Influence of long-term exposure to loads on the annular sections' strength and rigidness

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Abstract. A numerical experiment was carried out to study rigidity, critical force, and bearing capacity of reinforced concrete racks with annular section under short-term and long-term loading. The effect of long-term loading was estimated in the numerical experiment by changing the coefficient φ_l from 1 to 1.8 times 0.2, as well as the modulus of deformations $E_{b,\tau}$, taking into account the operating conditions (W = 40-75%). At the same time, the external load on the rack N was taken in the experiments as a multiple of the critical force N_{cr} from 0.2 to 1.0, and the relative eccentricity δ_e of the load application varied from 0.15 to 1.35, which made it possible to estimate the stress state of the struts in an extended range of possible loadings. The results obtained made it possible to identify qualitative and quantitative regularities of rigidity changes, critical force and bearing capacity of annular struts during short-term and long-term load application.

1 Introduction

Investigation on the centrifuged concrete properties, the strength and deformability of reinforced concrete structures of annular section, are devoted to the works of I.N. Akhverdov [1], V.M. Batashev [2,3], S.A. Dmitriev [4], A.P. Kuzis [5,6], V.N. Lebedev, T.F. Nagornaya [3] and others.

The research results of these authors were used as the basis for calculating the structures of the annular section according to the SNiP 2. 03.01-84 norms. The methodology for calculating such structures in the new standards BC 63.13330.2018 [7] has not undergone significant changes. However, we analyzed in detail some features of the calculation according to the new standards in [8].

It should be noted that most of the above-mentioned studies, including ours [8, 10], were based on the results of the short-term loads' impact on structures. Insufficient attention has been paid to the study of the long-term loadings influence on the operation of structures with an annular section.

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2 Main part

In this work, which is a continuation of the previous studies [8-10], the results of a numerical experiment on the study of the bearing capacity, bending rigidity and the critical force of annular struts under short-term and long-term loads are presented. A cylindrical support was adopted as a test sample PTL according to GOST 22687.2, the parameters of which are given in Table 1.

Table 1. Parameters of the investigated PTL support

Support type according to GOST 22687.2	Strut diameters, mm		Wall thickness, mm	Class and number of reinforcement		Reinforcement prestressing level
	External	Internal		Stress A-IV (A600)	Non-stress A-IV (A600)	
SC20.2-1.0	800	640	80	22d14	30d14	$0.8R_{sp,n}$

Note. The number and diameter of the reinforcement corresponds to the most stressed strut section at the pinching level.

The assessment of the stress state of the structure under short-term and long-term loading was carried out according to the norms BC 63.13330.2018 methodology [7].

The relative height of the annular elements' compressed zone of concrete ξ_{cir}:

$$\xi_{cir} = \frac{N+R_s A_{s,tot}}{R_b A_b+(R_{sc}+1{,}7R_s)A_{s,tot}} \quad (1)$$

Where $A_{s,tot} = A_{sp} + A_s$; A_{sp} , A_s are the areas of stress and non-stress reinforcement, respectively.

Bearing capacity of the annular section M_{ult} :

$$M_{ult} \leq \left(R_b A_b r_m + R_{sc} A_{s,tot} r_s\right) \frac{\sin(\pi\xi_{cir})}{\pi} + R_s A_{s,tot}(1 - 1.7\xi_{cir}) z_s \quad (2)$$

Where $z_s=(0.2+1.3\xi_{cir})r_s$., by that $0.15 < \xi_{cir} \leq 0.6$

D-pillar flexural rigidity and critical force N_{crc} were determined, respectively, by the formulas (3) and (4):

$$D = D_b + D_s = \frac{0.15\, E_b\, I_b}{\varphi_l(0.3+\delta_e)} + 0.7 E_s I_s \quad (3)$$

Where D_b is concrete section rigidity, D_s is reinforcement rigidity;

I_b and I_s are the moments of inertia, respectively, of the concrete section and reinforcement;

$\delta_e = \frac{e_0}{H}$ *is* relative eccentricity of external load application N,

H defines outside diameter of the strut beam;

$\varphi_l = 1$ with short-term load.

$$N_{cr} = \frac{\pi^2 D}{l_0^2} \quad (4)$$

In a numerical experiment, the value of the longitudinal force *N* in the formula (1) varied within (0.2-1.0) N_{cr}, and the magnitude δ_e =0.15-1.35.

The effect of long-term impact of loads on bending rigidity and critical force was taken into account by changing the coefficient φ_l and concrete deformation modulus $E_{b,\tau}$ by the formulas (5) and (6).

$$\varphi_l = 1 + \beta \frac{M_l}{M} \tag{5}$$

where β=1 – for heavy concrete; M_l and *M are the* moments from long-term and full loads, respectively.

$$E_{b,\tau} = \frac{E_b}{1+\varphi_{b,cr}} \tag{6}$$

where $\varphi_{b,cr}$ is a creep coefficient of concrete, depending on the strength of concrete and ambient water percentage in accordance with [7].

In a numerical experiment to expand the field of possible loadings of the strut, the change in rigidity D and critical force N_{cr} was investigated for the short-term and long-term loading, depending on the relative eccentricity δ_e = 0,15-1,35 (multiples of 0.15). And when assessing the bearing capacity of the Mult compressive strut, depending on the relative height of the compressed zone ξ_{cir} the value of N was taken as a multiple of N_{cr} from 0.2 to 1.

Within the framework of this article, it is not possible to show the obtained research results in detail, however, the most characteristic and significant dependences are presented.

Table 2 shows the numerical values of the rigidity D_b concrete section of the compressive strut, and Table 3 shows rigidity D of a reinforced concrete section with short-term and long-term loading for different values φ_l and operating conditions.

Table 2. Concrete section of the compressive strut rigidity D_b, $10^{-11}\cdot$ N·mm^2

δe	0.15	0.3	0.45	0.6	0.75	0.9	1.05	1.2	1.35
φ_l =1.0 (short-term loading)									
E_b - initial	1525.29	1143.97	915.17	762.64	653.70	571.98	508.43	457.59	415.99
φ_l =1.2 (long-term loading)									
E_b - initial	1271.07	953.31	762.64	635.54	544.75	476.65	423.69	381.32	346.66
$E_{b,\tau}$ (W>75%)	552.64	414.48	331.58	276.32	236.85	207.24	184.21	165.79	150.72
$E_{b,\tau}$ (W=40-75%)	453.95	340.47	272.37	226.98	194.55	170.23	151.32	136.19	123.81
$E_{b,\tau}$ (W< 40%)	353.08	264.81	211.85	176.54	151.32	132.40	117.69	105.92	96.29
φ_l =1.4 (long-term loading)									
E_b - initial	1089.49	817.12	653.70	544.75	466.93	408.56	363.16	326.85	297.13
$E_{b,\tau}$ (W>75%)	473.69	355.27	284.22	236.85	203.01	177.63	157.90	142.11	129.19
$E_{b,\tau}$ (W=40-75%)	389.10	291.83	233.46	194.55	166.76	145.91	129.70	116.73	106.12
$E_{b,\tau}$ (W< 40%)	302.64	226.98	181.58	151.32	129.70	113.49	100.88	90.79	82.54
φ_l =1.6 (long-term loading)									
E_b - initial	953.31	714.98	571.98	476.65	408.56	357.49	317.77	285.99	259.99
$E_{b,\tau}$ (W>75%)	414.48	310.86	248.69	207.24	177.63	155.43	138.16	124.34	113.04
$E_{b,\tau}$ (W=40-75%)	340.47	255.35	204.28	170.23	145.91	127.67	113.49	102.14	92.85
$E_{b,\tau}$ (W< 40%)	264.81	198.61	158.88	132.40	113.49	99.30	88.27	79.44	72.22
φ_l =1.8 (long-term loading)									

E_b - initial	847.38	635.54	508.43	423.69	363.16	317.77	282.46	254.21	231.10
$E_{b,\tau}$ (W>75%)	368.43	276.32	221.06	184.21	157.90	138.16	122.81	110.53	100.48
$E_{b,\tau}$ (W=40-75%)	302.64	226.98	181.58	151.32	129.70	113.49	100.88	90.79	82.54
$E_{b,\tau}$ (W< 40%)	235.38	176.54	141.23	117.69	100.88	88.27	78.46	70.62	64.20

Table 3. Reinforced concrete section of the compressive strut rigidity *D*, $10^{-11}\cdot$ N·mm²

δe	0.15	0.3	0.45	0.6	0.75	0.9	1.05	1.2	1.35
φ_l =1.0 (short-term loading)									
E_b - initial	2332.06	1950.74	1721.95	1569.42	1460.47	1378.76	1315.20	1264.36	1222.76
φ_l =1.2 (long-term loading)									
E_b - initial	2077.85	1760.08	1569.42	1442.31	1351.52	1283.43	1230.47	1188.10	1153.43
$E_{b,\tau}$ (W>75%)	1359.42	1221.25	1138.36	1083.09	1043.62	1014.01	990.99	972.57	957.49
$E_{b,\tau}$ (W=40-75%)	1260.73	1147.24	1079.15	1033.75	1001.33	977.01	958.09	942.96	930.58
$E_{b,\tau}$ (W< 40%)	1159.85	1071.58	1018.62	983.31	958.09	939.18	924.47	912.70	903.07
φ_l =1.4 (long-term loading)									
E_b - initial	1896.27	1623.89	1460.47	1351.52	1273.70	1215.33	1169.94	1133.62	1103.91
$E_{b,\tau}$ (W>75%)	1280.47	1162.04	1090.99	1043.62	1009.79	984.41	964.67	948.88	935.96
$E_{b,\tau}$ (W=40-75%)	1195.88	1098.60	1040.24	1001.33	973.53	952.69	936.48	923.51	912.89
$E_{b,\tau}$ (W< 40%)	1109.41	1033.75	988.36	958.09	936.48	920.26	907.65	897.57	889.31
φ_l =1.6 (long-term loading)									
E_b - initial	1760.08	1521.75	1378.76	1283.43	1215.33	1164.26	1124.54	1092.77	1066.77
$E_{b,\tau}$ (W>75%)	1221.25	1117.63	1055.46	1014.01	984.41	962.20	944.93	931.12	919.81
$E_{b,\tau}$ (W=40-75%)	1147.24	1062.12	1011.05	977.01	952.69	934.45	920.26	908.91	899.63
$E_{b,\tau}$ (W< 40%)	1071.58	1005.38	965.66	939.18	920.26	906.08	895.04	886.22	878.99
φ_l =1.8 (long-term loading)									
E_b - initial	1654.16	1442.31	1315.20	1230.47	1169.94	1124.54	1089.24	1060.99	1037.88
$E_{b,\tau}$ (W>75%)	1175.20	1083.09	1027.83	990.99	964.67	944.93	929.58	917.30	907.25
$E_{b,\tau}$ (W=40-75%)	1109.41	1033.75	988.36	958.09	936.48	920.26	907.65	897.57	889.31
$E_{b,\tau}$ (W< 40%)	1042.16	983.31	948.00	924.47	907.65	895.04	885.24	877.39	870.97

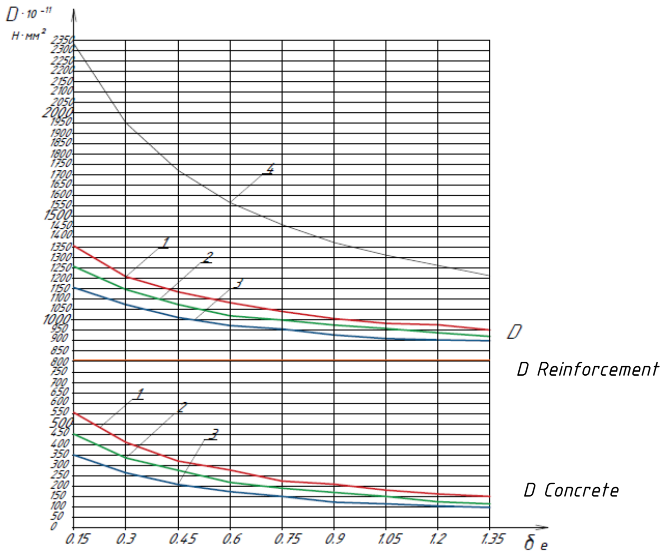
It should be noted that the concrete section rigidity of the compressive strut D_b according to formula (3) varies proportionally E_b and inversely proportional to the load duration factor φ_l. Therefore, in Tables 2, 3 and in the graphs in Fig. 1 the values D_b are given under various φ_l for the initial modulus of elasticity E_b (short-term load) and $E_{b,\tau}$ (continuous load) at three values of operating conditions.

Analysis of these graphs (refer with Fig. 1) shows that the rigidity of the compressive strut D_b (all other things being equal), the main influence is exerted by the relative eccentricity of the load application δ_e. In this case, the functional dependence $D_b = f(\delta_e)$ and $D = f(\delta_e)$ is nonlinear, which is obvious from the formula (3).

Operating conditions W – ambient water percentage and associated values $E_{b,\tau}$ have less impact on rigidity D_b and D, and the form of the function $D_b = f(\delta_e)$ and $D = f(\delta_e)$ remains unchanged, and the graphs converge with magnification δ_e.

So, for example, the rigidity D_b (by $\varphi_l = 1.2$ and W = more 75%) changed from $552.64\cdot10^8$ kNmm² (by $\delta_e = 0.15$) to $150.72\cdot10^8$ kNmm² (by $\delta_e = 1.35$) , that is, it decreased by 3.66 times. Moreover, for any value δ_e moisture change W= 40÷75%, leads to a decrease in rigidity D_b in 1.565 times. This pattern is true for every row and every column of values D_b (refer with Table 2).

Influence on eccentricity δ_e full rigidity D (refer with Table 3) affects several times less than D_b, which is explained by the weight fraction of reinforcement rigidity D_s in the total rigidity of the compressive strut section.



1 – by W > 75%; 2 – by W = 40-75%; 3 - by W < 40%; 4 – with intermittent loading.

Fig. 1. Change in rigidity D_b – concrete section and D – reinforced concrete section from relative eccentricity (at $\varphi_l = 1.2$);

So, for example, the rigidity D (by $\varphi_l = 1.2$ and W = more 75%) is changed from 1359.42 $\cdot 10^8$ kNmm^2 (by $\delta_e = 0.15$) to 957.49 $\cdot 10^8$ kNmm^2 (by $\delta_e = 1.35$) , that is, decreased in 1,42 times.

At the same time, the change in the water percentage of the environment W with prolonged exposure to load on full rigidity D much less than D_b.

For example, changing W=40-75% ($\varphi_l = 1.2$, $\delta_e = 0.15$) leads to a decrease in rigidity with 1359.42$\cdot 10^8$ kNmm^2 to 1159.85$\cdot 10^8$ kNmm^2 , i.e. by 17%. Moreover, in each row and each column of Table 3, this change will be different, which is associated with the influence of the rigidity of the reinforcement D_s on the total rigidity of the compressive strut D section.

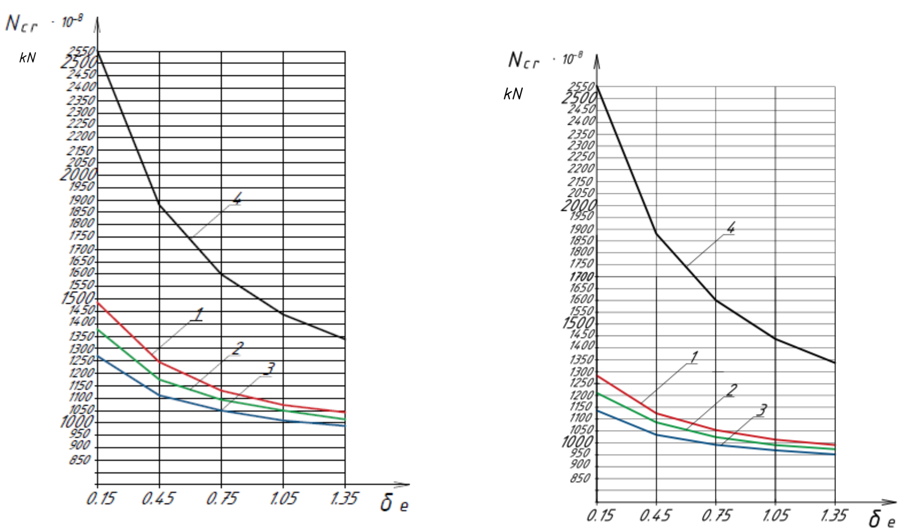
Table 4 shows the numerical values of the critical force of the compressive strut N_{cr} depending on the relative eccentricity δ_e and the coefficient φ_l, taking into account the duration of the load, and in fig. 2 - graphs of changes $N_{cr} = f(\delta_e)$.

It should be noted that the nature of the change in function $N_{cr} = f(\delta_e)$ is similar to the function $D = f(\delta_e)$, which is obvious from the formula (4).

Table 4. Critical force change $N_{cr} \cdot 10^{-8}$, kN depending on relative eccentricity and water percentage *W*.

$\phi_l/\delta e$	$\varphi_l = 1$	$\varphi_l = 1.2$	$\varphi_l = 1.4$	$\varphi_l = 1.6$	$\varphi_l = 1.8$
		W > 75%			
0.15	2554.80	1489.25	1402.77	1337.90	1287.45
0.45	1886.41	1247.08	1195.19	1156.27	1126.00
0.75	1599.96	1143.30	1106.23	1078.43	1056.81

1.05	1440.82	1085.64	1056.81	1035.19	1018.37
1.35	1339.55	1048.95	1025.36	1007.67	993.91
		W = 40÷75%			
0.15	2554.80	1381.14	1310.10	1256.81	1215.37
0.45	1886.41	1182.22	1139.59	1107.62	1082.76
0.75	1599.96	1096.96	1066.52	1043.68	1025.92
1.05	1440.82	1049.60	1025.92	1008.16	994.34
1.35	1339.55	1019.46	1000.09	985.55	974.25
		W < 40%			
0.15	2554.80	1270.63	1215.37	1173.93	1141.70
0.45	1886.41	1115.91	1082.76	1057.89	1038.55
0.75	1599.96	1049.60	1025.92	1008.16	994.34
1.05	1440.82	1012.76	994.34	980.53	969.79
1.35	1339.55	989.32	974.25	962.95	954.16

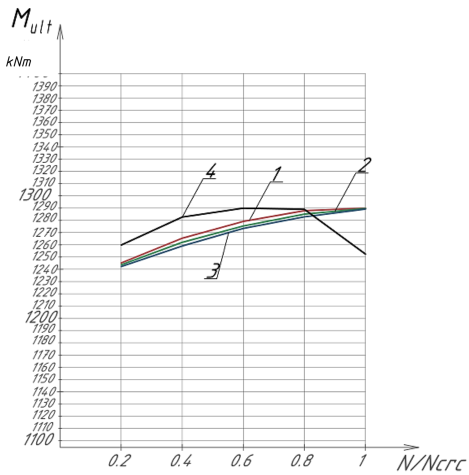


1 – by W > 75%; 2 – by W = 40-75%; 3 - by W < 40%; 4 – with intermittent loading.

Fig. 2. Change in critical force N_{cr} from relative eccentricity a) by $\varphi_l = 1.2$; b) by $\varphi_l = 1.8$

These graphs analysis shows that the main influence on the critical strength of the compressive strut N_{cr} has a relative eccentricity of the load application δ_e. In this case, the influence of the load duration factor φ_l on the critical force of the compressive strut N_{cr} disproportionate to the change in value φ_l. This is due to the lack of a clear influence of the coefficient φ_l for rigidity D_s.

Incomplete studies of the bearing capacity of the compressive struts M_{ult} showed that the main influence on the bearing capacity is exerted by the value of the relative compressed zone of concrete ξ_{cir} and the relationship N/N_{crc}. Wherein M_{ult} is increased with increasing N/N_{crc}, reaching the maximum value at a certain value N/N_{crc} (refer with Fig.3).



1 – by W > 75%; 2 – by W = 40-75%; 3 - by W < 40%; 4 – with intermittent loading.

Fig. 3. Change in bearing capacity M_{ult} depending on the N/N_{crc} proportion

3 Conclusion

1. Rigidity D of the annular struts with increasing eccentricity of load application δ_e decreases with both short-term and long-term exposure to loads. In this case, the functional dependence $D=f(\delta_e)$ is non-linear.
2. Prolonged exposure to loads leads to a decrease in the rigidity of the concrete section D_b proportional to the increase in the coefficient φ_l and inversely proportional to the change in the deformation modulus $E_{b,\tau}$. (refer with Fig. 1). For any combination φ_l and δ_e change in environmental water percentage W from 75% till 40% leads to a decrease in rigidity D_b for 1,565 times. A change in the relative eccentricity of the load application from 0.15 to 1.35 leads to a decrease in rigidity D_b in 3,66 times for any values φ_l and W.
3. The parameters φ_l and $E_{b,\tau}$ influence to the full rigidity of the compressive strut section D affects less than the concrete section D_b rigidity (refer with Table 3). W change from 75% till 40% for each φ_l from 1,2 till 1,8 leads to a decrease in total rigidity D by δ_e = 0,15 from 17% to 13%, and at δ_e =1,35 from 6% to 4,1%. This is a decrease in the influence of parameters φ_l and W the total rigidity is related to the weight fraction of the reinforcement rigidity D_s in the overall rigidity of the compressive strut D.
4. Critical force of the annular strut N_{cr} (ceteris paribus) is decreased with increasing eccentricity of load application δ_e both for short-term and long-term loading. Functional dependence $N_{crc} = f(\delta_e)$ is nonlinear (refer with Fig. 2). With φ_l increase there is a decrease in critical force N_{cr} out of proportion to the value φ_l .
5. Preliminary study of the bearing capacity of the compressive strut M_{ult} (according to formula 2) revealed that M_{ult} is increased with increasing ratio N/N_{cr}, reaching a maximum within the acceptable values N/N_{cr}=0.1÷1 (refer with Fig.3).

The authors plan to continue researching the bearing capacity of the compressive struts M_{ult} depending on different combinations φ_l, δ_e, $E_{b,\tau}$, N/N_{crc} for the purpose of building dependency monograms M_{ult} from N/N_{crc} and percentage of compressive strut reinforcement.

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