RESEARCH ARTICLE | MAY 31 2023

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AIP Conference Proceedings 2684, 030033 (2023)
https://doi.org/10.1063/5.0120475

Improving the Operating Suitability of Reinforced Concrete Structures in an Aggressive Environment

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Abstract. The issues of ensuring long-term reliable operation of building structures and creating conditions for environmental safety with the exclusion or minimization of negative impact on the environment due to failures are considered. Measures to overhaul the station for neutralization of acidic and alkaline industrial liquids – an object of increased environmental hazard, taking into account the existing defects and damage are presented. The calculation of the bearing capacity of the most damaged reinforced concrete members of the structural system is performed using the extreme properties of concrete strains and the variational method in the theory of plasticity. The stain diagram of compressed concrete, which is limited by the point of maximum strain energy, is given. The dependences for determining the parameters of the dangerous normal cross-section of structures during bending on the characteristics of the compressive strength of concrete, which is established by the results of non-destructive testing are obtained. The dependences specified in the theory of plasticity of dependence for strength definition of reinforced concrete elements in an inclined section are resulted. When developing measures to protect structures, aggressive influences are taken into account. For protection against moisture and action on reinforced concrete designs of the aggressive environment waterproofing of penetrating action and elastic water-resistant two-component and chemically resistant polymers are applied.

INTRODUCTION

When designing construction objects, their impact on the environment is assessed taking into account the functional purpose [1–5], but it is very difficult to fully predict the consequences of accidents of buildings and structures (sudden failures). Particular attention is paid to the strategy of environmental assessment, analysis of the specifics of the impact of functional processes on the environment, prevention of negative consequences [6–10]. The introduction of safety factors for responsibility (liability coefficients) of construction objects to the values of the ultimate design load according to the classes of consequences increases the reliability of buildings and structures and reduces the risks of their failure by increasing the initial safety margins. This does not exclude the risk of accidents and negative consequences, especially with a high level of physical wear and the impact of aggressive environments. To do this, it is necessary to reasonably assess the technical condition of both individual structures and buildings (structures) as a whole. Due to long-term operation, the natural physical wear of building structures leads to a significant reduction in their bearing capacity, including the level of insecurity in guaranteeing the integrity of structures for a certain period before reinforcing (condition unsuitable for normal operation) and inability to guarantee it (emergency condition). One of the directions of continuation of reliable operation of buildings and constructions is specification of bearing capacity of members of structural system on the general theoretical basis taking into account influence of physical wear and effective protection of designs against action of the aggressive environment.

Reliability and Durability of Railway Transport Engineering Structure and Buildings
AIP Conf. Proc. 2684, 030033-1–030033-8; https://doi.org/10.1063/5.0120475
Published by AIP Publishing. 978-0-7354-4501-7/$30.00

The purpose of the study is to develop a method of preserving reinforced concrete structures of high environmental hazards under the influence of aggressive environments using extreme strain properties of concrete to assess the bearing capacity of structural systems and use to protect against aggressive environments elastic waterproof two-component chemical-resistant polymers.

RESULTS OF THE INSPECTION OF THE BUILDING OF THE STATION OF NEUTRALIZATION OF ACIDIC AND ALKALINE PRODUCTION FLUIDS

As an example of removal of an ecologically dangerous object from the emergency situation, the neutralization station is considered, which is a block of shops, designed for preliminary neutralization of acidic and alkaline industrial liquids. The building has 2 floors and a basement, where there are tanks for neutralization products and cleaning of production fluids. Mark of the beam bottom is 8.400, the top of the basement floors is -4.800.

Structures of the 1st and 2nd floors are prefabricated reinforced concrete, basement structures: walls, bottom, columns, floors are cast-in-place reinforced concrete.

Process fluids contain chlorides Cl^- (800 mg/l), sulfates SO_4^- (600 mg/l), carbon dioxide CO_2 (700 mg/l). Hydrogen index of liquid environment is pH <5.0. The humid regime of the basement in the winter is wet.

As a result of inspection physical wear of designs is fixed: loss of initial physical and technical parameters of physical durability, namely indicators of durability, deformability, opening of cracks in bearing elements; heat protection and tightness of enclosing structures. Physical wear is caused by a number of factors, the most important of which are faulty ventilation, complex engineering and geological conditions of the site, heat and humidity production impacts, the impact of aggressive environments. Limes leaching in cement, crystallization of sulfates, as well as periodic freezing and thawing, oil spillage have been established. Over the past two years, the corrosion rate has accelerated significantly. The result of the influence of liquid and gaseous environment on concrete is a decrease in its strength to 20% and pH, the occurrence of internal tensile stresses and the destruction of the structure of cement stone.

Corrosion of steel reinforcement has led to more negative consequences. The surrounding concrete has lost its protective functions under the influence of carbon dioxide or newly formed salts. Cracks appeared in the concrete cover, through which oxygen, carbon dioxide and water penetrate, which led to intense corrosion of the reinforcement. Corrosion products put pressure on the concrete, as a result of which the concrete cover broke off. There is uniform and local (spot and selective) corrosion.

Of the two processes of degradation of reinforced concrete structures (corrosion of concrete and corrosion of reinforcement), the latter was much more intense, and it is he who most significantly affects the bearing capacity of structures and determines the durability of reinforced concrete.

According to the materials of the survey, the schemes of reinforcement of structures, the degree of damage and the actual strength characteristics of concrete and reinforcement are established.

The most worked were:

- reinforced concrete 12-meter covering beam with parallel belts.

There is corrosion damage to the longitudinal reinforcement up to 10% of the cross-sectional area and shear reinforcement up to 12%; exfoliation of the concrete cover, cracks along the reinforcing bars, deflection up to 20 mm are fixed; physical wear is 30%;

- reinforced concrete 6-meter girder of the 1st floor: corrosion of longitudinal reinforcement up to 25% of the cross-sectional area and cross-section of reinforcement up to 30%, the results of non-destructive testing revealed a decrease in concrete strength compared to the design class C30/35 to C25/30;
- 1st floor column: reduction of concrete strength by 10%, corrosion damage of longitudinal reinforcement up to 35%; there are cracks along the longitudinal reinforcement along the entire height of the column; physical wear reaches 50%;
- 1st floor column: reduction of concrete strength by 10%, corrosion damage of longitudinal reinforcement up to 35%; there are cracks along the longitudinal reinforcement along the entire height of the column; physical wear reaches 50%;
- basement columns: reduction of concrete strength by 20%, corrosion damage of longitudinal reinforcement by 15%; due to the influence of aggressive environment there is cracking and peeling of the concrete cover of the basement columns; the depth of the damaged layer of concrete is up to 50 mm; in some areas the structure of concrete is disturbed with a weakening of the cross section by 15%; intensive soaking due to insufficient waterproofing and high groundwater level was recorded.

As a waterproofing, the project provided for coating the walls twice with bituminous mastic due to the lack of groundwater at the time of design to the mark – 6.000. As a result of long-term operation, groundwater has risen to the mark of 4.300 and enters the basement mainly at the junction of the walls with the bottom.

The survey also identified two areas of low-quality cast-in-place concrete walls and bottoms: (high porosity).

For further safe operation of the neutralization station, it is necessary to specify the residual bearing capacity of the structures and to carry out measures to reinforce and protect the structures in accordance with the results of the calculation.

APPLICATION OF EXTREME PROPERTIES OF CONCRETE STRAIN FOR CALCULATION OF BEARING CAPACITY

An in-depth study of the phenomenon of concrete and reinforced concrete shear, to which a number of scientific works. Extreme strain properties of concrete are used to calculate the strength of reinforced concrete structures [11, 12].

The diagram of strain of compressed concrete in the form of fractional-rational function is considered

$$\frac{\sigma_c}{f_{cd}} = \frac{k\eta - \eta^2}{1+(k-2)\eta}, \tag{1}$$

where $k=E_{cd}\varepsilon_{c1,cd}/f_{cd}$, $\eta=\varepsilon_c/\varepsilon_{d,cd}$, E_{cd} – modulus of elasticity of concrete; f_{cd} – design compressive strength of concrete.

It is proposed to limit the dependence between stresses and strains by the point ε_{cu1}, which corresponds to the maximum strain energy (Fig. 1). At the value of strain ε_c exceeding the value of ε_{cu1} there is a macrodestructuring of concrete.

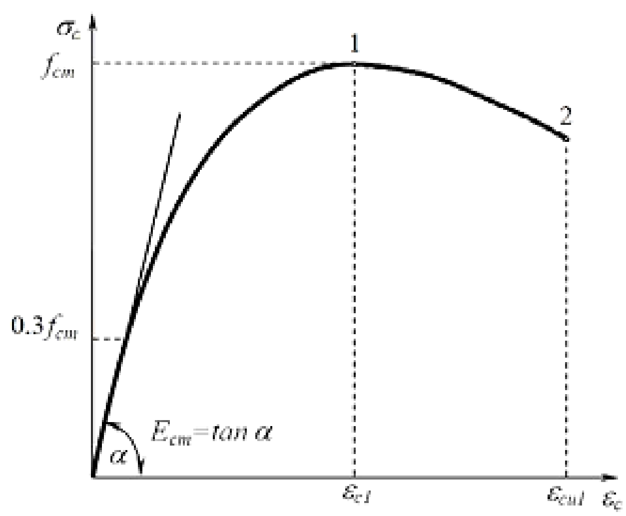

FIGURE 1. Diagram of the mechanical state of concrete under compression

The value of the ultimate strain of concrete ε_{cu1} is proposed to be found from the equation

$$\sigma_{cu}\varepsilon_{cu1} = \max(\sigma_c\varepsilon_c), \tag{2}$$

where σ_c – stress in concrete, σ_{cu} – stresses corresponding to the ultimate strains of concrete.

The design scheme of the reinforced concrete member in the normal cross section is shown in Fig. 2. When solving the strength problem, the parameters of the normal cross-section are determined: χ – the relative distance from the point of application of the equivalent N_c in concrete to the compressed face of the element and x – the height of the compressed zone of concrete. To set the parameter χ, the characteristics of the strain diagram are used: S and A – the area and first moment of mass of the stress diagram, ω – the coefficient of completeness of the stress diagram.

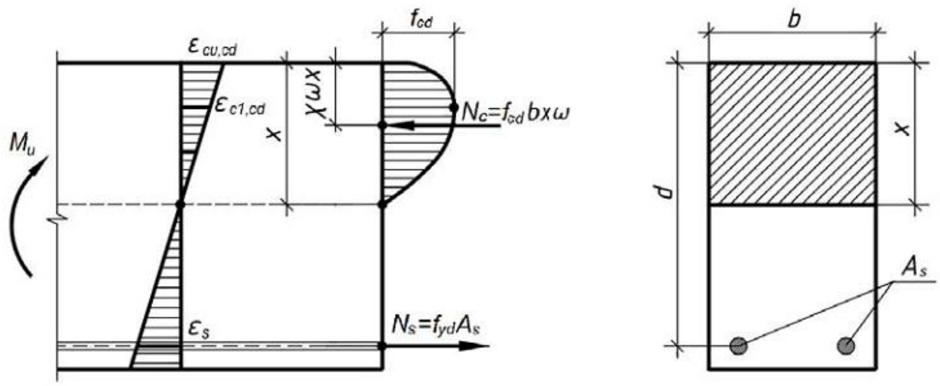

FIGURE 2. Design scheme of reinforced concrete member in normal section

The value of the strain level ε_{cu} is based on an extreme criterion

$$M_{Rd} = \max M(\varepsilon_c) = M(\varepsilon_{cu}) = f_{cd}bd^2\bar{\xi}\omega(1-\chi\bar{\xi}\omega), \tag{3}$$

where the relative height of the compressed zone of concrete is

$$\bar{\xi} = \frac{x}{d} = \frac{f_{yd}A_s}{f_{cd}\gamma_{c1}bd\omega}, \tag{4}$$

here f_{yd} – the design resistance of the longitudinal tensile reinforcement, A_s – the cross-sectional area of the longitudinal reinforcement.

Due to the fact that it is very difficult to determine the strain characteristics of concrete of the existing structure on the basis of research data as a result of approximation the dependences of the parameters of normal cross section on the characteristics of concrete resistance to compression f_{cd} were obtained

$$\eta_{cu1,cd} = 4/3 + 0.0035\sqrt{(35 - f_{cd})^3} \tag{5}$$

$$\eta_u = 1.4(1 - 0.003 f_{cd}), \tag{6}$$

$$\omega = 0.819 \times (1 - 0.003 f_{cd}), \tag{7}$$

$$\chi = 0.518\sqrt[4]{1 + 0.005 f_{cd}}\ . \tag{8}$$

When calculating the strength in the inclined section, the truss analogy and the disk model methods [13, 14] are used, specified by the variation method in the theory of plasticity [15–18]. The method received experimental confirmation [19, 20].

The problems of shear strength within a strip inclined at an angle θ to the longitudinal axis of the element and a concrete wedge that simulates a compressed zone over a dangerous crack are solved.

The design scheme for the inclined compressed strip is given in [12], the scheme of forces when calculating the action of the shear force on the inclined crack is shown in Fig. 3.

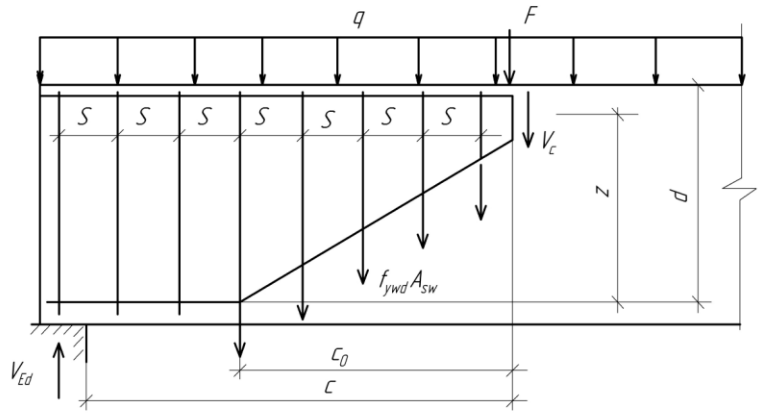

FIGURE 3. Schemes of forces in an inclined section.

By approximating the results of calculations using the extreme properties of strains, the dependences for engineering assessment of bearing capacity on inclined sections are obtained

$$V_{Rd,\max} = \frac{f_{cd}\nu(1+5\rho_w E_s / E_{cd})bz}{\cot\theta + \tan\theta}, \tag{9}$$

$$V_{Rd,s} = V_c + V_{sw} = (0.15 f_{cd} d^2 / c + q_{sw} c_o)b, \tag{10}$$

where E_s – modulus of elasticity of reinforcement; $\rho_w = A_{sw} / (bs)$, here b – section width; s – step of shear reinforcement; $z = 0.9d$, c – projection of the inclined section on the longitudinal axis of the element; $c_o = \sqrt{\frac{2 f_{ctd} d^2}{q_{sw}}}$ – projection of an inclined crack on the longitudinal axis of the element, here f_{ctd} – design tensile strength of concrete, q_{sw} – intensity of shear reinforcement; $\nu = 0.6(1 - f_{ck} / 250)$, here f_{ck} – characteristic compressive strength of concrete.

ESTIMATION OF BEARING CAPACITY OF A FLOOR GIRDER OF THE 1ST FLOOR

The resistance of concrete to shear, taking into account the peculiarities of the stress state, is proposed to be. As an example, let's consider the calculation of the girder of the 1st floor of the neutralization station.

Output data:

- the actual cubic strength of concrete in compression, established by the results of non-destructive testing, $f_{cm,cube}$=40 *MPa*, class of concrete C25/30, $f_{cd} = 17\ MPa$, $f_{ck} = 22\,MPa$, $f_{ctd} = 1.2\ MPa$, $E_{cd} = 25\ GPa$; the relative strain of concrete at the maximum value of stresses is $\varepsilon_{c1,cd} = 1.69 \times 10^{-3}$;

- longitudinal reinforcement in the tensile zone in the areas without damages 4Ø28 class A400C is established in 2 levels along the height; $f_{yd} = 364\,MPa$, $E_s = 2.1 \times 10^5\ MPa$, in the middle, taking into account the corrosion damage of the span, the cross-sectional area is $A_s = 2463 \times 0.75 = 1847\ mm^2$;

-shear reinforcement 2Ø12 class A400C: $f_{ywd} = 285\,MPa$, intense corrosion damage of the reinforcement is fixed at a distance from the support of 0.7 – 2.2 *m*, the average step of the reinforcement on the damaged area is $s = 175\,mm$; taking into account corrosion damage, the cross-sectional area is equal to $A_{sw} = 226 \times 0.7 = 158\,mm^2$.

Cross section of a girder: *b*=300 *mm*, *h*=800 *mm*, *d*=730 *mm*.

From the static calculation the values of the bending moment in the middle of the span $M_{Ed} = 410\ kNm$ and the shear force in the dangerous inclined section at a distance $c = 3d$ from the support $V_{Td} = 390\ kN$ are established.

The calculation of strength in the normal cross section is performed by formulas (3 – 8):

$$\bar{\xi} = \frac{364 \times 1847}{17 \times 0.9 \times 300 \times 730 \times 0.777} = 0.258 < \bar{\xi}_R = 0.605,$$

$$\eta_{cu1,cd} = 4/3 + 0.0035\sqrt{(35-17)^3} = 1.6,$$

$$\eta_u = 1.4(1 - 0.003 \times 17) = 1.33,$$

$$\omega = 0.819 \times (1 - 0.003 \times 17) = 0.777,$$

$$\chi = 0.518\sqrt[4]{1 + 0.005 \times 17} = 0.529.$$

We check the condition $\eta_u = 1.33 < \eta_{cu1,cd} = 1.6.$

$$M_{Rd} = f_{cd} b d^2 \bar{\xi}\omega(1 - \chi\bar{\xi}_R\omega) = 17 \times 0.9 \times 300 \times 730^2 \times 0.258 \times 0.777 \times (1 - 0.529 \times 0.258 \times 0.777) = 438.3\ kNm,$$

$$M_{Rd} = 439.8\ kNm > M_{Ed} = 410\ kNm.$$

The calculation of the strength in the inclined section is carried out according to the formulas (9) and (10):

$$V_{Rd,\max} = \frac{17 \times 0.9 \times 0.547 \times \left(1 + 5 \times 3.01 \times 10^{-3} \times 210/25\right) \times 300 \times 660}{2.5 + 0.4} = 643.6\ kN,$$

where $\rho_{sw} = A_{sw}/(bs) = 158/(300 \times 175) = 3.01 \times 10^{-3}.$

$$V_{Rd,s} = (0.15 \times 17 \times 0.9 \times 730/3 + 285 \times 3.01 \times 10^{-3} \times 1.59 \times 730) \times 300 = 466.2\,kN,$$

where $\frac{c_o}{d} = \sqrt{\frac{2 \times 1.2 \times 0,9}{3.01 \times 10^{-3} \times 285}} = 1.59,$ $V_{Rd} = 466.2\ kN > V_{Ed} = 390\ kN.$

The bearing capacity of the girder of the 1st floor is provided. The technical condition is satisfactory. Effective protection measures must be taken.

MEASURES TO REINFORCE AND PROTECT STRUCTURES

Based on the results of calculations of bearing capacity and assessment of the technical condition of the structures of the neutralization station, measures have been developed to reinforce and protect them.

The column of the 1st floor, which bearing capacity is not provided, is reinforced, but integrity at the moment of reinforcing is provided – a technical condition is not suitable for normal operation. Reinforcing is performed by installing a steel casing (Fig. 4). The joint operation of the existing column and reinforcement elements is achieved by tightening the inclined struts with an inclined *i*=0.03 bolts and installing them in the design vertical position. For this purpose, in corners of struts in the middle of height apertures in one shelf are arranged.

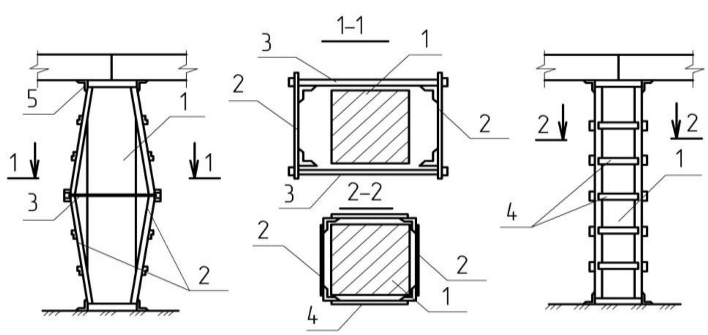

FIGURE 4. Reinforcing of the column with a steel casing: 1 – column; 2 – struts from corners and laths; 3 – tension mounting bolts; 4 – connecting strips that are welded after the struts are installed; 5 – angle stops.

The bearing capacity of other structures is provided, but there are damages that affect their durability, and measures should be taken to protect (repair) the following sequence. Drain groundwater from the basement.

Before installing the penetrating waterproofing, the corrosion products of reinforcement and concrete of the damaged wall structure should be removed mechanically. At the place of the greatest penetration of soil moisture, clean the cracks, blow them out with compressed air, moisten them and fill them with "Drizoro" grouting cement (Spain). Protect damaged areas of bottom and wall concrete by creating an adhesive layer between old and new concrete and restore the weakened section by filling sinks, pores, areas of loose concrete. To do this, use the repair solution by Drizono within 20 minutes from the moment of its preparation. In the place of adjoining of walls to the bottom transitional sides are arranged. The first layer of Vandex waterproofing solution manufactured by Vandex Int (Switzerland) is applied to the cleaned and moistened surface of the bottom and walls with a stiff brush. The next layer is applied in a direction perpendicular to the previous one. The total thickness of the coating is 1.5 – 3.0 *mm*. After about 5 – 7 days, the material, reacting to moisture in the pores and capillaries of old concrete, creates crystalline neoplasms that compact the structure of concrete and make it impossible to filter groundwater. For mechanical and chemical protection of a waterproofing of a floor in 1 – 2 days the covering from acid-resistant tiles is arranged.

In order to ensure the durability of the basement columns during the repair, the influence of the aggressive environment is taken into account. Thus, the operating conditions of the basement of the neutralization station are characterized by constant humidification of the lower part of the column with production fluids, which include sulfates and chlorides, constant action of carbon dioxide at high humidity over 80%, as well as periodic humidification of the upper part of the column. Liquid environment in relation to concrete and reinforcement is moderately aggressive, gaseous environment, which contains carbon dioxide, in relation to concrete is weakly aggressive. The maximum degree of aggressiveness is accepted for designing of protection – the environment is moderately aggressive. The damaged layer of concrete is replaced with a new one of fine-grained concrete. Materials of the Polirem (Ukraine) are recommended. To create an adhesive layer between old and new concrete and protection of reinforcement, two-component materials Polymer SGi622+ are used, which are applied with a brush in thin layers on the prepared surface of reinforcement and concrete. From the action of the liquid environment, the columns up to a height of 1.5 m from the floor level are protected by acid-resistant ceramic tiles, which are placed on the solution with Polymer SGi625 Extra. The waterproofing is attached to the pre-primed surfacing surface of the rolled material. The repaired surface of the basement column is higher than 1.5 m and the basement floor constructions are protected from the influence of the gaseous environment by a 0.15 mm thick paint coating. It is proposed to use enamel HV-785 and HS-710. When repairing the column on the 1st floor, the survey data are taken into account: uniform damage to the concrete cross-section to a depth of 30 *mm*, corrosion damage to the principal reinforcement up to 35%. Cold galvanizing is used to protect steel elements from corrosion. The primer from a zinc-filled composition Tsinol and a covering with two intermediate layers and a finishing layer from a metal-filled polyurethane paint are used. To ensure the durability of the column of the 1st floor after reinforcement, it is necessary to perform secondary protection of the repaired concrete surface with a paint coating.

To protect the 1st floor and floor structures, the concrete of the damaged structure must be removed. Then clean the surface mechanically, blow with compressed air, degrease, clean the bare reinforcement from corrosion products, apply an adhesive coating on the reinforcement (coating composition in parts by weight: Portland cement – 100, casein glue – 5, sodium nitrate – 10, water 30 – 40), moisten the concrete surface of the intact structure and restore the structure with fine-grained concrete.

CONCLUSIONS

To create conditions for reliable long-term operation of construction sites with high environmental hazards under aggressive influences of production processes, it is necessary to timely assess the technical condition of structural elements on the basis of a refined method of calculating their residual bearing capacity and take appropriate measures to reinforce and protect structures.

In the direction of refining the bearing capacity of concrete and reinforced concrete structures, the application of extreme properties of concrete strain and the theory of mechanics of deformable solids is promising.

The use of the strain diagram of compressed concrete in the form of fractional-rational function, equation $M_{Rd} = \max M(\varepsilon_c)$, variational method in the theory of plasticity and extreme criteria of energy and strain energy allows to solve problems of strength of reinforced concrete elements in normal section on bending moment and in inclined section on action of shear force.

Based on the obtained theoretical results for the engineering calculation of the strength of reinforced concrete structures, the approximate dependences of the calculated parameters of normal cross section on the actual compressive strength of concrete are offered, established by the results of non-destructive testing of existing objects, as well as calculation dependences to determine the ultimate shear force in the inclined section are refined. To increase the serviceability of reinforced concrete structures with a high level of groundwater penetrating into the middle of the basement, and under the influence of aggressive environments, it is proposed to use waterproofing penetrating action and elastic waterproof two-component polymer (cement binder, aggregate, modifying additives+ water dispersion) for protection of reinforcement and priming of concrete and two-component reinforced highly elastic chemically resistant polymer for restoration of concrete structure.

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