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Non-uniform corrosion of steel rebar and its influence on reinforced concrete elements` reliability

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Abstract
Remarkable place of reinforced concrete structures in construction field has been noted in wide number of recent researches. Subsequently, their degradation due to aggressive environment has become the topical problem nowadays. Therefore, the formulation of reliable technique for corroded element strength decrement is of great importance, and could be achieved only with the use of complex experimental and theoretical analysis. In this article an attempt is made to propose the mathematical approach to corrosive process modelling, taking into consideration the specifics of its development. According to thorough literature review on existing studies, main specifics of the process were indicated for further suppositions and assumptions formulation. Accordingly, the complex theoretical investigation with corresponding mathematical computations was conducted and results of analytical modelling were discussed. As the initial data for analytical modelling results of previously conducted experiments were used. Analysis of the obtained results shows rather high correspondence with the real conditions of structural element exploitation, taking into consideration material anisotropy and complexity of the corroded zone spread along the rebar cross-section. Proposed methodology for limit force decrease evaluation in general demonstrates reliable results and could be used for further evaluation of corrosion impacts on reinforced concrete elements bearing capacity.

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1. Introduction

In the last few decades reinforced concrete structures have occupied remarkable place on the construction market and have become, probably, the most widely used construction material (Bobalo et. al., 2019; Christodoulou and Goodier, 2014). Considering the noteworthy prevalence of reinforced concrete structures in various application fields, issues of their reliability, possible damages and material deterioration have reached high topicality. As it was affirmed by Cherinin L. and Val D., 2012, the reinforcement corrosion is one of the major threads causing reduction of the construction safety. The same statement could be found in the number of other works (Tantele, et. al., 2017; Luo et. al., 2019; Li and Ye, 2018). Thus, the authors assume that the long-term performance of the corroded RC element is affected due to degradation chemical processes and corresponding decreasing of the effective area of the steel rebar. In recent years, a great number of experimental and theoretical investigations was conducted, aiming to thoroughly investigate this complex process, focusing on different micro- and macro-scale aspects (Yogalakshmi et. al., 2020; Matesová et.al. 2007; Sadeghi et. al., 2019). In general, authors agreethat the corrosion process in RC structures could occur in correspondence with various degradation mechanisms. As it was described in articles of Silva M. et. al., 2015 and Goya A. et. al., 2015. this process could be identified as the surface deterioration–aused by environmental influences, reduction reaction, which could result into conversion of the metal into another material. Subsequently, the geometrical, chemical and mechanical properties of the structural component are changed. It is also important to note, that the damaged layer spreading is mostly non-uniform, and depends on environmental conditions. The reliable determination of strength decrement could be achieved only with the use of appropriate complex technique of corrosion process simulation, which could take into consideration all the circumstances. In this article an attempt is made to propose the mathematical approach to corrosive process modeling, taking into account the specifics of its development.

2. Aims

The main purpose of this work is to conduct a thorough analysis of the corrosion process in the steel rebar and evaluate its impact on structural element strength reduction. In order to provide a complex theoretical investigation the corresponding mathematical computations will be conducted and results of analytical modeling will be discussed.

3. Analytical investigation

The exceptional aspects and specifics of the reinforcement material degradation are presented on the basis of particular samples with predetermined material properties. The samples are thermally $\varnothing 20$ mm A500C steel bars. The attention should be paid to specific non-uniform properties of the modeled samples, described in the previous study (Blikharskyy, 2019). On the basis of experimental investigation (Blikharskyy, 2019) results following assumptions are made in order to predefine the marginal conditions for theoretical modeling.

The rebar cross section could be considered as the composite heterogeneous surface-which consists of three zones with different physical, mechanical and chemical properties. The approximate model of the sample cross-section can be seen in Fig.1.

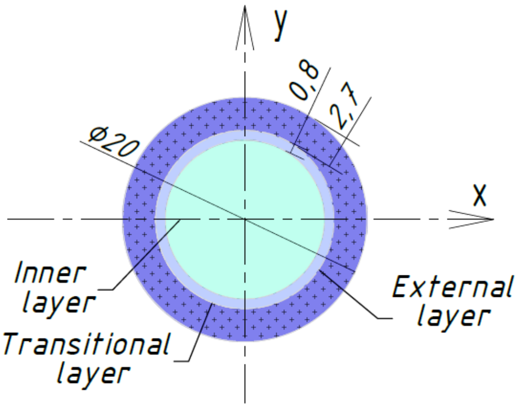

Fig. 1. Approximated three-zone model of the thermically strengthened Ø 20 mm rebar

1) The external layer- the thermally hardened zone-with assumed depth of $\delta^{I} = 2.7$ mm. The yield strength of the material is $\sigma^{I}{}_{0.2} = 650$ MPa.

2) The transitional layer with the averaged properties is considered with the use linearization rules. The layer thickness is $\delta^{II} = 0.8$ mm. The limit yield strength is:

$$\frac{d}{dx}\sigma_{0.2}^{II} = \lim_{x\to\infty}\frac{d}{dx_i}\sigma_{0.2i} = \frac{\sigma_{0.2}^{I}-\sigma_{0.2}^{III}}{\delta^{III}} = \frac{560-440}{0.8} = 150 \text{ MPa} \quad (1)$$

$$\sigma_{0.2}^{II} = \sigma_{0.2}^{I} - 0.5\delta^{II}\cdot\frac{d}{dx}\sigma_{0.2}^{II} = 545 \text{ MPa} \quad (2)$$

where $\sigma^{I}{}_{0.2}$, $\sigma^{II}{}_{0.2}$, $\sigma^{III}{}_{0.2}$ are the yield strengths of the first, second and third layers`, respectively; $\delta^{I}$, $\delta^{II}$, $\delta^{III}$ -the corresponding layers` thicknesses.

3) The third layer is situated in the middle of the rebar cross-section and, therefore, is not subjected to microstructural transformations during the thermal strengthening. The layer thickness is $\delta^{III} = 6.5$ mm and its mechanical properties are sufficiently lower than those of the first layer. Thus, the yield strength of the material is $\sigma^{III}{}_{0.2} = 440$ MPa.

During the mathematical computations the elastic state of work of the material, it will be considered–where the stress does not exceed the yield strength of the material ($\sigma \le \sigma_{0.2}$). Thus, the limit strength of the material will be equal to the yield strength of the particular layer, which at this moment is subjected to aggressive impact, namely $[\sigma] = \sigma_{0.2}$. Such assumption is taken into consideration because further increment of the stress in the steel bar could result in interruption of the joint work, as strain in the reinforcement reaches the creep stage.

The corrosion process could be associated with complicated mechanism, which depends on various environmental and timescale factors and is identified by different development scenarios. Namely, the damaged layer could spread uniformly, when the effect of aggressive action is applied equally, along the perimeter of the rebar. However, such type of the steel deterioration is unlikely to occur in real-life conditions, as the corrosion impact usually has more localized unsymmetrical form. Therefore, the study will be focused on the situation, when the effective cross-section of the rebar is reduced by dismemberment of separate segments, as illustrated by Figures 2 and 3. As could be observed when such type of the corrosion occurs, the separate zones are accessed by aggressive environment, when the other part of the cross-section could still effectively bear the load.

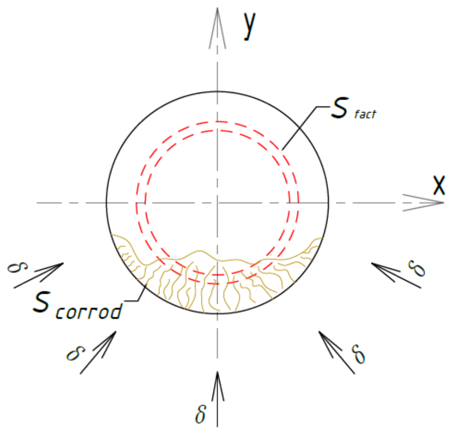

Fig. 2. The corrosion layer spread

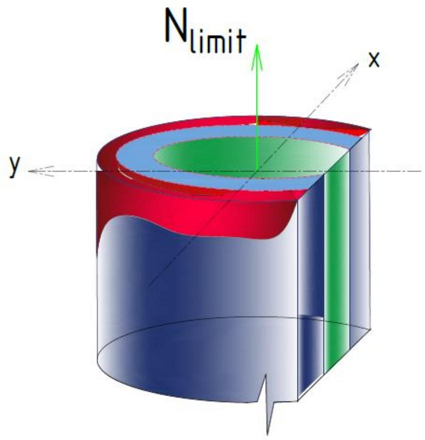

Fig. 3. The principal loading scheme

Such type of the impairments` distribution is associated with complicated geometrical changes and offset of the gravity center from O to O` (Fig. 4). Therefore, a certain eccentricity of the load takes place. A particular stress state could be identified as non-central tension; thus, certain complication of the sample`s performance should be taken into account.

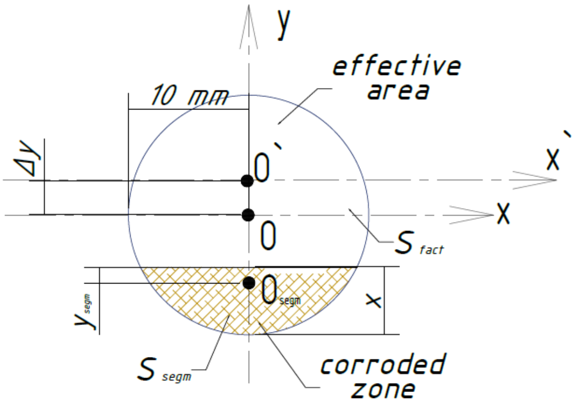

Fig. 4. Geometrical properties` changes along the cross-section

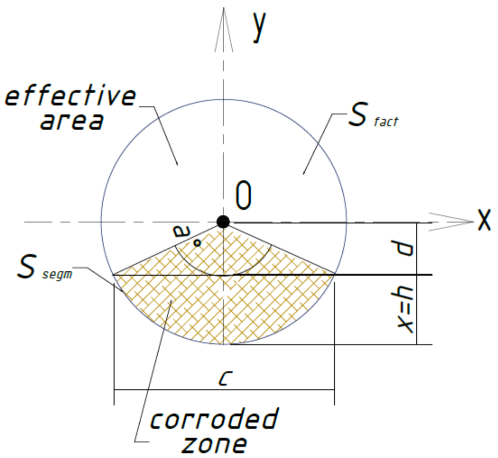

Fig. 5. Geometrical parameters of the corroded zone

Generally, the limit state of the steel rebar will occur when the following condition is fulfilled:

$$\frac{N_{\max}^{i}}{S_{fact}^{i}}+\frac{M_{\max}^{i}}{W_{fact}^{i}}=\frac{N_{\max}^{i}}{S_{fact}^{i}}+\frac{N_{\max}^{i}\cdot e}{W_{fact}^{i}}=\sigma_{0.2}^{i} \qquad (3)$$

Main geometrical parameters of the rebar cross-section (r, c, h, d), identified in Fig. 4, 5 will be used in following computations (eqs.4-19).

After corrosion occurs, the cross-section area of the rebar will be reduced according to following formula:

$$S_{fact}^{i}=S_{init}-S_{segm}=\pi\cdot r^{2}-(r^{2}\cdot\arcsin\left(\frac{c}{2r}\right)-\frac{c}{4}\sqrt{4r^{2}-c^{2}}) \qquad (4)$$

where S_{fact}^{i}, is the actual value of the cross-section, S_{init}, S_{segm} -the initial value of the area and the corroded field area respectively, $h=x$ the thickness of the corroded layer n each particular stage, r -the initial radius of the steel bar (fig.4). Parameter c could be defined as:

$$c=2\sqrt{h\cdot(2r-h)} \qquad (5)$$

The load of the limit value of $N_{\max}^{i}$ is initially applied to the cross-section gravity center (fig. 4); however, due to corrosion the bending moment appears:

$$M_{\max}^{i}=N_{\max}^{i}\cdot\Delta y_{i} \qquad (6)$$

where the offset of the force application point:

$$\Delta y_{i}=y_{gc}-r \qquad (7)$$

The coordinate of the cross-section gravity could be calculated as:

$$y_{gc}=\frac{S_{init}\cdot r-S_{segm}\cdot(x-y^{segm})}{S_{init}-S_{segm}} \qquad (8)$$

where the gravity center of the corroded segment is:

$$y^{segm}=\frac{4}{3}\cdot\frac{r\cdot\sin^{3}\theta}{(2\theta-\sin 2\theta)}-(r-x) \qquad (9)$$

where θ is the segment center angle value (fig.5) equal to:

$$\theta=2\arccos\left(1-\frac{x}{r}\right) \qquad (10)$$

Resistance moment of the rebar cross section could be calculated through the well-known equation:

$$W_{\min} = \frac{I_x}{y_{\max}} \tag{11}$$

where the maximum distance from the neutral line is:

$$y_{\max} = \max((y_{gc} + x);(2r - y_{gc} - x)) \tag{12}$$

The value of inertia moment on each particular corrosion stage will be equal to:

$$I_x = I_{xinit} + I_x^{segm} = \left(\frac{\pi \cdot r^4}{4}\right) + I_x^{segm} + S_{segm} \cdot (\Delta y_i + \frac{4}{3} \cdot \frac{r \sin^3 \theta}{(2\theta - \sin 2\theta)})^2 = \left(\frac{\pi \cdot r^4}{4}\right) + \left(\frac{r^3}{8}\right) \cdot \left(\frac{\pi r \cdot 2\theta}{180} - \frac{r^4}{8} \cdot \sin\theta \cdot \cos\theta\right) - S_{segm} \cdot \Delta y_i^2 \tag{13}$$

where I_{xinit}, I_x^{segm} are the corresponding inertia moments of the initial cross-section and the corroded part respectively.

After the corresponding calculations being conducted the critical load value, which could perceive the steel bar is:

$$N_{\max}^i = \frac{\sigma_{0.2}^i}{\left(\frac{1}{S_{fact}^i} + \frac{\Delta y_i}{W_{fact}^i}\right)} = \frac{\sigma_{0.2}^i}{\left(\frac{1}{S_{fact}^i} + \frac{y_{\max} \cdot \Delta y_i}{I_x}\right)} \tag{14}$$

Minor mathematical computations allow to transverse the formula (14) as the following:

$$N_{\max}^i = \frac{\sigma_{0.2}^i}{\frac{1}{\pi r^2} + \frac{3}{2} r^6 \cdot (\pi - \frac{k_2}{2}) \cdot (\frac{\pi}{8} - \frac{\pi\theta}{720} - \frac{4 k_2 \sin^3\theta}{9(\theta - k_1)})} \tag{15}$$

where the coefficients, mentioned in the equation (15) could be calculated as:

$$k_1 = \sin\theta \cdot \cos\theta = (1 + 2 \cdot \left(\frac{x}{r}\right)^2 - 3\left(\frac{x}{r}\right)) \cdot \sqrt{\frac{x}{r} \cdot (2 - \frac{x}{r})} \tag{16}$$

$$k_2 = \frac{\pi}{90} \cdot \arccos(1 - \frac{x}{r}) - 2 \cdot (1 - \frac{x}{r}) \cdot \sqrt{\frac{x}{r} \cdot (2 - \frac{x}{r})} \tag{17}$$

Another form of the coefficients could be received through introduction of the ratio $\delta = \frac{x}{r} = \frac{2x}{d}$ (eqs. 18, 19):

$$k_1 = 4(1 + \delta \cdot (2\delta - 3)) \cdot \sqrt{\delta(2 - \delta)} \tag{18}$$

$$k_2 = \frac{\pi}{90} \cdot \arccos(1 - \delta) - 2(1 - \delta) \cdot \sqrt{\delta(2 - \delta)} \tag{19}$$

After that the actual values of the corroded layer thickness are substituted into the eqs. (14-19) and corresponding results of the limit force reduction are received (Table 1).

Table 1. The limit force reduction at different corrosion stages

Stage	x_i, mm	S_{fact}^i, mm²	$N_{\max}^i$, kN	Percentage of $N_{\max}^i$ decrease, %
I stage $x_i \in [0; 2.7]$ $[\sigma] = 650$ MPa	0	314.159	204.204	0.00
	1	308.127	198.322	2.83
	2	297.649	188.495	7.65
	2.5	291.334	182.835	10.42
II stage $x_i \in [2.7; 3.5]$ $[\sigma] = 545$ MPa	3	284.45	148.298	27.34
	3.5	277.075	143.122	29.88
III stage $x_i \in [3.5; 10]$ $[\sigma] = 440$ MPa	4	269.27	111.278	45.48
	5	252.58	102.615	49.72
	6	234.73	93.956	53.97
	7	216.0	85.428	58.14
	8	196.65	77.102	62.22
	9	176.9	69.01	66.19
	10	156.92	61.159	70.03

The data analysis includes also indication the following functional dependencies:

$$f(x) = N_{\max}(x) \tag{20}$$

$$f(x) = N_{\max}\left(\frac{S_{fact}^i}{S_{innit}}\right) \tag{21}$$

$$f(x) = \frac{N_{\max}^i}{N_{innit}}\left(\frac{S_{fact}^i}{S_{innit}}\right) \tag{22}$$

The above cited dependencies (20-22) could be approximated in the form of 6-order polynom (eq.23):

$$f(x) = a_1 \cdot x^6 + a_2 \cdot x^5 + a_3 \cdot x^4 + a_4 \cdot x^3 + a_5 \cdot x^2 + a_6 \cdot x^1 + a_7 \cdot x^0 \tag{23}$$

The polynomial coefficients $a_1 ... a_7$ were obtained through approximation with high accuracy level (determination coefficient $R^2 \approx 1$). Thus, the functional dependencies (20-22) will be the following:

$$N_{\max}(x) = -0.0063x^6 + 0.264x^5 - 4.3527x^4 + 35.322x^3 + -142.62x^2 + 233.85x^1 + 75.814x^0 \quad R^2 = 0.9897 \tag{24}$$

$$N_{\max}\left(\frac{S_{fact}^i}{S_{innit}}\right) = -84085x^6 + 4 \cdot 10^6 x^5 - 6 \cdot 10^6 x^4 - +6 \cdot 10^6 x^3 - 3 \cdot 10^6 x^2 + 872474x^1 - 99033x^0 \quad R^2 = 0.9908 \tag{25}$$

$$\frac{N^i_{\max}}{N_{innit}}\left(\frac{S^i_{fact}}{S_{innit}}\right) = -4119.6x^6 + 17797x^5 - 31671x^4 + 29724x^3 - \\ -15519x^2 + 4274.7x^1 - 485.22x^0$$

$$R^2 = 0.9908 \qquad (25)$$

4. Results and discussion

Results of mathematical modeling were presented in the graphical form (Fig. 6-7), demonstrating the kinetics of steel bar bearing capacity changes at each corrosion rate. The graphs outline the major parameters of strength changes, taking into account the anisotropic character of material properties along the rebar cross-section. Therefore, the destruction process could be analyzed and thorough discussion of obtained data could be conducted.

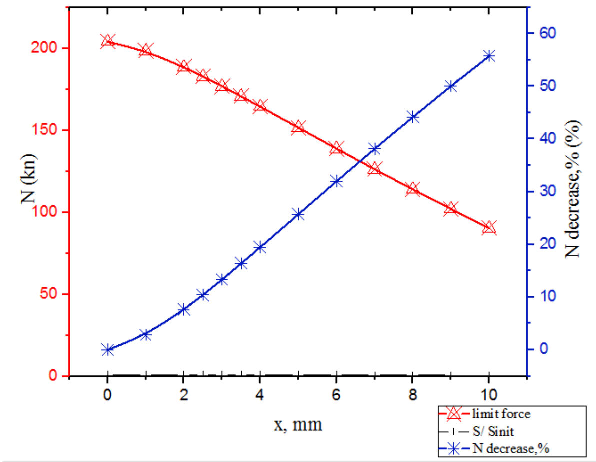

Fig. 6. Graphical representation of $f(x) = N_{\max}(x)$

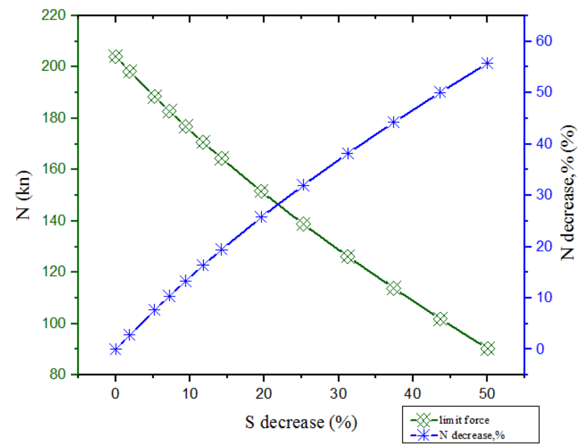

Fig. 7. Graphical representation of $f(x) = N_{\max}\left(\frac{S^i_{fact}}{S_{innit}}\right)$

Graphs 5-6 indicate relative decrease of the rebar bearing capacity, depending on corrosion depth and rebar cross-section reduction.

It could be seen-that graph on fig. 7 shows relatively linearized pattern of rebar strength decrease, depending on cross-section decrease. However, according to graph in Figure 6 the limit force decrease on the first corrosion stages is smoother with more sharp degradation after the corrosion depth reaches the value of 2 mm (10% sample diameter). Such divergences could be explained by functional argument choice. Therefore, it could be assumed the relative cross-section area reduction, used in Figure 7 does not fully reveal the complicity of sample geometrical properties changes.

Thereby, in general, the strength changes are non-linear, due to geometrical complicity of the process and material anisotropy.

It is important to notice that the proposed method does not fully represent the real-life corrosion process, as the number of external factors is not taken into account. Thus, the material structure on the micro-scale should be taken into consideration, as different layers of the rebar have different chemical and mechanical properties and will have different respond to aggressive impact. Another indicator, which could contribute to the research, is the time-scale factor which could demonstrate the kinetics of strength changes more completely.

5. Summary and conclusion

The analytical research on the basis of experimental data was conducted regarding the issue of steel bar non-uniform corrosion; received results were analysed, divergences and possible ways for research improvement were indicated. In the article the major emphasize was made towards the non-uniform corrosion of the steel bar, which generally demonstrates the real exploitation conditions of the reinforcement. In addition the thorough literature review and theoretical research on the issue of corrosion development was conducted and main specifics of the process were indicated for further suppositions and assumptions formulation. Corresponding mathematical computation were conducted and functional dependencies were found, which reveal non-linear character of the sample bearing capacity reduction.

It could be concluded that the process of thermally strengthened steel bar degradation due to aggressive impacts is rather complex and depends on various factors: environmental conditions, type of the reinforcement, initial stress-strain state, etc. In order to provide more veracious modelling of the problem could be recommended to include into research exact data on material response to aggressive environment, as well as take into account external factors.

The proposed methodology for limit force decrease evaluation and analysis of its influence on structural element bearing capacity in general demonstrates reliable results and wide perspectives for its further improvement and implementation. More thorough analysis of the problem could provide more complex investigation and complete technique for corrosion impacts assessment, which will be of great significance in both theoretical fields as well as in practical application during existing structures reconstruction.

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钢筋的非均匀腐蚀及其对钢筋混凝土构件可靠性的影响

關鍵詞
腐蚀
钢钢筋
材料各向异性
数学建模

摘要

钢筋混凝土结构在建筑领域中的显着地位已引起广泛的研究。随后，它们由于侵略性环境而退化已经成为当今的热门问题。因此，制定可靠的腐蚀元素强度递减技术非常重要，只有通过复杂的实验和理论分析才能实现。在本文中，考虑到其开发的特殊性，试图提出一种用于腐蚀过程建模的数学方法。根据有关现有研究的详尽文献综述，指出了该过程的主要细节，以用于进一步的假设和假设表述。因此，进行了带有相应数学计算的复杂理论研究，并讨论了分析建模的结果。使用先前进行的实验作为分析建模结果的原始数据。对所得结果的分析表明，考虑到材料的各向异性和沿钢筋横截面扩展的腐蚀区的复杂性，与结构元素开采的实际条件具有相当高的对应性。提出的极限力降低评估方法论总体上证明了可靠的结果，可用于进一步评估腐蚀对钢筋混凝土构件承载力的影响。