Method of calculating volumetric scaffold of monolithic slab formwork

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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, often using structures with a complex geometric structure. This article proposes a methodology for calculating the permissible load on the scaffold racks from the conditions of strength and stability using the classical approaches of materials mechanics and structural mechanics for this purpose, in order to optimize the consumption of materials and to identify real "steps" of racks horizontally and vertically, while observing the requirements for such structures for strength and stability. Cases of non-standard arrangement of outside scaffold racks of monolithic slab’s formwork are considered.

1. Introduction

Recently, both in our country and abroad, complex innovative technologies have been developed and introduced into production [1–18], the implementation of which makes increased demands on the infrastructure. In the construction of buildings and structures intended for the implementation of complex technological operations [19-29], 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 racks connected by horizontal links (figure 1).

The issue of calculating permissible loads was considered in [30 -36], however, due to the great responsibility imposed on the obtained results, additional studies are required.

This article proposes a methodology for calculating the permissible load on scaffold racks from the conditions of strength and stability, which made it possible to give specific recommendations for manufacturing some standard sizes of scaffolds.

2. Research methodology

Collecting the load on the intermediate scaffold rack (halfway span on each side of the rack) (figure 2), we obtain the value of the reducing force acting on the intermediate rack:

\[ N = S \cdot L^2 = \Delta \cdot \gamma \cdot L^2 \]  

where 
- \( S \) – specific weight of slab, N/m²
- \( \Delta \) – slab thickness, m;
- \( \gamma \) – volumetric weight of slab material, N/m³.
\( L \) – distance between racks, m.

Obviously, the \( N/4 \) load acts on the corner racks, and \( N/2 \) on the outside racks.

\[ \text{Figure 1. Scheme of load on racks of volumetric scaffold of monolithic slab formwork.} \]

\[ \text{Figure 2. Load distribution on racks.} \]

Figure 3 shows dependencies between the load on the intermediate rack \( N \) and horizontal span \( L \) for various values of the slab specific weight \( S \) and the slab thickness \( \Delta \).

In case of nodal transmission of the vertical load on the rack of the volumetric scaffold, the rigid joints of the spatial structure when calculating the internal forces can be considered as swivel joints [30]. In this case, the structural bearing capacity is determined by the stability of the pivotally fixed rack’s element of length \( h \), where \( h \) is the distance between the horizontal links of the element. In a real design, the joint has a flange and wedge connection and is not absolutely rigid, which goes to the margin of safety.
Figure 3. The dependence of the load on the rack $N$ on the span $L$.

In the practice of designing metal structures, the calculation of compressed racks by the coefficient of reduction of permissible stress is formalized [31].

The value of the permissible critical stress in the rack according to the stability criterion

$$[\sigma_s] = \varphi [\sigma_c]$$  \hspace{1cm} (2)

where $\varphi$ – coefficient of reduction of permissible stress, depending on the rack flexibility $\lambda$; $\sigma_c$ – permissible compression stress.

Permissible compressive force acting on the rack

$$[N] = A[\sigma_s]$$ \hspace{1cm} (3)

where $A$ – cross-sectional area of the rack.

The coefficient of reduction of permissible stresses $\varphi$ is determined in such a way that the experimentally observed spread of ultimate loads is overlapped. Coefficient $\varphi$ depends on rack flexibility

$$\lambda = \mu \frac{l}{i}$$ \hspace{1cm} (4)

where $l = h$ – rack section length (distance between joints);
$i$ – inertia radius of the rack cross-section;
$\mu$ – coefficient of reduction of length, depending on the type of fastening the ends of rack.

Successively, inertia radius of the rack cross-section:

$$i = \sqrt[3]{\frac{J}{A}}$$ \hspace{1cm} (5)

where $J$ – cross-sectional area moment of inertia;
$A$ – cross-sectional area of the rack;
where $D$ – outer diameter of the rack; $d$ – inner diameter of the rack.

For swivel joints of the ends of the rack section $\mu = 1$ (which goes to the margin of stability safety, because for other connection conditions $\mu < 1$).

The dependence of the compression stress coefficient $\varphi$ on the rack flexibility $\lambda$ for carbon basic steels is presented in the table 1 (for reference, presented the correspondence of the rack flexibility $\lambda$ to the length of the rack section between horizontal links $h$ for pipe $D = 59$ mm) [31]:

**Table 1.** Dependence of the compression stress coefficient $\varphi$ on the rack flexibility $\lambda$.

| $\lambda$ | 0 | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 | 110 | 120 | 130 | 140 |
|-----------|---|----|----|----|----|----|----|----|----|----|-----|-----|-----|-----|-----|
| $\varphi$ | 1 | 0.99 | 0.96 | 0.94 | 0.92 | 0.89 | 0.86 | 0.81 | 0.75 | 0.69 | 0.60 | 0.52 | 0.45 | 0.40 | 0.36 |
| $h$, m    | - | -   | 0.60 | 0.80 | 1.00 | 1.20 | 1.40 | 1.60 | 1.80 | 2.00 | 2.20 | -    | -    | -    | -    |

Figure 4 shows the dependence of the coefficient $\varphi$ on the rack flexibility of the rack section $\lambda$ (length $h$).

![Figure 4](image_url)

**Figure 4.** Dependence of the coefficient of reduction of permissible stress $\varphi$ on the rack flexibility $\lambda$.

Permissible compressive force on the rack:

$$[N] = A \cdot [\sigma_s] = A \cdot \varphi \cdot [\sigma_y]$$  \hspace{1cm} (8)

Yield strength of rack material [32]:

$$[\sigma_y] = \frac{R_s \cdot \gamma_c}{\gamma_f}$$  \hspace{1cm} (9)

where $R_s = 220$ MPa – compression resistance for pipes made from basic carbon steels;
\[ \gamma_c = 0.95 \] – working conditions coefficient [31];
\[ \gamma_f = 1.2 \] – load safety factor [33]

\[ \left[ \sigma_f \right] = \frac{220 \cdot 0.95}{1.2} = 174.2 \text{ MPa} \]

Figure 5 shows the dependence between permissible force (mass) on the rack [N] (t) and the rack section length \( h \) (sm) for the pipe \( D = 59 \text{ mm} \).

3. Results obtained

As the results of work, an example of calculating the formwork is given below:

Given: the thickness of the slab \( \Delta = 0.3 \text{ m} \). According to the chart (figure 2) or formula (1) for the selected span of the racks \( L = 2.5 \text{ m} \), we determine the load on the rack \( N = 4 \text{ t} \). According to the permissible load [N] = 4.5 t (figure 5) we determine the span of horizontal links \( h = 2.2 \text{ m} \).

Taking, for example, the span \( L = 3 \text{ m} \), we determine the load \( N = 6.75 \text{ t} \) (figure 2) and the load (figure 4) determine the span of horizontal links in height \( h = 1.5 \text{ m} \).

When calculating the scaffolds racks having a significant height \( H \) the load acting on the lower section should be considered, not only from the slab, but also from the own weight of the scaffolds. Thus, from the permissible load \( N \) should be subtracted all the overlying part of scaffold.

\[ G = n \left( h \cdot G_f + 2L \cdot G_h \right) + 2L \cdot G_h \]  \hspace{1cm} (10)

where \( n = H/h \),
\( H \) – scaffold height;
\( h \) – span between horizontal links;
\( L \) – span between racks;
\( G_f \) – linear weight of rack pipe;
\( G_h \) – linear weight of horizontal pipe.

Initial data:
Option 1:
Rack pipe: \( D = 59 \text{ mm}, d = 55 \text{ mm} \left( \delta = 2 \text{ mm} \right) \)
Horizontal pipe: $D = 48 \text{ mm}, d = 42.6 \text{ mm (}\delta = 2.7 \text{ mm)}$

Option 2:
Rack pipe: $D = 48 \text{ mm}, d = 42.6 \text{ mm (}\delta = 2.7 \text{ mm)}$

Material: basic carbon steel, $R_S = 220 \text{ MPa}$

Permissible load

$$[\sigma_f] = \frac{220 \cdot 0.95}{1.2} = 174.2 \text{ MPa}$$

| Table 2. Rack specifications. |
|-----------------------------|
| Option | $A$, sm$^2$ | $J$, sm$^4$ | $i$, sm | $h$, m | $\lambda$ | $\varphi$ | $[N]$, kN |
|---|---|---|---|---|---|---|---|
| 1. $D = 59 \text{ mm}$ | 3.58 | 14.56 | 2.02 | 0.5 | 24.6 | 0.951 | 59.30 |
| | | | | 1 | 49.5 | 0.89 | 55.50 |
| | | | | 1.5 | 47.25 | 0.785 | 48.95 |
| | | | | 2 | 99 | 0.60 | 37.42 |
| 2. $D = 48 \text{ mm}$ | 3.84 | 9.89 | 1.6 | 0.5 | 31.25 | 0.938 | 62.71 |
| | | | | 1 | 62.5 | 0.847 | 56.69 |
| | | | | 1.5 | 93.7 | 0.656 | 43.90 |
| | | | | 2 | 125 | 0.425 | 28.43 |

Tables 1 and 2 show the calculation data for the permissible specific load from the slab $S$ ($\text{kg/m2}$) and the slab thickness $\Delta$ (m) for the specific slab weight $\gamma = 25 \text{ MPa}$ depending on the parameters of the scaffold:

$L$ – span between racks;
$h$ – span between horizontal links for scaffold of various heights $H$ (m).

4. Summary

The permissible specific load on the intermediate scaffold stand is calculated with a total standard safety factor $n = 1.26$ (rack stress is $[\sigma] = 174.2 \text{ MPa}$).

Given a certain idealization of the calculation scheme, inaccuracy in manufacturing and assembling scaffold elements, material defects and experience of using similar structures, the safety factor $n$ can be increased. In this case, the permissible specific load and the slab thickness are reduced in proportion to the increase in safety factor.

The above technique can be successfully implemented in the production of new effective technologies and equipment [34–40].

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