Improving methodology for calculating scaffolding formwork of monolithic slabs in building constructions

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Abstract. Currently, when designing various residential buildings, there has been a tendency to use monolithic reinforced concrete to cover significant spans. The article proposes the calculation of the outside racks of volumetric scaffold. The bearing capacity of the outside racks is reduced due to eccentric compression of the racks. Alignment of the bearing capacity of the racks provides a span decrease in the placement of outside racks. At the same time, all racks experience central compression and work in the same conditions. This article is a continuation of the paper dedicated to the calculation of volumetric scaffolding of monolithic slab formwork, published in this volume. Article considers the calculation of the outside racks of formwork scaffold, which, in contrast to the intermediate ones, experience bending stresses due to asymmetric load.

1. Introduction
Implementation of complex innovative production processes [1–17] places high demands on infrastructure. In the construction of buildings and structures intended for the implementation of complex technological operations [18–27], monolithic reinforced concrete slabs of significant areas are often used. During their construction, the formwork of the slabs is based on volumetric scaffold, consisting of vertical posts connected by horizontal links.

The issue of calculating permissible loads on various structures was considered in [28–40], however, due to the great responsibility imposed on the results obtained, additional studies are required.

This article proposes a methodology for calculating the permissible load on the outside racks of scaffold of a monolithic slab formwork (figure 1), based on the conditions of strength and stability, which made it possible to give specific recommendations for manufacturing some standard sizes of scaffolds.

2. Research subject
Considering the load on the extreme rack (figure 2, figure 3), it is worth noting that when the carrier beam “lays out” at \( l_0 \neq 0.5L \), eccentric loading on the rack takes place. In this case, the first span \( l_1 \) and subsequent should be less than the permissible \( L \).

Some sources recommend reducing the span between outside racks in half, compared with the span between the intermediate.

Consider the rack layout for different overhang of the outside beam \( l_0 \), meaning that the bearing capacity of the intermediate racks (loaded centrally) \( S \) and the permissible span of their placement \( L \) are known.
Figure 1. Volumetric scaffold of monolithic slab formwork.

Figure 2. Determination of the load on outside racks.

Figure 3. Center rack load.
Denote the beam overhang from the outside rack $l_0$, $l_1$ – the length of the first span, $l_2$ – of the second span, etc., $L$ – pitch of intermediate racks. Then, according to the load scheme (figure 2), on the first outside rack act forces $N_0$ and $N_1$ (figure 3):

$$N_0 = S \cdot l_0 \cdot L \quad ; \quad N_1 = S \cdot \frac{l_1}{2} \cdot L$$  \hspace{1cm} (1)

The compressive force acting on the outside rack

$$N = N_0 + N_1 = \left( l_0 + 0.5l_1 \right) LS$$  \hspace{1cm} (2)

Compressive stresses:

$$\sigma_c = \frac{N}{A} = \left( l_0 + \frac{l_1}{2} \right) \cdot \frac{L \cdot S}{A}$$  \hspace{1cm} (3)

Accepting the linear dependence of the beam pressure on the fork (figure 4), we write the formula for the bending moment acting on the rack

$$M_b = \left( N_1 - N_0 \right) \frac{2}{3} a = \left( \frac{l_1}{2} - l_0 \right) LS \cdot \frac{2}{3} a$$  \hspace{1cm} (4)

and bending stress

$$\sigma_b = \frac{M_b D}{J} = \frac{\left( 0.5l_1 - l_0 \right) D}{J} \cdot \frac{2}{3} a \cdot L \cdot S$$  \hspace{1cm} (5)

$$\sigma_b = \left( \frac{l_1}{2} - l_0 \right) \frac{aD}{3l^2} \frac{SL}{A}$$  \hspace{1cm} (6)

Figure 4. Outside rack load.

Permissible stress

$$[\sigma] = \frac{SL^2}{A}$$  \hspace{1cm} (7)
We equate maximum stresses in the outside rack $\sigma = \sigma_c + \sigma_b$ and permissible stress

$$\frac{SL^2}{A} = \frac{SL}{A} \left[ \left( l_0 + \frac{l_1}{2} \right) + \omega \left( \frac{l_1}{2} - l_0 \right) \right] \tag{8}$$

where

$$L = l_0 \left( 1 - \omega \right) + \frac{l_1}{2} \left( 1 + \omega \right) \tag{9}$$

For rack $D = 59\text{ mm}$

$$\omega = \frac{aD}{3l^2} \tag{10}$$

Expression (9) connects the beam overhang $l_0$ and the first span length $l_1$ with the permissible pitch of the intermediate racks $L$. Moreover, the stresses in the outside rack from eccentric loading do not exceed the permissible ones.

If $l_0 = L/2$

$$L = \frac{L}{2} \left( 1 - 4.18 \right) + \frac{l_1}{2} \left( 1 + 4.18 \right) \tag{12}$$

than $l_1 = L$

If $l_0 = L/4$

$$L = \frac{L}{4} \left( 1 - 4.18 \right) + \frac{l_1}{2} \left( 1 + 4.18 \right) \tag{13}$$

than $l_1 = 0.7L$, i.e for load balancing the first span should be $0.7L$.

Having taken in the expression (9) the value $l_0'$ equal to half the first span $l_0' = 0.7L/2$ we can find the length of the second span $l_1'$, at which the load on the racks is equalized:

$$L = \frac{0.7L}{2} \left( 1 - 4.18 \right) + \frac{l_1'}{2} \left( 1 + 4.18 \right) \tag{14}$$

Thus $l_1' = l_2 = 0.81L$

Performing similar calculations further for $l_0'' = l_0'/2 = 0.81L/2$ we find the length of third span $l_1'' = l_3 = 0.877L$.

For $l_0''' = l_0''/2 = 0.877L/2$, $l_1''' = l_4 = 0.95L$.

Thus, with a sequential increase in the distance between racks $l_i$, the load on the racks is equalized to the fourth span.

Note that in the absence of beam overhang, i.e. $l_0 = 0$, from expression (9) it follows that

$$L = 0.5l_1 \left( 1 + 4.18 \right) \tag{15}$$

and the length of the first span $l_1 = 0.385L$.

Taking further in the expression (9) $l_0' = l_1/2 = 0.1925L$, we obtain the value of the second span $l_1' = l_2 = 0.62L$. Performing similar calculations, we obtain $l_3 = 0.766L; l_4 = 0.857L; l_5 = 0.91L; l_6 = 0.95L; l_7 = 0.97L; l_8 = 0.98L$.

Thus, the load equalizing on the intermediate racks in the absence of overhanging of the carrier beam occurs to the eighth span.
Table 1 presents the lengths of the first eight spans of the grid of racks depending on the overhang of the carrier beam, at which the stresses in the racks are equal to the permissible (for racks $D = 59$ mm).

**Table 1.** Dependence of span length on beam overhang for rack $D = 59$ mm.

| $k$ – span reduction factor $l_i = kL$ | $l_1$ | $l_2$ | $l_3$ | $l_4$ | $l_5$ | $l_6$ | $l_7$ | $l_8$ |
|-------------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|
| 0.5                                 | 1     | 1     | 1     | 1     | 1     | 1     | 1     | 1     |
| 0.4                                 | 0.877 | 0.924 | 0.953 | 0.971 | 0.982 | 0.99  | 1     | 1     |
| 0.35                                | 0.815 | 0.883 | 0.93  | 0.955 | 0.973 | 0.983 | 0.99  | 1     |
| 0.25                                | 0.70  | 0.81  | 0.883 | 0.926 | 0.955 | 0.972 | 0.983 | 0.99  |
| 0.15                                | 0.570 | 0.735 | 0.837 | 0.90  | 0.938 | 0.962 | 0.977 | 0.986 |
| 0                                  | 0.385 | 0.620 | 0.766 | 0.857 | 0.910 | 0.930 | 0.970 | 0.980 |

For racks $D = 48$ mm coefficient $\omega$ in formula (9) is equal to

$$\omega = \frac{aD}{3i^2} \cdot \frac{8.5 \cdot 4.8}{3 \cdot 2.56} = 5.31$$  \hspace{1cm} (16)

Expression (9) looks like:

$$L = -l_0 \cdot 4.31 + 0.5 \cdot l_1 \cdot 6.31$$  \hspace{1cm} (17)

**Table 2.** Dependence of span length on beam overhang for rack $D = 48$ mm.

| $k$ – span reduction factor $l_i = kL$ | $l_1$ | $l_2$ | $l_3$ | $l_4$ | $l_5$ | $l_6$ | $l_7$ | $l_8$ |
|-------------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|
| 0.5                                 | 1     | 1     | 1     | 1     | 1     | 1     | 1     | 1     |
| 0.4                                 | 0.863 | 0.906 | 0.936 | 0.956 | 0.970 | 0.980 | 0.99  | 1     |
| 0.35                                | 0.795 | 0.86  | 0.904 | 0.935 | 0.955 | 0.970 | 0.979 | 0.986 |
| 0.25                                | 0.658 | 0.767 | 0.840 | 0.891 | 0.926 | 0.950 | 0.965 | 0.976 |
| 0.15                                | 0.520 | 0.673 | 0.777 | 0.848 | 0.896 | 0.929 | 0.951 | 0.967 |
| 0                                  | 0.317 | 0.533 | 0.681 | 0.782 | 0.851 | 0.898 | 0.930 | 0.952 |

3. **Summary**

1. The bearing capacity of outside racks is reduced due to the eccentric compression of the racks. Equalizing of bearing capacity of the racks provides a decrease in the pitch of the placement of outside racks (see tables 1 and 2).

2. The optimal overhang of carrier beam $l_0$ is equal to half the span of intermediate racks $L$. Moreover, all the racks are subjected to central compression and work under the same conditions.

From the point of view of the structural strength of the scaffolds, such a layout of racks is determined by the bearing capacity of the beam. In a beam with overhang $l_0 = 0.5L$, the maximum bending moment is equal to the beam moment without overhang ($l_0 = 0$), i.e. they are equally strong.

3. In the absence of technical ability to make the overhang of the carrier beam beyond the grid of racks by $l_0 = 0.5L$, the loads on the outside racks will be uneven.

In this case, it is necessary to follow the recommendations of tables 1, 2 at least for the first two to three spans. With further arrangement of the racks with pitch of $L$, the permissible load on the rack should be reduced by $(l_1/L)^2$, where $l_1$ is the first span, the length of which is taken $L$. 
References

[1] Bratan S and Roshchupkin S 2018 Synthesis of lunberger stochastic observer for estimation of the grinding operation state MATEC Web of Conferences 224 01133. DOI: 10.1051/matecconf/201822401133

[2] Bratan S, Kolesov A, Roshchupkin S and Stadnik T 2017 Theoretical-probabilistic model of the rotary belt grinding process MATEC Web of Conferences 129 01078. DOI: 10.1051/matecconf/201712901078

[3] Bratan S, Vladeskaya E and Kharchenko A 2017 Improvement of quality of details at round grinding in the conditions of a floating workshop MATEC Web of Conferences 129 01083. DOI: 10.1051/matecconf/201712901083

[4] Pakhaliuk V, Polyakov A, Kalinin M. and Bratan S 2016 Evaluating the impact and norming the parameters of partially regular texture on the surface of the articulating ball head in a total hip joint prosthesis Tribology Online 11(1) pp 527-539. DOI: 10.2474/trol.11.527

[5] Bardovskii A D, Gerasimova A A, Keropyan A M and Bibikow P Y 2018 Influence of the mechanical characteristics of harp screen material on screening process Izvestiya Ferrous Metallurgy 61(9) pp 678-682. DOI: 10.17073/0368-0797-2018-9-678-682

[6] Bardovsky A D, Gerasimova A A and Basyrov I I 2019 Study of oscillating process of harp screens Lecture Notes in Mechanical Engineering 0(9783319956299) pp 133-139. DOI: 10.1007/978-3-319-95630-5_14

[7] Bibikov P Y, Bardovskiy A D and Keropyan A M 2019 Investigation of press classification process of weak rocks Materials Today: Proceedings 19 pp 2552-54. DOI: 10.1016/j.matpr.2019.08.207

[8] Solomonov, K., Tishchuk, L. Virtual and physical simulation forming of flat workpieces under upsetting (2019) Procedia Manufacturing, 37, pp. 467-471. DOI: 10.1016/j.promfg.2019.12.075

[9] Chichenev N A 2015 Import-replacing re-engineering of the drive of the rollers in the intermediate roller table of a continuous bloom caster Metallurgist 58(9-10) pp 892-895. DOI: 10.1007/s11015-015-0013-9

[10] Durelli A J, Chichenev N A and Clark J A 1972 Developments in the optical spatial filtering of superposed crossed gratings Experimental Mechanics 12(11) pp 496-501. DOI: 10.1007/BF02320745

[11] Efremov D B, Gerasimova A A, Gorbatyuk S M and Chichenev N A 2019 Study of kinematics of elastic-plastic deformation for hollow steel shapes used in energy absorption devices CIS Iron and Steel Review 18 pp 30-34. DOI: 10.17580/cisirsr.2019.02.06

[12] Gerasimova A, Gorbatyuk S and Efremov D 2020 Modeling of tool for cold extrusion of steel and tooling with proportional bandaging Solid State Phenomena 299 SSP pp 513-517. DOI: 10.4028/www.scientific.net/SSP.299.513

[13] Gerasimova A A, Keropyan A M and Girya A M 2018 Study of the Wheel–Rail System of Open-Pit Locomotives in Traction Mode Journal of Machinery Manufacture and Reliability 47(1) pp 35-38. DOI: 10.3103/S1052618818010065

[14] Glukhov L M, Gorbatyuk S M, Morozova I G and Naumova M G 2016 Effective Laser Technology for Making Metal Products and Tools Metallurgist 60(3-4) pp 306-312. DOI: 10.1007/s11015-016-0291-x

[15] Gorbatyuk S, Kondratenko V and Sedykh L 2019 Investigation of the Deep Hole Drill Stability When Using a Steady Rest Materials Today: Proceedings 11 pp 258-264. DOI: 10.1016/j.matpr.2018.12.140

[16] Gorbatyuk S, Kondratenko V and Sedykh L 2019 Influence of critical speed when working shafts with symmetrically located monolithic weighting on the accuracy of work surfaces Materials Today: Proceedings 19 pp 2361-64. DOI: 10.1016/j.matpr.2019.07.695
[17] Gorbatyuk S, Kondratenko V and Sedykh L 2019 Influence of critical speed when working shafts with asymmetrically located monolithic weighting on the accuracy of work surfaces Materials Today: Proceedings 19 pp 2117-20. DOI: 10.1016/j.matpr.2019.07.222
[18] Kondratenko V E, Gorbatyuk S M and Devyat'yarova VV 2019 Stroitelnaya mekhanika (Moscow: Izd.Dom NITU MISIS) ISBN 978-5-907226-27-2.
[19] Feodos'ev V I 2000 Soprotivlenie materialov (Moscow: Izd. MGGU)
[20] SNiP II-23-81 Stal'nye konstruktsii (Moscow: Stroiizdat)
[21] GOST 24258-88 Sredstva podmashchivaniya. Obshchie tekhnicheskie usloviya
[22] Gorbatyuk S M, Morozova I G and Naumova M G 2017 Development of the working model of production reindustrialization of die steel heat treatment Izvestiya Ferrous Metallurgy 60(5) pp 410-415. DOI: 10.17073/0368-0797-2017-5-410-415
[23] Gorbatyuk S M, Osadchii V A and Tuktarov E Z 2011 Calculation of the geometric parameters of rotary rolling by using the utomated design system autodesk inventor Metallurgist 55(7-8) pp 543-546. DOI: 10.1007/s11015-011-9465-8
[24] Gorbatyuk S, Pashkov A and Chichenev N 2019 Improved Copper-Molybdenum Composite Material Production Technology Materials Today: Proceedings 11(1) pp 31-35. DOI: 10.1016/j.matpr.2018.12.102
[25] Gorbatyuk S M, Pashkov A N, Zarapin A Y and Bardovskii A D 2019 Development of Hot-Pressing Technology for Production of Aluminum-Based Metal-Matrix Composite Materials Metallurgist 62(11-12) pp 1261-66. DOI: 10.1007/s11015-019-00784-0
[26] Gorbatyuk S M, Pavlov V M, Shapoval A N and Gorbatyuk M S 1998 Experimental use of rotary rolling mills to deform compacts of refractory metals Metallurgist 42(5-6) pp 178-183. DOI: 10.1007/BF02766359
[27] Gorbatyuk S M, Romanov S P and Morozova I G 2019 Computer Simulation of the Cooling System for Rollers of the Finishing Stand of a Wide-Strip Hot-Rolling Mill and the Development of a New Scheme of Cooling Metallurgist 63(7-8) pp 836-840. DOI: 10.1007/s11015-019-00897-6
[28] Karelin I N, Sedykh V D and Sedykh L V 2013 Modernization of a sharply bending elbow in a steel pipeline Chemical and Petroleum Engineering 49(5-6) pp 351-354. DOI: 10.1007/s10556-013-9754-0
[29] Keropyan A M 2016 Features of interaction of traction wheels of an electric locomotive and a diesel locomotive with rails in the conditions of open mountain works Journal of Friction and Wear 37(1) pp 78-82. DOI: 10.3103/S0967091208120074
[30] Keropyan A, Gerasimova A and Goloshapov K 2017 Influence of the track gradient on the contact temperature at the wheel-rail zone for open-pit locomotives MATEC Web of Conferences 129 06009. DOI: 10.1051/matecconf/201712906009
[31] Keropyan A, Gorbatyuk S and Gerasimova A 2017 Tribotechnical Aspects of Wheel-Rail System Interaction Procedia Engineering 206 pp 564-569. DOI: 10.1016/j.proeng.2017.10.517
[32] Keropyan A M, Gorbatyuk S M, Bibikov P Y and Bardovskii A D 2019 Influence of Roughness of Working Surfaces of the Wheel–Rail System of Open-Pit Locomotives with an Implementable Adhesion Coefficient Journal of Friction and Wear 40(1) pp 73-79. DOI: 10.3103/S1068366619010082
[33] Mazhirin E A, Chichenev N A and Zadorozhnyi V D 2008 Modernizing the track units of the 2800 thick-sheet mill at OAO Ural'skaya Stal' Steel in Translation 38(12) pp 1048-50. DOI: 10.3103/S0967091208120255
[34] Naumova M G, Morozova I G, Zarapin A Y and Borisov P V 2018 Copper alloy marking by altering its surface topology using laser heat treatment Metallurgist 62(5-6) pp 464-469. DOI: 10.1007/s11015-018-0682-2
[35] Nikolaev V A, Rusakov A D and Chichenev N A 1996 Forecasting a multiroll mills rolls hardness Stal' 9 pp 58-60
[36] Radyuk A G, Gorbatyuk S M and Gerasimova A A 2011 Use of electric-arc metallization to recondition the working surfaces of the narrow walls of thick-walled slab molds *Metallurgist* **55**(5-6) pp 419-423. DOI: 10.1007/s11015-011-9446-y

[37] Slobodyanik T M and Balakhnina E E 2019 Dynamics of elementary differential composed of elastic bodies *Mining Informational and Analytical Bulletin* **2019**(9) pp 204-210. DOI: 10.25018/0236-1493-2019-09-0-204-210

[38] Slobodyanik T M and Balakhnina E E 2020 Dynamic analysis of elementary differential gear with rigid links *IOP Conference Series: Materials Science and Engineering* **709**(3) 033066. DOI: 10.1088/1757-899X/709/3/033066

[39] Tarasov Y S, Radyuk A G and Gorbatyuk S M 2018 Effect of the Thermal Insulation of the Inner Wall on the Thermal Condition of the Air Tuyeres of Blast Furnaces *Metallurgist* **61**(9-10) pp 745-750. DOI: 10.1007/s11015-018-0558-5

[40] Zakharov A N, Gorbatyuk S M and Borisevich V G 2008 Modernizing a press for making refractories *Metallurgist* **52**(7-8) pp 420-423. DOI: 10.1007/s11015-008-9072-5