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THE USE OF ELEMENTS OF COMPUTATIONAL INTELLIGENCE IN PROBLEMS OF FORECASTING OF CORRODING CONSTRUCTIONS DURABILITY

The modeling is considered of behavior of metal structures with changing geometric characteristics, which functioning in aggressive external environments. Information about the parameters of the external environment is incomplete or inaccurate. To formalize this information proposed to use the mathematical apparatus of the theory of fuzzy sets and interval analysis. The opportunities of the application of the ways have been examined.

Key words: *fuzzy sets theory, interval analysis, modeling, forecasting of construction durability, computational intelligence.*

Introduction. In the different branches of industry and building one the mechanical systems with changing characteristics are widely used, the actuality of the problem of modeling their behavior being caused by it. The example of such systems can be constructions functioning in the external aggressive mediums and corroding. One the peculiarities of this article is that the parameters of aggressive medium (AM) are examined like quantities the information of which are incomplete or inaccurate. If the parameter of aggressive medium is examined as the corrosion rate when being absence of voltage it will be obviously that its significance cannot be determined uniquely.

In the real conditions this parameter depends on the whole range of factors: medium temperature, its moisture, grade of saturation of different elements and others. On the one hand quantitative characteristics of all these factors are determined with difficulty, on the other hand — can change in the wide range during the whole term of exploitation. When setting the task the medium is known in the best case to have that or another grade of aggression which can be described with help of linguistic variable [1, 4].

Statement of the problem. Traditionally for solving the task of forecasting of durability of corroding constructions the determinate method has been used (corrosion rate was supposed given dotty quantity) and following statement (further the task in the precise setting) has been used:

$$\begin{gathered} t^* = \min\left\{t_1, t_2, \ldots, t_N\right\}, \\ t_i : \left[\sigma\right] - \sigma_i\left(t, \overline{c}\right) \ge 0,\ i = \overline{1, N}, \\ \sigma_j^* - \sigma_j\left(t, \overline{c}\right) \ge 0,\ j \in J. \end{gathered} \tag{1}$$

Here $t*$ — the design value of the durability of the construction; N — quantity of the elements in the system; J — quantity of the elements working on compression; $[\sigma]$ — assumed voltage; $\sigma_i(t,\bar{c})$ — current voltage in *i*-element; $\sigma_j^*(t,\bar{c})$ — critical voltage of stability loss; $\bar{c}$ — vector of the parameters of the aggressive environment, in this capacity, the paper considers v_0 — corrosion rate of unloaded material.

When modeling corrosive process in the work the influence of the mechanical voltage on the corrosion rate is taken into account, that results in the appearance of the feedback in the scheme of solving the task of forecasting of durability [2].

Solving the task of forecasting of durability in particular allows to determine the predictable significance of durability of every element taking into account changes of voltages in them and, therefore, in the whole system.

As it has been mentioned above, information about parameters AM is incomplete and corrosion rate can be set by some interval $\tilde{v}_0 \in [v_0^-; v_0^+]$, levels of which are determined by the significance of the linguistic variable — «grade of medium aggression». This interval is treated as a large number of possible significances which the parameter corrosion rate can take in the process of modeling behavior of corroding construction (fig. 1).

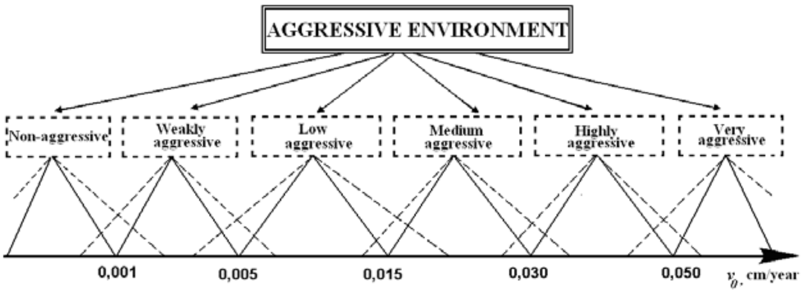

Fig. 1. *The scale of conditional partitioning into intervals of values linguistic variable «degree of aggressiveness of the environment»*

Then fuzzy setting task of forecasting of durability can be written:

$$t^* = \min\{t_1, t_2, \ldots, t_N\},$$
$$t_i : [\sigma] - \sigma_i(t, \tilde{v}_0) \geq 0,\ i = \overline{1,N},. \quad (2)$$
$$\sigma_j^* - \sigma_j(t, \tilde{v}_0) \geq 0,\ j \in J.$$

The procedure of calculation of forecasting durability of the element liable to corrosion or determination of its the calculation of strained condition (SC) in some moment of time supposes the joint using of some numeral method of calculation SC (in this work — method of final elements (MFE)) and numeral method of solving the Cauchy task for system of differential equations (SDE) describing corrosion process. As a model of accumulation of geometrical damages V. M. Dolynskiy model is examined [2]:

$$\frac{d\delta_i}{dt} = \tilde{v}_0 \left[1 + k\,\sigma_i \left(\overline{\delta} \right) \right], \tag{3}$$

where δ_i — depth of corrosion damage of *i*-element of the construction; k — coefficient taking into account the influence of strained condition on the corrosion rate.

Solving this SDE is possible only numerically, for example, by Euler method [2, 3] at that solving the task SC is done in every unit of the temporary net:

$$\delta_i^s = \delta_i^{s-1} + h_t^s \cdot \tilde{v}_0 \cdot \left(1 + k \cdot \sigma_i^{s-1} \left(\overline{\delta}^{s-1} \right) \right). \tag{4}$$

Here s — number of iteration; h_t — step of integration.

Methods of formalization of incomplete information. It is obviously that probabilistic stochastic method can be alternative to the determinative method of solving tasks of forecasting durability at inaccurate data. However, at that it is necessary to carry out rather non-trivial conditions (for example, statistical stability, knowledge of distribution of laws of random quantity or their parameters, information of which, as a rule, is absent). That's why the using of this method is connected with some difficulties.

Two directions can be noted for formalization of incomplete information which have appeared practically simultaneously, these are the mathematical device of the fuzzy sets theory (FST) and the device of classical interval analysis (IA). They can be used depending on solvable tasks and problems. Let's examine the possibility of their using when solving this kind of tasks.

The interval analysis and its methods have a value in the tasks where ambiguities appear from the very beginning and are the essential pats of setting tasks [6, 7]. Let's note that using the intervals doesn't require knowledge of the laws or parameters of distribution of random quantity. The interval quantity can have and can't have the distribution on interval. Moreover all points of the interval are «equitable» (but it doesn't mean that they are distributed on the interval equally, if, of course, there is no statistical information).

When solving the tasks of forecasting of durability in the statement (2) the device of interval analysis has been used. Since the parameter AM is examined as interval quantity so it is reasonable to use interval methods for solving SDE. For this purpose a wide range of double and interval methods can be used [7]. In this case double solving of the task of forecasting of durability of corrosive constructions can be received.

However, it ought to take into account a range of peculiarities of these methods, for example, so called effect of Moor overspeeding or effect of unpacking which is connected only with inside properties of interval methods regardless of mistakes of numeral solvents [7].

In the most cases guaranteed marks of the error of the result are necessary. Then a posteriori marks of the numeral solvent, for example, based on the majorizing function by Lozinckiy.

It should be noted not going into detailed describing these methods that in this article for the construction of double solvent of Cauchy task for SDE type (3) with the parameter given by interval the task was being solved approximately with using the method by Runge-Kutta of the first order. As a result the interval solvent of Cauchy task has been received $[t^*_{\min}; t^*_{\max}] = [t^*(v_0^+); t^*(v_0^-)]$, the width of which, when it is necessary, can be accurated.

Obviously, the using interval analysis allows to formalize incomplete information about AM parameters and receive the interval of numeral solvent of the task of the forecasting of durability. However, there are some specific peculiarities of using of the interval numeral methods, which are a feature of the class of differential equations systems describing corrosion wear (3). For determination in the quality of corrosive element let's examine a rod of a circular section at the monoaxial loading. These problem aspects are described in sufficient detail in [3].

If there is a possibility of the construction of the belongings function of the corrosion $\mu(v)$ rate it is reasonable to use the device FST. For formalizing fuzzy data α -level principle of summarizing is used [4]. In the article the construction of the belongings function is made with using direct expert marks [4, 5].

Using levels of the sets allows to receive not only the interval of changing the significance of the durability but also its significance defuzzy [5] simultaneously with corresponding significance of the belongings function $\mu(t)$.

Using interval numeral methods or the device of the fuzzy sets theory at SDE solvent, describing the process of the accumulation of the geometrical damages, allows to take into account fuzzy character of the medium parameter, however, it is mated with large calculating inputs. Especially this problem becomes actual in the case when the task of forecasting of the durability is a part of more general task — the determination of optimal parameters of corrosive constructions, when limit functions suppose the determination of the durability of the construction and the solvent of the task of nonlinear mathematical programming at every step.

Procedures for representing the corrosion rate as a fuzzy value in the form of a tuple of its values, as well as converting a fuzzy set of longevity values into a clear number are well known [1, 4]. Naturally, their implementation does not represent any computational complexity and does not have a significant effect on the speed of the algorithm. Significantly greater complexity from this point of view is the task of determining the values of the tuple of longevity, corresponding to the values of the tuple of corrosion rates.

From the analysis of the formulas of the analytical formulas [2] follows that there is a relationship between the rate of corrosion v_0^i and the value t^i. Therefore, for any value v_0^i, the value t^i can be determined by the formula:

$$t^j = t^i \cdot \frac{v_0^i}{v_0^j}. \tag{5}$$

Then it is possible to use this relationship to calculate all values of the tuple of longevity using only one known solution t^i. There will be no significant increase in computing costs in this case.

Unfortunately, this approach turns out to be applicable only for statically determinate systems.

In fact, two factors influence the change in stresses in the elements of a statically indeterminate truss: the change in the cross-sectional area of the rod and the change in internal forces due to a change in the stiffness of all elements, which in turn depends on the rate of corrosion. This fact is confirmed by the following graphic illustration, shown in fig. 2.

Obviously, the described situation can lead to a deliberately wrong decision, that is, not only the form of the durability property function, but also the boundaries of the fuzzy set itself, in this case $[t_i^-; t_j^+]$ changes significantly. Thus, the hypothesis that, knowing the tuple of the corrosion rate, one can use formula (5) and obtain the corresponding tuple of longevity, is refuted by numerical experiments.

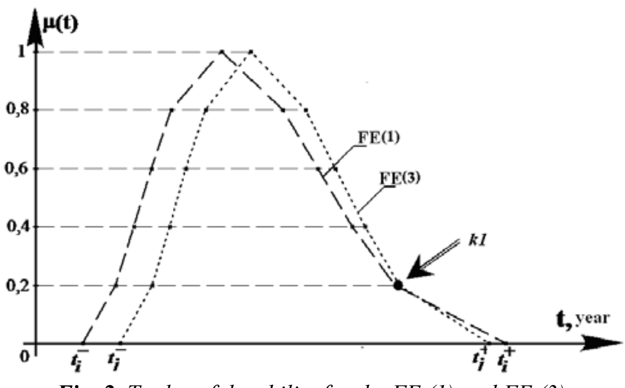

Fig. 2. *Tuples of durability for the FE (1) and FE (3)*

The results are given for two finite elements (FE): FE (1) and FE (3). In this case, proposed to use the representation of the durability of the construction as a fuzzy set in the following form:

$$\tilde{t} = \sum_{k=1}^{k1} \frac{\mu\left(t_i^k\right)}{t_i^k} \& \sum_{k=k1+1}^{2\cdot N_\alpha - 1} \frac{\mu\left(t_j^k\right)}{t_j^k}, \tag{6}$$

where $t_i^k, t_j^k \in [t_i^-; t_j^+], k1 \in \left[1; 2\cdot N_\alpha - 2\right]$, *k1* — is the number of the element of the tuple in which the functions that determine its limiting state change.

In order to avoid such situations in the calculation of the constraint functions that determine the limiting state of the construction, it is necessary to calculate all the elements of the tuple of longevity.

Thus, the determination of the durability of corrosive structures involves calculating the longevity for all points in the tuple of corrosion rate. Consequently, the use of α-levels leads to a multiple increase in computational costs, and the problem of improving the efficiency of the computational algorithm acquires an independent value.

In order to improve the efficiency of computational methods using FST, it is proposed to use several neural networks that allow us to determine the rational parameters of numerical procedures for a system of differential equations of the form (3).

Numeral results. For numeral illustration the solvent of the task of forecasting of the durability of the rod stretched by the force Q is examined. Initial data: $Q = 12\ kN$; limiting voltage $\left[\sigma\right] = 240\ MPa$; starting external $R = 2{,}5$ cm and inner $r = 1{,}25\ cm$; integration step $h_t \in \left[0{,}5; 3\right]$; coefficient of influence of voltages $k = 0{,}003\ MPa^{-1}$; given limiting significance of error of the numeral solvent $\left[\varepsilon\right] = 5 - 6\ \%$.

When solving the task of the forecasting of durability to avoid mentioned above supernumerary situations [3]. Euler method has been used. The quantity of α-levels was taken equal to six.

Dephased significance of the durability t_{def} when using the fuzzy sets theory has been obtained by the centroid method [4, 5]; t_{av} average significance of the interval of the durability $\left[t^*_{\min}; t^*_{\max}\right]$.

For bigger obviousness the author deliberately gives a quantity t_{av} to demonstrate an impossibility of using an average mark of the significance of the durability (table 1).

Table 1

The results of solving the problem of forecasting in various productions

v_0, **cm/year**	t^*, **years**	$t_{av}=\frac{t_{\min}+t_{\max}}{2}$ **years**	t_{av_tuple}, **years**	t_{def}, **years**
Different statements				
0,1	5,16	–	–	–
Precise statement (IA)				
[0,90; 0,11]	[4,62; 5,68]	5,15	–	–
[0,06; 0,14]	[3,63; 8,56]	6,09	–	–
Fuzzy statement (FST)				
[0,09; 0,11]	[4,69; 5,74]	5,22	5,19	5,08
[0,06; 0,14]	[3,69; 8,61]	6,15	5,52	5,97

Where the mean for all elements of the tuple: $t_{av\_tuple}=\frac{\sum_{i=1}^{2\cdot N_\alpha-1} t^i}{2\cdot N_\alpha-1}$.

Note that in order to obtain a tuple of durability (Fuzzy statement), the problem was solved for all points of the velocity tuple [4, 5] and point values (defuzzy) values were obtained: $v_{0def}=0{,}1$ cm/ year ; $h_t=1{,}42323$ year; $t_{def}=5{,}97425$ year $\left(\mu\left(t_{def}\right)=0{,}9455\right)$; $\varepsilon_{def}=0{,}05638$.

On the base of the analysis of the numeral experiments it should be noted that given methods allow to obtain and estimate the result at the precise or fuzzy data. At its bottom the method of the interval analysis is formalized and algorithmed well enough. Using set levels allows to obtain the defuzzy significance of the durability with its function of belonging $\mu(t)$, which allows to establish the grade of belongings t_{def} to the fuzzy set $\tilde{t}$.

Conclusions. The methods of formalization of inaccurate or incomplete information about parameters of external aggressive medium with the help of the mathematical analysis of the fuzzy sets theory and interval analysis are suggested. The possibilities of their using and some problem aspects when solving tasks of the forecasting of the durability of corrosive constructions are examined. When using the mathematical apparatus of the theory of fuzzy sets with the aim of increasing the efficiency of computational methods, it is suggested to use artificial neural networks. The use of neural networks allows us to obtain rational parameters of numerical procedures.

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Розглянуто моделювання поведінки металевих конструкцій зі змінними геометричними характеристиками, які функціонують в агресивному зовнішньому середовищі. Інформація про параметри зовнішнього середовища є неповною або неточною. Для формалізації цієї інформації запропоновано використовувати математичний апарат теорії нечітких множин та інтервального аналізу.

Ключові слова: *теорія нечітких множин, інтервальний аналіз, моделювання, прогнозування довговічності конструкцій, обчислювальний інтелект.*

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