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Research paper

Comparative Analysis of Deflections and Crack Opening Widths in Reinforced Concrete Whole Beams Under the Action of Single, Low-Cycle Repetitive and Low-Cycle Alternating Loads

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Abstract

Article contains a comparative analysis of the deflections and the crack opening widths in the reinforced concrete whole beams affected by single, low-cycle repeated and short-cycle alternating loads according to experimental data. Experimental studies have shown that the stress-strained state of the whole beams affected by low-cycle repeated and short-cycle alternating loads significantly differs from the stress-strained state of the same beams affected by nonalternating static loads.
Following parameters of the stress-strained state were determined: crack resistance and deformability, crack opening widths and deflections have considerably higher values. This is caused to certain extent by the change in the concrete structure after repeated and alternating loads. The concrete structure, affected by alternating loads, changes due to the formation of microcracks, which increase from cycle to cycle, forming the main cross-cutting cracks, dividing the beam by length into separate blocks. Due to this, the beam stiffness decreases and the deflections increase, as well as the crack opening widths.

***Keywords**: reinforced concrete whole beams, short-cyclic repetitive and alternating loads, deflections, crack opening widths.*

1. Introduction

In recent years statically undeterminate reinforced concrete beams have been getting wide spread in the construction. Their reliability and durability during the operation period is evaluated not only by their carrying capacity, but also by the permissible values of deflections, crack opening widths, etc. Undeterminate reinforced concrete beams are used in constructing of various types of buildings and structures, especially in cast reinforced concrete. At this stage the stress-strain state and the general performance of undeterminate reinforced concrete affected by short-cycle repeated and alternating loads are not sufficiently studied. Problems related to the limited function of deformation diagrams, ignoring crack opening widths, still require careful study. Based on the above-stated study of the performance of such structures, including the development of deflections affected by the above mentioned loads, is an actual problem.

2. Problem statement and significance

Many scientists [1, 2, 3, 4, 5, 6] and others were engaged in the study of the stress-strained state and the general performance of reinforced concrete whole beams. But among all the diversity of research and suggestions, the calculation of statically undeterminate beams still raises a lot of difficulties. In most cases performance and the stress-strain state of whole beams were studied under single-valued static loads. Initial power models of calculating of static-undeterminate structures [1] in most cases considered their limit state, therefore, during operating load these calculation methods worked satisfactorily. The calculation methods on the basis of nonlinear model deformation suggested by modern scientists [2, 3, 4, 5, 6] allow us to describe the performance of static-undeterminate structures more accurately. The performance of the reinforced concrete whole beams affected by low-cycle repetitive loads was researched in works [6, 7, 8]. The performance studies of the whole beams affected by low-cycle alternating loads are practically absent.

3. The purpose and tasks of the research

1. To find out the effect of low-cycle repetitive and alternating loads on the deflections size and the crack opening widths of the reinforced concrete whole beams.
2. To perform a comparative analysis of the deflection values.

4. Main body

To accomplish this goal, experimental researches of performance and the stress-strain state of reinforced concrete beams with central prop affected by low-cyclic repetitive and alternating loads were carried out. The beams were made of concrete class C25/30. The reinforcement was carried out by two welded frames of working armature class A400, diameter of 12 mm, a cross-reinforcement class A240, diameter of 6 mm. Reinforcement of beams is double symmetrical - two longitudinal bars in the bottom and upper part of the beam section. The spacing between transverse bars in supporting areas: 100 mm, in spans: 200 mm. The whole beams with 2 identical spans length 1500 mm each, cross section dimensions of 100x160 mm were tested using a special power traverse with hydraulic press PG-200. Loading of beams was carried out by four concentrated forces, two forces on each span, applied according to the scheme shown in Fig. 1, which also shows the location of measuring devices.

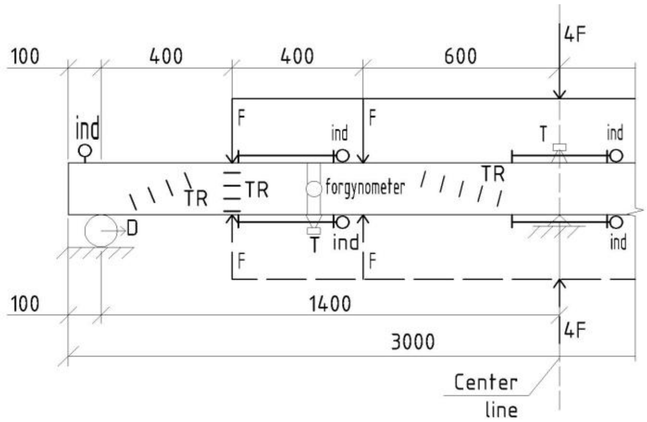


Fig. 1: Scheme of force application and measuring devices placing.

The scheme of beams testing in a special powerplant using press PG-200 is shown in Fig. 2.

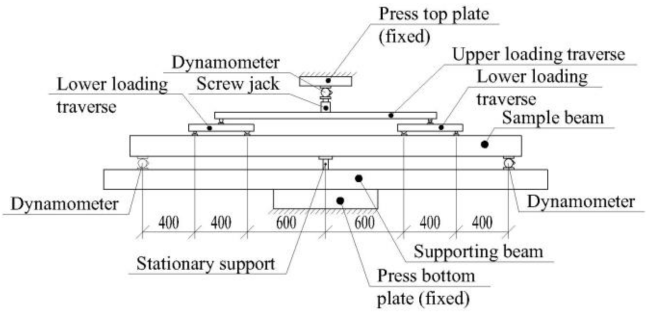


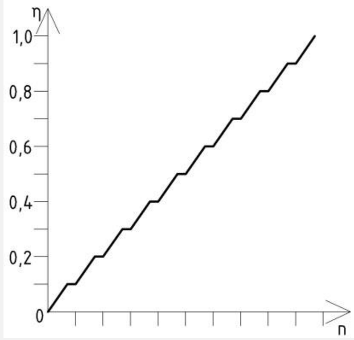
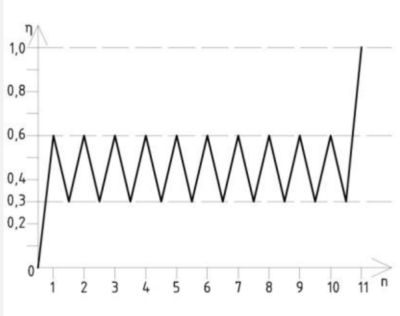
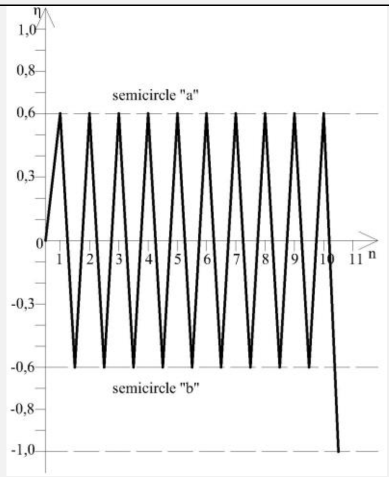
Fig. 2: Test scheme of beams with central prop

Specimens were tested according to the following loading modes: single static loading until fracture to determine load levels; low-cyclic repetitive load with the upper level 0.6 and lower level 0.3; low-cyclic alternating load at level 0.6. The number of cycles of low-cyclic loads - 10. After ten cycles of low-cyclic loads the beams were brought to fracture. Schemes of load modes of experimental specimens are shown in Table 1.

During the beams testing, following aspects were measured: concrete and reinforcement deformations, deflections and possible outermost supports displacement.

Concrete deformations were measured by watch-type indicators with a graduation of 0.002 mm on the basis of 200 mm and resistive-strain sensor with a base of 50 mm, applied periodically on the spans where the maximum bending moments appeared under the first force from the outermost support and the maximum negative moments over the central support, as well as on oblique sections from the support to the places of forces application on the beam

Table 1: Diagrams of beams loading modes

Beam code	Loading modes	Type of load
BDS-1 BDS-2 BDS-3		Single short-term, graduated up to destruction
BLCR-1 BLCR-2 BLCR-3		Short-time, low-cyclic repeated loading with the level (0,3-0,6) with destruction after 10 cycles
BLCAL-1 BLCAL-2 BLCAL-3		Short-term, low-cyclic alternating loading (level 0,6) with destruction after the 10 cycle

Reinforcement deformation was measured using Gugenberger strain gauge on the basis of 20 mm with a graduation of 0.001 mm and resistive-strain sensors on the basis of 20 mm, applied on the reinforcing bars at the spots of appearing of maximum efforts. Beams deflections were measured by deflection gauge type 6 PAI LISI with a graduation of 0.01 mm. Outermost supports displacement was determined by watch-type indicators. The appearance and opening of cracks during the beams testing were observed visually and using a microscope MP6-3 with a graduation of 0.002 mm.

The use of this method of experimental studies of beams performance with special designed equipment and the use of modern measuring devices allowed to study the action of the above mentioned loads, real stress-strain state of normal and oblique beams sections, as well as its change during the test process.

The deformation, cracking and destruction mechanism of the whole beams differs from performance of single-span reinforced concrete bending elements even under single static load (during the first half-cycle). During further cyclic loads, the stress-strain state of the beams changed after each cycle.

If we compare the stress-strain state of the beams under the action of low-cyclic repetitive and low-cyclic alternating loads, there is also a significant difference. Also, the beams deflections differed in their values depending on the load mode. Deflection values results were studied at each half-cycle and at each cycle. Below is an analysis of deflection results. The deflections of experimental specimens with single static load during the fracture amounted to the following quantities: BDS-1 – 2,27 cm, BDS-2 – 2,24 cm, BDS-3 -2,26 cm.

The impact of low-cycle repetitive loads on the beam deflections development was studied on beams BLCR-1,2,3. The deflections were measured under the first force starting from the outmost support in the places of the most span bending moments. The nature of deflections development was studied on the above mentioned beams.

When loading beams with a low-cycle repetitive load to the upper level $\eta = 0,6$, corresponding to the force F=16.5 kN , and unloading to the lower level, corresponding to the force F=8.5 kN, from cycle to cycle there was a change of deflections at the upper level, but at the lower level it was insignificant. So, while loading up to the upper level at first half-cycle the deflection was equal to 0.82 cm, at the second half-cycle — 0.87 cm, at the third — 0.74 cm, from the fourth to the tenth half-cycle deflections values were in the range of 0.75...0.76 cm. As for the lower level (unloading beams to $\eta = 0,3$), there also were no special changes in deflections from one to another half-cycle.

So at the first half-cycle, the beams deflection amounted 0.75 cm, at the second — 0,65 cm, at the third, fourth and fifth half-cycle deflection was also 0.64 cm, and from sixth through tenth half-cycle — 0.62. Analyzing the deflection changes values under the impact of low-cycle repetitive loads it can be stated that deflections under the low load levels were practically stable. If to compare the deflections with a single static load and under a low-cycle repetitive load, the difference is not significant at the same level of loads.

When the force is equal to 16.5 kN the deflection under static load was 0.83 cm, and under repetitive load the maximum deflection was 0,87 cm. Increase of deflection in this case was caused by decrease of beams stiffness, as due impact of cyclic loads the cracks emerged in the stretched zone of the beams at the first cycle developed during the next half-cycles. Comparative deflections values under fracture-driving force: single static load — 2.24 cm, 2,27cm and 2,26 cm; low-cycle repetitive loads — respectively 2.51 cm, 2.53 cm and 2.53 cm.

So, the deflection values variations are quite minor. This indicates that strength and deformation characteristics of beams are similar. Fracture-driving force applied on the beams were, respectively, under a single load: 32.5 kN; 32,53 kN; 32,51 kN and under repetitive load: 30,0 kN; 30,02 and 30,0 kN.

Of considerable interest is the study of deflections in whole beams with central prop and their change under the impact of low-cycle alternating loads. The analysis of the deflection changes values under the low-cycle alternating loads has showed that the deflections values of the half-cycle "b" are slightly higher. In the first half cycle "a" the deflection amounted to 0,8 cm, in the half cycle "b" — 0,93 cm, in the fifth half-cycle — 0.96 cm and 0.98 cm. Starting from the fifth cycle, the deflection were practically stabilized in both half-cycles. At fracture-driving load of F=27.5 kN the deflection amounted to 3.2 cm (average value of 3 beams).

The increase of the deflections values under low-cycle repetitive and alternating loads, in comparison with single static loads is due to the fact that starting from the first load-unload half-cycle a change in concrete structure takes place due to the formation of microcracks, their further developing and interconnecting. That is, the destruction of concrete takes place. This phenomenon mostly occurs in the beams cross sections, where maximum forces appear. The results of deflection values are shown in table 2.

Table 2: Deflections values of the for the various loads

Type of load	Beam code	Size of deflection, sm	Average deflection, sm	Note
Short-lived, one-time, static, step-by-step to destruction	BDS -1	2,27	2,257	
	BDS -2	2,24		
	BDS -3	2,26		
Little cycles repeated levels $\eta = 0{,}6$ $\eta = 0{,}3$	BLCR -1	2,51	2,523	Destruction of beams after 10 cycles
	BLCR -2	2,53		
	BLCR -3	2,53		
Low-cycle variable levels $\eta = 0{,}6$ $\eta = 0{,}3$	BLCAL -1	3,18	3,196	Destruction of beams after 10 cycles
	BLCAL -2	3,21		
	BLCAL -3	3,20		

The scheme of crack opening under low-cycle repetitive and alternating load also differs significantly from the scheme of crack opening under single static load, which greatly affects the performance property of reinforced concrete whole beams.

Low-cycle repetitive load on reinforced concrete whole beams leads to cracks developing up to 4-5 load cycle after which the cracks width opening and closing is more stable as seen on Fig. 3.

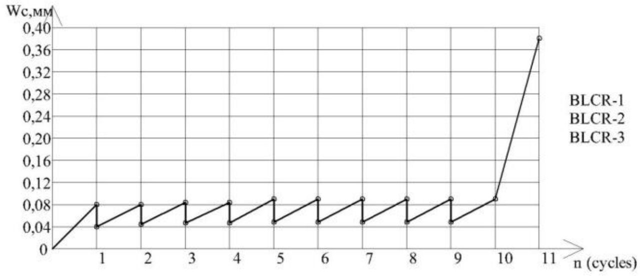


Fig. 3. Change of normal cracks width in beams under repetitive loading up to the level $\eta = 0{,}6$ and unloading to the level $\eta = 0{,}3$ ($W_{C(cm)}$ - crack width at the level $\eta = 0{,}6$ (average value for 3 beams) $W'_{C(cm)}$ crack width at the level $\eta = 0{,}3$).

Above the level of cyclic load up to destruction after 10 cycles the growth of the width of cracks opening increased. The maximum value of crack opening widths at beams fracture was higher than under single static load. This is also explained by the change in the structure of concrete due to the residual values of the crack opening widths at the level of $\eta = 0.3$ at low-cycle repetitive loads. Further cracks development was observed at load increasing up to fracture, when at a load level of $\eta = 0.8$ of the destructive level inclined cracks began to open and there was a significant development of inclined and normal cracks and crack opening widths. Alternating load on reinforced concrete whole beams leads to cracks appearing and slight development of normal crack widths at 1-2 cycles (Fig. 4). From 3-rd to 5-th cycles a stabilization of crack openings occurs. Under alternating loads after 5 cycle, normal cracks practically divided the beam section into separate blocks having merged with stretched and compressed section zones. After that, there happened further development of crack opening widths at 7-10 cycles as a result of concrete destruction through crossing of the beam by normal cracks. When loading beams at the 7 cycle the inclined cracks appeared. The width of their disclosure after 10 cycles was W=0.25 mm. When loading beam after the 10 cycle up to the load level of $\eta = 0.8$ of the destructive level, the width of inclined cracks is W=0.5

mm.

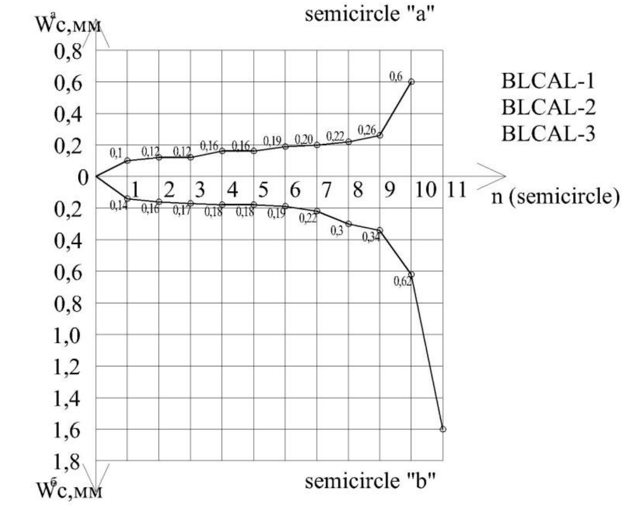


Fig. 4. . Change of normal cracks width in beams under alternating loading at the level $\eta = 0,6$ (average value for 3 beams).

($W^{(a)}_{C(cm)}$ *- width of crack openings at chalf-cycle " a",*

w $W^{(б)}_{C(cm)}$ *width of crack opening at chalf-cycle " b")*

Analysis of the crack opening widths changing graphs makes it clear that under low-cycle repetitive load above shown levels, cracks develop up to 4-5 cycles and then stabilize at approximately the same level. Further development of cracks is observed only when the load level is higher than the cyclic one. Analysis of the crack opening widths graph under alternating low-cycle load (Fig. 4) is significantly different from the graph shown on Fig. 3. It can be seen from the graph, the development of normal crack opening widths from cycle to cycle increases up to the 4-th cycle, then occurred a stabilization of normal crack opening widths, and after the 7-th cycle the opening width increased by half cycles, and after 10 cycles it reached values in half-cycle "a" - 0.6 mm, and in half-cycle "b" – 0.62 mm.

5. Conclusions

On the basis of experimental studies of performance of reinforced concrete beam with central prop under the influence of low-cyclic repetitive and alternating loads, it should be noted that the above-mentioned loads substantially affect the stress-strain state of beams, the size of the deflections and the crack opening widths. Under the low cycle loads at the level of $\eta = 0,6$ deflection increased by 10%, and at destruction level deflections increased by 12%. Under alternating loads deflections increased respectively by 13% - and 40% compared with single loads. Under low-cycle alternating loads, crack opening stabilization at a load level of $\eta = 0.6$ at 2-4 cycles and their slight closure at a load level of $\eta = 0.3$ were observed. Further development of cracks was observed only with increasing loading to level of fracture. Under alternating loads, a brief stabilization after the 4-th cycle was observed. Further low cycle alternating load after the 6-th cycle affected the value of the normal and inclined crack opening widths. The increase of the crack opening widths occurred due to violation of the concrete structure, violation of reinforcement adhesion with concrete in the spots of cracks appearing, decrease of the cross sections stiffness and increase of their deformability. All these changes in deflection, crack development and crack opening widths must be taken into account while designing constructions which undergo such loads during the operation. Although, the additional research is required for further accumulation of experimental data.

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