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CALCULATION OF DAMAGE RC CONSTRUCTIONS ACCORDING TO DEFORMATION MODEL

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This article presents results of a theoretical study of reinforced concrete beams with damaged reinforcement. The change of micro-hardness of a reinforcing rebar's with a diameter of 20 mm of A500C steel in the radial direction is investigated and the thickness of the heat-strengthened layer is established. It is established that the thickness of the thermo-strengthened steel layer of the reinforcing bar with a diameter of 20 mm of A500C is approximately 3 mm. It is shown that the strength characteristics of this layer are on 50 % higher compared to the core material of the rebar, while the plasticity characteristics are lower. The aim of the work is to determine the strength and deformability of reinforced concrete structures without damaging the reinforcement and in case of damage. Determining the impact of changes in the physical characteristics of reinforcement on the damage of reinforced concrete structures, according to the calculation to the valid norms, in accordance with the deformation model. To achieve the goal of the work, theoretical calculations of reinforced concrete beams were performed according to the deformation model, according to valid norms. This technique uses nonlinear strain diagrams of concrete and rebar and is based on an iterative method. According to the research program 3 beam samples were calculated. Among them were undamaged control sample with single load bearing reinforcement of ∅20 mm diameter – BC-1; sample with ∅20 mm reinforcement with damages about 40 % without changes in the physical and mechanical properties of reinforcement – BD-2 and sample with ∅20 mm reinforcement with damages about 40 % with changes in the physical and mechanical properties of reinforcement – BD-3. The influence of change of physical and mechanical characteristics of rebar's on bearing capacity of the damaged reinforced concrete beams is established.

Key words: reinforced concrete beams, damaged reinforced concrete structures, damaged reinforcement, load-bearing capacity, calculation of RC contructions.

Introduction

The operation of reinforced concrete structures of buildings and structures often takes place in an aggressive environment. This applies to most industrial buildings, especially those with chemical production, open environments, marine coastal structures, and so on. The action of aggressive environments causes corrosion of concrete and reinforcement of reinforced concrete structures and, as a consequence, reduces their load-bearing capacity and serviceability. The most favorable conditions for corrosion of reinforced concrete structures occur in the chemical industry. Chemically active substances, aggressive to reinforced concrete structures, occur both directly in the production processes and in the environment due to the failure of process equipment, harmful emissions into the atmosphere. According to the Ministry of Regional Development of Ukraine, about 8.000 objects are in a state of emergency, 5.600 of them are recommended for modernization, and 2.140 for liquidation. More than 250 million m^3 of reinforced concrete structures are operated only at facilities of basic industries, where the resource is exhausted by more than 50 %, 13 % of public roads and 59 % of municipal bridges do not meet safety requirements and require repair and reconstruction, 30 % of berth structures front seaports due to environmental influences are in poor condition and subject to overhaul, and 39 % of seaport enclosures are emergency. It is therefore important issue of research bearing capacity of damaged reinforced concrete structures.

Review of scientific sources and publications

Reinforced concrete constructions are the most widely used elements of buildings and structures (Karpiuk et al., 2020, Kramarchuk et al., 2020, Pavlikov et al., 2018). During exploitation, all reinforced concrete structures are affected by external factors and need to be repaired or strengthened (Algburi et al., 2019, Azizov et al., 2019, Tayeh et al., 2019). Such factors may be as the negative impact of the environment, especially in petrochemical plants, low quality of work in monolithic concreting, due to poor quality areas of monolithic concrete is a long leaching of cement stone components, which leads to the formation of concrete defects, lack of reliable protective coating promotes the penetration of moisture and aggressive environments in concrete. Many factors affect, but as a result, reinforced concrete structures are damaged, in particular in the working rods of the reinforcement and require detailed calculation to assess the actual technical condition of such structures (Dmitrovic et al., 2019, Kos et al., 2019).

Corrosion of reinforcement in concrete is one of the main problems of durability faced in practice by civil engineers (Goyal et al., 2018, Kotesa et al., 2015, Vavrus et al., 2015). In (Cigada and Zappa, 2019), longitudinal controlled ultrasonic waves were used to monitor ulcerative and initial defects in steel rods in reinforced concrete structures, which mimics the phenomena of fading and delimitation caused by corrosion. Two ultrasonic techniques (pulse and pulse echo transmission) were used to monitor the whole and damaged sample. The developed technique is successfully used for real-time monitoring of reinforcement of reinforced concrete samples that undergo accelerated corrosion. Corrosion of steel in reinforced concrete leads to several major disadvantages. First, the reduction of the transverse sectional zone of reinforcement and its ductility leads to premature violation of elasticity. Secondly, the expansion of corrosion products causes concrete cracking and damage to the connection between concrete and reinforcement, as well as affects the stiffness of bent reinforced concrete elements, which reduces the overall load-bearing capacity of reinforced concrete beams.

Research of reinforced concrete elements, in which there are defects and damage from various factors, is a topical topic of research, but the number of such works is insufficient.

The aims and objectives of the study

The aim of the work is to determine the strength and deformability of reinforced concrete structures without damaging the reinforcement and in case of damage. Determining the impact of changes in the physical characteristics of reinforcement on the damage of reinforced concrete structures, according to the calculation to the valid norms, in accordance with the deformation model.

Materials and methods

The remarkable aspects and specifics of the reinforcement material degradation are presented on the basis of particular samples with predetermined material properties. The samples are thermally $\varnothing 20\text{ mm A500C}$ 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 calculations.

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

To achieve the goal of the work, theoretical calculations of reinforced concrete beams were performed according to the deformation model, according to the valid norms. This technique uses nonlinear strain diagrams of concrete and rebar and is based on an iterative method.

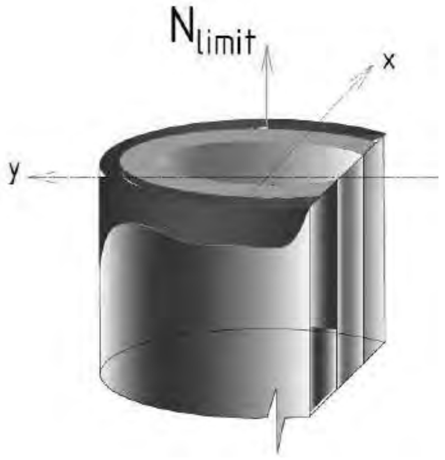


Fig. 1. Determination of compressive strength of masonry

Table 1

Mechanical Characteristics of reinforcement

Layer	Diameter, d, mm	Yield Strength, $\sigma_{0.2}$, MPa	Ultimate strength σ_b, MPa	Specific Elongation δ, %
Hardened	–	650.0	760.0	13.4
Core	15	440.0	560.0	16.4
Solid	20	570.0	650.0	15.3

The calculation is implemented with the assumption of the following prerequisites:

– the hypothesis of plane cross sections is accepted – strains along the section height are distributed according to the linear law;

– the averaged cross section with the greatest strain increment is accepted for calculation;

– in calculations the dependence between stress and relative strain of concrete and rebar as $\sigma - \varepsilon$ diagrams is accepted, while for concrete this dependence is assumed as nonlinear, and for rebar- as two-linear;

– the resistance of the concrete stretched zone is not taken into account.

When calculating bearing reinforced concrete elements of rectangular shape, according to the norms following equilibrium equations of external and internal forces in the normal section for samples were accepted (DSTU, 2010, Eurocode 2, 2004):

$$\frac{bf_{cd}\,\varepsilon_{c1}}{\aleph^0}\sum_{k=1}^{5}\frac{a_k}{k+1}\left(\frac{\varepsilon_{c(1)}^0}{\varepsilon_{c1}}\right)^{k+1}+\sum_{i=1}^{n}\sigma_{si}A_{si}=0, \tag{1}$$

$$\frac{bf_{cd}\,(\varepsilon_{c1})^2}{{\aleph^0}^2}\sum_{k=1}^{5}\frac{a_k}{k+2}\left(\frac{\varepsilon_{c(1)}^0}{\varepsilon_{c1}}\right)^{k+2}+\sum_{i=1}^{n}\sigma_{si}A_{si}(X_1^0-Z_{si})=M_0, \tag{2}$$

where b – calculated element cross section width; f_{cd} – the calculated compressive strength of the concrete; χ – the curvature of the cross-section bended axis; $\bar{\chi}$ – the relative curvature; a_k – polynomial coefficients; γ – the ratio between strain of the compressed zone concrete and limit strain of the compressed zone concrete; σ_{si} – stress in the i-th rebar; A_{si} – cross-sectional area of the i-th rebar;

x_1 – compressed concrete zone height; z_{si} – the distance between the *i*-th steel bar and the most compressed section plane.

The sequence of calculation of the stress-strain state parameters of the normal section was accepted according to (DSTU, 2010, Eurocode 2, 2004). It consists in the fact that at each step of the iterative calculation, the values of relative averaged strain of the stretched concrete fibers $\varepsilon_{c(2)}$ were determined basing on the pre-set value of the strain of the compressed concrete fibers $\varepsilon_{c(1)}$. In equations (1) and (3), the values of longitudinal forces were chosen in such way so that the equilibrium conditions (2) and (4) are fulfilled. When the specified calculation accuracy for a given value of the strain was reached, the calculation was stopped and the corresponding value of the longitudinal force from the equations (1) and (3) was determined. Then, at a given value of the compressed fibers` strain $\varepsilon_{c(1)}$, it was increased by the value $\Delta\varepsilon_{c(1)}$ and the calculation was repeated until the requirement $\varepsilon_{c(1)} \ge \varepsilon_{cu1}$ was fulfilled, as it was accepted as a criterion of carrying capacity of reinforced concrete columns exhaustion due to the achievement the limit values by the most compressed concrete fibers. After the calculation is completed, following values were obtained: strains of compressed and stretched fibers of concrete, main rebar, reinforced samples of additional strengthening (carbon strip), curvature of the normal section bended axis, the value of additional eccentricity due to bending of the reinforced concrete column for the corresponding value of longitudinal axial force.

When the strains $\varepsilon_{c(1)}$ exceeded the limit values ε_{cu1} by iterations, the value of the load, at which $\varepsilon_{c(1)} = \varepsilon_{cu1}$ was redefined. This value is accepted as a load, at which the exhaustion of the reinforced concrete columns` bearing capacity was reached and could be used for further comparison with those determined during experimental studies.

Results of investigation

According to the research program 3 beam samples were calculated. Among them were undamaged control sample with single load bearing reinforcement of ∅20 mm diameter – BC-1; sample with ∅20 mm reinforcement with damages about 40 % without changes in the physical and mechanical properties of reinforcement – BD-2 and sample with ∅20 mm reinforcement with damages about 40 % with changes in the physical and mechanical properties of reinforcement – BD-3.

Experimental samples used in the research had the length of 2100 mm, 100 mm weight and 200 mm height. The beams` concrete composition: C: S: R =1:1, 16:2, 5 with W/C=0.375. The cement used – M-500, sand quartz without impurities with a size module M_k=2.00, granite rubble of fractions 5–10 mm – 66 %, 10–20 mm – 33 %.

The reinforcement of samples: A500C steel bars, diameter was ∅20 mm. Reinforcement of compressed zone and transverse reinforcement are made of ∅5 B 500 bars. Transverse reinforcement ∅5 B500C has 75 mm spacing.

When calculating non-centrally compressed columns the following output data was accepted for experimental-theoretical studies performed in this paper:

– section parameters (width and height): b = 100 mm, h = 200 mm;

– concrete parameters: C30/35: f_{cd} = 25.5 MPa; $\varepsilon_{cu,1}$ = 0.0031; $\varepsilon_{cu,3}$ = 0.00293; ε_{c1} = 0.00172;

– for this concrete class the polynomial coefficients: a_1=2.6219; a_2=-2.425; a_3=0.98327; a_4=-0.17908; a_5=-0.00107.

Rebar’s parameters:

– sample BC-1 1Ø20 A500C: f_{yd}=570 MPa; E_S=210 GPa; A_S=314.0 mm^2;

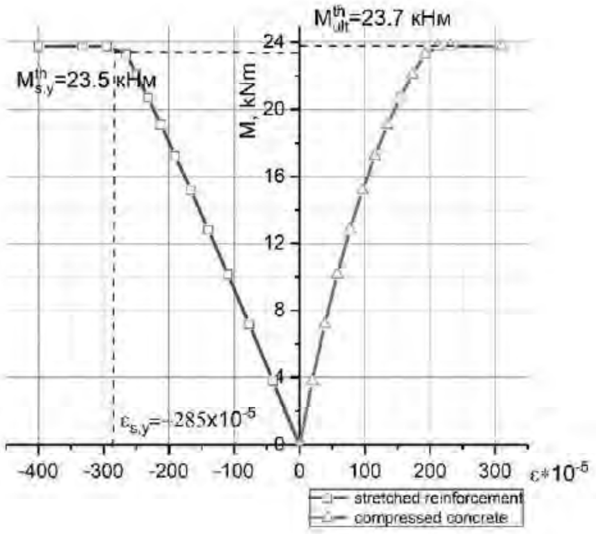
– sample BD-2 1Ø20 A500C with damages about 40 % (which corresponds to area of the 15 mm diameter samples): f_{yd}=570 MPa; E_S=210 GPa; A_S=176.6 mm^2;

– sample BD-3 1Ø20 A500C with damages about 40 % (which corresponds to area of the 15 mm diameter samples): f_{yd}=400 MPa; E_S=210 GPa; A_S=176.6 mm^2;

The calculation results of the calculated strain and bearing capacity values for the beams shows that the use of equation (1, 2) according to (DSTU, 2010, Eurocode 2, 2004), for the determination of the bending moment are presented in Fig. 2 and Table 2.

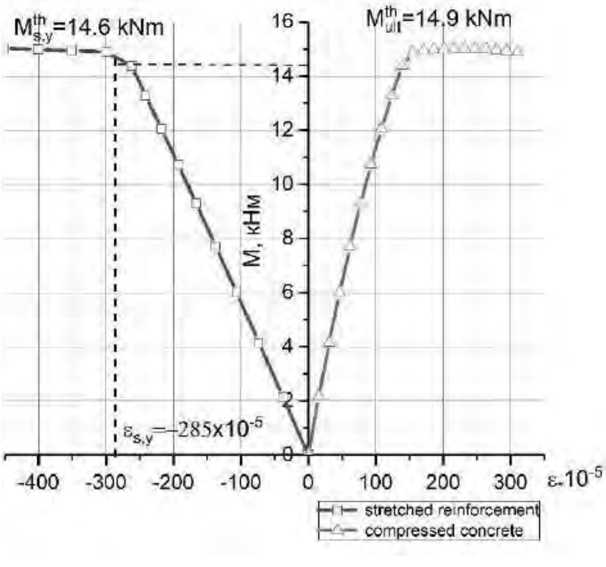
In the beam BC-1, according to the theoretical calculation (Fig. 2), the yield strength strain ($\varepsilon_S = 280 \cdot 10^{-5}$) of the main steel bars occurred at $M_{s,y}^{th} = 23.5$ kNm (Fig. 2), further loading was accompanied by significant increase in the strain of the reinforcement and concrete. The load at which the compressed concrete reached the limit strain ($\varepsilon_{cu1} = 310 \cdot 10^{-5}$) was $M_{ult}^{th} = 23.7$ kNm.

Fig. 2. The graphs of the strains` calculated values of the stretched main steel rebar's (stretched reinforcement) and the compressed concrete (compressed concrete) for beam BC-1



In the beam BD-2, according to the theoretical calculation (Fig. 3), the load at which the deformation of the main rebar reached the yield strength ($\varepsilon_S = 280 \cdot 10^{-5}$) was $M_{s,y}^{th} = 14.6$ kNm.

Fig. 3. The graphs of the strains` calculated values of the stretched main steel rebar's (stretched reinforcement) and the compressed concrete (compressed concrete) for beam BD-2



The load at which the compressed concrete reached the limit strain ($\varepsilon_{cu1} = 310 \cdot 10^{-5}$) was $M_{ult}^{th} = 14.9$ kNm.

In the beam BD-3, according to the theoretical calculation (Fig. 4), the load at which the deformation of the main rebar reached the yield strength ($\varepsilon_s = 280 \cdot 10^{-5}$) was $M_{s,y}^{th} = 11.5$ kNm. The load at which the compressed concrete reached the limit strain ($\varepsilon_{cu1} = 310 \cdot 10^{-5}$) was $M_{ult}^{th} = 11.9$ kNm.

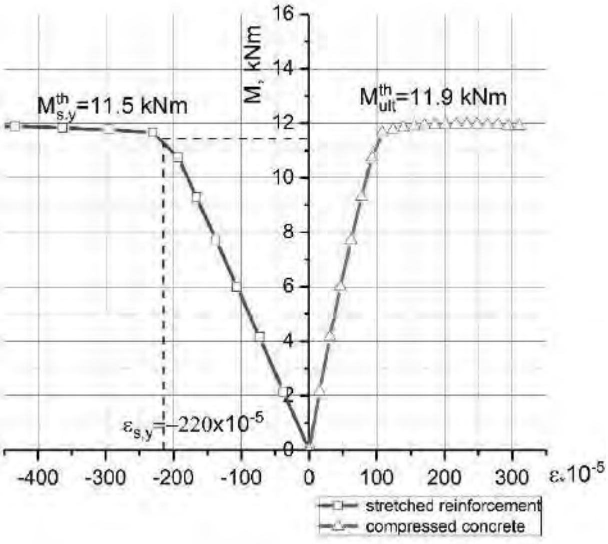


Fig. 4. The graphs of the strains` calculated values of the stretched main steel rebar's (stretched reinforcement) and the compressed concrete (compressed concrete) for beam BD-3

Table 2

Bearing capacity of beams

Sample mark	Moment which corresponds to the limit strain of the main rebars, kNm	Deviation in the bearing capacity values, %	Moment which corresponds to the limit strain of the concrete, kNm	Deviation in physical destruction, %
BC-1	23.5	–	23.7	–
BD-2	14.9	36.7	14.6	38.4
BD-3	11.9	49.4	11.5	51.5

This could be explained by the fact that in the damaged samples the main load-bearing reinforcement zone is the thermally-strengthened outer layer. Therefore, the deviation of the bearing capacity of the damaged specimens without taking into account changes in the physical and mechanical properties of reinforcement was in average 37 % and of the damaged specimens with taking into account changes this was 50 %.

Conclusion

In this article, by the theoretical research based on previous experimental research of reinforcement were identified the strength and strain parameters of reinforced concrete beams with damages, which causes the exhaustion of the bearing capacity.

The deviation of the bearing capacity of the damaged specimens without taking into account changes in the physical and mechanical properties of reinforcement was in average 37 % and of the damaged specimens with taking into account changes this was 50 %.

Changes in the physical and mechanical characteristics of thermally reinforced reinforcement must be taken into account in the design and examination of reinforced concrete structures

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РОЗРАХУНОК ЗА ДЕФОРМАЦІЙНОЮ МОДЕЛЛЮ ЗАЛІЗОБЕТОННИХ КОНСТРУКЦІЙ З ПОШКОДЖЕННЯМИ

У цій статті представлені результати теоретичного дослідження залізобетонних балок з пошкодженою робочою арматурою. Досліджено зміну мікротвердості стальної арматури діаметром 20 мм із сталі класу А500С у радіальному напрямку та встановлено товщину термічно-зміцненого шару. Встановлено, що товщина термічно-зміцненого сталевого шару арматурного стержня діаметром 20 мм А500С становить приблизно 3 мм. Виявлено, що міцнісні характеристики цього шару на 50 % вищі порівняно з матеріалом серцевини арматури, тоді як характеристики пластичності нижчі. Метою роботи є визначення міцності та деформативності залізобетонних конструкцій без пошкодження арматури та у разі її пошкодження. Визначення впливу змін фізико-механічних характеристик арматури на несучу здатність залізобетонних балок, що зазнали пошкоджень, згідно до діючих норм, що базуються на деформаційній моделі розрахунку. Ця методика використовує нелінійні діаграми деформацій бетону та арматури та базується на ітераційному методі розрахунку. Відповідно до програми досліджень було розраховано три зразки залізобетонних балок з різними параметрами. Серед них були непошкоджені контрольні зразки з одиночною робочою арматурою діаметром 20 мм – BC-1; зразок з арматурою ∅20 мм із пошкодженнями близько 40 % без змін фізико-механічних властивостей арматури – BD-2 та зразок з армуванням ∅20 мм із пошкодженнями близько 40 % із зміною фізико-механічних властивостей арматури – BD-3. Встановлено вплив зміни фізико-механічних характеристик арматури на несучу здатність пошкоджених залізобетонних балок. Для залізобетонних балок з пошкодженням 40 % робочої арматури без врахування зміни фізико-механічних характеристик арматури несуча здатність знижується на 37 % порівняно з контрольними непошкодженими зразками. Враховуючи зміну фізико-механічних характеристик, несуча здатність залізобетонних конструкцій з пошкодженням 40 % робочої арматури знижується на 50 % порівняно з контрольними зразками.

Ключові слова: залізобетонні конструкції, пошкодження залізобетонних конструкцій, пошкодження робочої арматури, несуча здатність, розрахунок залізобетонних конструкцій.