Impact of low-cycle loads on deflections and width of crack opening of concrete beams with different types of reinforcement

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Abstract. The article presents the studies of the impact of low-cycle loads on experimental samples of concrete beams with different types of reinforcement – unstressed steel bars; steel pre-stressed reinforcement and unstressed reinforcement (mixed reinforcement); basalt-plastic reinforcement. Influence of low-cycle loads on the width of cracks opening and deflections of concrete beams were established. The research results of beams with steel reinforcement without pre-stressing, with pre-stressing and the beams with basalt-plastic reinforcement have shown interrelated proportional relative increase of the width of cracks opening and increase of deflections. Suggestions for consideration of the impact of low-cycle loads during the calculation of bending concrete beams reinforced with steel or basalt-plastic reinforcement by the second group of limit states were proposed. Coefficients determined experimentally for calculating the deflections and the width of cracks opening of the beams were introduced into the equation. Taking into account the impact of low-cycle loads during the calculation of bending concrete structures reinforced with steel or basalt-plastic reinforcement will provide higher reliability of such structures performance.

1. Introduction
Low-cycle loads are non-frequent changes of force or other external parameters in time during the alternation of loading and unloading that causes deformation throughout the body or in its finite regions, the final result of which is low-cycle fatigue. Low-cycle loads are the loads the repetition number of which is tens, hundreds, and sometimes thousands of times during the whole service life of the structure.

The studies performed by the scientists under the guidance of Professor E. M. Babych established that the main process of deformation of concrete is finished after the first ten cycles. In Ukraine, the scientists carried out a fundamental study of the reinforced concrete structures performance under the impact of low-cycle loads [1, 2].

P. M. Koval and R. I. Polyuha established that the bridge structures are subject to the impact of low-cycle loads of high level which significantly affect the bridge spans. These loads include passing over the bridges of the loads that exceed the design values, field tests and other cases of cyclic loads [3, 4].

The perspective direction in construction is the use of non-metal composite reinforcement in structures of transport facilities. In Ukraine, the design norms were developed [5] based on the research...
of concrete elements reinforced with fiberglass and basalt-plastic reinforcement by Yu. A. Klimov and O. S. Soldatchenko [6]. In a number of countries of the world, the research of concrete structures reinforced with non-metallic composite reinforcement was carried out, a number of projects with such elements was implemented; 400 bridges with non-metallic composite reinforcement are under operation in the USA and Canada; relevant design norms were developed [7, 8].

Requirements for the calculation of reinforced concrete bridge structures are set out in DBN V.2.3-14 [9]. Calculation methods, rules for the design and construction of concrete structures with non-metallic composite reinforcement are given in DSTU-N B V.2.6-185 [5], mechanical characteristics of strength of the basalt-plastic reinforcement are also presented there.

Safety, operational availability and durability requirements are established for reinforced concrete and basalt concrete structures.

To ensure the safety requirements, reinforced concrete and basalt concrete structures should have such initial properties that with the required degree of reliability for various calculated situations during construction and operation and exclude the possibility of any deterioration or failure of the operational availability that can cause damage to life or health of the people, property or the environment during the entire design service life in accordance with the clause 4.2.1 of DBN V.2.3-22 [10].

To ensure the requirements of operational availability, the basalt concrete and reinforced concrete structures should have such initial properties that with an appropriate degree of reliability for different calculation impact prevent the formation or excessive crack opening, excessive displacements, fluctuations and damages that complicate normal operation.

To ensure the durability requirements, the basalt concrete and reinforced concrete structure should have such initial properties that would meet the safety and operational availability requirements in the established service life taking into account the impact of various design influences (prolonged load action, repeated loading, adverse climatic, technological influences, changes in temperature and humidity, changes in freezing and melting, aggressive impacts, etc.) on the geometrical characteristics of the structures and the mechanical properties of the materials in accordance with DBN B.1.2-15 [11].

The purpose of the study is to determine the impact of low-cycle loads on the width of crack opening and deflection of concrete beams reinforced with steel and basalt-plastic reinforcement.

Under the guidance of Koval P. M., the impact of a static loads and of low-cycle loads on the beam samples was studied for obtaining the experimental data on the stress-strain state of concrete beams reinforced with steel and basalt-plastic reinforcement, and a comparative analysis of the results was performed [3, 4, 12, 13]. The concrete beams of the same span and cross section reinforced with different types of reinforcement – unstressed steel bars; steel prestressed reinforcement and unstressed reinforcement (mixed reinforcement); basalt-plastic reinforcement – were investigated.

2. Research methodology

Experimental samples were reinforced concrete and basalt concrete beams with a cross section of 100 × 200 mm and a length of 2100 mm.

Five series of beams without prestressing were manufactured from concrete of B20; B25; B30; B35; B40 strength classes. Concrete beams were reinforced with unstressed longitudinal single steel bars of 12 mm diameter, A-III strength class and 2080 mm length. In the extreme thirds of the span, transversal reinforcement with steel bars of 3 mm diameter, Vr-1 strength class and 180 mm length was provided. The spacing of transversal reinforcement bars was 100 mm, the total number of transversal reinforcement bars was 16 pcs. The upper reinforcement included two bars of 3 mm diameter, Vr-1 strength class and 730 mm length. The reinforcement ratio of the structure’s cross section was $\rho_{tor}=0.00642$. The design of beams is shown in Figure 1, the studies are described in papers [3, 4].
Beams with pre-stressed reinforcement were manufactured from the concrete of B30 strength class. Concrete beams were mixed reinforced by the pre-stressed cable K-7 of 9.5 mm diameter and two bars of 8 mm diameter, A-III strength class and 2080 mm length. In the extreme thirds of the span, transversal reinforcement with steel bars of 3 mm diameter, 100 mm of spacing, Vr-I strength class and 180 mm length was provided. The upper reinforcement included two bars of 3 mm diameter, Vr-I strength class and 730 mm length. The reinforcement ratio of the structure’s cross section was $\rho_{f,tot} = 0.00865$. The pre-stressed K-7 cable reinforcement had the cross-section area of 1 cm² and the tensile strength of 120 MPa. The design of beams is shown in Figure 2; the studies are presented in [13].

Basalt concrete and basalt-fiber concrete beams were reinforced with single longitudinal basalt-plastic reinforcement bar of ANPB of 2080 mm length (diameter was varied by series: 4, 6, 8, 10, 12 or 13 mm). In the extreme thirds of the span, transversal reinforcement with steel bars of 6 mm diameter, A-I strength class and 180 mm length was provided. The spacing of transversal reinforcement bars was 100 mm; the total number of transversal reinforcement bars was 16 pcs. The upper reinforcement included two steel bars of 6 mm diameter, A-I strength class and 730 mm length in the extreme thirds.
of the span. The reinforcement ratio of the structure's cross section $\rho_{f,tot}$ was 0.00073 at Ø4 mm; 0.00158 at Ø6 mm; 0.00286 at Ø8 mm; 0.00446 at Ø10 mm; 0.00649 at Ø12 mm; 0.0077 at Ø13 mm. In total, 48 basalt concrete and basalt-fiber concrete beams were manufactured and tested under static and low-cycle loads. The design of beams is shown in Figure 3, the studies are described in [14].

In all cases, the beams were tested on a power bench by the application of two point forces located in the thirds of the span according to the scheme of pure bending (Figure 4) with different types of loads (static and low-cyclic). The basis of the tests was $N=10$ cycles (Figure 6). On the twin beams at the single static loading, the values of the destructive load $P_{cr}$ were determined. The basic loading level to which the samples were subjected to was 0.6 $P_{cr}$. In order to simulate the additional loading of the structure to a higher level, after the first six cycles with a maximum loading level of 0.6$P_{cr}$, at the seventh and the eighth cycles the load level was brought to 0.75 $P_{cr}$. The ninth cycle was carried out with a maximum loading level of 0.6 $P_{cr}$, and the tenth – again to 0.75 $P_{cr}$, after which the beams were destroyed by a one-time application of increasing load with fixation of the destructive value (Figure 6).

The levels and the number of low-cycle loadings were assigned based on the studies by Polyuha R. I. [3, 4] of the passage of the overweight vehicles on Ukrainian highway bridges.

Figure 3. Design of the basalt concrete beam:
1 – a bar of basalt reinforcement;
2 – 2Ø6 A-I;
3 – 16Ø6 A-I.

Figure 4. Static test pattern of prototype beam samples.
Figure 5. General views of prototype beam samples testing.

Figure 6. Chart of the loading change on the prototype sample at testing the beams for the effect of low cycle loading.

During testing of beams the deflections, crack formation moments, the width of cracks opening, relative fibrous deformation of concrete were measured.

3. Research results
Experimental studies have established that high level low-cycle loads did not affect the carrying capacity by bend moment of reinforced concrete, basalt concrete and basalt-fibrous concrete beams. Therefore, the calculations for the first group of boundary states of such structures under the influence of low-cycle loads do not require any additions.

As experimental studies have shown, with the action of high level low-cycle loads in the bent beam concrete and basalt concrete structures, the width of cracks opening increases and deflections grow. Therefore, it is expedient to make additions to the calculations of such structures for the second group of boundary states under the influence of low cycle loads.

It is proposed to determine the width of the opening of the normal to the longitudinal axis of the cracks arc in the beam reinforced concrete and basalt concrete structures of the bending bridge structures under the action of low cycle loads by the equation (3.85) of the DBN V. 2.3 -14 [9] taking into account the empirical coefficient considering the effect of cyclic displacements:

\[ a_{cr} = \psi_{cr} \sigma \frac{\sigma}{E} \psi \leq \Delta_{cr} \] (1)

where \( \psi_{cr} \) – coefficient taking into account the effect of cyclic loads; \( \sigma \) – tensile stress equal to the stress \( \sigma_s \) of unstressed reinforcement in the most tensioned (extreme) rods, and for the stressed
reinforcement it corresponds to the increase of stresses $\Delta \sigma_p$ after reducing of preliminary concrete reduction; $E$ – modulus of elasticity, respectively, for unstressed $E_s$ and stressed reinforcement $E_p$ adopted in accordance with Table 3.17 DBN V. 2.3 -14 [9]; $\psi$ – coefficient of cracks opening which is determined depending on the radius of reinforcement (taking into account the impact of the concrete of the tension zone, the deformation of the reinforcement, its profile and operating conditions of the element) and adopted in accordance with 3.109 DBN V. 2.3 -14 [9].

The effect of low-cycle loads on the deflections of the beam reinforced concrete and basalt concrete of bridge bending structures is taken into account by the introduction of the coefficient in the formula (3.92) of equation DBN B.2.3-14 [9] $\psi_{cy}^{f}$:

$$ f = \psi_{cy}^{f} \sum \frac{\Delta M(x)}{\rho}(x) \Delta x, $$

(2) where $\psi_{cy}^{f}$ – coefficient taking into account the effect of cyclic loads; $\Delta M(x)$ – the value of the bending moment in the cross section $x$ depending on the temporary load applied in the direction of the deflection $f$, which is defined; $\frac{1}{\rho}(x)$ – the curvature of an element in the same cross-section under temporary load; $\Delta x$ – length of the section with constant value $\frac{1}{\rho}(x)$.

The values $\psi_{cy}^{pre}$ and $\psi_{cy}^{f}$ of the coefficients were obtained from experimental data of the research of reinforced concrete beams without pre-stressing and with pre-stressing, and of basalt concrete and basalt-fibrous concrete beams under the influence of low cycle loads.

The beams of the same size were tested for low-cycle loads by R. I. Polyuha (reinforcement steel A-III), Ya. I. Kovalchyk (pre-stressed reinforcement cables K-7) and O. Ya. Hrymak (basalt-plastic reinforcement). Table 1 shows the coefficients $\psi_{cy}^{pre}$ and $\psi_{cy}^{f}$ defined in the studies of R. I. Polyuha, Ya. I. Kovalchyk and O. Ya. Grymak [4, 13, 14].

### Table 1. Coefficients $\psi_{cy}^{pre}$ and $\psi_{cy}^{f}$ for beams with different reinforcement.

| Author          | Reinforcement          | $\psi_{cy}^{pre}$ | $\psi_{cy}^{f}$ |
|-----------------|------------------------|-------------------|-----------------|
| R.I. Polyuha [4] | A-III                  | 1.18              | 1.09            |
| Ya.I. Kovalchyk [13] | Pre-stressed cables | 1.41              | 1.12            |
| O.Ya. Hrymak [14] | Basalt plastic         | 1.12              | 1.11            |

As can be seen from the results of testing the beams with steel reinforcement and beams with basalt-plastic reinforcement under the influence of low-cycle loads, a relative increase in the width of the cracks opening and the increase of deflections are found. Somewhat higher coefficients that take into account the effect of low cycle loads are inherent for the beams with pre-stressed reinforcement, so it is advisable to investigate such beams with different reinforcement ratios.

The performance of the full-scale reinforced concrete structures for the effect of low-cycle loads was studied by R. I. Polyuha when testing the superstructures of the bridges [4]; full-scale testing of prefabricated reinforced concrete beams of bridges of 18, 21, 24 and 33 m [12, 13] length were conducted by S. V. Stoyanovskyh and Ya. I. Kovalchyk. Comparison of experimental and theoretical data yielded satisfactory results.
To verify the proposed equation (1), we used the data of the paper [12] by S. V. Stoyanovich obtained during the testing of prefabricated reinforced concrete prestressed beam "3Bet-120", with length of 24 m (Figure 7). The test program included 5 loading cycles up to the levels of 0.94 and one loading cycle 0.98$P_{cr}$ (the design load at which point the beam did not collapse).

According to the norms [9], the width of the crack opening of this beam was calculated at given loading levels (Figure 8). When calculating the width of crack opening at a load of 0.98$P_{cr}$, a coefficient $\psi_{crc} = 1.59$ is used (for a level of 0.75$P_{cr}$). Thus, the estimated value of the width of the crack opening almost coincides with the actual experimental value, the difference in 5 cycles is 5.56 %, and the difference in 6 cycles makes 4.82 %.

![Figure 7. The cross section of the prefabricated beam "3Bet-120".](image)

![Figure 8. Width of cracks opening of the beam "3Bet-120" of length 24 m with low cycle loads: $a_{crc}^{exp}$ is obtained experimentally; $a_{crc}^{theor}$ is obtained theoretically using the equation (1).](image)

4. Practical significance
Taking into account the effect of low-cycle loads in the calculation of bended concrete structures, reinforced with steel or basalt-plastic reinforcement, enables to obtain theoretical deflections and widths of cracks opening, close to the real ones, which will ensure designing such structures with higher reliability.

5. Conclusions
1. Investigation of beams with different types of reinforcement for the effect of low-cycle loads showed quite close results among themselves in terms of the relative increase in the width of the cracks opening and the increase of deflections.

2. It is proposed to calculate the width of cracks opening in reinforced concrete and basalt concrete beams while taking into account the effect of low-cycle loads of high level by introducing the coefficient into the equation $\psi_{ycyc}$ (3.85) of DBN V. 2.3-14 [9] which, depending on the type of reinforcement of beams, with repeated loads of the level 0.6$P_{cr}$ is taken in the range from $\psi_{ycyc}^{exp} = 1.12$ to 1.41, at a loading level of 0.75$P_{cr}$ – within the range from $\psi_{ycyc}^{exp} = 1.4$ to 1.59 (Table 1).
3. When determining the deflections of reinforced concrete and basalt concrete beams, it is suggested to take into account the effect of low-cycle loads of high level by introducing the coefficient $\psi_{cyc}$ into equation (3.92) of DBN V.2.3-14 [9] which, depending on the type of the beam reinforcement, at the repeated loads of 0.6$P_{cr}$ level are accepted in the range from $\psi_{cyc} = 1.09$ to 1.12, at a load level of 0.75$P_{cr}$ within the range from $\psi_{cyc} = 1.42$ to 1.67 (Table 1).

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