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Probability distribution functions for service loads of frame scaffoldings

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Abstract. The paper discusses service load measurements (weight of construction materials, small equipment and workers) conducted on 120 frame scaffoldings all over Poland in 2016–2018. Despite the fact that the scaffolding should ensure the safety of its users, most accidents on construction sites are caused by fall from height. Service loads are one of the elements affecting the safety of scaffolding use. On the basis of the studies, maximum load on one platform and maximum load on a vertical scaffolding module for one day were obtained. They were treated as the random variables of the maximum values. Histograms and probability density functions were determined for these variables. The selection of a probability distribution consisted in the selection of a probability density function by means of fitting curves to the study result histograms using the method of least squares. The analysis was performed for distribution Weibull and Gumbel probability density functions which are applied for maximum values of random variables. Parameters of these functions can be used for the purposes of the reliability analysis to calibrate partial safety factors in simulation of service load during the scaffolding failure risk assessment. Besides, the probability of not exceeding the standard loads provided for frame scaffoldings for 120 weeks was established on the aforementioned basis. The results of the presented research show that in Poland there is a high probability of exceeding the permissible service loads in one year and thus there is a high risk of scaffolding damage.

Key words: scaffolding; service load; extreme events; probability distribution function; safety.

1. Introduction

Service (usage) loads, including the weight of construction materials, small equipment and users, are the principal loads of construction scaffoldings. Another important load is the action of wind. Depending on the location, service period and purpose, scaffolding can also be loaded with temperature, snow, ice, or inertia forces induced by the movement of scaffolding or other dynamic actions.

Environmental loads are random processes, both in time and space. The statistics of the wind velocity field and methods of selecting them have been described in: [1–3], among others. Authors of [1] and [3] selected the Weibull probability density distribution with regard to the maximum wind velocity, while authors of [2] suggested the Gumbel distribution for the purposes of the distribution of maximum wind velocity values. On the basis of such distributions, a standard wind velocity is determined. The value is determined in such a way, that the wind of a greater velocity than the standard one occurs once in 50 years. Other characteristics of wind are the power spectral density (PSD) and the correlation function describing the wind velocity changes at one point in the domain of frequency and time. In the case of the wind action, the Davenport power spectral density is used most often, however, the literature mentions other functions describing power spectral densities, such as Harris's, Lumley's and Panofsky's, or Shiotani's. In the case of such standards, functions are used to determine the number of the dynamic load cycles of a structure. Since the wind velocity creates a field of random processes in a space, a subsequent set of the wind velocity characteristics contains autocorrelation and a density function. The functions in question are used for the purposes of simulation of the wind velocity field in time and space respectively by means of the WAWS (Weighted Amplitude Wave Superposition) or ARMA (Auto-Regressive Moving Average) methods.

In the literature one can also find statistical analyses of snow load. Authors of the paper [4] conducted a statistical analysis of the thickness of the snow layer in Poland. On that basis they selected the Gumbel distribution for the purposes of the snow load density distribution. Similar analyses were described for Italy in [5] and for Switzerland in [6]. The latter draws focus on the fact that the Gumbel distribution cannot be applied in a description of the snow layer thickness in mountain regions. As in the case of wind, the distributions of the maximum snow load values are used to determine standard values.

Nowadays, there are not too many publications on statistical description of service loads available. Statistical load descrip-

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tion is indispensable as far as the structural reliability analysis is concerned. For this reason, publications of 1970s and 1980s contained information about the service load probability distribution with regard to all kinds of structures. An exhaustive list of the probability distribution of all kinds of loads can be found in [7]. The data was compiled on the basis of the paper [8], continued in [9], [10]. According to [7], the Gumbel distribution is the maximum service load probability distribution. In recent years, no publication has seemed to contain any results of measurements of static service loads. Reliability analyses are usually based on standard recommendations available, for example, in [11] and [12]. Recent service load studies mainly regard dynamic loads, such as the passage of vehicles on bridges (e.g., [13–16]), loads during earthquakes (e.g., [17, 18]) and explosions (e.g., [19, 20]).

Scaffolding service loads, both static and dynamic ones, have not been statistically analyzed yet. The standards EN 12811-1 [21], AS/NZS 1576.1 [22] and 29 CFR 1926 [23] specify restrictions on the service load, for example, EN 12811-1 [21] contains load classes and related maximum platform load values. In exceptional situations, remarks regarding maximum permissible (characteristic) load – different from the standard one – are attached to the technical documentation during the design process. Therefore, one could assume that the topic of scaffolding loads is closed. Nevertheless, the studies conducted by the authors, under the project PBS3/A2/19/2015 "Model of the risk assessment of construction disasters, accidents and dangerous occurrences at the workplace using construction scaffolding", have shown that the common use of scaffolding results in the fact that such structures are often loaded without taking into consideration any existing recommendations, while service loads should be considered a random process in the scaffolding reliability analysis.

The studies under the project PBS3/A2/19/2015 were conducted on 120 scaffoldings all over Poland. The following tasks were performed (comp. [24–30]) as part of the studies during one working week: scaffolding inventories (including detailed geodesic measurements), damage inventories, service load inventories, wind action measurements, free vibration measurements, measurements of the scaffoldings vibration resulting from the operation of construction machines, measurements of forces in supports, bearing capacity studies, the load-bearing capacity of anchors, measurements of temperature, pressure, sound pressure levels, lighting, as well as surveys on general information regarding scaffolding and its users, an analysis of the compliance with health and safety regulations, a construction site organisation analysis, scaffolding user surveys, measurements of the user's energy expenditure and changes in their other physiological parameters when working on a scaffolding. On the basis of the results of the studies a potential accident risk assessment model was constructed, the elements of which were described in [25–27, 30, 31]. The results of measurements of service loads were used in the aforementioned model to assess the probability of a scaffolding failure during one working week at the maximum load determined during the measurements. The potential of the studies in question is much greater, e.g., they may be useful for the analysis of the reliability and the usage safety assessment of a structure. This requires maximum load probability distributions in relation to one platform, as well as a total maximum load on a vertical scaffolding module – and this paper is precisely focused on this problem.

2. Description of research methods

The statistical analysis of scaffolding service load required an inventory of scaffolding loads. The studies consisted of the observation of a single scaffolding for five consecutive days which constitute a working week in Poland. Each day, three study rounds were performed at the following times: 1st round – 8.00–10.00, 2nd round – 11.00–13.00, 3rd round – 14.00–16.00. In each study round, load symbols were put on the scaffolding scheme, on subsequent loaded platforms. If there was a worker on a platform, an arrow accompanied by the letter C was put there. If there were building materials – an arrow with an estimate material mass in kilograms. Example diagrams with inventory results are shown in Fig. 1. In order to determine weights, the following principles were considered:

- It is assumed that an average weight of the human body is 78 kg, but a construction worker usually wears heavy work clothes required by health and safety regulations, as well as uses tools, therefore each arrow with the symbol C was assigned the weight of 1.0 kN. It is also recommendation Australian/New Zealand standard AS/ZS 157.1 cite22.
- The weight of building materials was an estimate, and for this reason when determining it, an approximate value of the gravitational acceleration equaling 10.0 m/s^2 was assumed.

Subsequently, on the basis of the study reports, the following was determined for each vertical module j of scaffolding k on particular i-th day:

- maximum load value from among the loads acting on the platforms in j-module Q_{ijk},
- maximum value of the load acting at the same moment and summed up for all the platforms in j-vertical module P_{ijk},
- maximum value of a uniformly distributed load on a platform in the j-module, calculated from the following equation:

$$q_{ijk} = \frac{Q_{ijk}}{l_j}, \tag{1}$$

- maximum value of a uniformly distributed load, summed up for all platforms of the j-vertical module, calculated from the following equation:

$$p_{ijk} = \frac{P_{ijk}}{l_j}, \tag{2}$$

where: the vertical module is a fragment of the scaffolding between adjacent frames, l_j – the length of the j-platform and, simultaneously, the length of the j-module, which equals the distance between the frame planes.

The selection of the maximum values of the platform load in the j-module consisted in selecting the highest value out of three inventory reports from three measuring rounds on a given day. For example (Fig. 1), in 1st round no load was determined

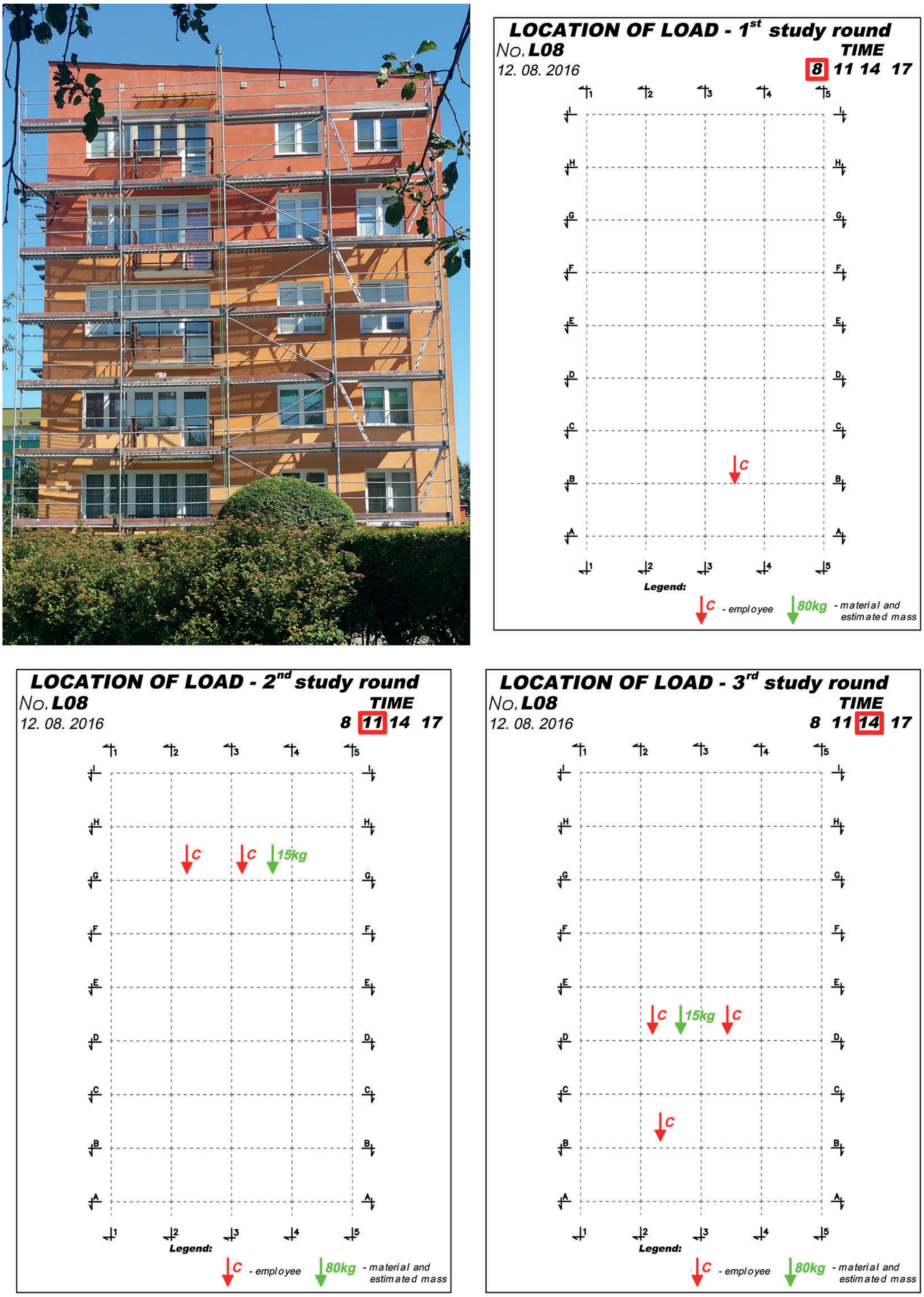

Fig. 1. The view of the scaffolding and sheets of load inventory results on 5th day of the mesurement

in the second module between axes 2–3, in 2nd round – the load of 1.0 kN was determined, and in 3rd round – the maximum platform load amounted to 1.15 kN. Hence, the maximum platform value for the module in question amounted to $Q_{52k} = 1.15$ kN. When determining the maximum load of the whole vertical module, load values obtained in each inventory round are summed up and then the maximum value is selected. For example (Fig. 1), with regard to 2nd module, in 1st round no load was determined, in 2nd round – the load of 1.0 kN was determined, and in 3rd round – the maximum platform load amounted to 1.15 kN + 1.00 kN = 2.15 kN, i.e., the maximum load of the whole vertical module was $P_{52k} = 2.15$ kN.

The studies are error-burdened, as scaffoldings were often made available only when the contractor decided the scaffolding in question would not be fully used. To eliminate this error, the days when workers were absent from scaffoldings were ignored. On the other hand, if a worker was at his workplace, they must have got there. For this reason, from the module with ladders to workplaces the load value of 1.0 kN as the sum of loads resulting from the weight of the human body and tools and material which might have been carried was inserted. The lists for the scaffolding in Fig. 1, composed of four vertical modules, were put in Tables 1–2. The columns containing the results of the service load inventory concerning the module with communication are bolded.

Table 1
List of the maximum loads of single platforms Q_{ijk}

Q_{ijk} [kN] – maximum load of the platform		Module width			
		3.07 m	3.07 m	3.07 m	3.07 m
Day	Day i	Module j			
		1	2	3	4
Monday	1	0.0	2.00	2.10	**1.00**
Tuesday	2	0.0	1.15	1.00	**1.00**
Wednesday	3	0.0	2.00	1.00	**1.00**
Thursday	4	0.0	2.03	2.00	**1.00**
Friday	5	0.0	1.15	1.15	**1.00**

Table 2
List of maximum loads in a single vertical module of the scaffolding P_{ijk}

P_{ijk} [kN] – sum of maximum loads of the platform in vertical module		Module width			
		3.07 m	3.07 m	3.07 m	3.07 m
Day	Day i	Module j			
		1	2	3	4
Monday	1	0.0	2.00	2.10	**1.00**
Tuesday	2	0.0	1.15	1.00	**1.00**
Wednesday	3	0.0	2.00	1.00	**1.00**
Thursday	4	0.0	2.03	2.00	**1.00**
Friday	5	0.0	2.15	1.15	**1.00**

Service load measurements were performed on 120 frame scaffoldings all over Poland. In respect to each scaffolding a table containing a list of the maximum values of the analysed parameters was prepared. It was assumed that every number in a table corresponds to one sample. As a result, 3350 values of random variables for the maximum platform load values, and 3350 values of random variables for the maximum values of vertical scaffolding module loads were obtained.

3. Statistical analysis

3.1. Basic statistical characteristics. Random variables q_e and p_e were determined in the following way:

$$q_e = q_{ijk} = \max\left(q_{e1}, q_{e2}, q_{e3}, \ldots, q_{en}\right), \tag{3}$$

$$p_e = p_{ijk} = \max\left(p_{e1}, p_{e2}, p_{e3}, \ldots, p_{en}\right), \tag{4}$$

where: q_{ei} are random variables describing loads on the subsequent platforms of a given module on a given day, sampled from the population of the cumulative distribution function $F_q(x_q)$, p_{ei} are random variables describing the sum of platform loads in a given vertical module on a given day, sampled from the population of the cumulative distribution function $F_p(x_p)$. Table 3 presents the basic characteristics of random variables q_e and p_e.

Table 3
Basic characteristics of variables q_e and p_e

Statistical characteristics	Random variable	
	q_e	p_e
Maximum value [kN/m]	3.33	3.33
Number of observations	3350	3350
Average value [kN/m]	0.31	0.35
Standard deviation [kN/m]	0.32	0.37
Skewness coefficient [/]	3.04	2.64

3.2. Selection of probability distribution function. Quoting from Castillo et al. [32], the cumulative distribution functions of the random variables described by means of Eqs. (3) and (4), can be determined using the following equation:

$$\begin{aligned} G_q(x_q) &= P(q_e < x_q) = \\ &= P(q_{e1} < x_q) \cdot P(q_{e2} < x_q) \cdot \ldots \cdot P(q_{en} < x_q) = \\ &= \prod_{i=1}^{n} P(q_{ei} < x_q) = F_q^n(x_q), \end{aligned} \tag{5}$$

$$\begin{aligned} G_p(x_p) &= P(p_e < x_p) = \\ &= P(p_{e1} < x_p) \cdot P(p_{e2} < x_p) \cdot \ldots \cdot P(p_{en} < x_p) = \\ &= \prod_{i=1}^{n} P(p_{ei} < x_p) = F_p^n(x_p). \end{aligned} \tag{6}$$

Since there are not enough data to determine the probability distribution of random variables p_{ei} and q_{ei}, according to [32] probability distribution for random variables determined to be maximum values in a set, are determined as limited distributions. On the other hand, the limit form of the maximum value probability distribution is described by means of one of the Gumbel, Weibull or Frechet distributions. If it is assumed that random variables p_{ei} and q_{ei} are described by means of one of the following distributions: normal, exponential, log-normal or steady-state, then the probability distribution of their maximum values is described by the Gumbel or Weibull distributions. These two distributions are also recommended in the papers [7,33] and [34], as distributions of maximum structure load values, and for this reason the formula for these two types of distribution shall be determined further.

Since there will be references to distribution function parameters later in the paper, for the clarity of the text, below are formulas for these distributions. The Gumbel distribution (the Fisher–Tippett type I distribution) of the maximum values of random variable x is described by the following formula:

$$f(x) = \frac{1}{\widehat{\delta}} e^{\frac{x-\widehat{\lambda}}{\widehat{\delta}} - e^{\frac{x-\widehat{\lambda}}{\widehat{\delta}}}} \tag{7}$$

and the cumulative distribution function is described by the following formula:

$$G(x) = e^{-e^{-\frac{x-\widehat{\lambda}}{\widehat{\delta}}}}, \tag{8}$$

where:

$$\widehat{\delta}^2 = \frac{6s_x^2}{\pi^2}, \tag{9}$$

$$\widehat{\lambda} = \bar{x} - 0.5772156649\,\widehat{\delta}. \tag{10}$$

While the Weibull distribution (the Fisher–Tippett type III distribution) of the maximum values of random variable x is described by the following formula:

$$f(x) = \frac{\beta}{\tilde{\delta}} \left(\frac{x-\tilde{\lambda}}{\tilde{\delta}}\right)^{\beta-1} e^{-\left(\frac{x-\tilde{\lambda}}{\tilde{\delta}}\right)^{\beta}} \tag{11}$$

and the cumulative distribution function of the distribution:

$$G(x) = 1 - e^{-\left(\frac{x-\tilde{\lambda}}{\tilde{\delta}}\right)^{\beta}}, \tag{12}$$

where:

$$\tilde{\delta}^2 = \frac{s_x^2}{\Gamma\left(1+\frac{2}{\beta}\right) - \left[\Gamma\left(1+\frac{1}{\beta}\right)\right]^2}, \tag{13}$$

$$\tilde{\lambda} = \bar{x} - \tilde{\delta}\Gamma\left(1+\frac{2}{\beta}\right), \tag{14}$$

Euler's function

$$\Gamma(y) = \int_0^{\infty} t^{y-1} e^{-t}\,\mathrm{d}t. \tag{15}$$

In Eqs. (7)–(15) parameter $\bar{x}$ denotes the average value of random variable x, and s_x signifies the standard deviation of random variable x.

The formulas describing distribution functions are simpler and for this reason in most cases the distribution selection consists in approximation of a cumulative distribution function on the basis of study results (comp. [4, 35]). Here, the selection of a probability distribution shall consist in the selection of a probability density function by means of fitting curves to the study result histograms using the method of least squares. The first step is the selection of the length of a class interval. When intervals are too short, graphs "shift" from zero to high values. With an increase in the length of an interval, graphs become smoother, and at the interval lengths of 0.20 kN/m and 0.25 kN/m can form a basis for approximation of the service load probability distributions. Figures 2 and 3 show the histograms of random variables, respectively, q_e and p_e at these interval lengths.

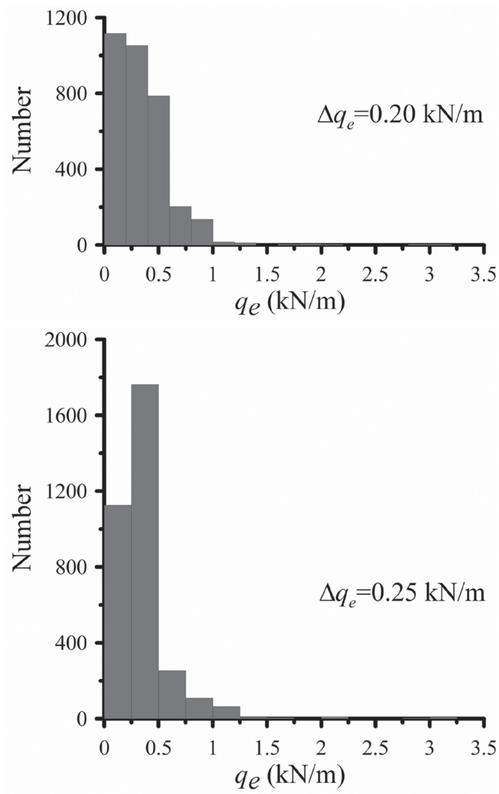

Fig. 2. Histograms of the service load tests for single platforms

As stated before, distribution equations are selected by means of the method of least squares. An illustration of the process with regard to single platform loads is show in Fig. 4. Figure 4a presents a vertical bar graph based on reduced quantity histograms by diving them by the length of an interval

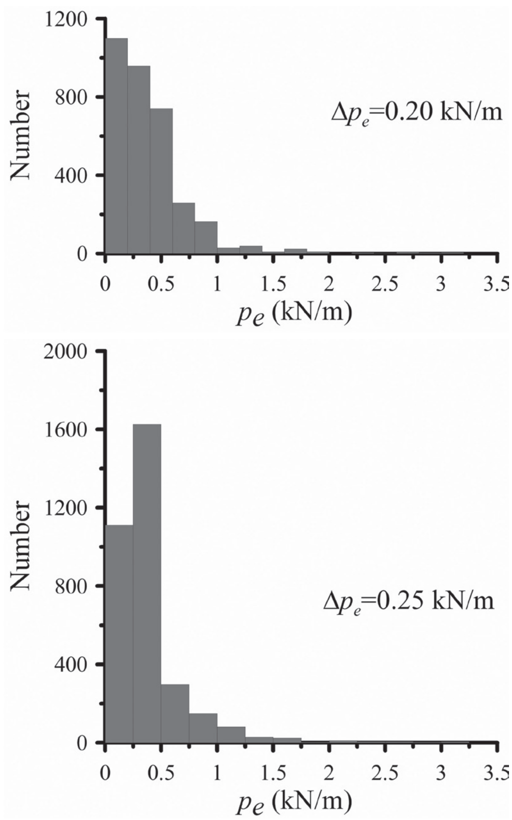

Fig. 3. Histograms of the service load tests for vertical scaffolding modules

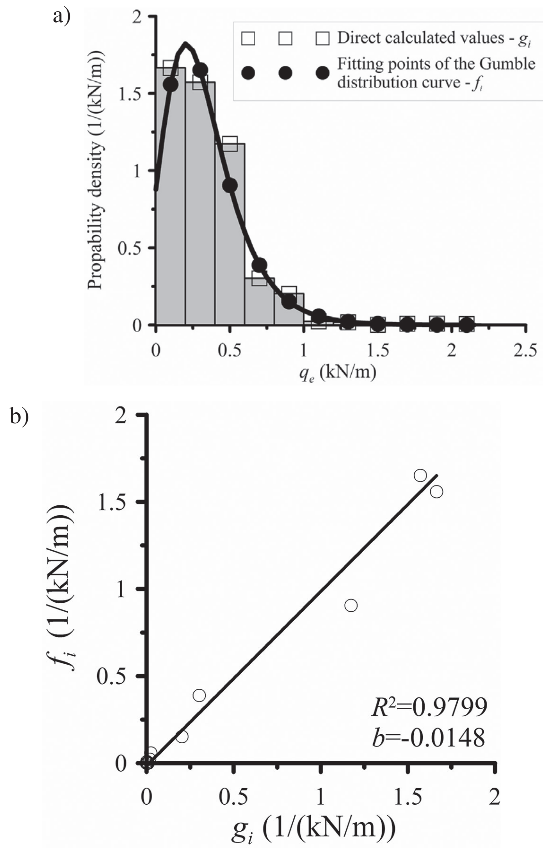

Fig. 4. The Gumbel distribution equation selection: a) probability distribution, b) the system of the points of the coordinates (g_i, f_i) in relation to the straight line of the equation $y = x + b$

$\Delta q_e = 0.2$ kN/m. The points of the values of g_i at the vortices of the graph constitute the basis for fitting a graph of the equation describing a probability distribution. In this case it is the Gumbel distribution described by the Eq. (7). In the drawing in question also the points of the values of function f_i, determined in relation to the midpoints of particular class intervals i, were marked. Figure 4b shows the distribution of subsequent points in relation to variable x_i, further referred to as fitting points, of the coordinates (g_i, f_i) around the straight line $y = x + b$. Square of Pearson's coefficient R^2 was calculated for each result of the distribution selection from the following formula (comp. [36]):

$$R^2 = \frac{\left[\sum_{i=1}^{n} (g_i - \overline{g})(f_i - \overline{f})\right]^2}{\sum_{i=1}^{n} (g_i - \overline{g})^2 \sum_{i=1}^{n} (f_i - \overline{f})^2}, \tag{16}$$

where: f_i and g_i – the values of the sought function and the values obtained in the studies for variablex_i, $\overline{f}$ and $\overline{g}$ – the average values of functions f and g for set of points n. If the distribution equation considered the study points located exactly on the curve, the fitting points would be precisely located on the straight line $y = x + b$, and the value of coefficient R^2 would equal 1.0. The further the fitting points are located from the straight line $y = x + b$, the more the value of the coefficient R^2 decreases, and the fitting is less precise and reliable.

The values of the function parameters are listed in Table 4 and 5. The values of coefficients R^2 are quite high in all the cases. Also, the values of the average random variables calculated based on curves approximate the values obtained in the studies. Only in one case the relative error exceeds the value of 5% and equals 9%. The values of standard deviations are burdened with the relative error to a higher degree – in one case it reaches 54% and concerns the fitting of the probability distribution functions with regard to the interval of 0.25 kN/m. The values of standard deviations are less error-burdened at the class interval length of 0.20 kN/m than the ones determined for the interval of 0.25 kN/m, therefore, the functions fitting the histograms at the class interval length of 0.2 kN/m were deemed the final study result. Moreover, comparing the values of the standard deviations obtained for different distributions, it is obvious that the values of the standard deviations for the Gumbel distribution with the error of 19% for variable q_e and 24% for variable p_e are closer to the values obtained in the studies. Additionally, the Gumbel distribution is a limiting distribution for random variables characterised by more often occurring distributions. The mentioned results are arguments in favour of the Gumbel distribution as better describing the maximum service load distribution of scaffolding. Similar conclusions regarding the type of a probability distribution function for maximum values of service loads during construction were given in paper [37].

Table 4
Results of the selection of the Gumbel probability distribution coefficients

Random variable	Interval length Δq_e [kN/m]	$\widehat{\lambda}$ [kN/m]	$\widehat{\delta}$ [kN/m]	R^2	$\bar{x}_d$ [kN/m]	s_{xd} [kN/m]	Error $\frac{\lvert\bar{x}_d-\bar{x}\rvert}{\bar{x}}$	Error $\frac{\lvert s_{xd}-s_x\rvert}{s_x}$
q_e	0.20	**0.2033**	**0.2019**	0.9799	0.3198	0.2589	0.0316	0.1909
	0.25	0.2502	0.1161	0.9977	0.3172	0.1489	0.0232	0.5347
p_e	0.20	**0.1929**	**0.2178**	0.9829	0.3187	0.2794	0.0894	0.2449
	0.25	0.2568	0.1357	0.9919	0.3351	0.1740	0.0426	0.5297

Table 5
Results of the selection of the Weibull probability distribution coefficients

Random variable	Interval length Δq_e [kN/m]	$\widehat{\lambda}$ [kN/m]	$\widehat{\delta}$ [kN/m]	β	R^2	$\bar{x}_d$ [kN/m]	s_{xd} [kN/m]	Error $\frac{\lvert\bar{x}_d-\bar{x}\rvert}{\bar{x}}$	Error $\frac{\lvert s_{xd}-s_x\rvert}{s_x}$
q_e	0.20	**–0.0844**	**0.4472**	**1.8780**	0.9866	0.3130	0.2180	0.0097	0.3188
	0.25	–0.0415	0.4003	2.1363	0.9598	0.3127	0.1759	0.0087	0.4503
p_e	0.20	**–0.0875**	**0.4974**	**2.0150**	0.9533	0.3536	0.2277	0.0103	0.3846
	0.25	–0.0533	0.4595	2.2098	0.9665	0.3535	0.1955	0.0100	0.4716

3.3. Summary of the study results. The results of the selection of probability density functions are Gumbel and Weibull distributions which are shown in Fig. 5. An example application of the results is in determination of the probability of exceeding service load according to three standards: European EN 12811-1 [21], Australian and New Zealand AS/NZS 1576.1 [22], and American 29 CFR 1926 [23]. This information is important, amongst others, in the process of designing scaffoldings using the methods of structure reliability and failure risk assessment. A list of permissible service loads for platforms for the most commonly used scaffoldings according to the above-mentioned standards is given in Table 6.

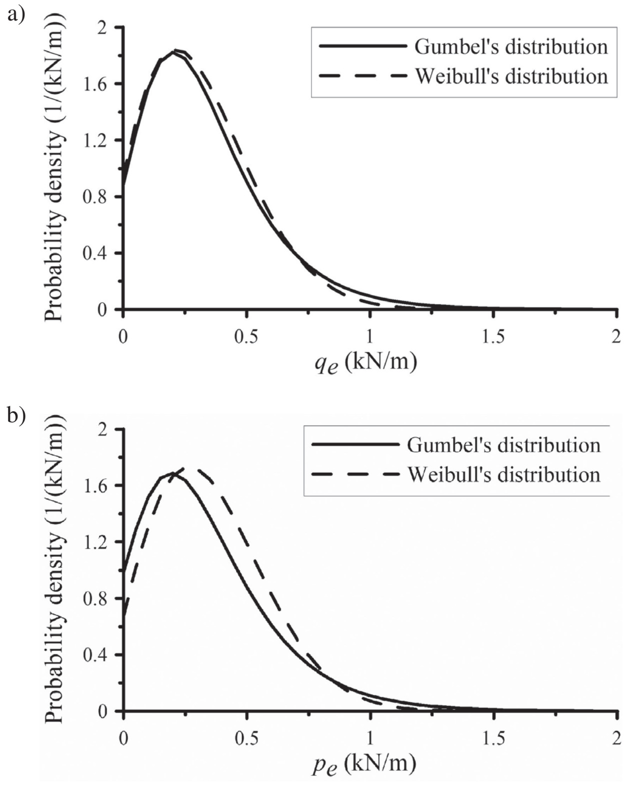

Fig. 5. Probability density distributions of scaffolding service loads for 120 scaffolds during one weeks of their operation: a) of single platforms, b) of vertical scaffolding modules

The probability that a platform or entire scaffolding vertical module load do not exceed permissible service load is determined as the values of the cumulative distribution function for this load and, also, located in Table 6. In the calculations the cumulative distribution functions described by the formulas of the Gumbel distribution (8) and the Weibull distribution (12) were used. The results were obtained on the basis of loads inventories performed during one working week (usually 5 days) for 120 scaffoldings. As proven in paper [37], the probability of occurrence of the maximum service load and thus not exceeding the permissible service load depends on the duration of construction. For the k-scaffolding this will mean the time of its exploitation T_{sk}, which in this paper is calculated in weeks. The second parameter, which influences the probability of not exceeding the permissible values of the service load on construction sites in the given region, is the number of scaffolding N_s. The formula, describing the probability of not exceeding the limit value and taking into account both parameters, will take the form:

$$P_{ac}(N_s) = \prod_{k=1}^{N_s} \tilde{P}^{\frac{T_{sk}}{120}}, \tag{17}$$

where $\tilde{P}$ – the probability of not exceeding the limit values for 120 scaffolding for the service life of each scaffolding equal to one working week.

Table 6
The probability of not exceeding the permissible service load on 120 scaffoldings during one working week

The name of standard		EN 12811-1	AS/NZS 1576.1	29 CFR 1926
The name of a load category		3rd class	medium duty	medium duty
Permissible service load		2.0 kN/m^2	4.4 kN/platform	2.39 kN/m^2
Permissible service load per meter of a platform length	for width equals 0.7m	1.4 kN/m		1.68 kN/m
	for length equals 3.0m		1.47 kN/m	
Platform load	Gumbel distribution	0.99733977	0.99811854	0.99933476
	Weibull distribution	0.99992646	0.99996889	0.99999809
Vertical module load	Gumbel distribution	0.99608993	0.99716314	0.99891737
	Weibull distribution	0.99988739	0.99995342	0.99999742

Figure 6 shows the probability of exceeding the permissible service load according to three standards depending on the number of scaffoldings N_s, assuming that the average time of exploitation is $T_s = 12$ weeks. On the horizontal axis, scaffoldings are counted in thousands. The order of scaffolding number results from the estimation of the number of scaffoldings which are assembled annually in Poland. According to the data of The General Office of Building Control in 2015–2019 [38], in one year in Poland there were put into operation an average of 30 242 objects as: multi-family buildings, collective housing buildings, hotels and accommodation buildings, public buildings, industrial and warehouse buildings, transport infrastructure facilities. This means that in Poland much more than 30 000 scaffoldings are assembled annually, because they are assembled on all the listed facilities under construction and, additionally, are used for renovation and construction works that do not require formal notification about the ending of construction. Unfortunately, for the number of scaffoldings of tens of thousands there is a high probability of exceeding the permissible service loads. Therefore, the approach of American regulations [23], according to which the load bearing capacity of scaffolding platforms should be four times greater than the permissible service load, is justified.

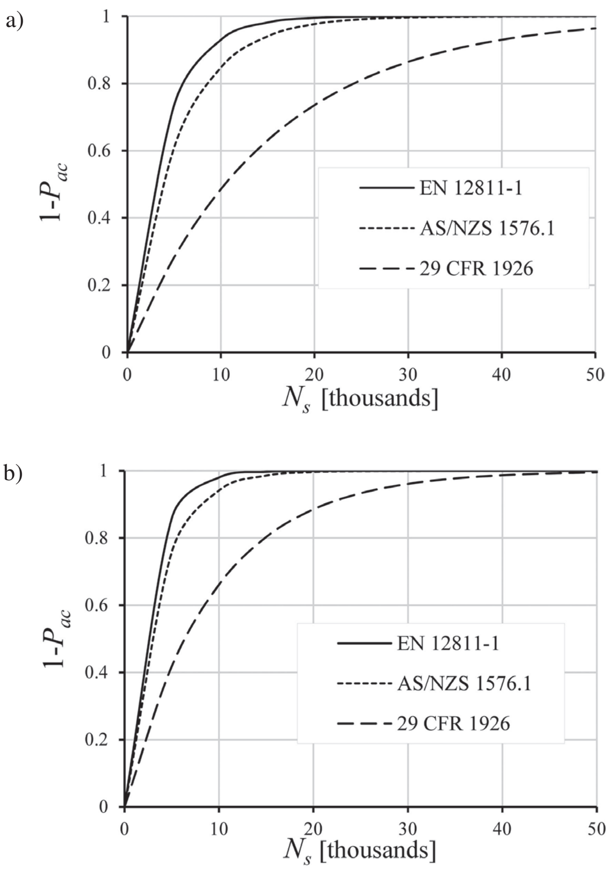

Fig. 6. The probability of exceeding the permissible service load for the statistical population of scaffoldings at the assumption average exploitation time $T_s = 12$ weeks and depending on the size of this population: a) for single platforms, b) for vertical scaffolding modules

4. Conclusion

Due to the technological development the construction work methods change, and as a result, these affect the construction scaffolding load. Furthermore, scaffoldings became higher and of more sophisticated geometry. Service loads are one of the elements affecting the safety of scaffolding use. For this reason, the reliability analysis as a scaffolding design method should continue to be developed. This requires parameter distributions describing the condition and load of a scaffolding.

The paper presents methodology of scaffolding service load measurements. On the basis of the measurements conducted on 120 frame scaffoldings all over Poland, the probability density of maximum service loads was determined as Gumbel' and Weibull's functions. Having compared the 1st and 2nd order statistical moments, one can conclude that the probability density description by means of Gumbel's function is closer to the study results. Unfortunately, the results of the presented research show that in Poland there is a high probability of exceeding the permissible service loads and thus there is a risk of scaffolding damage.

However, considering that it was the first study of this type, the scaffolding service load measurements should be continued in the future to increase the statistical sample. Despite the aforementioned reservation, the functions determined in the paper can be used for the purposes of the reliability analysis to calibrate partial safety factors and in simulation of service load during the scaffolding failure risk assessment.

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References

[1] R.I. Harris and N.J. Cook, "The parent wind speed distribution: Why Weibull?", *J. Wind Eng. Ind. Aerodyn.* 131, 72–87 (2014).
[2] T.M. Lystad, A. Fenercib, and O.Øiseth, "Evaluation of mast measurements and wind tunnel terrain models to describe spatially variable wind field characteristics for long-span bridge design", *J. Wind Eng. Ind. Aerodyn.* 179, 558–573 (2018).
[3] J.A. Żurański, *Effects of the climatic and topographic conditions on wind loads on building structures,* Prace Naukowe Instytutu Techniki Budowlanej, Warsaw, 2005.
[4] J.A. Żurański and A. Sobolewski, *Snow loads in Poland in designing and diagnostics of structures*, Prace Naukowe Instytutu Techniki Budowlanej, Warsaw, 2016.
[5] P. Croce, P. Formichi, F. Landi, P. Mercogliano, E. Bucchignani, A. Dosio, and S. Dimova, "The snow load in Europe and the climate change", *Clim. Risk Manag.* 20, 138–154 (2018).
[6] J. Blanchet, C. Marty, and M. Lehning, "Extreme value statistics of snowfall in the Swiss Alpine region", *Water Resour. Res.* 45(5), W05424 (2009).
[7] B. Ellingwood, T.V. Galambos, J.G. MacGregor, and C.A. Cornell, Development of a probability based load criterion for American National Standard A58, NBS Special Report 577, U.S. Department of Commerce, National Bureau of Standards, 1980.
[8] R.B. Corotis and V.A. Doshi, "Probability models for live-load survey results", *J. Struct. Div.* 103(6), 1257–1274 (1977).
[9] R.B. Corotis and V. Jaria, "Stochastic nature of building live loads", *J. Struct. Div.* 105(3), 493510 (1979).
[10] P.L. Chalk and R.B. Corotis, "Probability model for design live loads", *J. Struct. Div.* 106(10), 2017–2033 (1980).
[11] A.S. Nowak and A.M. Rakoczy, "Uncertainties in the building process", *Bull. Pol. Acad. Sci. Tech. Sci.* 61(1), 129–135 (2013).
[12] M.G. Stewart, "Optimization of serviceability load combinations for structural steel beam design", *Struct. Saf.* 18(2/3), 225–238 (1996).
[13] V. Kamjoo and C.D. Eamon, "Reliability-based design optimization of a vehicular live load model", *Eng. Struct.* 168, 799–808 (2018).
[14] Y. Liu, L. Liu, B. Stratman, and S. Mahadevan, "Multiaxial fatigue reliability analysis of railroad wheels", *Reliab. Eng. Syst. Saf.* 93(3), 456–467 (2008).
[15] F. Schmidt, B. Jacob, and F. Domprobst, "Investigation of truck weights and dimensions using WIM data", *Transp. Res. Procedia* 14, 811–819 (2016).
[16] A.S. Nowak, "System reliability models for bridge structures", *Bull. Pol. Acad. Sci. Tech. Sci.* 52(4), 321–328 (2004).
[17] J. Bojórquez, S.E. Ruiz, B. Ellingwood, A. Reyes-Salazar, and E. Bojórquez, "Reliability-based optimal load factors for seismic design of buildings", *Eng. Struct.* 151, 527–539 (2017).
[18] D. Sun, B. Chen, and S. Sun, "Study based on bridge health monitoring system on multihazard load combinations of earthquake and truck loads for bridge design in the southeast coastal areas of China", *Shock Vib.*, 829380, 1–12 (2015).
[19] M.G. Stewart, "Reliability-based load factor design model for explosive blast loading", *Struct. Saf.* 71, 13–23 (2018).
[20] M.G. Stewart, M.D. Netherton, Y. Shi, M. Grant, and J. Mueller, "Probabilistic terrorism risk assessment and risk acceptability for infrastructure protection", *Aust. J. of Struct. Eng.* 13(1), 1–17 (2012).
[21] EN 12811-1:2003. Temporary works equipment – Part 1: Scaffolds – Performance requirements and general design. European Committee for Standardization, Brussels, 2003.
[22] AS/NZS 1576.1. Scaffolding. Part 1: General requirements, Council of Standards Australia and Council of Standards New Zealand, Sydney, 2010.
[23] 29 CFR 1926. Safety and health regulations for construction. Scaffold Specifications, Electronic Code of Federal Regulations, https://ecfr.federalregister.gov/current/title-29/subtitle-B/chapter-XVII (accesed April 2021).
[24] P. Jamińska-Gadomska, J. Bęc, T. Lipecki, and A. Robak, "Verification of the façade scaffolding computer model", *Arch. Civ. Eng.* 64 (1), 41–53 (2018).
[25] E. Błazik-Borowa, *Loads and actions on scaffolding as engineering structures*, Lublin University of Technology, Lublin, 2018, [in Polish].
[26] H. Bojar, F. Silveira, M. Rebelo, E. Czarnocka, and K. Czarnocki, "Health behaviours in scaffold use risk assessment model – SURAM", *Ann Agric Environ Med.* 26(1), 138–142 (2019).
[27] M. Jabłoński, I. Szer, and J. Szer, "Probability of occurrence of health and safety risks on scaffolding caused by noise exposure", *J. Civ. Eng. Manag.* 24(6), 437–443 (2018).
[28] T. Lipecki, P. Jamińska-Gadomska, J. Bęc, and E. Błazik-Borowa, "Façade scaffolding behavior under wind action", *Arch. Civ. Mech. Eng.* 20, 27 (2020).
[29] M. Pieńko, A. Robak, E. Błazik-Borowa, and J. Szer, "Safety conditions analysis of scaffolding on construction sites", *Int. J. Civ. Env. Eng.* 12(2), 72–77 (2018).
[30] I. Szer, E. Błazik-Borowa, and J. Szer, "The influence of environmental factors on employee comfort based on an example of location temperature", *Arch. Civ. Eng.* 63(3), 163–174 (2017).
[31] B. Hoła and T. Nowobilski, "Analysis of the influence of socio-economic factors on occupational safety in the construction industry", *Sustain.* 11, 4469 (2019).
[32] E. Castillo, A.S. Hadi, N. Balakrishnan, and J.M. Sarabia, Extreme value and related models with applications in engineering and science, John Wiley & Sons, New Jersey, 2005.
[33] M. Nagode and M. Fajdiga, "The influence of variable operating conditions upon the general multi-modal Weibull distribution", *Reliab. Eng. Syst. Saf.* 64, 383–389 (1999).
[34] A.S. Nowak and K.R. Collins, Reliability of structures, Taylor & Francis Group, New York, 2013.

[35] D. Pekasiewicz, "Analysis of chosen estimation methods of maximum statistic limit distribution parameters", *Quant. Meth. Econom.* 16(4), 75–84 (2015), [in Polish].
[36] E. Błazik-Borowa, J. Szer, A. Borowa, A. Robak, and M. Pieńko, "Modelling of load-displacement curves obtained from scaffold components tests", *Bull. Pol. Acad. Sci. Tech. Sci.* 67(2), 317–327 (2019).
[37] M.G. Stewart, "Effect of construction and service loads on reliability of existing RC buildings", *J. Str. Eng.* 127(10), 1232–1235 (2001).
[38] Construction activity (Ruch Budowlany), General Office of Building Control, https://www.gunb.gov.pl/strona/ruch-budowlany, (accesed November 2020), [in Polish].