

Equations for calculating and forecasting the change of the proportional limit based on the time of corrosion effect

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ABSTRACT: The proportional limit in stress-strain diagrams is a linear law that applies to all steel elements, including steel. Corrosion negatively affects steel, and this article explores the change in the proportional limit depending on the corrosion category defined in standards. Experimental data was processed using the stochastic method, and empirical values were compared. Stress and relative strain were illustrated as a function of time, and polynomial approximation was used to calculate and forecast the effect of corrosion on the proportional limit. The study found that strain and stress values are consistent, but their reference time differs.
KEYWORDS: Proportional limit, Equations, Corrosion, Forecasting.

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I. INTRODUCTION

According to the classical theory of mechanics of materials, at the beginning of the working diagram of the material there is a linear function, also known as Hooke's Law [20]. The greatest stress up to which Hooke's law is valid is called the proportional limit (fig.1) is a critical point (point A on fig.1) on the stress-strain curve, indicating the transition from linear to nonlinear behaviour.

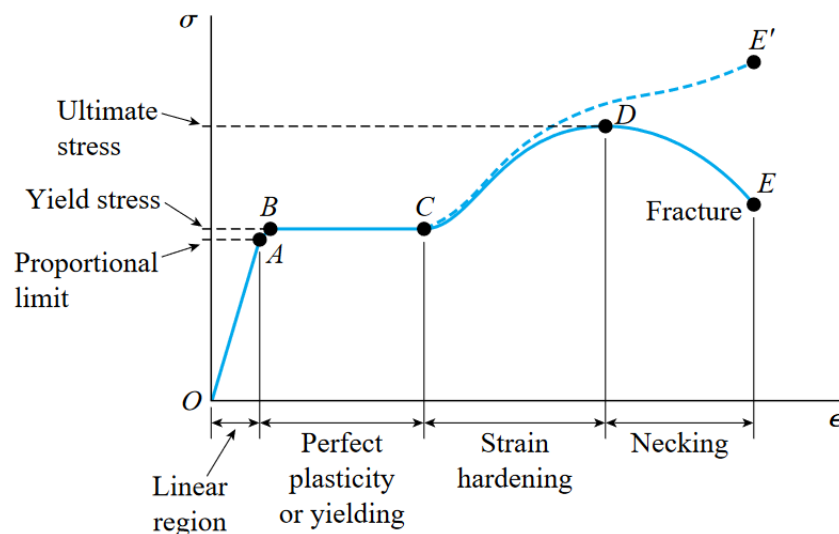


Figure 1. Classical stress-strain curve with marked main points and zones [20]

It represents the highest stress at which a material responds proportionally to the applied strain. Beyond this point, the material exhibits irreversible deformation and cannot recover to its original shape. Understanding this concept is essential for understanding material behaviour under mechanical load – this is a point of the working diagram of the material when the condition is met:

$$\frac{\varepsilon}{\sigma} = \frac{1,5}{E} \quad (1)$$

where:
 ε - strain; σ - stress; E – Young's module

The proportional limit in materials is the maximum stress they can withstand, with a linear correlation between stress and strain [20]. This limit is crucial for determining a material's mechanical performance and structural integrity and can be demonstrated through stress-strain curves from experiments. From available experimental data [1-5,12,14,22,24] it is found that in corroded steel specimens, Young's modulus does not follow its linear functionality but is a cubic equation. This is because corrosion directly affects the mechanical properties of steel such as: loss of geometric characteristics, structural changes, loss of mechanical properties and others [1-5,12,14,22,24]. The proportional limit serves as an indicator of the maximum stress a material can sustain while maintaining its elastic behavior [20]. The fact that chloride-induced corrosion could also deteriorate the ductility of steel should not be overlooked [11].

There are many studies that investigate the influence of corrosion on the mechanical properties of steel [1-5,9,12-14,22,24], but none of these studies give a clear and definite practical solution for calculation, and all of them are related to experimental data processed by relevant mathematical models and/or theoretically derived formulas that are difficult to apply in practice, i.e. to be able to perform the calculation quickly and easily. Since steel from an elastic material will become a brittle material after corrosion, and it is characterized by a very low degree of elasticity, the determination of a proportionality limit depending on the time of the corrosion effect would provide us with an opportunity to predict at which point in time the strain of the corroded steel will become plastic and plastic /residual/ deformations will be present before the onset of material yield is reached. The essential difference is that in ductile materials there is a distinct yield point, while in brittle materials the yield point is absent and/or if present, it is negligible. If we have a corrosive effect, then the creep site will look like a brittle material, hence the need to be able to define a limit of proportionality, so that we can be sure that there are no plastic deformations.

II. Method for constructing forecasting equations

Depending on selection of processing options and on the trends and patterns existing in the research data, some forecasting methods will perform better than others for a given database set. A forecasting method that is appropriate for one study may not be appropriate for another. It is also unlikely that a forecasting method that provides good results at one stage of a scientific research cycle will remain appropriate throughout the entire period of problem study [8].

Deterministic models are systems in mathematics, computer science, and physics that do not involve chance in the development of future system states [16]. These models produce the same result from an initial state or initial state and can be described using differential equations of physical laws. In mathematics, deterministic systems study the theory of chaos, where the future state can be theoretically predicted if the initial state is known. However, the accuracy of measuring the initial state limits the knowledge of the future state, and chaotic systems are characterized by a strong dependence on initial conditions. In computer science and technology, deterministic models represent successive machine states and operations are defined by the previous state. The algorithm of deterministic processes ensures that the same result will always be available with given input parameters [16]. Non-deterministic algorithms, such as pseudo-random number generators, can be applied to deterministic machines, but they are not as reliable due to the impact of corrosion on the random development of unrelated quantities.

In probability theory, a stochastic process is the opposite of a deterministic process and is a mathematical model of systems and phenomena that seem random [17,19,21]. These processes are widely used in various disciplines, including biology, chemistry, ecology, neurology, physics, and engineering fields like image processing, signal processing, information theory, computer science, and cryptography. The term "random function" can also be used to denote a stochastic process because it can be interpreted as a random element in a functional space [19]. Stochastic processes can be divided into different categories, such as random walks, Markov processes [17], Levi processes, Gaussian processes, random fields, refresh processes, and branching processes. The Stochastic Process Study uses mathematical knowledge and techniques from probability, calculus, linear algebra, set theory, topology, and branches of mathematical analysis such as real analysis, theory of measures, Fourier analysis, and functional analysis [21]. The Stochastic Process Theory is considered an important contribution to mathematics and remains an active subject for research both theoretically and applications. Instead of working with one possible realization of the process over time, there is uncertainty in its stochastic process for its future development described by probability distributions. This means that even if the initial condition is known, there are many possibilities for how the process can evolve, with some conversions being more likely than others [23]. For example, the study of certain parameters in corroded steel implies that they are independent random variables, suggesting that the data processing model should be the stochastic method [23].

The approximation theory in mathematics focuses on approximating functions with simpler ones and quantifying their mistakes [15,18]. It is closely related to function approximation through generalized Fourier

series, which is based on summation of orthogonal polynomials. The approximation of a function using operations is particularly interesting, as it aims to be as close as possible to the actual function with an accuracy close to that of floating-point arithmetic. This is achieved by using a high degree or narrowing polynomial over which the polynomial must approach the function. Polynomials are useful for approximating more complex functions due to their simple form [15,18]. In this case, any function or data from experiments made in the form of a function can be described with certainty by an equation of the form:

$$f(x) = a_0 + a_1 \cdot x + a_2 \cdot x^2 + \dots + a_n \cdot x^n(2)$$

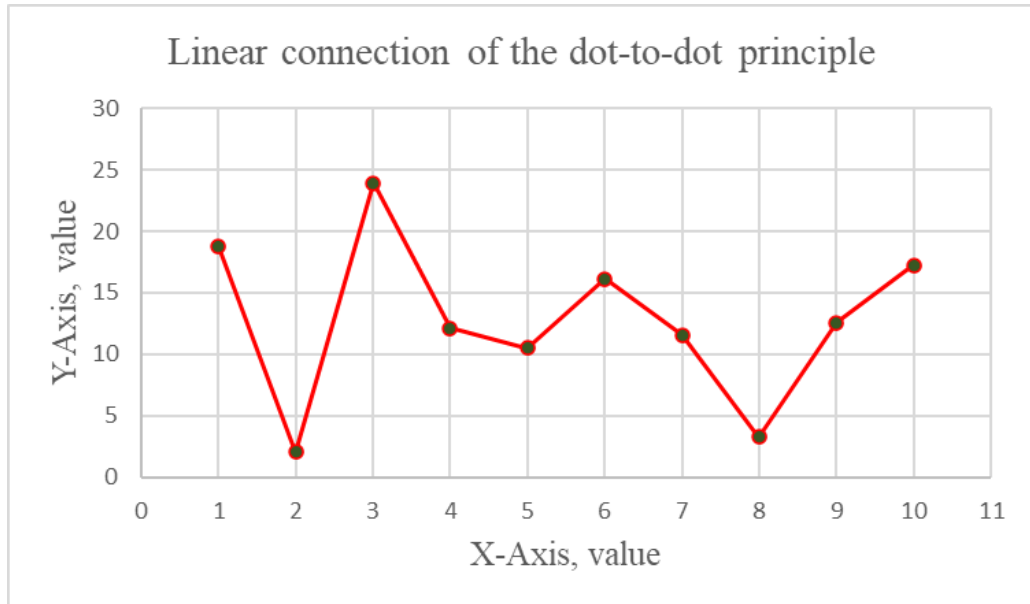


Figure 2. Graph of linear connection with “angles”

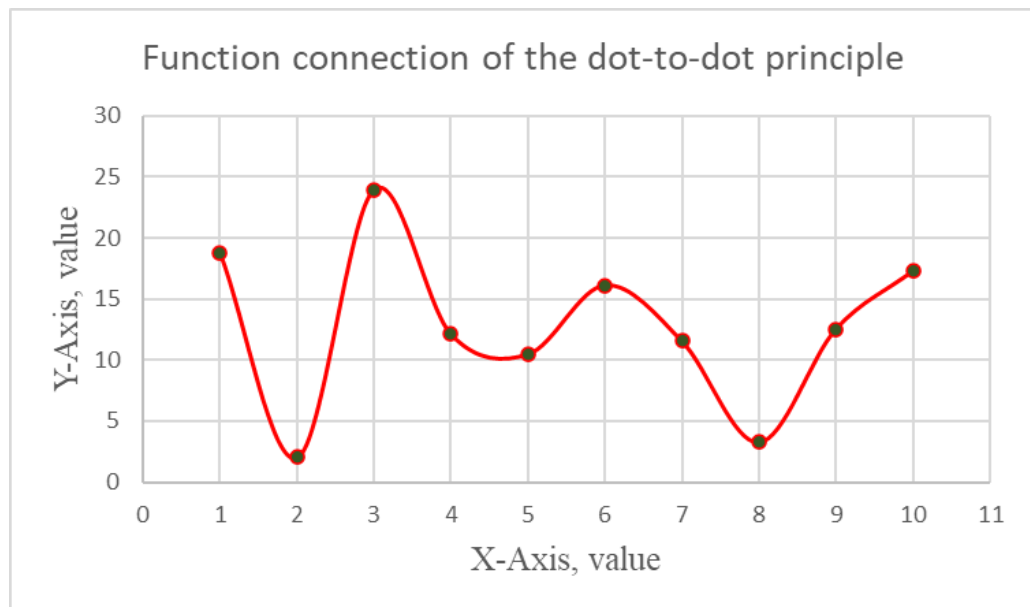


Figure 3. Graph of function connection without “angles”

In situations where we have point values instead of knowing the function expression, finding a polynomial that passes through these points is enough. This is known as interpolating polynomial. If we know the function $f(x)$ exactly at several points, we want to approximate its behavior between these points [15,18]. This is equivalent to linear assembly (fig.2), but it is often more accurate to find a curve without "angles" (fig.3).

III. Equations for calculating and forecasting

There are international standards such as ISO 9223, ISO 12944 and others by which the corrosion category is determined [26-28]. Usually, the ISO 9223 standard also serves for experimental tests within one year [10]. In general, this is the rate at which corrosion removes a portion of the member's cross-section. In order to compile these standards, the well-known formula for determining the corrosion rate is used:

$$C_r = \frac{87,6.W}{D.A.T} \quad (3)$$

where:

Cr – corrosion rate, [mm/y]; W – loss of mass, [mg]; D – material density, [g/cm³]; A – area on section, [cm²]; T – time on corrosion influence, [hours].

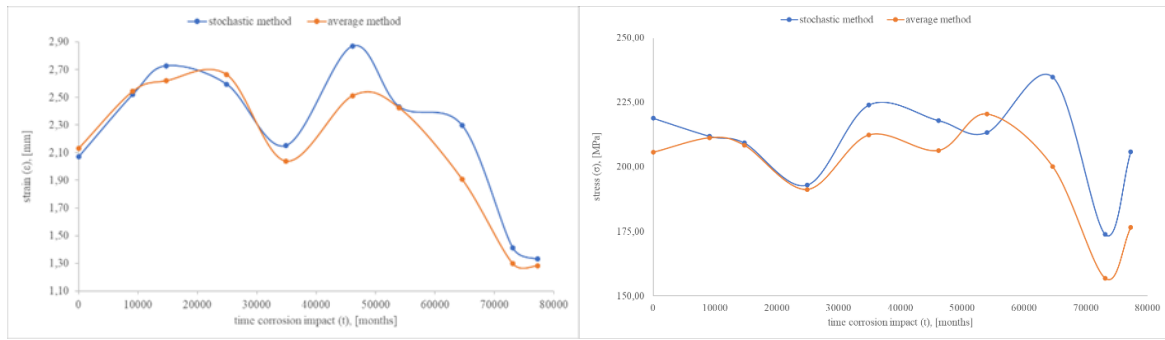
As can be seen from this formula, the rate depends on the natural and environmental conditions in which the element is found. Therefore, the corrosion categories are divided depending on the conditions. For the current needs, the ISO standard is used because in this standard 6 types of corrosion categories are affected and respectively the conditions to which each category corresponds are described. On the other hand, the studies [6-7,25] are bound precisely to these 6 categories and to have correspondence, the same is used. Applying the methods of mathematics and polyponal approximation, using the available data from experiments [1-5,12-14,22,24] compiles the equations for calculating and predicting the influence of corrosion on point the proportional limit. A dependence on the type of $\epsilon(t)$ and $\sigma(t)$ (where t is a time in months) is obtained and the equations for each corrosion category are established. This method has been applied several times so far [1,6-7,22,25] in various papers.

3.1 Corrosion category C1: Corrosion category C1 has a very low corrosion rate that varies from 0 to 0,0013 [mm/y]. On table 1 is present a result after processing by stochastic method and average method for strain and stress - $\epsilon(t)$ and $\sigma(t)$. In fig. 4a shows the relationship between the change in relative strain versus the action time of overtime due to the corrosion effect of category. Using the polynomial approximation [1,6-7,18,22,25] from fig. 4a, functional dependence for the strain point in dependence of the time of the influence of the corrosion (in months) is established in equations – eq. 4 (using a stochastic method) and eq. 5 (using an average method).

Table 1. Results after processing

time [months]	Strain of proportional limit, [mm]		Stress of proportional limit, [MPa]	
	Stochastic method	Average method	Stochastic method	Average method
0	2,070	2,130	218,91	205,68
9138	2,521	2,543	211,9	211,3
14769	2,727	2,619	209,3	208,4
24923	2,595	2,664	193,0	191,3
34892	2,151	2,039	224,0	212,4
46154	2,870	2,511	218,0	206,4
54000	2,432	2,423	213,4	220,5
64615	2,296	1,907	234,9	200,2
73108	1,414	1,299	173,9	156,9
77262	1,331	1,282	205,9	176,6

In fig. 4b shows the relationship between the change in relative strain versus the action time of overtime due to the corrosion effect of category. Using the polynomial approximation [1,6-7,18,22,25] from fig. 4b, functional dependence for the strain point in dependence of the time of the influence of the corrosion (in months) is established in equations – eq. 6 (using a stochastic method) and eq. 7 (using an average method).



a) b)

Figure 4. Graph of the variation – a) strain - $\varepsilon(t)$; b) stress - $\sigma(t)$

- The stochastic strain equation is (eq.4):

$$\varepsilon(t) = 4,7562239485042848 \cdot 10^{-40} \cdot t^9 - 1,677658016573874 \cdot 10^{-34} \cdot t^8 + 2,472790975 \cdot 10^{-29} \cdot t^7 - 1,9733039162081 \cdot 10^{-24} \cdot t^6 + 9,2311596340327980 \cdot 10^{-20} \cdot t^5 - 2,5607472917642749 \cdot 10^{-15} \cdot t^4 + 4,0599624820046138 \cdot 10^{-11} \cdot t^3 - 3,34033365812319 \cdot 10^{-7} \cdot t^2 + 1,1340782123 \cdot 10^{-3} \cdot t + 2,070 \quad (4)$$

- The average strain equation is (eq.5):

$$\varepsilon(t) = 2,9130673773726471 \cdot 10^{-40} \cdot t^9 - 1,0628748687995107 \cdot 10^{-34} \cdot t^8 + 1,6267636446511487 \cdot 10^{-29} \cdot t^7 - 1,3533281286967523 \cdot 10^{-24} \cdot t^6 + 6,6258706347106649 \cdot 10^{-20} \cdot t^5 - 1,9308205162959904 \cdot 10^{-15} \cdot t^4 + 3,225830232278 \cdot 10^{-11} \cdot t^3 - 2,8022408527386206 \cdot 10^{-7} \cdot t^2 + 1,000835342972686 \cdot 10^{-3} \cdot t + 2,130 \quad (5)$$

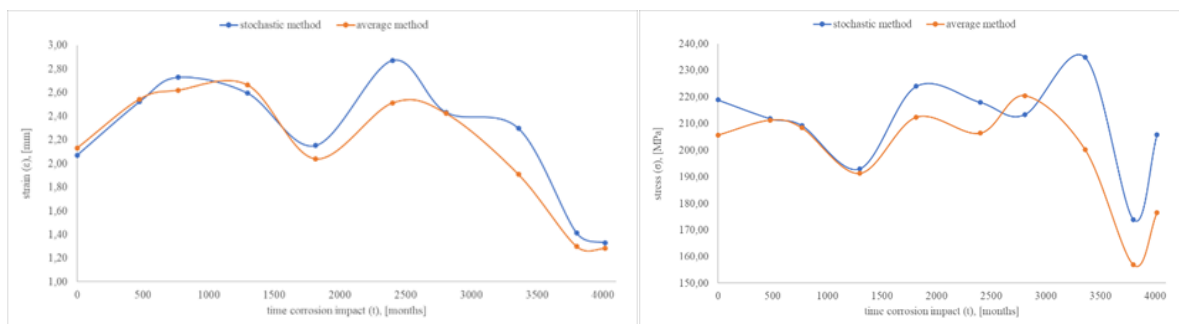
- The stochastic stress equation is (eq.6):

$$\sigma(t) = -1,2629384766297993 \cdot 10^{-39} \cdot t^9 + 8,5820366306018301 \cdot 10^{-34} \cdot t^8 - 1,91330048850145 \cdot 10^{-28} \cdot t^7 + 2,0789371057655 \cdot 10^{-23} \cdot t^6 - 1,2478989000757844 \cdot 10^{-18} \cdot t^5 + 4,2682280173128 \cdot 10^{-14} \cdot t^4 - 8,07094539 \cdot 10^{-10} \cdot t^3 + 7,631775481002 \cdot 10^{-6} \cdot t^2 - 2,81966349670 \cdot 10^{-2} \cdot t + 218,910 \quad (6)$$

- The average stress equation is (eq.7):

$$\sigma(t) = -1,3548748229370384 \cdot 10^{-38} \cdot t^9 + 4,9701415034542850 \cdot 10^{-33} \cdot t^8 - 7,631380314806482 \cdot 10^{-28} \cdot t^7 + 6,3623058951283094 \cdot 10^{-23} \cdot t^6 - 3,1226417988345039 \cdot 10^{-18} \cdot t^5 + 9,1313254657727180 \cdot 10^{-14} \cdot t^4 - 1,5285804494941485 \cdot 10^{-9} \cdot t^3 + 1,3101398566887 \cdot 10^{-5} \cdot t^2 - 4,3003012174020541 \cdot 10^{-2} \cdot t + 205,680 \quad (7)$$

3.2 Corrosion category C2:Corrosion category C2 has a low corrosion rate that varies from 0,0013 to 0,025 [mm/y].Table 2 presents results processed using stochastic and average methods for strain and stress - $\varepsilon(t)$ and $\sigma(t)$. Figure 5a illustrates the relationship between relative strain change and action time due to corrosion effect. Polynomial approximation [1,6-7,18,22,25] establishes functional dependence for strain point in dependence of time of corrosion influence (in months) in equations - equations 8 (using a stochastic method) and equation 9 (using an average method).



a)

b)

Figure 5. Graph of the variation – a) strain - $\varepsilon(t)$; b) stress - $\sigma(t)$

Table 2. Results after processing

time [months]	Strain of proportional limit, [mm]		Stress of proportional limit, [MPa]	
	Stochastic method	Average method	Stochastic method	Average method
0	2,070	2,130	218,91	205,68
475	2,521	2,543	211,9	211,3
768	2,727	2,619	209,3	208,4
1296	2,595	2,664	193,0	191,3
1814	2,151	2,039	224,0	212,4
2400	2,87	2,511	218,0	206,4
2808	2,432	2,423	213,4	220,5
3360	2,296	1,907	234,9	200,2
3802	1,414	1,299	173,9	156,9
4018	1,331	1,282	205,9	176,6

Figure 5b illustrates the relationship between relative stress change and action time due to corrosion effect. Polynomial approximation [1,6-7,18,22,25] establishes functional dependence for stress point in dependence of time of corrosion influence (in months) in equations - equation 10 (using a stochastic method) and equation 11 (using an average method).

- The stochastic strain equation is (eq.8):

$$\varepsilon(t) = 1,7089118672317119 \cdot 10^{-28} \cdot t^9 - 3,1345942809393256 \cdot 10^{-24} \cdot t^8 + 2,4026025098301430 \cdot 10^{-20} \cdot t^7 - 9,9701197493765045 \cdot 10^{-17} \cdot t^6 + 2,4253179435445673 \cdot 10^{-13} \cdot t^5 - 3,4984671849657929 \cdot 10^{-10} \cdot t^4 + 2,884181823018 \cdot 10^{-7} \cdot t^3 - 1,2338745325756 \cdot 10^{-4} \cdot t^2 + 2,178294462287816 \cdot 10^{-2} \cdot t + 2,070 \quad (8)$$

- The average strain equation is (eq.9):

$$\varepsilon(t) = 1,0472713473159577 \cdot 10^{-28} \cdot t^9 - 1,9870867651454296 \cdot 10^{-24} \cdot t^8 + 1,5815452112980907 \cdot 10^{-20} \cdot t^7 - 6,8419276664290240 \cdot 10^{-17} \cdot t^6 + 1,7419323855933239 \cdot 10^{-13} \cdot t^5 - 2,6395898589470038 \cdot 10^{-10} \cdot t^4 + 2,29315381185895 \cdot 10^{-7} \cdot t^3 - 1,03581614286 \cdot 10^{-4} \cdot t^2 + 1,92361777980328 \cdot 10^{-2} \cdot t + 2,130 \quad (9)$$

- The stochastic stress equation is (eq.10):

$$\sigma(t) = -4,6195851512790537 \cdot 10^{-28} \cdot t^9 + 1,618753836585730 \cdot 10^{-23} \cdot t^8 - 1,870945276878788 \cdot 10^{-19} \cdot t^7 + 1,055488963446235 \cdot 10^{-15} \cdot t^6 - 3,2915174737909732 \cdot 10^{-12} \cdot t^5 + 5,8506781305396841 \cdot 10^{-9} \cdot t^4 - 5,75046565557846 \cdot 10^{-6} \cdot t^3 + 2,82662540824 \cdot 10^{-3} \cdot t^2 - 5,428846463623 \cdot 10^{-1} \cdot t + 218,910 \quad (10)$$

- The average stress equation is (eq.11):

$$\sigma(t) = -4,8733396439012295 \cdot 10^{-27} \cdot t^9 + 9,296029575779131 \cdot 10^{-23} \cdot t^8 - 7,422185603254489 \cdot 10^{-19} \cdot t^7 + 3,2176681781620977 \cdot 10^{-15} \cdot t^6 - 8,2119029042451441 \cdot 10^{-12} \cdot t^5 + 1,2486637237217132 \cdot 10^{-8} \cdot t^4 - 1,08688064376598 \cdot 10^{-5} \cdot t^3 + 4,8437160498 \cdot 10^{-3} \cdot t^2 - 8,26609628597139 \cdot 10^{-1} \cdot t + 205,680 \quad (11)$$

3.3 Corrosion category C3:Corrosion category C3 has an average corrosion rate that varies from 0,025 to 0,05 [mm/y]. Table 3 presents results processed using stochastic and average methods for strain and stress - $\varepsilon(t)$ and $\sigma(t)$. Figure 6a illustrates the relationship between relative strain change and action time due to corrosion effect. Polynomial approximation establishes functional dependence for strain point in dependence of corrosion time (in months) in equations (eq. 12 and eq. 13).Figure 6b illustrates the relationship between relative stress change and action time due to corrosion effect. Polynomial approximation establishes functional dependence for stress point in dependence of corrosion time (in months) in equations (eq. 14 and eq. 15).

- The stochastic strain equation is (eq.12):

$$\varepsilon(t) = 8,7552851248540739 \cdot 10^{-26} \cdot t^9 - 8,0300304061157143 \cdot 10^{-22} \cdot t^8 + 3,0775685422190515 \cdot 10^{-18} \cdot t^7 - 6,3859161340478285 \cdot 10^{-15} \cdot t^6 + 7,7678259285956415 \cdot 10^{-12} \cdot t^5 - 5,6031726590624818 \cdot 10^{-9} \cdot t^4 + 2,3101082376817885 \cdot 10^{-6} \cdot t^3 - 4,942839051062654 \cdot 10^{-4} \cdot t^2 + 4,36463169528778 \cdot 10^{-2} \cdot t + 2,070 \quad (12)$$

- The average strain equation is (eq.13):

$$\epsilon(t) = 5,3674808394532715 \cdot 10^{-26} \cdot t^9 - 5,092289940539715 \cdot 10^{-22} \cdot t^8 + 2,0266028320801982 \cdot 10^{-18} \cdot t^7 - 4,3839449112770371 \cdot 10^{-15} \cdot t^6 + 5,5812486839628876 \cdot 10^{-12} \cdot t^5 - 4,2293365835617465 \cdot 10^{-9} \cdot t^4 + 1,837555426186442 \cdot 10^{-6} \cdot t^3 - 4,151589794458045 \cdot 10^{-4} \cdot t^2 + 3,8566723576146697 \cdot 10^{-2} \cdot t + 2,070 \quad (13)$$

- The stochastic stress equation is (eq.14):

$$\sigma(t) = -2,3810483526813459 \cdot 10^{-25} \cdot t^9 + 4,159807072063978 \cdot 10^{-21} \cdot t^8 - 2,401514963075917 \cdot 10^{-17} \cdot t^7 + 6,7708808946216867 \cdot 10^{-14} \cdot t^6 - 1,0555177113064597 \cdot 10^{-10} \cdot t^5 + 5,3805413804821895 \cdot 10^{-8} \cdot t^4 - 4,6105087537092795 \cdot 10^{-5} \cdot t^3 + 1,1335181228424245 \cdot 10^{-2} \cdot t^2 - 1,0891172360974972 \cdot t + 218,910 \quad (14)$$

- The average stress equation is (eq.15):

$$\sigma(t) = -2,498174109784568 \cdot 10^{-24} \cdot t^9 + 2,382765260538307 \cdot 10^{-20} \cdot t^8 - 9,5128745983660118 \cdot 10^{-17} \cdot t^7 + 2,0621927264228677 \cdot 10^{-13} \cdot t^6 - 2,6318265414139366 \cdot 10^{-10} \cdot t^5 + 2,0012980791742344 \cdot 10^{-7} \cdot t^4 - 8,7125893240207485 \cdot 10^{-5} \cdot t^3 + 1,9423490246730079 \cdot 10^{-2} \cdot t^2 - 1,6587834784606574 \cdot t + 218,910 \quad (15)$$

Table 3. Results after processing

time [months]	Strain of proportional limit, [mm]		Stress of proportional limit, [MPa]	
	Stochastic method	Average method	Stochastic method	Average method
0	2,070	2,130	218,91	205,68
238	2,521	2,543	211,9	211,3
384	2,727	2,619	209,3	208,4
648	2,595	2,664	193,0	191,3
907	2,151	2,039	224,0	212,4
1200	2,87	2,511	218,0	206,4
1404	2,432	2,423	213,4	220,5
1680	2,296	1,907	234,9	200,2
1901	1,414	1,299	173,9	156,9
2009	1,331	1,282	205,9	176,6

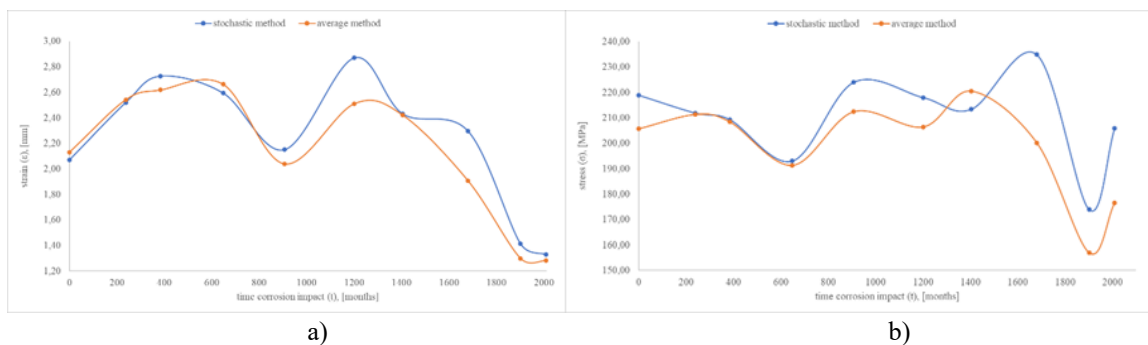


Figure 6. Graph of the variation – a) strain - $\epsilon(t)$; b) stress - $\sigma(t)$

3.4 Corrosion category C4:Corrosion category C4 has a high corrosion rate that varies from 0,05 to 0,08 [mm/y].

In fig. 7a shows the relationship between the change in relative strain versus the action time of over time due to the corrosion effect of category. Using the polynomial approximation [1,6-7,18,22,25] from fig. 7a, functional dependence for the strain point in dependence of the time of the influence of the corrosion (in months) is established in equations – eq. 16 (using a stochastic method) and eq. 17 (using an average method). On table 4 is present a result after processing by stochastic method and average method for strain and stress - $\epsilon(t)$ and $\sigma(t)$. In fig. 7b shows the relationship between the change in relative stress versus the action time of over time due to the corrosion effect of category. Using the polynomial approximation [1,6-7,18,22,25] from fig. 7b, functional

dependence for the stress point in dependence of the time of the influence of the corrosion (in months) is established in equations – eq. 18 (using a stochastic method) and eq. 19 (using an average method).

Table 4. Results after processing

time [months]	Strain of proportional limit, [mm]		Stress of proportional limit, [MPa]	
	Stochastic method	Average method	Stochastic method	Average method
0	2,070	2,130	218,91	205,68
149	2,521	2,543	211,9	211,3
240	2,727	2,619	209,3	208,4
405	2,595	2,664	193,0	191,3
567	2,151	2,039	224,0	212,4
750	2,87	2,511	218,0	206,4
878	2,432	2,423	213,4	220,5
1050	2,296	1,907	234,9	200,2
1188	1,414	1,299	173,9	156,9
1256	1,331	1,282	205,9	176,6

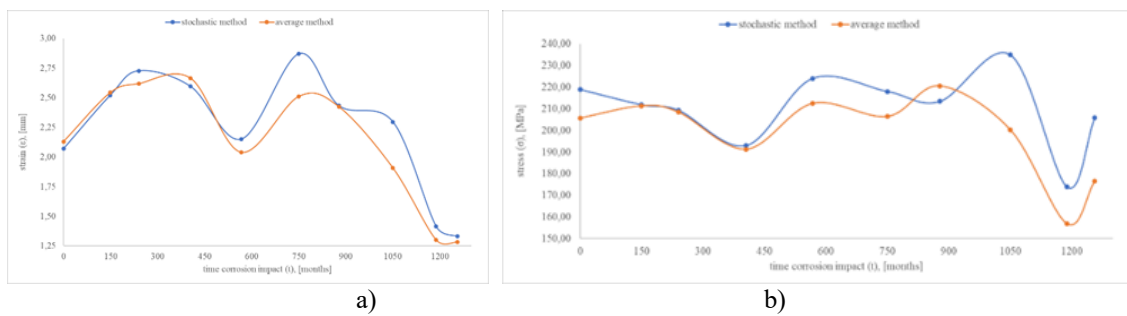


Figure 7. Graph of the variation – a) strain - $\varepsilon(t)$; b) stress - $\sigma(t)$

- The stochastic strain equation is (eq.16):

$$\varepsilon(t) = 5,999835992032586 \cdot 10^{-24} \cdot t^9 - 3,4397511034137152 \cdot 10^{-20} \cdot t^8 + 8,2406463399956458 \cdot 10^{-17} \cdot t^7 - 1,0688667603050666 \cdot 10^{-13} \cdot t^6 + 8,127365556712299 \cdot 10^{-11} \cdot t^5 - 3,6646980822792728 \cdot 10^{-8} \cdot t^4 + 9,4449313640337727 \cdot 10^{-6} \cdot t^3 - 1,2633669929963 \cdot 10^{-3} \cdot t^2 + 6,975213399079 \cdot 10^{-2} \cdot t + 2,070 \quad (16)$$

- The average strain equation is (eq.17):

$$\varepsilon(t) = 3,677737129236475 \cdot 10^{-24} \cdot t^9 - 2,1812558908992629 \cdot 10^{-20} \cdot t^8 + 5,4268816867336588 \cdot 10^{-17} \cdot t^7 - 7,3390546068537642 \cdot 10^{-14} \cdot t^6 + 8,5841247968096236 \cdot 10^{-11} \cdot t^5 - 2,7672888949467169 \cdot 10^{-8} \cdot t^4 + 7,51704846841126 \cdot 10^{-6} \cdot t^3 - 1,0618942801698119 \cdot 10^{-3} \cdot t^2 + 6,168864517046278 \cdot 10^{-2} \cdot t + 2,130 \quad (17)$$

- The stochastic stress equation is (eq.18):

$$\sigma(t) = -1,6230284591400489 \cdot 10^{-23} \cdot t^9 + 1,77834615918744 \cdot 10^{-19} \cdot t^8 - 6,4257509226481254 \cdot 10^{-16} \cdot t^7 + 1,1332601713862929 \cdot 10^{-12} \cdot t^6 - 1,1048267396500221 \cdot 10^{-9} \cdot t^5 + 6,139816502575666 \cdot 10^{-7} \cdot t^4 - 1,8869617308085507 \cdot 10^{-4} \cdot t^3 + 2,9010198373649605 \cdot 10^{-2} \cdot t^2 - 1,743272971564717 \cdot t + 218,910 \quad (18)$$

- The average stress equation is (eq.19):

$$\sigma(t) = -1,71351808686424 \cdot 10^{-22} \cdot t^9 + 1,0216314163620528 \cdot 10^{-18} \cdot t^8 - 2,549649100602435 \cdot 10^{-15} \cdot t^7 + 3,4551290848892701 \cdot 10^{-12} \cdot t^6 - 2,7565913560054436 \cdot 10^{-9} \cdot t^5 + 1,3104658896179152 \cdot 10^{-6} \cdot t^4 - 3,5668806282743891 \cdot 10^{-4} \cdot t^3 + 4,9721724169531696 \cdot 10^{-2} \cdot t^2 - 2,6557315385659646 \cdot t + 205,680 \quad (19)$$

3.5 Corrosion category C5:Corrosion category C5 has a very high corrosion rate that varies from 0,08 to 0,2 [mm/y].Figure 8a illustrates the relationship between relative strain change and action time over time due to

corrosion effect. Using polynomial approximation, functional dependence for strain point is established in equation 20 (using a stochastic method) and eq.21 (using an average method). Table 5 presents results after processing by stochastic and average methods for strain and stress - $\epsilon(t)$ and $\sigma(t)$. Figure 8a illustrates the relationship between relative stress change and action time over time due to corrosion effect. Using polynomial approximation, functional dependence for stress point is established in equations 22 (using a stochastic method) and eq.23 (using an average method).

Table 5. Results after processing

time [months]	Strain of proportional limit, [mm]		Stress of proportional limit, [MPa]	
	Stochastic method	Average method	Stochastic method	Average method
0	2,070	2,130	218,91	205,68
59	2,521	2,543	211,9	211,3
96	2,727	2,619	209,3	208,4
162	2,595	2,664	193,0	191,3
227	2,151	2,039	224,0	212,4
300	2,87	2,511	218,0	206,4
351	2,432	2,423	213,4	220,5
420	2,296	1,907	234,9	200,2
475	1,414	1,299	173,9	156,9
502	1,331	1,282	205,9	176,6

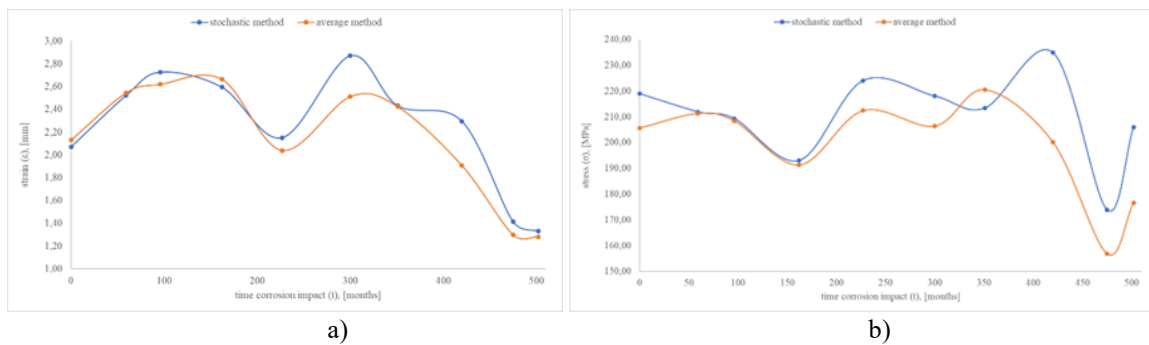


Figure 8. Graph of the variation – a) strain - $\epsilon(t)$; b) stress - $\sigma(t)$

- The stochastic strain equation is (eq.20):

$$\epsilon(t) = 2,3038258824652119 \cdot 10^{-20} \cdot t^9 - 5,2805195971169 \cdot 10^{-17} \cdot t^8 + 5,0576160883299724 \cdot 10^{-14} \cdot t^7 - 2,6225993435276872 \cdot 10^{-11} \cdot t^6 + 7,9718377259304063 \cdot 10^{-9} \cdot t^5 - 1,4368115220020867 \cdot 10^{-6} \cdot t^4 + 1,47985401261478 \cdot 10^{-4} \cdot t^3 - 7,9072166587308354 \cdot 10^{-3} \cdot t^2 + 1,7426975091279229 \cdot 10^{-1} \cdot t + 2,070 \quad (20)$$

- The average strain equation is (eq.21):

$$\epsilon(t) = 1,4058622222156954 \cdot 10^{-20} \cdot t^9 - 3,332904804862512 \cdot 10^{-17} \cdot t^8 + 3,3144123106534126 \cdot 10^{-14} \cdot t^7 - 1,7914748265735462 \cdot 10^{-11} \cdot t^6 + 5,6983033818443615 \cdot 10^{-9} \cdot t^5 - 1,0786578046151475 \cdot 10^{-6} \cdot t^4 + 1,1703719155662423 \cdot 10^{-4} \cdot t^3 - 6,600389797149427 \cdot 10^{-3} \cdot t^2 + 1,52991976542266 \cdot 10^{-1} \cdot t + 2,130 \quad (21)$$

- The stochastic stress equation is (eq.22):

$$\sigma(t) = -5,5145431358569076 \cdot 10^{-20} \cdot t^9 + 2,5608842459536787 \cdot 10^{-16} \cdot t^8 - 3,775781846338 \cdot 10^{-13} \cdot t^7 + 2,6893968875467025 \cdot 10^{-10} \cdot t^6 - 1,0543060686795274 \cdot 10^{-7} \cdot t^5 + 2,3503097910172139 \cdot 10^{-5} \cdot t^4 - 2,8925352263123785 \cdot 10^{-3} \cdot t^3 + 1,7779413999189486 \cdot 10^{-1} \cdot t^2 - 4,2662227549317757 \cdot t + 218,910 \quad (22)$$

- The average stress equation is (eq.23):

$$\sigma(t) = -6,51711152932123 \cdot 10^{-19} \cdot t^9 + 1,5537462943990216 \cdot 10^{-15} \cdot t^8 - 1,5503952313586989 \cdot 10^{-12} \cdot t^7 +$$

$$8,3993227295071144.10^{-10}.t^6 - 2,6784751107165208.10^{-7}.t^5 + 5,0880285508636739.10^{-5}.t^4 - 5,5310730395416704.10^{-3}.t^3 + 3,0766527852017855.10^{-1}.t^2 - 6,5463151111927704.t + 205,680 \quad (23)$$

3.6 Corrosion category CX:Corrosion category CX has an extremely high corrosion rate that varies from 0,2 to 0,7 [mm/y].Figure 9a illustrates the relationship between relative strain change and action time due to corrosion effect. Using polynomial approximation, functional dependence for strain point is established in equations 24 (using a stochastic method) and eq.25 (using an average method). Table 6 presents results after processing by both methods for strain and stress - $\epsilon(t)$ and $\sigma(t)$. Figure 9b illustrates the relationship between relative stress change and action time due to corrosion effect. Using polynomial approximation, functional dependence for stress point is established in equation 26 (using a stochastic method) and eq.27 (using an average method).

Table 6. Results after processing

time [months]	Strain of proportional limit, [mm]		Stress of proportional limit, [MPa]	
	Stochastic method	Average method	Stochastic method	Average method
0	2,070	2,130	218,91	205,68
17	2,521	2,543	211,9	211,3
27	2,727	2,619	209,3	208,4
46	2,595	2,664	193,0	191,3
65	2,151	2,039	224,0	212,4
86	2,87	2,511	218,0	206,4
100	2,432	2,423	213,4	220,5
120	2,296	1,907	234,9	200,2
136	1,414	1,299	173,9	156,9
143	1,331	1,282	205,9	176,6

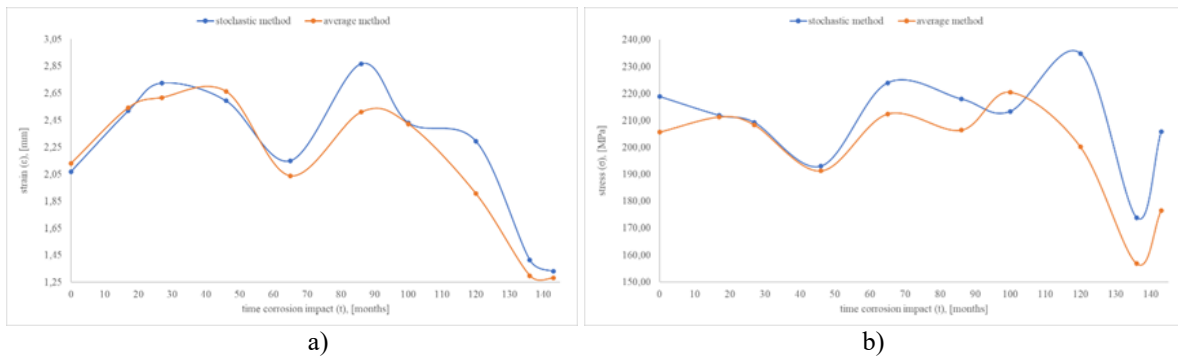


Figure 9. Graph of the variation – a) strain - $\epsilon(t)$; b) stress - $\sigma(t)$

- The stochastic strain equation is (eq.24):

$$\epsilon(t) = 1,808675530712108.10^{-15}.t^9 - 1,182307794855488.10^{-12}.t^8 + 3,2284281246556614.10^{-10}.t^7 - 4,7705102281042225.10^{-8}.t^6 + 4,129592346897562.10^{-6}.t^5 - 2,1179274597436754.10^{-4}.t^4 + 6,2012712772082.10^{-3}.t^3 - 9,4141561719018427.10^{-2}.t^2 + 5,9081028920008327.10^{-1}.t + 2,070 \quad (24)$$

- The average strain equation is (eq.25):

$$\epsilon(t) = 1,0803309141862616.10^{-15}.t^9 - 7,30698683564308.10^{-13}.t^8 + 2,0727227316024278.10^{-10}.t^7 - 3,194837601428119.10^{-8}.t^6 + 2,8968663309163941.10^{-6}.t^5 - 1,5624622753412657.10^{-4}.t^4 + 4,828306694534999.10^{-3}.t^3 - 7,75632194697054.10^{-2}.t^2 + 5,1382636018591388.10^{-1}.t + 2,130 \quad (25)$$

- The stochastic stress equation is (eq.26):

$$\sigma(t) = -2,056173235655489.10^{-15}.t^9 + 4,246950743578228.10^{-12}.t^8 - 2,0029872916941288.10^{-9}.t^7 +$$

$$4,287763714484875 \cdot 10^{-7} \cdot t^6 - 4,9364318210086465 \cdot 10^{-5} \cdot t^5 + 3,194821422438193 \cdot 10^{-3} \cdot t^4 - 1,1335523090626587 \cdot 10^{-1} \cdot t^3 + 1,9998299464220755 \cdot t^2 - 13,785160790774738 \cdot t + 218,910 \quad (26)$$

- The average stress equation is (eq.27):

$$\sigma(t) = \sigma(t) = -5,0686081188735156 \cdot 10^{-14} \cdot t^9 + 3,449183129829458 \cdot 10^{-11} \cdot t^8 - 9,820304108101215 \cdot 10^{-9} \cdot t^7 + 1,5173825643904976 \cdot 10^{-6} \cdot t^6 - 1,3794435987529087 \cdot 10^{-4} \cdot t^5 + 7,4662440777194892 \cdot 10^{-3} \cdot t^4 - 2,3112681692345116 \cdot 10^{-1} \cdot t^3 + 3,6593940097517721 \cdot t^2 - 22,175009798455623 \cdot t + 205,680 \quad (27)$$

IV. Conclusion

The study reveals that the change in proportional limit point strain influenced by time of corrosion is non-linear 9th-degree function with different coefficients. This confirms that the stress-strain curve on steel's mechanical properties follows a functional dependence of the 9th degree. To predict calculations, established equations must be substituted with various components and factors. These equations are specific to the S355JR type of steel and can help determine when corroded steel members will lose their mechanical properties and brittle failure. This information can be used to schedule repair activities and optimize the use of corroded steel structures. The study emphasizes the need for more accurate engineering practices. It is interesting that the values of strain and stress are the same, but only the time to which they refer is different. For the lower corrosion categories, these values are reached after a rather long stage of the time of the corrosion effect. At the higher values of the corrosion category, these values are obtained in a relatively short period, i.e. these values will be obtained depending on the corrosion category. This is because formula 2 shows that corrosion rate is determined depending on time (It assumes that the corrosion process is linear over time and the mass loss can be attributed solely to corrosion), and a standard by which corrosion categories categorized determines values per unit of time. The logic follows from here that a stronger corrosion effect means that these values will be achieved in a shorter time, a weaker corrosion effect will achieve these values in a longer time. The paper focuses on analyzing experimental data from S355JR steel corrosion samples to predict changes in proportional limit over time. It aims to find a practical equation for determining proportional limit changes over time. The proposed formulas and mathematical model are based on theoretical justification and experimental results and can be used in corrosion impact assessment. The coefficients should be chosen according to the normative code of safety for the structural steel element. The obtained results unequivocally find that there is probably a correlation between the development of corrosion and the strength of steel. The established equations can serve as calculations with sufficient practical accuracy for engineers, considering the effect of corrosion on the steel element. In turn, they can also serve to predict the probable values of deformation and/or stress for the purpose of prevention and planning of follow-up actions. Although these equations were derived with the help of experimental data and mathematical processing of the result, their credibility should also be carried out through direct application in practice. Through these equations, mathematical dependence is established by which the factors of the corrosion effect are significantly considered. An effect on the geometry of the cross-section, leading to fractures mainly due to reduced geometrical characteristics rather than mechanical properties. Changing the proportional limit in corroded elements leads to a sudden change in the behavior of the material, with the steel becoming brittle due to corrosion.

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