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RELIABILITY ASSESSMENT DUE TO WEAR

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Evaluation of structural reliability under processes of deterioration presents very important problem in design. The structure's wear shows a reduction of bearing capacity in time that for one's turn leads to increasing the probability of failure. The reasons for long duration and irreversible change of structural features can be corrosion in steel structures, decomposition in wood structures, ageing in polymer structures, and processes of abrasion or erosion also. The problem of defects accumulation should be mentioned too, when reduction of the bearing capacity connects with load's value and its duration.

The models and peculiarities of corrosion wear and its influence on bearing capacity are discussed in this paper.

1. MODELS OF CORROSION WEAR

Corrosion is an important factor in reducing of reliability and durability due to different kinds of structures or equipments. From 10% to 12% of fabricated and used steel is lost annually due to destructive effects of corrosion. In spite of widely used protection methods, the quantity of steel destroyed is growing almost proportionally to the accumulated stores of steel. Losses from corrosion average are between 2% to 4% of GDP in almost every country. About 30% of structural steel is subjected to atmospheric corrosion, and 75% is subjected to atmospheric and aggressive corrosion simultaneously [1]. Under corrosion's influence the initial cross-section of a structural element is decreased, and consequently so its bearing capacity. Fig.1 presents the types of corrosion for structural steel.

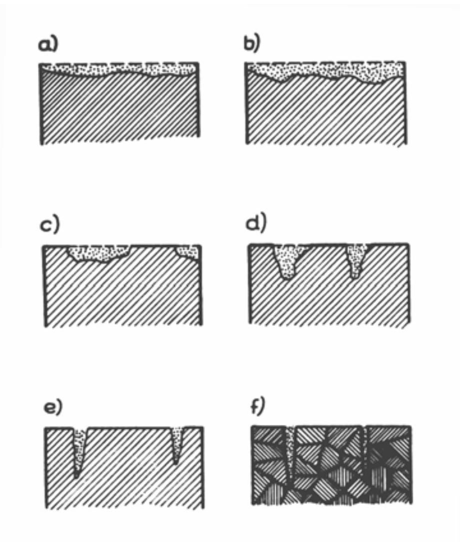

Fig.1 Types of corrosion of a structural steel.
a) Uniformly distributed wear. b) Irregular distributed wear.
c) Corrosion with spots. d) Corrosion with ulcers.
e) Corrosion with points. f) Corrosion with cracks.

The speed of a corrosion process depends upon degree of aggressive environment and is changing with 0.05mm/year to 1.6mm/year. The damage of structural steel in soil depends on the duration of an exposure, as shown in Fig.2. Data are based on 16 types of soil. Similarly, the damage of the steel from atmospheric corrosion is shown in Fig.3. Distribution of corrosion speed (measured at the inner reservoir surface along its height) for different products is presented in Fig.4.

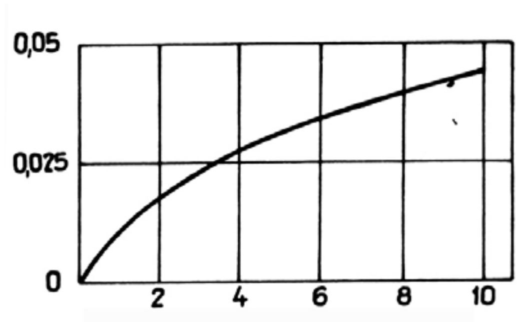

Fig.2 Corrosion of structural steel in soil over years.
Y*-axis shows the mean depth of corrosion in mm.;* X-axis shows the years of duration.

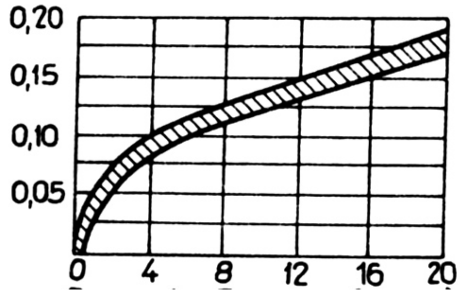

Fig. 3 Corrosion of structural steel in open air.
Y-axis shows the average depth of corrosion (mm).
X-axis shows the years of duration.

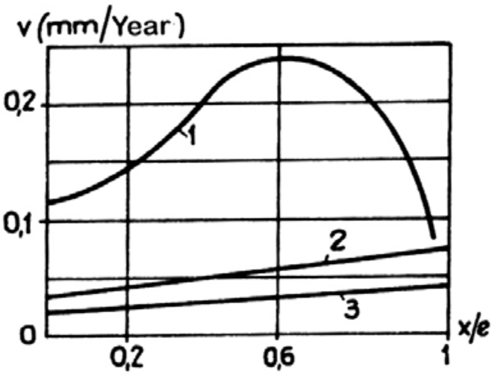

Fig. 4 Variation of corrosion's speed
1. Gasoline. 2. Kerosene. 3. Diesel.

The evaluation of structural durability depends essentially on the choice of the model that is capable to reflect the influence of an aggressive environment. When modeling corrosion processes, there are important damage characteristics to consider, such as depth of defect (δ) and corrosion speed (v=dδ/dt). Classification of mathematical models of corrosion (based on empirical approach) presents in Table 1 [1,2,3]. The kinetics of the corrosion process in different metals for different aggressive environments looks very similar, and this fact presents the opportunity to use these models in design.

In general, processes of wear can be presented as time-dependent random functions of time. Type of processes depends on maintenance conditions, methods of structure's fabrications, steel's composition and others.

Table 1

#	Models of corrosion	Functional relationship
1	$\delta = v_0 t$	Linear
2	$v_t = kt^{-n}$	Power
3	$\delta = a + b\lg t$	Logarithmic
4	$\delta = \ln(kt)$	Logarithmic
5	$v_t = v_0 \exp(-\alpha t)$	Exponential
6	$v_t = mt^2 \exp(-t/\tau)$	Exponential
7	$\delta = \delta_0[1-\exp(-t/\tau)]$	Exponential
8	$\delta = \frac{a}{1+b\exp(-ct)}$	Exponential
9	$v_t = \frac{t}{at^2+bt+c}$	Fractionally linear
10	$\delta = \frac{\delta_0 t}{1+at}$	Fractionally linear

Models of long-term processes presents as random time processes, but its uncertainty defines, due to random, independent from time parameters. Such kind of random processes were called "deterministic random processes "[4].

In the case that all loads F_i presents independent random values, probability of no failure during working life can be expressed as:

$$P(n)=P\,[R_1 > F_1, R_2 > F_2, ..., R_n > F_n], \qquad (1)$$

where $R_1, R_2, ..., R_n$- values of bearing capacity in considered time intervals. If designate $R_n = R_0\varphi(n),$ then n=t –term of maintenance in years; R_0-initial (random) value of bearing capacity; $\varphi(n)$- monotonically decreasing nonnegative function (i=1,2,3,n.), satisfying to the conditions: $\varphi(0)=1$; $\varphi(\infty)=0; d\varphi/dt<0.$ It should be mentioned also the additive property of φ (t) function, independence of wear's process in the subsequent time interval t_i from previous process's value in time t_{i-1}, i.e. $\varphi(t_1)\varphi(t_2)=\varphi(t_1+t_2)$.

$F_1, F_2, ..., F_n$ - Loads, corresponding to considered time intervals.

2. UNIFORMLY DISTRIBUTED CORROSION WEAR

This problem is illustrating in considering a steel pipeline's section (cylindrical tube), subjected to inner pressure, changes of the temperature and corrosion. The inner pressure F and steel yield stress R_y are random values with given distributions. The corrosion process considers deterministic. The limit state condition is taken in the form: $S_i \le Ry$. Here S_i - intensiveness of stresses in considered cylindrical shell. In accordance with Guber-Mises condition [5], general case looks as:

$$S_i = \frac{1}{\sqrt{2}}\sqrt{(S_1 - S_2)^2 + (S_2 - S_3)^2 + (S_1 - S_3)^2} \tag{2}$$

In discussed situation S_2=0, and the radial and the tangential stresses reads: $S_1 = \frac{FD_i}{2h}, S_3 = \frac{FD_i}{4h} - \alpha E \Delta\theta.$

Here F is the inner pressure, and its maximum value is random for some time intervals; D_i- inner diameter of the pipe; α-parameter of linear extension; E-modulus of elasticity; $\Delta\theta$- temperature drop (difference between temperature of the pipeline during use and assembly).

The reliability condition expresses as follows:

$$\frac{3F^2 D_i^2}{16h^2} + \alpha^2 E^2 \Delta\theta^2 \le R_y^2 \tag{3}$$

As temperature's drop presents an uncertain value with unknown distribution, then temperature's stresses are given as some part of the yield stress.

$$\alpha E \Delta\theta = R_y \sin\chi \tag{4}$$

χ is a value of angle in the given interval [0,π/2]. The condition (3) presents now in the form:

$$F \le \frac{4h}{\sqrt{3}D_i} R_y \cos\chi \tag{5}$$

Corrosion wear causes a reduction of tube thickness as $h = h_0\varphi(t),$ where h_0 is the initial thickness. In accordance with the Table 1 one can takes:

$$\varphi(t) = \exp(-t/\tau) \tag{6}$$

From (6) comes:

$$h = h_0 - \delta[1 - \exp(-t/\tau)] \tag{7}$$

where δ is the depth of corrosion bubble. It is assumed that the corrosion process in interval t_2 is independent of the preceding values in interval t_1, so that $\varphi(0, t + t_1) = \varphi(o, t) + \varphi(t, t + t_1)$. It is assumed also that time t takes only discrete values: t=n, where n is number of years or months. An assumption is made for pressure F supposing that statistic data belong to some period of time, a month, for example. From all observations, maximum values selects only. If the time interval is large in comparison with correlation zone, then Fisher-Tippet distribution (second type) of maximum values can be used [6].

$$\text{P (x)} = \exp\ [-(x/\xi)^{-\eta}] \tag{8}$$

If $v_F = s_F / \overline{F}, \overline{F}$ are correspondingly the coefficient of variation and the mean value, then parameters ξ and η are determinated from the solution of two equations, which includes gamma functions.

$$\begin{aligned} 1 + v_F{}^2 &= \Gamma(a)\Gamma(b) \\ \xi &= \overline{F}/\Gamma(a) \end{aligned} \tag{9}$$

Gamma functions are:

$$\Gamma(a) = \int_0^{\infty} e^{-z} z^{a-1} dz,$$
$$\Gamma(b) = \int_0^{\infty} e^{-z} z^{b-1} dz. \qquad (10)$$

The case when b=0 and η=2 is excluded.
For yield stress Weibull distribution is applied.

$$\text{P (x) = 1- } \exp[-(x/\omega)^{\mu}] \qquad (11)$$

Form's parameter μ is expressed through coefficient of variation $v_R = s_R / \overline{R}$:

$$v_R = \frac{\sqrt{\Gamma(1+2\mu) - [\Gamma(1+1/\mu)]^2}}{\Gamma(1+1/\mu)} \qquad (12)$$

Values v_R and μ define scale parameter ω.
Taking into account (8) and (11) the reliability function is written in the form:

$$\text{P (n) = -} \int_0^{\infty} \exp[-(\frac{4h_0 x \cos\chi}{\sqrt{3}D_i\xi})^{-\eta}] \sum_{i=0}^{n-1} \varphi^{-\eta}(t) d[\exp\{-(x/\omega)^{\mu}\}] \qquad (13)$$

Example. After statistic data processing of pressure in pipelines and yield stress the following values of the distribution parameters were defined: ξ = 73.5; η = 65; ω = 42.5; μ = 23.5.Coefficients of variations are: $v_F = 0.0201; v_R = 0.0522$. Temperature stresses (9.4) show essential influence on pipeline's reliability. When χ = π / 3, P (n) is close to zero. P (n) values for different n are presented in the Table (2).

Table 2

τ	χ	Values of function P (n)						
		Time in years						
		1	5	10	15	20	25	30
100	0	0.9989	0.9989	0.9989	0.9989	0.9987	0.9962	0.9860
100	6	0.9989	0.0087	0.9968	0.9880	0.9590	0.8600	0.6000
100	4	0.9560	0.8500	0.5800	0.1800	-	-	-
120	0	0.9989	0.9989	0.9989	0.9989	0.9989	0.9975	0.9872
120	6	0.9989	0.9941.	0.9941	0.9750	0.9600	0.8990	0.8060
120	4	0.9560	0.8790	0.6870	0.3790	-	-	-
150	0	0.9989	0.9989	0.9989	0.9989	0.9988	0.9985	0.9900
150	6	0.9989	0.9988	0.9980	0.9900	0.9760	0.9570	0.3200
150	4	0.9989	0.8820	0.7500	0.5200	0.3800	-	-

From (13) the member responsible for corrosion process's influence is picked out:

$$\lambda = \left[\sum_{i=0}^{n-1} \varphi^{-\eta}(i)/n\right]^{\frac{\mu}{\eta+\mu}} \qquad (14)$$

where λ characterizes decreasing of reliability in regard of corrosion's development.

Parameter τ in (6) and in Table 2 defines intensiveness of uniform corrosion. Physical sense of this value consists in decreasing of initial tube's thickness. This essential decreasing is possible under large values of τ = 100…150.

Results of many experiments and real observations demonstrated [1,.3] the influence of stresses in structures to the speed of corrosion. Especially large is this influence in places of concentrations of stresses. Dependence between corrosion's speed and increasing level of stresses can be as linear as nonlinear. If to take dependence between the intensiveness of stresses and the depth of the corrosion's penetration such as $\delta = \alpha t^{\beta} \exp(kS_i)$, and substituting it in the formula for the circular stresses in cylindrical shell $S_1 = \frac{FD_i}{2h}$, then the condition of the failure reads:

$$\frac{FD_i}{2\left[h_o - \alpha t^{\beta} \exp(kS_i)\right]} > R_y \tag{15}$$

After decomposition into the row $\exp(kS_i) \cong 1 + kS_i$, expression (15) performs to:

$$F< 2\left[h_o - \alpha t^{\beta}\left(1 + \sqrt{3}kRy/2\right)\right]/D_i \tag{16}$$

Here the expression in brackets takes into account influence of stress state at speed of corrosion. If to take the same distribution for inner pressure (8) and for yield stress (11), and to consider process of corrosion as a function of discrete argument then the expression for reliability function can be written in the form:

$$P(n) = -\int_0^{\infty} \prod_{i=1}^{n} \exp\left\langle -\frac{2\left[x\left(h_o - \alpha i^{\beta}\left(1 + \sqrt{3}xk/2\right)\right)\right]}{D_i \xi}\right\rangle^{-\eta} d\exp\left[-\left(\frac{x}{\omega}\right)\right]^{\mu} \tag{17}$$

Expression (17) allows to evaluate the reliability of pipelines, subjected to continuous corrosion and to take into account influence of stress state to the corrosion's depth penetration or corrosion's speed.

3. IRREGULAR DISTRIBUTED CORROSION WEAR

A problem of structural durability and the protection from a local corrosion turns out to be very important as well. Local corrosion leads to some local destruction seen on the surface of the structure in the form of spots, ulcers, points or cracks (Fig.1). Appearance of this destruction in time is random too.

Corrosion cavities' ensemble is based on the following assumptions:

- Events, which have to do with the appearance of various numbers of cavities at disjoint time intervals are independent.
- Probability of corrosion's cavity appearance in the arbitrary time interval t is proportional to the length of this interval with the factor of proportionality equal to μ.
- Probability of the two or more events appearance through an extremely small time interval presents an infinitely small value of more high order.

The simultaneous realization of all these assumptions should be present and have an existence of the primary flow of events – a uniform Poisson process. Such process can be described by the system of differential equations:

$$\frac{dP_0}{dt} = \mu P_0$$

$$\ldots\ldots\ldots\ldots \tag{18}$$

$$\frac{dP_n}{dt} = \mu(P_{n-1} - P_n)$$

Initial conditions for this system of equations are:

P_n (t) = 1, when n=0

P_n (t) = 0, when n=1,2, (19)

There will be only one solution for the system (9.18) and together with the conditions (9.19) it can be presented as the Poisson distribution:

$$P_n(t) = \frac{[\mu(t-t_0)^n}{n!\exp[-\mu(t-t_0)]} \quad (20)$$

From (20) probability of the fact follows that in the moment $t \geq t_0$ the system is in the state n (n = 1,2,3,). If the number of cavities appearing in some time interval submits to Poisson distribution, then the amount time before appearance of the next cavity possesses exponential distribution [7].

$$P(t) = \exp(-\mu t). \quad (21)$$

The number of experimental data that connects with investigations of kinetic due to cavity growth or an increase of cavities number is very small. Experimental dependences were received in [8]:

$$\mu = \mu_{gr}(1-e^{-\beta t}) \quad (22)$$

Here μ_{gr}, β are empiric coefficients. Value μ_{gr} varies in wide limits and measures as number of defects to unit of structural surface.

Important parameters for considered type of irregular corrosion are - maximum depth of a cavity, its diameter and square of a cavity.

The random value of a cavities depth δ_k (k-random point on structural surface) is distributing in the final interval $[0,h_0]$, where h_0 is the thickness of structural element. It is considered that this value had uniform distribution, i.e.

$$P_\delta(x) = \begin{cases} 0 & x < 0 \\ x / h_0 & 0 \leq x \leq h_0 \\ 1 & x > h_0 \end{cases} \quad (23)$$

Distribution of the maximum depth for n cavities, i.e. $\delta_n = \max \{x_1, x_2, x_3,\dots,x_n\}$ is well known from theory of extreme values [9] and can be taken as exponential.

$$\begin{aligned} P_{\delta n} &= \exp\ [-\ n\ (h_0-x)] & 0 \leq x \leq h_0 \\ P_{\delta n} &= 1 & x > h_0 \end{aligned} \quad (24)$$

The next important parameter is the diameter of considered cavity, due to an assumption that this cavity has cylindrical form (Fig.5). Let the depth of the cavity is equal to x. Then the possible region for variation of diameter is the chord AB with the length $2\sqrt{2rx - x^2}$, and r is the external radius. An assumption is taken that the random value of diameter y_i has uniform distribution in the interval $[0,\ 2\sqrt{2rx - x^2}\ ]$.

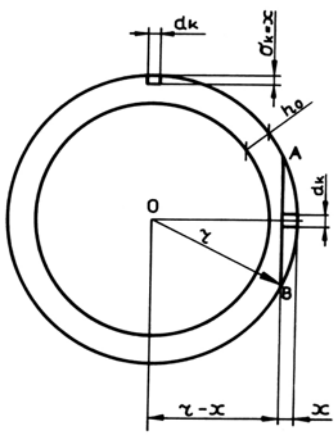

Fig.5. Element of ring's cross-section

P_d (y) =0 if y<0

$$P_d(y) = \frac{y}{2\sqrt{2rx - x^2}} \qquad \text{if } 0 < y < 2\sqrt{2rx - x^2} \tag{25}$$

$$P_d(y) = 1 \qquad \text{if } y > 2\sqrt{2rx - x^2}$$

Distribution of the maximum diameter for n cavities $d_n = \max(y_1, y_2, y_3, \ldots y_n)$ is:

$$P_{dn} = \exp[-n(2\sqrt{2rx - x^2}, \qquad 0 \le y \le 2\sqrt{2rx - x^2}$$

$$P_{dn} = 1, \qquad y > 2\sqrt{2rx - x^2} \tag{26}$$

Third parameter of this cavity is its square A_k. The knowledge of the maximum square value is important in solution of the considered problem. There are some difficulties, however, unclear even in the theory of order statistics. The point is that the maximum δ_n value doesn't always correspond to the maximum value of d_n. If to agree with this position then the solution will be received in safety margin. Two kinds of versions can be offered, distribution of maximum depth's value δ_n and distribution of diameter's value d_k for k-cavity in the first case, and otherwise: distribution of maximum diameter's value d_n, and distribution of depth's value δ_k in the second case.

Types of $P_A(x)$ distributions are written for three cases:

Case 1:

$$P_{\delta n}(x) = \exp[-n(h_0 - x)], x \in [0, h_0],$$

$$P_{dn}(y) = \frac{y}{2\sqrt{2rx - x^2}}, 0 \le y \le 2\sqrt{2rx - x^2}. \tag{27}$$

The square of the cavity A_k is equal to the square of the segment at Fig.5:

$$A_k = r^2 \arcsin\frac{y}{2r} - \frac{y}{2}\sqrt{r^2 - \frac{y^2}{4}} + [x - r + \sqrt{r^2 - \frac{y^2}{4}}]y \tag{28}$$

The maximum possible value of the cavity square A_k will be when $x = h_0$ and $y = 2\sqrt{2rh_0 - h_0^2}$.

In pipes of large diameter x / r, y / 2r values are highly small numbers and possible reasonable approximation will be $A_k = xy$, and it follows:

$$P_{Ak}(A) = \frac{An}{2\sqrt{2r}} \int_0^{h_0} \exp[-n(h_0 - x)] x^{-\frac{3}{2}} dx \tag{29}$$

A_k is here uniformly distributed at interval [0,A*] random value.

Case2:

$$P_{\delta n}(x) = \frac{x}{h_0}, x \in [0, h_0]$$

$$P_{dn}(y) = \exp\left[-n\left(2\sqrt{2rx - x^2} - y\right)\right], y \in \left[0, 2\sqrt{2rx - x^2}\right] \tag{30}$$

Distribution of A_k is:

$$P_{Ak}(A) = \frac{1}{h_0} \int_0^{h_0} \exp\left[-n\left(2\sqrt{2rx - x^2} - \frac{A}{x}\right)\right] dx \tag{31}$$

Case 3:

$$P_{\delta n}(x) = \exp\left[-n(h_0 - x)\right], x \in \left[0, h_0\right]$$

$$P_{dn}(y) = \exp\left[-n\left(2\sqrt{2rx - x^2} - y\right)\right], y \in \left[0.2\sqrt{2rx - x^2}\right] \tag{32}$$

It follows:

$$P_{Ak}\,(A) = \int_0^{h_0} \exp\left(-2\sqrt{2rx - x^2} - \frac{A}{x}\right) d\left[\exp\left(-n\left(h_0 - x\right)\right)\right] \qquad (33)$$

The last case, as it was written before, leads to safety margin.

Example 1. Reliability of pipeline subjected to one-sided irregular corrosion.

Dimensions of the resulting cavity-depth and diameter are increasing in time in such degree that the failure of pipe will occur i.e. formation of a reach-through hole will take place. Time, t_n before this hole will appear calculates from the expression:

$$\int_0^{t_n} v(t)dt = h_0 - \delta_n \qquad (34)$$

Here δ_n – maximum depth from an ensemble of n cavities; v(t) = $v_0$exp(-αt) – corrosion's speed (Table 1,5). From (34) we get:

$$t_n = \frac{1}{\alpha} \ln \frac{v_0}{h_0 - \delta_n} \qquad (35)$$

Time distribution $P(t_n < t)$ to reach –through hole can be written as:

$$P_n(t) = P\left\{\delta_n \geq \left[h_0 - \frac{v_0}{\alpha}\left(1 - \exp\left(-\alpha t\right)\right)\right]\right\} = 1 - \exp\left[-n\frac{v_0}{\alpha}\left(1 - \exp\left(-\alpha t\right)\right)\right] \qquad (36)$$

After averaging on "n" it follows:

$$P\,(t) = \sum_{n=0}^{\infty} \frac{\left(\mu t\right)^n}{n!} \exp\left\{1 - \exp\left[1 - \exp\left(-\alpha t\right)\right]\right\} \qquad (37)$$

Example 2. Design of structural members under central tension.

Cylindrical element having a ring cross-section is considered. This element is subjected to irregular corrosion under deterministic load F. If A_0 is initial value of cross-section (t = 0), A_k is square of cavity with given distribution $PA_k(A,)$ then the condition of no failure will be:

$$F / (A_o - A_k) < R_y \quad \text{or } A_k < A_0 - F / R_y \qquad (38)$$

Substituting the last expression into distribution function as an argument and carrying out an average on n and R_y probability of no failure in t moment is:

$$P(t) = \exp(-\mu t) \sum_{n=0}^{\infty} \frac{(\mu t)^n}{n!} \int_0^{\infty} P_{Ak}\left(A_0 - \frac{F}{R_y}\right) p\left(R_y\right) dR_y \qquad (39)$$

Here $p(R_y)$ – is density of yield stress distribution. In numerical example the following data are taken. External diameter D = 6.26in; initial thickness h_0 = 0.24in; F = 127929ft; $\mu = \mu_{gr}[1 - \exp(-\beta t)]$ and β = 0.05; $\overline{R}_y$ = 290Mpa; s_{Ry} = 25Mpa. Parameters of the cavity are $\overline{d}_k = \overline{\delta}_k = 0.008$in. Results of numerical realization are shown at Fig.6

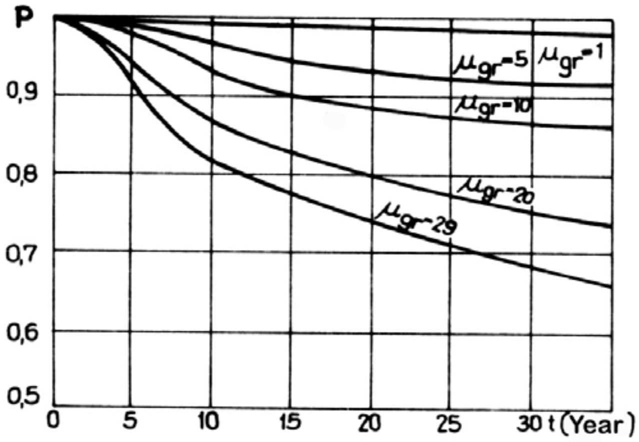

Fig.6 The reliability function

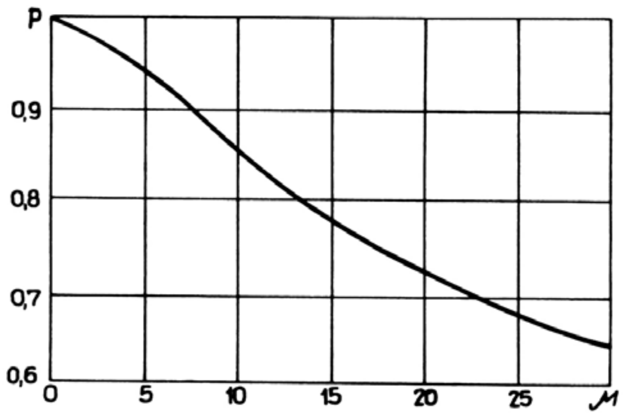

Fig.7 Variation of the function of reliability
due to number of cavities

4 CALIBRATION OF MODEL PARTIAL FACTOR

Partial factor for model uncertainties can be determined from comparison with identical structures operating in normal or in aggressive environment. Let us consider the structure under load F and with resistance equal to R. In case when random value of the load maximum for the definite period of time (one year, for example) has distribution $P_F(x)$ and year's load maximums are independent random values, the reliability function can be written as follows

$$P_1(n) = \int_0^\infty P_F^n(x) dP_R(x) \tag{40}$$

It is assumed that there is a structure operating in aggressive environment in the terms of uniformly corrosion. To guarantee the sufficient reliability level in the design it is necessary to go on additional expense of structural material such as increasing cross-section square, for example. The condition of no failure is

$$\widetilde{F} \le \gamma_D \widetilde{R} \tag{41}$$

Though the corrosion process is continuous in time it is proposed to consider the function $\varphi(t)$ which influences to geometric characteristics of cross-section as a function of discrete argument $\varphi(n)$. (41) to nth year could be rewritten as

$$F \le \gamma_D R\varphi(n) \tag{42}$$

Reliability function will be

$$P_2(n) = \int_0^\infty \prod_{i=1}^n P_F\left[\gamma_D x\varphi(i)\right]dP_R(x) \tag{43}$$

The equation for definition of γ_D arrives from the equality (40) to (43).

$$\int_0^\infty \prod_{i=1}^n P_F\left[\gamma_D x\varphi(i)\right]dP_R(x) = \int_0^\infty P_F^n(x)dP_R(x) \tag{44}$$

If we consider tensioned non-corrosive structural element then (41) can be presented as

$$F \le RA_0 \tag{45}$$

Where A_0 -initial cross-section square.

Function of reliability will be

$$P_1(n) = \int_0^\infty P_F(xA_0)dP_R(x) \tag{46}$$

For corroding structural element cross-section square is - $A_0\gamma_D$, and γ_D>1. The failure condition can be expressed as

$$F \le \gamma_D A_0\varphi(n)R \tag{47}$$

Reliability function (43) will be

$$P_2(n) = \int_0^\infty \prod_{i=1}^n P_F\left[\gamma_D A_0 x\varphi(i)\right]dP_R(x) \tag{48}$$

Equality (44) for the fast n value allows to determinate γ_D. Fisher-Tippet distribution (8) was chosen for $P_F(x)$. Equality (44) will be performed to

$$\int_0^\infty \exp\left[-n\left(\frac{xA_0}{\xi}\right)^{-\eta}\right]dP_R(x) = \int_0^\infty \prod_{i=1}^n \exp\left[-\left(\frac{\gamma_D A_0 x\varphi(i)}{\xi}\right)^{-\eta}\right]dP_R(x) \tag{49}$$

From here, it follows

$$\gamma_D = \frac{1}{[n\sum_{i=1}^n \varphi^{-\eta}(i)]^{\frac{1}{\eta}}} \tag{50}$$

Introducing corrosion model in the form of (6) and presenting the sum in (50) in the row we will get

$$\gamma_D = \frac{1}{\left\{n\left[\exp\left(\frac{\eta}{\tau}\right) + \exp\left(\frac{2\eta}{\tau}\right) + \ldots + \exp\left(\frac{n\eta}{\tau}\right)\right]\right\}^{\frac{1}{\eta}}} \tag{51}$$

After transformation we get

$$\gamma_D = \frac{\exp\left(\frac{n+1}{\tau}\right) - 1}{n\left[\exp\left(\frac{\eta}{\tau}\right) - 1\right]} \tag{52}$$

Table 3 contains modal factor's values in accordance with (52)

Table 3

n	η	γ_D $\tau = 100$	γ_D $\tau = 150$	γ_D $\tau = 200$
10	10	1.0666	1.0461	1.0364
	20	1.1304	1.0828	1.0612
	30	1.2098	1.1280	1.0920
15	10	1.0657	1.0439	1.0337
	20	1.1374	1.0851	1.0618
	30	1.2263	1.1354	1.0958
20	10	1.0665	1.0433	1.0327
	20	1.1443	1.0881	1.0632
	30	1.2401	1.1424	1.0999

Aggressiveness of environment can be classified depending on parameter τ: heavily aggressive $\tau = 100$, middle aggressive $\tau = 150$, weakly aggressive

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