Deflections of partially previously strained reinforced concrete constructions at repeated loadings

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Abstract. The behavior of partially prestressed structures under repeated loads is considered. The effect of repeated loads on the deflections of partially prestressed structures is studied. The analysis of the deflections after the influence of the cycles of reloading on the deflections of partially prestressed structures at various levels of reloading carried out. It revealed that after the formation of cracks, the stiffness of the cross sections of the beams significantly decreases, because of which an acceleration of the increment of deflections observed. The linearity of the graphs of the dependence of the deflection on the moment violated: a characteristic break point appears, the deflection lines become convex in the direction of the load axis. In contrast to specimens without prestressing or fully prestressing, in the partially prestressed elements, three characteristic break points of deflection curves corresponding to crack formation, yield stress of tensile and non-tensile reinforcement can be distinguish.

1. Introduction

When exposed to repeated, cyclic and seismic loads, partially prestressed structures have more efficient performance due to ductility and energy absorption. Therefore, the article discusses partially prestressed structures designed for regions with high seismicity indicators.

The effect of reloading on the deflections of partially prestressed concrete structures studied in the works of Arslanbekov M. M., Babich E. M., Golovin N. G., Stasyuk M. I. It known that repeated loads increase the deflection in comparison with the first loading in 1.5 ... 2.8 times. Depending on the classes and the ratio of prestressed and non-tensioned reinforcement, repeated application of the load increases the deflection by 30 ... 70% compared with a single loading. At a high load level (η> 0.9), the maximum and residual deflections can increase by more than 2 times in comparison with those obtained in the first cycle. Moreover, the main processes of deflection formation take place in the first 20 cycles of reloading. At average levels of reloading (η=0.6 ... 0.7), stabilization of maximum deflections occurs after 3 ... 5 cycles. When exposed to beams without load between successive cycles during the day, the residual deflection decreases by 10 ... 15%.

The increment of deflections during repeated loads is due to an increase in the opening width and height of normal cracks, intensification of creep and plastic deformations of concrete in the compressed zone at alternating stresses, and the possible formation of cracks in the compressed zone.
2. Methods

Under the action of the moment from the external load \( M \), close to the moment of crack formation \( M_{crc} \), the relative increase in the deflections is higher than under the action of the moments \( M \), significantly exceeding \( M_{crc} \). In the work of Klebleev E.K. at \( M_{crc} \approx 0.5M_u \), after 24 cycles of testing prestressed beams in \( 0.5M_u - 0 \) mode, the deflections increased 1.8 times; with a test mode of \( 0.75M_u - 0 \) – 1.4 times, and with \( 0.9M_u - 0 \) - only 1.2 times. The analysis shows that upon repeated loading the relative increase in the deflections for partially prestressed concrete beams is mainly influenced by the state of the stressed sections during the first application of the load. Research M.I. Stasyuk found that after the second application of the load at \( M/M_u < 0.4 \), the relative increase in total deflections compared to the first loading \( f_2/f_1 \) is 1.4 ... 2.7 times, and at \( M/M_u \geq 0.4 \) - \( f_2/f_1 \) = 1.02 ... 1.4. It proposed to calculate the increase in total deflections by averaged linear relationships:

\[
\text{at } \rho' = \frac{M}{M_u} < 0.4 \quad f_2 = f_1 (2.89 - 3.86 \rho'); \quad (1)
\]

\[
\text{at } \rho' = \frac{M}{M_u} \geq 0.4 \quad f_2 = f_1 (1.61 - 0.56 \rho'); \quad (2)
\]

Linear. After the formation of cracks, the stiffness of the cross sections of the beams decreases markedly, resulting in an acceleration of the increment of deflections. The linearity of the \( M-f \) graphs is broken: a characteristic break point appears, the deflection lines become convex towards the load axis. In partially prestressed elements, there are three characteristic break points of the deflection curves corresponding to crack formation, yield stress of tensile and non-tensile reinforcement.

3. Results and discussion

Processing the available test results of the beams made it possible to establish a correlation between the relative increase in the deflections and the partial prestress coefficient (Figure 1). The obtained value of the correlation coefficient \( r_{\eta k} = 0.846 \) indicates the presence of a significant relationship between \( \eta_f \) and \( k_p \). It revealed that the amount of prestressed reinforcement is the main reason for the increment of deflections during repeated loads of the operational level. The confidence interval with an average value \( \overline{\eta_f} = 1.342 \) corresponding to the confidence probability \( P = 0.95 \) is \( J_\eta = (1.155; 1.529) \) (see Figure 1).

It is of interest to determine the suitability of the formulas of the current standards for calculating the deflections of reinforced concrete elements after repeated application of loads of the operational level \( (M/M_u = 0.5 \ldots 0.7) \).
Figure 1. The dependence of the relative increase in deflections during repeated loads on the partial stress coefficient.

Authors: 1 - N.G. Golovin ($k_p = 0; 0.33; 0.67; 1.0$); 2 - M.M. Arslanbekov ($k_p = 0; 0.41; 0.63; 0.74; 0.87$); 3 - R.Kh. Mirmukhamedov ($k_p = 0$); 4 - E.K. Klebleev ($k_p = 1$); 5 ($k_p = 1$); 6 ($k_p = 0.85 ... 0.8$); 7 ($k_p = 0.56$) - M.I. Stasyuk; 8 - Z. Yusupov ($k_p = 0$).

To adjust the magnitude of the deflections in the framework of the calculated dependencies of the norms, when exposed to repeated loads of the operating level, we propose for practical calculations to take the value of the coefficient $\nu$, characterizing the elastoplastic properties of concrete, equal to 0.3. This is justified by the following considerations. During the application of short-term repeated loads, the opening width and crack height increase, which leads to the fact that the value of $\nu$ initially decreases relatively sharply, and then practically does not change in the stress range in concrete of the corresponding operational stage of operation of the element and is within 0.3 ... 0.4. It is easy to verify the validity of the need to reduce the coefficient $\nu$ from 0.45, adopted in the norms to 0.3 for short-term reloading, by considering the ratio

$$\nu = \frac{M_s y b}{\varepsilon_{bm} E_b b \bar{x} z}.$$  \hspace{1cm} (3)

where $\varepsilon_{bm}$ and $\bar{x}$, respectively, the average deformation of concrete and the average height of the compressed zone.

Repeated loading has the greatest effect on deflections at high load levels $M_{max}/M > 0.9$. After 180...200 cycles of repeated loading, the deflections increase by 2...2.5 times, and the deformation of concrete in the compressed zone by 1.5...1.7 times, the deformation of non-tensile reinforcement by 1.2...1.3 times, and tensile only 10...15%. Thus, an increase in the deflections is associated with an increase in the width of the crack opening due to the partial loss of adhesion of the reinforcement to concrete and the shutdown of stretched concrete between and above the cracks.
For partially prestressed bending elements, the curvature of areas with normal cracks in the stretched zone on the Nth cycle at the maximum cycle time \( M_{\text{max}} \) is recommended to be determined by the formula

\[
\left( \frac{1}{r} \right)_{\text{max,N}} = \frac{M_{\text{max},N} \cdot \psi_{sN}}{z(A_{sp}E_{sp} + A_{s}E_{s}) \cdot (h_o - x)} - \frac{P \psi_{sN}}{(A_{sp}E_{sp} + A_{s}E_{s}) \cdot (h_o - x)},
\]

Where

\[
x = \varphi_2 (\varphi_1 + \varphi_\psi + \varphi_\phi) \cdot h_o,
\]

\[
\varphi_2 = \beta \left\{ \frac{2(\varphi_n + \varphi_s (a'/h_o))}{\beta(\varphi_2 + \varphi_n)^2} \right\};
\]

\[
\beta = \alpha^* \mu \frac{\psi_p \varphi_{b1}}{\psi_{sN} \varphi_{b1}}; \quad \alpha^* = \frac{E_{sm}}{E_b}; \quad \mu = \frac{A_{sp} + A_s}{bh_o};
\]

\[
\varphi_1 = \frac{(A'_{sp} + A'_{s}) \psi_{sN}}{(A_{sp} + A_s) \psi_b}; \quad \varphi_2 = \frac{(b_f - b)h_f'}{\beta bh_o}; \quad \varphi_n = \frac{1}{1 - \frac{y + r}{e_{s,tot}}};
\]

\[
z = (h_o - x/3) \cdot \left( \frac{1 + \lambda (h_o - 0.5h_f') / (h_o - x/3)}{1 + \lambda} \right);
\]

\[
\lambda = \frac{(2 - h_f'/x) \cdot (b_f' - b)h_f'}{bx}; \quad e_{s,tot} = \frac{M_{\text{max,N}}}{p}.
\]

In formulas (4)...(10):

\( \varphi_{b1} \) and \( \varphi_{b2} \) are coefficients that take into account the influence of short-term and long-term creep of concrete, respectively; \( \varphi_{b2} = 1; \)

\( y \) and \( r \) are the distance from the center of gravity of the reduced section to the center of gravity of the cross-sectional area of the reinforcement \( S \) and the core point, respectively; other designations of parameters are accepted according to the current standards.

In the process of cyclic deformation, the parameters \( \psi_s, x, \) and \( z \) included in formula (4) change in a complex way. Given the limited experimental data on the patterns of change in these quantities, the features associated with the application of repeated loads were taken into account using the coefficient \( \psi_{sN} \). For the case of repeated loading, we recommend using the ratio

\[
\psi_{sN} = \frac{\sqrt{e_{sm}}}{\sqrt{e_{sm}} + \sqrt{\left( \frac{1}{\psi_{s,crc}} - 1 \right) e_{sm,crc} \cdot c}},
\]

where \( e_{sm} \) is the average deformation of the reinforcement in the areas between the cracks; in practical calculations it is allowed to take \( \psi_{sN} = 0.4; \)

if cracks have already formed in the fiber, there is no concrete tensile diagram, then \( e_{sm,crc} = e_{sp} = 0; \)
coefficient $c$ according to numerical simulation takes values from 0.9 to 1.5; in practical calculations of reinforced concrete structures $c = 1$.

The calculated values of the deflections are determined taking into account the dependencies proposed above for partially prestressed beams subjected to repeated high-level loads. Deflections were determined by the well-known formula

$$f_{\text{max},N} = \rho_m (1/r)_{\text{max},N} \cdot l_o^2,$$  \hspace{2cm} (12)

Where $(1/r)_{\text{max},N}$ is determined by the formula (4) at the maximum level of reloading.

The initial data for the calculation are borrowed from the work of Babich E. M. [3]: $\eta_{\text{max}} = M_{\text{max}} / M_u = 0.92$; $k_p = 0.7$; $\rho_m = 23/216$; $b \times h = 100 \times 200$ mm; $l_o = 1850$ mm; $\mu = 1.15\%$; $\varepsilon_{BR} = 1.5 \cdot 10^{-4}$; Deflections are calculated for the 1st, 20th, 180th and 200th cycles.

The comparison results shown in Figure 2. As can be seen from Figure 2, the proposed calculation method gives a satisfactory agreement with the experimental data. At the same time, it shown that the calculation according to the methodology of existing norms underestimates the effect of repeated loading. Moreover, underestimation increases with an increase in the number of cycles.

![Figure 2. Change in deflections of the experimental beam.](image)

○ - The calculated values of the deflections according to the formula (12)
● - The calculated values of the deflections according to the norms at $\nu = 0.3$ and $\psi_s = 1$
☒ - Calculated values of residual deflections

4. Summary and recommendations
- repeated loads, increase the deflection by 1.5...2.8 times in comparison with the first loading.
- depending on the classes and the ratio of prestressed and non-tensile reinforcement, deflections during repeated loads increase by 30...70% compared with a single loading.
- at high load levels ($\eta > 0.9$), the maximum and residual deflections increase by more than 2 times. The main processes of deflection formation take place in the first 20 cycles of reloading.
- at average levels of reloading ($\eta = 0.6...0.7$), stabilization of maximum deflections occurs after 3 ... 5 cycles. When exposed to beams without load between successive cycles during the day, the residual deflection decreases by 10...15%.
- to adjust the values of deflections within the framework of the calculated dependences of the norms, when exposed to repeated loads of the operating level, we propose for practical calculations to take the value of the coefficient $\nu$, characterizing the elastoplastic properties of concrete, equal to 0.3.

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