Analysis of the load bearing capacity of scaffoldings used in Poland

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Abstract. The paper presents static-strength analyses of 120 scaffoldings used on construction sites in Poland in the period 2016-2018. The geometry of each analysed scaffolding was taken from measurements made on the construction sites, and the scaffolding loads were determined on the basis of the standards requirements. The results of scaffolding inventory, surveying measurements, measurements of axial forces in standards, and measurements of scaffolding accelerations during vibrations were used to create numerical scaffolding models. For each scaffolding, buckling load analysis and linear static analysis were performed for four load cases which took into account self-weight, parallel and perpendicular wind actions and service load. On the basis of numerical analyses, it was found that 14 scaffoldings could fail due to loss of stability. For 56 scaffoldings, the ultimate limit state condition was not met in at least one group of components, therefore 47% of tested scaffoldings should not be approved.

1. Introduction

Scaffoldings are temporary structures that are used on most construction sites. They ensure safety of people working at height or in places with difficult access. The specificity of scaffoldings use means that their users are more prone to accidents than other construction workers. From 2011 to 2014, 479 people fell from scaffoldings located in Poland [1]. The direct causes of falls from scaffolding are mainly: leaning on handrails, shear of deck hooks or lack of decks, but also failure of scaffolding and its falling over together with people.

The necessity of performing static and strength calculations for scaffoldings was demonstrated, among others, by Żółtowski [2]. The paper [2] describes failure of scaffolding mounted inside the distillation column with a diameter of 5.3 m and a height of about 57 m, located at Petrochemia in Płock. The scaffolding was made using an older type of tubular system. The tubular elements had an outer diameter of 48.3 mm, but the walls of the elements had various thickness: 2.9; 3.7 and 4.0 mm. Furthermore, significant steel corrosion was also found in the elements. During the use of the scaffolding, the standards buckled, joints were damaged and eventually horizontal load-bearing elements were damaged and the scaffolding collapsed. As a result, two people were killed and three were injured. Static-strength calculations performed after the disaster showed the bearing capacity of the elements was significantly exceeded.

Another example of scaffolding failure occurred in 2010 at the historic building in Gostyń [3]. The scaffolding was used to enable maintenance works for building towers at 38.5 m. During the storm, the
access tower of scaffolding was detached from the building and the working platforms were moved by the wind to the roof and outside the building. In the result, building’s historic tiles were destroyed. The direct cause of the scaffolding failure in Gostyń was a strong wind, but a detailed static and strength analysis of the structure showed that the structure did not meet the ultimate limit state requirement. The failure did not take place earlier, because the scaffolding was just assembled and no construction works were carried out on it before the storm.

According to the National Regulation [4] scaffoldings that are different from those described in the producer’s documentation should be assembled on the basis of individual projects. The projects of atypical scaffoldings should be prepared in accordance to the standards EN 12810-2 [5] and EN 12811-1 [6] recommendations. Such designs have not been prepared for the two scaffoldings which failures were described above. In order to check whether other scaffoldings in Poland would meet the requirements of EN 12810-2 [5] and EN 12811-1 [6], static-strength analyses of 120 scaffoldings used at construction sites in 2016-2018 were performed. For each scaffolding, the geometry used in calculations was corresponding to the one measured at the construction site, whereas scaffolding loads were determined on the basis of standard requirements.

2. Description of research methods

2.1. In situ measurements

The research on scaffoldings was performed by five research teams, as a part of the ORKWIZ project (full title: „Modelling of risk assessment of construction disasters, accidents, and dangerous incidents at workplaces using scaffoldings”). The subject of the study were frame scaffoldings, mostly set up at buildings facades. The total number of 120 scaffoldings was tested during the research. Scaffoldings were located in various parts of Poland. Each scaffolding was assigned a symbol, consisting of a letter denoting the given research team (D, E, L, W and P), and a subsequent number in the tests of the given team (e.g. W15).

On each of the construction sites where scaffoldings were tested, the measurements lasted one working week. The methodology of the studies, the results and their analyses are presented, among others, in works [7]-[20]. The results of a detailed inventory of scaffoldings, geodetic measurements, measurements of normal forces in standards and accelerations measured in various points of scaffoldings during vibrations were used in the research described in this paper.

As part of the inventory of each scaffolding, the following information was collected: type of scaffolding system; scaffolding schemes with marked: base jacks, standards, decks, handrails, toe-boards, bracings, anchors, ladders and other scaffolding elements; type of platforms; presence of protective covering and its type; dimensions of mudsills; presence of earthing and lightning protection mounted on a scaffolding. Photographic documentation included photos with all the elements listed above. Then, on this basis, 3D drawings were developed in the Autocad. The documentation prepared this way enabled accurate mapping of each scaffolding. In case of scaffoldings, seemingly small changes have a great impact on the effort of individual elements of the structure.

Scaffoldings geometry measurements were supplemented with geodetic surveying (Figure 1a). As part of these measurements, the location of pairs of points which lie on the circumferences of the circular cross-sections of standards was determined. On the basis of these points, the cross-sectional centres of standards were determined, and the scaffolding geometry was developed based on their locations. The method of measuring and creating scaffolding geometry based on the results of these measurements has been described in detail in [11].

Measurements of normal forces in standards were made using an instrument designed especially for this purpose, shown in Figure 1b. The device consists of two parts and each of these parts is comprise of a rigid frame and a force sensor placed on it. Before the measurement, each part was positioned under one stand of a scaffolding frame. The frame of the device was positioned with the screws so that the force sensor indicated zero. Then the base jacks were unscrewed and the scaffolding rested on the force sensors. After that, readings of normal forces values in the standards of one frame were taken. For each
scaffolding three frames at the lowest level of scaffolding were chosen to be tested: one with attached bracing, one without it and one at the end of the structure. The method of measurement and analysis of the results has been described in detail in [10].

The study of dynamic parameters consisted of measuring accelerations of selected points below the highest level of decks. The signal analyser and accelerators from Brüel & Kjær were used. Based on the acceleration changes measured over time, the frequencies of free vibrations and scaffolding damping parameters were determined. The Fast Fourier Transform (FFT) analysis was performed for each of the measured signals. Based on these results, the frequencies of free vibrations and damping parameters were determined. The research methodology and analysis of the results were thoroughly presented in [7].

![Images](a) (b) (c)

**Figure 1.** Measuring stations [11]: (a) geodetic measurement, (b) measurement of forces in standards, (c) measurement of accelerations during scaffolding vibrations

### 2.2. Numerical analysis

Numerical models and calculations were made for each scaffolding using the Autodesk Simulation Multiphysics 2013. The models took into account geometric imperfections defined as the distances between the location of standards connections in real and ideal geometry of the structure. Figure 2 shows an example of numerical model for scaffolding W12. Static scheme of the remaining scaffoldings are included in [8]. Geometric characteristics of elements cross-sections and characteristic yield limits – \( f_{yk} \) (Table 1) were adopted on the basis of information from manufacturers or from the own research. The calculated yield stress was determined from the formula \( f_y = f_{yk} / \gamma_M \), where the partial safety factor \( \gamma_M \) was equal to 1.1.

To determine the frequencies of natural vibrations for each scaffolding, static calculations including only the self-weight of the scaffolding were carried out. Based on the resultant frequencies and forms of natural vibrations, the supports modelling anchors were calibrated and the rigidity of elastic supports modelling cooperation between the analysed scaffolding and adjacent scaffoldings was selected. For some scaffoldings, mainly low ones with low self-weight, cooperation with the ground was also modelled with the use of elastic supports. Then, normal forces in standards from static calculations for verified static scaffolding schemes, were compared with measured values. These results showed for some standards, a possible lack of full support on the ground, which was verified on the basis of soil tests and information from scaffolding inventory. During scaffolding tests on construction sites, it was checked if the standards were loaded. The methodology of boundary conditions selection in scaffolding models has been described, among others, in [21], while the impact of the adopted static schemes was checked in [22] and [23].
Figure 2. Static scheme of W12 scaffolding for cases: (a) LC1, (b) LC4. Load cases description summarized in Table 2

Table 1. Characteristic yield strength $f_{yk}$ [MPa]

| Scaffolding system | The number of scaffoldings | Standards | Base jacks | Transoms | Other components |
|--------------------|---------------------------|-----------|------------|----------|-----------------|
| Altrad Mostostal   | 36                        | 315.0     | 235.0      | 315.0    | 315.0           |
| Plettac            | 33                        | 320.0     | 235.0      | 235.0    | 235.0           |
| Layher             | 23                        | 320.0     | 320.0      | 320.0    | 320.0           |
| Delta              | 8                         | 315.0     | 235.0      | 235.0    | 235.0           |
| RUX                | 5                         | 235.0     | 235.0      | 235.0    | 235.0           |
| Hunnebeck          | 5                         | 235.0     | 235.0      | 235.0    | 235.0           |
| RR-0,8             | 5                         | 235.0     | 235.0      | 235.0    | 235.0           |
| BAL                | 2                         | 460.0     | 270.0      | 400.0    | 270.0           |
| Termosprzęt        | 2                         | 235.0     | 235.0      | 235.0    | 235.0           |
| PERI               | 2                         | 235.0     | 235.0      | 235.0    | 235.0           |
| Omega              | 1                         | 235.0     | 235.0      | 235.0    | 235.0           |

For verified scaffolding models stability and linear static analyses were performed. The calculations were made for 4 load cases, in accordance with EN 12811-1 [6] and summarized in Table 2. The characteristic wind action was determined from the formula:

$$F_k = c_s \sum A_i c_{f,i} w_{k,i}.$$  

where: $A_i$ – the reference area, $c_{f,i}$ – the aerodynamic force coefficient, $c_s$ – the site coefficient, $w_k$ – the characteristic wind velocity pressure, $i$ – index of the scaffolding element. A detailed description of the scaffolding wind load determination methodology can be found in [17].

The static-stress analyses were performed as linear calculations, because the obtained results not only confirm the possible exceedance of the load capacity of structural elements, but also show the scale of failure risk, measured as the quotient of normal stress caused by the design load, and the calculated yield stress. Stability analyses were made for scaffoldings with characteristic loads.
Table 2. Load cases

| Load case | Self-weight $\gamma_f$ [kN/m²] | Service load | Wind load |
|-----------|--------------------------------|--------------|-----------|
| LC1       | 1.5                            | 2.0 highest level | 1.5 0.2 perpendicular 1.5 |
| LC2       | 1.5                            | 2.0 highest level | 1.5 0.2 parallel 1.5 |
| LC3       | 1.5                            | 0.5 highest level | 1.5 EN 1991-1-4 [24] perpendicular 1.5 |
| LC4       | 1.5                            | 0.5 highest level | 1.5 EN 1991-1-4 [24] parallel 1.5 |

$q_k$ – characteristic value of a service load, $w_k$ – the characteristic wind velocity pressure, $\gamma$ – partial safety coefficient.

3. Calculation results

3.1. Results of buckling analysis

The results of the stability analysis are buckling forms and critical load multipliers $\alpha_{cr}$. Figure 3 shows the number of scaffoldings for individual ranges of $\alpha_{cr}$. The multiplier $\alpha_{cr}$ took values from 0.2 to 24.9. The scaffoldings for which $\alpha_{cr}$ values were less than 1 were obtained only for cases with the wind perpendicular to the facade. There were 3 such scaffoldings for LC1 and 14 for LC3 load case. All these scaffoldings had protective coverings. In the performed calculations the wind was assumed as working towards the facade. It was found out that this situation is more unfavourable for the structure than when the wind acts from the façade because when it pushes the scaffolding against the façade anchors stop working. They either buckle or change the geometry so that they do not participate in creating the rigidity of the scaffolding system. This results in the loss of global stability at the level of scaffolding which is not supported horizontally. The issue of low stiffness of anchors in the case of wind loads towards the facade was discussed in the paper [25] and the impact of coverings on scaffolding effort in case of tall buildings was presented in [26].

![Figure 3](image_url)

**Figure 3.** Histograms of the number of scaffoldings depending on the value of $\alpha_{cr}$ – critical load multiplier, for cases: (a) LC1, (b) LC2, (c) LC3, (d) LC4
3.2. Results of static analysis

The results of static calculations were: displacements, internal forces and normal stresses determined from the formula:

\[ \sigma = \frac{S}{A} + \frac{M_2}{W_2} + \frac{M_3}{W_3}. \]  (2)

where: \( S \) – normal force, \( M_2 \) and \( M_3 \) – bending moments about the main axes of the cross-section, \( A \) – cross-sectional area, \( W_2 \) and \( W_3 \) – section modules at bending about principal axes.

Normal stresses in the W12 scaffolding elements are shown in Figure 4, whereas Figure 5 presents histograms of the section load utilization coefficient determined from the formula:

\[ \kappa = \frac{\sigma}{f_y}. \]  (3)

The presented histograms are graphs showing the number of scaffoldings for which \( \kappa \) value was obtained for four groups of elements: base jacks, standards, transoms and the group of other elements (bracings, consoles, girders, etc.). As can be seen in Figure 5, scaffolding may exceed its bearing capacity if it is exposed to loads applied in accordance with EN 12811-1 [6]. The load capacity for base jacks was exceeded in 56 scaffoldings, for standards – in 53 scaffoldings, for transoms – in 35 scaffoldings and for other elements – in 42 scaffoldings.

**Figure 4.** Normal stress in elements of W12 scaffolding, for cases: (a) LC1, (b) LC2, (c) LC3, (d) LC4
In 56 scaffoldings the load capacity was exceeded for one or more component groups. It means that 47% of scaffoldings should not be approved for use. If the possibility of buckling was also taken into account, the number of defective scaffoldings increases to 59. Of the 49 scaffoldings with protective covering, 35 did not meet the $\kappa<1$ condition and the load capacity of their elements was exceeded in all load cases. The highest effort in standards and base jacks was observed for the LC3 and LC4 cases (self-weight and wind, respectively, perpendicular and parallel). Transoms were the elements with the least number of fail rate. The main reason for exceeding load capacity in base jacks is probably the wind load acting perpendicularly to the scaffolding. The other components of scaffolding had various applications, and on average 25% of them could fail regardless of the load case.

![Histograms of the $\kappa$ coefficient for: (a) base jacks, (b) standards, (c) transoms, (d) other elements](image)

**Figure 5** Histograms of the $\kappa$ coefficient for: (a) base jacks, (b) standards, (c) transoms, (d) other elements

4. Conclusions
Static analyses of 120 real scaffoldings tested in years 2016-2018 were carried out. It was found that if the applied load was equal to the one recommended in standards, 14 scaffoldings would fail due to the loss of stability and in 56 scaffoldings exceeding capacity of one or more component group would be exceed. This means that 47% of tested scaffoldings should not be approved for use.

Scaffoldings, which had been found to be in a state of emergency under the standard loads, did not suffer from disasters, as the probability of such loads is very low. Scaffoldings are structures with a relatively short service life and the occurrence of maximum wind load is low but not impossible. Usually, in the event of atypical use of scaffoldings or significant loads resulting from the type of carried out work, the construction managers commission additional analyses before scaffolding is being used. However, not every scaffolding is placed on a construction site or there is no one who could assess the situation. Furthermore, the standard recommendations were meant to minimize the risk of failure at the design stage. The lack of scaffolding calculations in technical projects or skipping the scaffolding design completely poses a risk to the health and life of scaffolding users.
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