Limit state of steel reinforced concrete round plates in the operational stage

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Abstract. The results of the study of round thin reinforced concrete thin reinforced concrete and steel concrete slabs with external sheet reinforcement at short and long operational load are presented. According to the results of theoretical and experimental studies, the behavior of thin plates at various stages of the stress-strain state and also the possible fracture patterns, taking into account the flexibility of the contour structures of the changing properties of the materials and the duration of operation, are revealed.

1. Introduction
At present, much attention is paid to the development of effective structural solutions for reinforced concrete and steel-concrete round slabs. There is a sufficiently accurate methodology for their calculation from elastoplastic materials, which allows simulating the behavior of the structure under prolonged operational load taking into account the redistribution of forces up to failure. However, these calculations are associated with complicated cumbersome calculations for which it is very difficult to normalize the calculated parameters.

2. Analysis of recent research
Simplified methods are also adopted that give fairly accurate solutions that are convenient for practical calculations of spatially statically indeterminate structures. Using this method, one can attribute the equilibrium method developed by Gvozdev A.A. [1], which has found a wide application in the calculations of the bearing capacity of reinforced concrete structures, including slabs [2-5], as well as in the calculations of composite rods and slabs with elastoplastic layers and elastoplastic bonds shear. Let us consider here the limiting state of composite plates, the type of which can be attributed to reinforced concrete steel-concrete slabs, due not only to the strength properties of the components making up the slab, but also to the properties of the means providing local work. As it shown in the theory of composite rods and plates, one of the possible forms of destruction of articulated structures is the loss of bearing capacity due to insufficient shear bond strengths [3-5,8-10].
In the works on steel-concrete slabs [8, 10] it is considered that the bearing capacity for shear bonds to be provided, for which it is recommended to assign the required anchoring intensity of sheet reinforcement with concrete from the condition of equality of shear forces perceived by the anchor to the ultimate force perceived by the cross section of the steel sheet. This condition is valid only in cases where the same work of ties-anchors in contact area is ensured. Therefore, in [8-10] to prevent
destruction by an unprofitable fracture pattern, it is considered necessary to take out the unifying means beyond the edge of the support plate. At present, there is no solution for taking into account real climatic conditions, there are also no criteria for limiting operational conditions for maximum span of a structure. The purpose of this study is to determine the stress state at various stages of assessing the ultimate long-term operational loads on reinforced concrete and steel-concrete plates of circular shape, as well as to study their operation in the operational stage and in the ultimate state.

3. Long-term deformed state of reinforced concrete round thin plates at high loading levels
(Presented by Academician of the Academy of Sciences of the Republic of Uzbekistan T. Sh. Shirinkulov). The authors consider the problem of a long stress-strain state of a round thin plate, taking into account the flexibility of the support contour and the geometric nonlinearity of the system under the action of a uniformly distributed load.

Considering that the thickness of a thin plate does not change along the radius except for the marginal zones, and its flatness allows the equation of equilibrium of elements to be written in the form.

\[
\frac{dw}{dr} \sigma_r = -\frac{qr}{2h} \left[ 1 + \left( \frac{dw}{dr} \right)^2 \right] \left( 1 + \frac{r}{h} \cdot \frac{dh}{dr} \right) + r \frac{dw}{dr} \sigma_\theta; \quad \sigma_\theta = \sigma_r \left( 1 + \frac{r}{h} \cdot \frac{dh}{dr} \right) + r \frac{d\sigma_r}{dr},
\]

(1)

where \( q \) is the load intensity, \( h \) is the plate thickness, \( r \) is the radial coordinate, \( w \) is the deflection. Radial \( \varepsilon_r \) and annular \( \varepsilon_\theta \) deformation of the element, considering the deflection of the plate is large as compared to the thickness. \( w > h \) for the field of geometric nonlinearity, we write as

\[
\varepsilon_r = \frac{du}{dr} + \frac{1}{2} \left( \frac{dw}{dr} \right)^2, \quad \varepsilon_\theta = \frac{u}{r}.
\]

(2)

where \( u \) is the radial displacement.

At high loading levels, a circular region of plastic deformations arises in the center of the thin plate. Within this area, based on the conditions of the Genka, we write

\[
\frac{\sigma_r}{\sigma_\theta} = \frac{2\varepsilon_r + \varepsilon_\theta}{2\varepsilon_\theta + \varepsilon_r}.
\]

(3)

In view of (1) and (3), we will have

\[
\sigma_r = \sigma_\theta = \sigma_y, \quad \varepsilon_r = \varepsilon_\theta, \quad \frac{dw}{dr} = -\frac{qr}{2h\sigma_y}.
\]

(4)

where \( \sigma_y \) is stress corresponding to the yield strength of the plate material. From here, taking into account (2), we obtain

\[
w = w_n + \frac{q}{2h\sigma_y} (r_n^2 - R^2), \quad u = \frac{u_n}{r_n} \cdot r + \frac{q^2}{16h^2\sigma_y^2} (r_n^2 - R^2) r,
\]

(5)

where \( w \) and \( u_n \) is deflection and radial displacement at the boundary of the plastic region; and from conditions of continuity of deformations is determined when \( r = r_n \); \( R \) is radius of the plate.

The results of the research showed that with the height of the plate \( h \leq 1/200d \) and high loading levels, a membrane stress-strain state is observed.

For these cases, carried out a theoretical analysis of the long-term stress-strain state in a geometrically nonlinear formulation showed that three areas can be distinguished in a thin plate with a compliant support contour:

1) a circular region where biaxial tension occurs on a large surface of the central part of the slab and the reinforcement stress reaches the yield stress \( \sigma_r = \sigma_\theta = \sigma_y \);

2) the annular region of elastic deformations with biaxial tension \( \sigma_\theta \leq \sigma_r < \sigma_y \);
3) the annular region of elastic deformations with a uniaxial stress state $\sigma_\theta = 0$, $\sigma_r > 0$.

As you move away from the contour, compressive forces drop sharply to a distance of about 1/10 of the radius of the coating. There is also the appearance of a region of zero forces, which later turn into tensile forces.

Numerical studies showed that in places where a thin slab adjoins the external supporting contour, the difference between radial and annular compression forces reaches 24%. With a decrease in the relative arrow of the deflection of thin plates, the difference in effort and deflection decreases.

One of the parameters studied that most significantly affects the operation of long-loaded thin plates is the flexibility of the support contour, the decrease in the longitudinal rigidity of which leads to an increase in the deflections which is determined by the geometric nonlinearity of the system.

For the operation stage on the deformable support contour, equating the ring deformations of the plate and the contour, we obtain;

$$A_k E_k \varepsilon_n P_n \varepsilon_{q_b} A_n P_n = 0.$$  \tag{6}

We write conditions (6) for a long-loaded thin coating plate:

$$B_k P_n \geq B_k P_k \varepsilon_{q_b} \varepsilon_{r_b},$$  \tag{7}

where $B_k = A_k E_k$, $B_n = A_n E_n$ – is stiffness of support contour $P_n = (1 + \varphi_r)$, $P_k = (1 + \varphi_p)$ - parameters of long-term deformation of the plate and the support contour;

$$\varphi_t = \frac{\varepsilon(t, \tau)}{\varepsilon_c} = C(t)(t, \tau) E_b(\tau).$$  \tag{8}

creep characteristic of concrete: $C(t)$ – creep measure; $E_b(\tau)$ – modulus of elasticity of concrete at the time of loading. For short-term loading, it is accepted $\varphi_t = 0$.

Studies have shown that the long-term operation of such structures does not significantly depend on the flexural rigidity of the contour even for asymmetric loads, and for axis-symmetric loads in most cases it is decisive.

$\sigma_r$, the dependence is obtained For the case of prolonged loading, when determining the bearing capacity corresponding to the stress in the reinforcement which is equal to the yield strength

$$q_a = k_4 \frac{R_{yp}(1 + \beta_2 \mu)}{r_c} \left[ \frac{R_{yp}(1 + \beta_2 \mu)}{E_b(1 - \alpha_2 \mu)} \right].$$  \tag{9}

It should be noted here that at this load in the near-voltage zones $\sigma_r$ and $\sigma_\theta$ do not reach the limit values. Durable material strength $R_{yp}$ on 15-20% is lower than for short-loaded structures.

Thus, by using the above expressions and following the force (7) in the field of nonlinear deformation, the long-term stress-strain state of a round thin plate in the operational stage is estimated depending on the nature of the long-term operation of the edge structures.

4. Results and discussion

The stress-strain state of an iron-concrete round flat-formed thin plate was experimentally studied, taking into account the joint work of the support ring [4, 6, 12, 14].

The scales of the models from the conditions of physical modeling were taken equal to M1:10, M1:15, M1:20 [5,6,13,15].

Models with a diameter of 1200 mm and a plate thickness of 5 mm were tested. The dimensions of the support ring were 100x50 mm. At the junction points of the plate to the support contour, 60 mm wide vuts were provided. The thickness of the vut was taken at the junction of the plate with the support ring 20 mm, gradually decreasing to the thickness of the plate in the direction of the center.
The model fields were reinforced with a single layer of welded mesh with 12.5x12.5 mm cells from 0.6 mm wire, the pitch of which was determined from the calculation, satisfying the condition for crack opening width \( a_{cr} \leq [a_{cr}] = 0.3 \text{ mm} \) in operational condition [7].

The reinforcement of the near-edge vut was carried out by installing a second layer of the mesh, designed for the action of the moments of the "edge effect". The support rings were reinforced with knitted frames consisting of a reinforcing wire of class Bp-1 by diameter 3 mm.

For the manufacture of models used fine-grained concrete composition \( \Pi/II = 1:2,12 \) and \( B/II = 0,45 \). Testing the models for evenly distributed load was carried out on a specially designed bench. The models were supported on the stand along the support ring through 12 supports. Models were loaded using piece goods weighing 0.1 and 0.2 kN. Physico-mechanical characteristics of the materials of the models were determined by testing special samples. Standard prismatic strength for fine concrete 15 MPa, elastic modulus 21,7-10^3 MPa, the Poisson's ratio \( \nu = 0,219 \). For a wire with a diameter of 6 mm, the yield strength is 235 MPa, and the temporary resistance is 317 MPa. For \( \varnothing 2 \) mm wire, the temporary resistance is 603 MPa.

Tests of models of plane-formed reinforced concrete thin slabs demonstrated the possibility of manufacturing and operation of such full-scale structures [1,6,8-10].

The results of the carried out studies showed that with increasing loads on a thin plate, both geometric and physical nonlinearities were revealed increasing at different loading levels. To assess this state at high loading levels, it was assumed that the value total deflection \( \omega \) of the plate consists of elastic \( \omega_e \) and inelastic (plastic) \( \omega_p \) components

\[
\omega = \omega_e + \omega_p. \tag{10}
\]

The modulus of concrete deformation was determined by the formula:

\[
E_b = \left(1 - \frac{\omega_p}{\omega}\right)E_b = \lambda \phi E_b. \tag{11}
\]

where \( E_b \) is the elastic modulus of concrete; the quantities \( \omega_e \) and \( \omega_p \) were determined by the results of the experiment [7,15].

The use of expression (11) in practical calculations, although convenient, but it requires the use of specific experimental results each time in the form of dependencies.

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\[
E = f(q) \quad \text{and} \quad \omega = f(q) \tag{12}
\]

for the designed structure. Ensuring these requirements is not always possible, therefore, to determine the modulus of concrete deformation, we used the developed analytical calculation method [7].

Let us analyze the deflections and deformations of the slab model in the most stressed areas and in the middle of the slab field (Figure 1). The maximum deflection was 40.4 mm, or 1/30 of the diameter. After unloading, the residual deflection of the slab was 38 mm. This implies, that when the plate and the contour element worked together, the rigidity of the plate was much less than the rigidity of the contour element.

Diagrams of deflections of a round thin plate in the center in the axisymmetric direction are close to a parabola (Figure 1). The maximum deflection was observed in the middle of its span, the minimum - in the marginal zones, which are characterized by jamming of the slab in the contour structures with the help of the structural wool. As it can be seen from the figure, under load 0.701 kN/m² the slab worked without visible cracks and with insignificant deformations. The deflection of a thin plate in the middle of its span was 1.95 mm, the maximum relative deformation in the lower stretched surface of the plate was 11.7·10⁻⁵. For the upper compressed surface, the deformation was 13·10⁻⁵. With an increase of load to 1.402 kN / m², cracks formed in the middle of the span on the lower surface of the plate.
The upper surface of the plate was still working in compression and relative deformations reached $20 \cdot 10^{-5}$. From this moment on, the plate worked inelastically, to evaluate its stress-strain state, the theory of calculating the bending of nonlinear flexible plates was used [2,4, 5-9].

A further increase of load to 2.103 kN/m² led to a stretching of the upper surface of the slab. Relative deformations amounted to $20 \cdot 10^{-5}$. To assess the stress-strain state of the plate, the theory of nonlinear calculation of absolutely flexible plates, such as a membrane, was used. In this case, the detected initial bending state passed into the membrane state [2,4,6,8-10].

At further loading stages, the formed cracks opened, developing along the length and width (Figure 1). On the bottom surface of the plate, meridional cracks appeared, truncated in the center of the plate. It should be noted that with increasing loads up to 1.402 kN/m², cracks were formed on the upper surface in the edge zones of the slab.

Where in compressive stresses appeared on the lower surface of the plate, which remained until the penultimate stage of loading, equal to 3.505 kN/m². At the last stages of loading, meridional cracks on the upper surface of the plate were connected with cracks on the lower surface and in the annular direction, which indicates the likelihood of local destruction of the center of the plate [7-9]. In this case, the maximum relative deformations in the radial direction amounted to $165,1 \cdot 10^{-5}$, and the stress in the reinforcement reached 247.5 MPa.

**Figure 1.** Deflections $\omega$ in the model of a round thin plate: a is the - graph of the dependence "load-deflection"; b – is a change in the shape of the surface along the axis of symmetry. Designations: 1-7 - loading stages; 1-9 - the studied points. —— experienced, - - - - theoretical deflection.

Deformations and stresses on the upper surface of the plate also approached these values. The support contour (ring) experiences a complex stress-strain state due to the action of bending and torque moments, accompanied by radial and ring forces of the field of a thin plate. Therefore, these...
structures, both in the vertical and horizontal directions, can be calculated as eccentrically compressed elements without taking into account the influence of torque. The presence of VUT reduces the region of tensile stresses in the field of the plate up to 0.1-0.15 span from the contour. Therefore, in engineering calculations, the vut structure can be considered as a support ring having a complex geometric section, which allows developing an effective structural solution of coatings. An increase in the external load led the tested models of thin plates to the stage of destruction, which can occur as a result of the destruction of the fields of round thin plates with reaching stresses in concrete and reinforcement [6,8] of limit values. The possibility of destruction of the support contour and the marginal contour zone of the slab experiencing a complex stress-strain state [9-12] are also shown. The assessment of the operational conditions of coating structures according to the criteria of crack resistance and displacements is adopted in accordance with the condition

\[ a_{rc} \leq [a_{rc,a}]; \quad \omega \leq [\omega_{a}] \]  

(13)

when \( a_{rc} \), \( \omega \) - is estimated cracks opening width and deflection from standard load; \([a_{rc,a}]\), \([\omega_{a}]\) – is the maximum width of the opening of cracks and deflections allowed in the operational state and regulated by instructive documents. When checking, the magnitude of the deflection for the adopted specific designed decisions is determined by the calculation of the plates taking into account the deformations of the support contour. In this case, the value of the maximum permissible deflection \([\omega_{a}]\) is taken equals to full deflection \(\omega_{1}\) taking into account the deflection from short-term application of the load, following to the conditions

\[ [\omega_{1}] = \omega_{0}[1 + E_{0}C(t, \tau)] \leq 0.1R \]  

(14)

where \( \omega_{1} \) – is a long deflection of the structure in operational condition; \( \omega_{0} \) - is the deflection of the structure at the time of the load. Estimated breaking load of the tested model of a thin round plate (membrane) - 4,63 kN/m², expected experimental breaking test load discrepancy - 6.04%.

Thus, a comparison of the calculated and experimental values of round flat-formed thin plates (membranes) according to the criteria of bearing capacity, resistance to cracking, and displacement confirmed the reliability of the obtained results of experimental and theoretical researches. As a result of the carried out tests, the specific features of the stress-strain state of the plates under consideration in the elastic stage and in the stages of crack formation and destruction were determined, the results of which allow us to develop new effective structural solutions for buildings using thin reinforced concrete round slabs coatings such as membranes concreted on the plane. The fundamental possibility of their manufacture, erection and operation are shown.

To implement the proposed method for solving problems, on determination of the stress-strain state of thin reinforced concrete round slabs taking into account the deformation of the support contour and inelastic properties of the material, an algorithm and a program for calculating the structures under consideration are developed, an analysis of the calculation results and comparison of their experimental data are made.

The application of the carried out research results opens up wide possibilities for the further implementation of reinforced concrete round thin flat-formed slabs (membranes) of coatings in buildings for various purposes. The application area of these structures can especially be expanded with the use of fiberglass reinforcement, fiber concrete and self-expanding cement in their manufacture. For high levels of operational loads, it is considered advisable to use steel concrete slabs, the operation of which is investigated below.

5. Load-bearing of steel concrete round slabs in the operational stage

We introduce the intensity coefficient of the connection of the steel sheet with concrete as the ratio of the total force perceived by the shear bonds to the force at which the stresses in the steel sheet reach the yield strength, which is the criterion for determining the breaking in contact or normal cross-section during operation [8,10].
\begin{equation}
k_u = \sum_{i=1}^{n} \frac{Q_i(t)}{\pi d A_i \sigma_{yd}}, \tag{15}\end{equation}

where \( Q_i(t) \) – is bearing capacity i-the connection shift in operation, \( \sigma_{yd}, A_i \) - yield strength of sheet reinforcement and steel sheet area per unit of section length; \( d \) – diameter of a slab.

If \( k_u < 1.0 \), then the ultimate state of the steel-concrete slab, in which the mechanical properties of the sheet reinforcement will not be used to the full extent. In case, when \( x_u > 1.0 \), the ultimate state is determined from the strength condition by the normal section and by the contact of the steel sheet with concrete.

We offer the following method for determining the bearing capacity. We will assume that the destruction of the slab during a long operational load will occur according to the well-known scheme, and the value \( \eta_i = \sigma_2 / \sigma_1 = const \) in steel and in concrete, is constant, or in the construction of a deformation of a nonlinear nature. Then, in the limiting state, the quantity \( \eta_i \), found from the elastic calculation will be valid for the points of the plate along the line of the plastic hinge. A long-term stress state in a section, perpendicular to the lines of a plastic hinge is adopted in the following form (Figure 2).

\begin{figure}
  \centering
  \includegraphics[width=\textwidth]{figure2.png}
  \caption{Long-term stress state of a steel-concrete slab along the lines of plastic joints}
\end{figure}

Designing all the forces acting in the section, we write:

\[ \sum X = 0; \sigma_{cd}(t)\chi(t) - \sigma_y(t)A_i = 0. \]

where from

\[ X(t) = \frac{q(t) - A_i}{\sigma_{cd}(t)}. \tag{16} \]

We compose the equation of the moments of all forces with respect to the neutral line

\[ dM_i(t) = \sigma_{cd}(t) \frac{x^2(t)}{2} + \sigma_y(t)A_i(h_o - x(t)). \tag{17} \]

In view of (15), we find the limiting moment along the line of plastic hinges in the stage of operation, where \( li \) is the length of the i-th section of the plastic hinge; \( \sigma_{sw}, \sigma_{cd}(t) \) is the ultimate stresses in steel sheet and concrete, taking into account the study of biaxial stress state \( \sigma_{cd}(t) \) - is long-term concrete strength under uniaxial compression, \( h_o \) – is working section height; \( A_i \) – is the area of sheet reinforcement per unit width of the plastic hinge.

In accordance with the plasticity condition according to the Mises energy theory, we have [2-4]:

\[ \sigma_{ul} = \sigma_y \sqrt{1 + \eta^2 - \eta} \tag{18} \]

where \( \sigma_y \) – is physical tensile strength; \( \eta \) - variable value along the line of the plastic hinge.

The volume of the plot of long deflections is assumed (Figure 3) to be equal to \( V = S \cdot w / 3 \), where \( S = \pi r^2 \) – base area The work of external forces with uniformly distributed continuous load.

\[ W_q = qV = \frac{q\pi^2 w(t)}{3}. \tag{19} \]
The work of external forces with continuous centrally applied concentrated force
\[ W_F = Fw(t). \]  
(20)

The work of internal forces from long loads
\[ A = -M_u \cdot 2\pi w. \]  
(21)

Equating the work of external and internal forces, we obtain expressions for determining the ultimate long-term load during the destruction of the plate along the normal section:
\[ q_u(t) = \frac{6M_u(t)}{r^2}. \]  
(22)

At prolonged centrally applied concentrated force
\[ F_d(t) = M_u(t) \cdot 2\pi. \]  
(23)

If the plate is closed along the contour, then the work of forces in the hinges located along the contour should be added to the work formula. Following [1, 2], we obtain expressions for the distributed and concentrated continuous load:
\[ q_u(t) = \frac{6(M_u(t) + \dot{M_u}(t))}{r^2}, \]  
(24)
\[ F_d = (M_u(t) + \dot{M_u}(t))2\pi, \]  
(25)

Where \( M_u(t) \) – is a longitudinal moment at plate bending

\[ M_u(t) = \int_0^t A_i \sigma(t) \left[ h_0 - \frac{0.5A_i \sigma(t)}{\sigma_{id}(t)} \right]. \]  
(26)

In the theory of composite rods and plates, for which one of the possible forms of destruction of articulated structures in a long operational stage is the loss of long-term bearing capacity due to insufficient shear bond strength. This allows you to determine the long-term limit values of the loads and ultimate deformation in the stage of ultimate equilibrium.

6. Conclusions
Based on the carried out researches limit state assessment of reinforced concrete and steel concrete thin round plates in a long operational stage, the following conclusions can be drawn:

According to the results of the studies, a method for calculating thin reinforced concrete and steel concrete round plates based on the theory of flexible plates taking into account the normalized parameters of nonlinear deformation of materials and deformations of the support contour has been developed.
- The conducted studies allow us to assess the stress-strain state of thin steel-reinforced concrete round plates at various systems and levels of long-term operational load.
- The obtained research results contribute to the further development of structural analysis methods, opening the real possibility of the widespread introduction of effective structural solutions of thin steel-reinforced concrete round slabs for the construction of buildings in various regions.

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