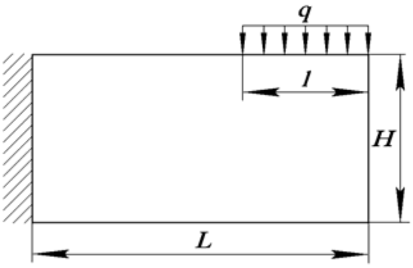


Fig. 2. Graphical illustration of computational algorithm

In this case, the condition for the existence of a numerical solution is satisfied for the entire domain of SDE parameter definition.

For a numerical illustration of the proposed method, consider a rectangular plate loaded in its



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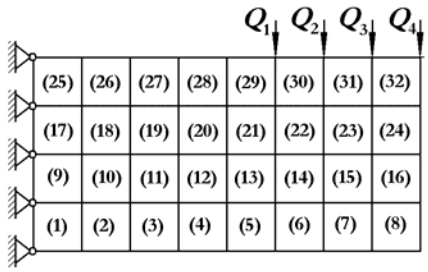

b

Fig. 3. The calculation scheme and the finite element model of the plate

plane by uniformly distributed load, and located in corrosive environment. The calculation scheme (a) and the finite element model (b) of the plate are presented in Fig. 3.

Parameters of the plate and corrosive medium were taken as follows:

– geometrical characteristics: L=40 cm; H=20 cm; h_0=1,5 cm;

– mechanical characteristics: E=2,1×10⁵ MPa; μ=0,3; σ*=[σ]=240 MPa;

– loading parametres: q=40 kN/cm; l=15 cm;

– parametres of corroding environment: v_0=0,1 cm/year; k=0,003 MPa^{-1}.

At the first stage, we determine the approximate value of the plate durability:

$$\tilde{t} = \min\left\{ \tilde{t}_1; \tilde{t}_2; \ldots; \tilde{t}_{32} \right\}, \qquad (9)$$

where $\tilde{t}_1; \tilde{t}_2; \ldots; \tilde{t}_{32}$ represent durability of the elements found using formula (7) with a constant value of internal forces. The value found in this way is determined by the durability of the first element and amount to $\tilde{t} = 3{,}8405$ years.

The obtained result is used to receive a calibration value of durability. The Cauchy problem for SDE (8) is solved by the Euler's method with recalculation. The distance between the nodes of the time grid is assumed to be equal to Δt=0,005, $\tilde{t}$ =0,0195 years. The solution for the three last nodes of the time grid is refined with the parabolic method. The calibration value of the plate durability is t_{et}=3,9731 years. To obtain a calibration solution, the problem of calculating the stressed state of a construction by the finite element method has been solved 204 times.

Some results obtained during the implementation of the first stage of the decomposition method are shown in Table. Here we provide the absolute values of forces and stresses (in parentheses) in structural elements.

At the second stage, the change in forces in the area of the first finite element of the structure is approximated with the third-degree polynomial using the data of the first four table rows.

The differential equation describing the process of corrosive destruction in the first element with the formalized dependence of the internal force on time is as follows:

$$\frac{d\delta}{dt} = v_0 \cdot \left(1 + k \cdot \frac{q_0 + \alpha_1 t + \alpha_2 t^2 + \alpha_3 t^3}{h_0 - 2\delta} \right), \qquad (10)$$

where a_1, a_2, a_3 – polynomial coefficients, h_0 – thickness of the plate while t=0,0.

The numerical solution of the equation (10) is obtained using the Euler's method with recalculation at Δt=0,0195 year. The obtained value of durability is t*=3,9562 years. The error in solving the problem relative to the reference solution is ≈0,5%. At the same time, FEM problem is solved five times, i.e. the computational costs decrease by more than 40 times.

Conclusions

The decomposition method for solving systems

The results of the solution with the Euler's method with variable time step

t, years	q_{eq}, kN/cm (σ_{eq}, MPa)				
	(1)	(2)	(3)	(4)	(5)
0,0	10,825 (72,17)	8,587 (57,25)	5,795 (38,64)	4,027 (26,85)	4,383 (29,22)
2,173	10,693 (110,09)	8,529 (86,09)	5,776 (56,91)	4,042 (39,23)	4,426 (43,08)
3,161	10,520 (148,52)	8,456 (113,96)	5,750 (73,39)	4,059 (50,15)	4,480 (55,72)
3,715	10,315 (188,11)	8,371 (141,04)	5,718 (88,16)	4,077 (59,77)	4,543 (67,32)
4,077	10,302 (238,50)	8,364 (168,68)	5,683 (101,93)	4,098 (68,63)	4,581 (78,58)

of differential equations modelling the process of corrosion deformation for plane-strained plates presented in this article can be generalized to other classes of constructions. According to the authors, the most promising usage of this method is represented in solving problems of optimal structure design with limitation on durability. In this case, the task of determining the durability is solved at each iteration of the search for the optimal project that leads to large computational costs. The application of the decomposition method solves the problem with minimal computational costs and high accuracy.

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Received 20.09.2017

ДЕКОМПОЗИЦИОННЫЙ МЕТОД РЕШЕНИЯ СИСТЕМ ДИФФЕРЕНЦИАЛЬНЫХ УРАВНЕНИЙ В ЗАДАЧАХ МОДЕЛИРОВАНИЯ ПРОЦЕССОВ КОРРОЗИОННОГО ДЕФОРМИРОВАНИЯ

Зеленцов Д.Г., Ляшенко О.А.

В настоящей работе предлагается и обосновывается метод решения систем дифференциальных уравнений (СДУ), моделирующих процесс изменения во времени напряжённо-деформированного состояния конструкций вследствие воздействия агрессивных сред (процесс коррозионного деформирования). Задачей моделирования является определение долговечности конструкции, то есть времени её безотказной работы. Размерность СДУ, которая моделирует процесс коррозионного деформирования, определяется конечно-элементной моделью исследуемого объекта. Правые части дифференциальных уравнений содержат функции механических напряжений. Для вычисления напряжений используется метод конечных элементов. Предлагаемый декомпозиционный метод основан на преобразовании исходных дифференциальных уравнений системы путём введения в них функций, описывающих влияние остальных уравнений, и последующем решении одного из этих уравнений. На основании анализа факторов, влияющих на изменение напряжения в области данного конечного элемента, предложено ввести в соответствующее дифференциальное уравнение функцию, аппроксимирующую изменение внутренних усилий во времени. В этом случае расхождение результатов решения исходной СДУ и отдельного уравнения будут определяться лишь погрешностью аппроксимации зависимости внутреннего усилия от времени. В работе показано, что это позволит многократно снизить вычислительные затраты. Кроме того, в настоящей статье для численного решения СДУ предлагается использовать модифицированный алгоритм метода Эйлера с переменным шагом интегрирования по аргументу. Результатом решения является определение долговечности корродирующих конструкций, то есть времени работы до момента исчерпания несущей способности. Для иллюстрации предлагаемого метода решена задача расчёта долговечности плосконапряжённой пластины, подверженной коррозионному износу. Приводятся результаты численных экспериментов, подтверждающие точность предлагаемого численного решения при минимальных вычислительных затратах. Предложенный в статье декомпозиционный метод решения СДУ, моделирующих процесс коррозионного деформирования плосконапряжённых пластин, может быть обобщён на другие классы конструкций.

Ключевые слова: декомпозиционный метод, агрессивная среда, процесс коррозионного деформирования, система дифференциальных уравнений, плосконапряжённые корродирующие пластины.

ДЕКОМПОЗИЦІЙНИЙ МЕТОД РОЗВ'ЯЗАННЯ СИСТЕМ ДИФЕРЕНЦІАЛЬНИХ РІВНЯНЬ В ЗАДАЧАХ МОДЕЛЮВАННЯ ПРОЦЕСІВ КОРОЗІЙНОГО ДЕФОРМУВАННЯ

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The article offers and justifies a method for solving systems of differential equations (SDE) that simulate time changes of stress and strain state due to the influence of corrosive environment (the process of corrosion deformation). The task of modelling is the determination of the construction durability that is the time of its flawless operation. The finite element model of the object under study determines dimension of SDE modelling the process of corrosion deformation. The right-hand sides of the differential equations contain functions of mechanical stresses. The finite element method is used for calculating stresses. The proposed decomposition method is based on the transformation of the initial differential equations by introducing in them functions describing the influence of the remaining equations and the subsequent solution of one of these equations. Based on the analysis of the factors influencing the stress change in the area of the given finite element, we propose to introduce into the corresponding differential equation a function approximating the change of internal forces over time. In this case, the discrepancy between the results of the initial SDE solution and an individual equation is determined only by the error in approximating the dependence of the internal force on time. The article shows that this allows a multi-rate reduction of computational costs. In addition, for a numerical solution of SDE, we propose to use a modified algorithm of the Euler method with a variable integration step by argument. The result of the solution is determination of corrosive construction durability, i.e. operating time before exhaustion of bearing capacity. To illustrate the proposed method, we solved the problem of calculating the durability of a flat-plate subjected to corrosive wear. The article provides the results of numerical experiments confirming the accuracy of the proposed numerical solution with minimal computational costs. The decomposition method for solving SDE modelling the process of corrosion deformation of plane-stressed plates can be generalized to other classes of constructions.

Keywords: decomposition method, corrosive environment, process of corrosion deformation, system of differential equations, plane-stress corroding plates.

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