ANALYSIS OF CALCULATION MODELS OF SCAFFOLDING CONSTRUCTIONS IN LIGHT OF EXPERIMENTAL TESTS RESULTS OF CONSTRUCTIVE SCAFFOLDING MODULE

Andrzej Misztela, Zbigniew Starczewski

Institute of Mechanised Construction and Rock Mining
Racjonalizacji Street 6/8, 02-673 Warsaw, Poland
tel.: +48 22 843 02 01 fax: +48 22 843 59 81
e-mail: a.misztela@imbigs.pl, z.starczewski@imbigs.pl

Abstract

The concern of the article is the analysis of multiple computational models of scaffolding construction, taking into account the experimental results obtained for a representative scaffolding construction module. Analyses of 25 distinct models have been performed, allowing selecting models that most accurately predict deformations of the real construction. The article deals with the issues of elastic-plastic second-order analysis in relation to the working anchored scaffolds and it is focused on the standardization of computational models for engineering calculations. Including in calculations the plastic bearing capacity reserve and using objective calculation procedures, allows optimal designing of the scaffolding and evaluating of the load capacity. Structural model analyses were carried out in terms of their conformity with the actual construction. For comparative purposes, the results of the analyses of individual models were evaluated according to different verification formulas to determine the extent of their applicability. The purpose of the article was to test the behaviour of the system under the influence of constant horizontal forces reflecting the influence of wind and rising from zero until destruction due to the vertical load.

Keywords: static analyses, scaffold structures, computational models, different verification formulas, load evaluating

1. Introduction

Static analyses of scaffold structures are usually carried out with assumption that the material of single construction rods is resilient over the entire deformation range of the structure subjected to external loads. In the elastic-linear material model, a linear relationship between stress and deformation is assumed as well as the return of deformation and stress values in the structure to the initial state after removal of the loads.

The elastic-plastic analysis can be particularly useful for determining the limit load capacity of formwork structures. Scaffold structures are generally statically indistinguishable, and cross sections are class 1 according to PN-90/B-03200. The limit of bearing capacity may be connected with using appropriate number of plastic joints, which cause a change of the structure into the mechanism. Reaching the limit may be also due to loss of stability after the critical loads have been exceeded. Scaffold structures are characterized by significant geometric imperfections (assembly loops, initial inclinations, and high susceptibility joints), which may cause that the limit loads significantly differ from the critical loads determined by the buckling analysis of the scaffold models without imperfections. All this causes that in cases of calculation of heavily loaded structures with low stiffness and with great imperfections; we should use computational models that directly map the real properties of the structure, in particular its imperfections and stiffness.

In the area of knowledge, covering the stability and strength of bar structures there is quite a rich literature. Items [1-4] belong to the canon of literature on this subject.

The problem of real testing of scaffolding constructions directed to determining the critical load combined with numerical simulations is of interest to a dozen or so researchers around the world. The research in this field is conducted in China, the United States, Australia and the United Kingdom. This is evidenced by publications in scientific journals such as Journal of Constructional Steel Research, Engineering Structures. Examples are [5-11]. The above-mentioned works concerned mainly the strength and stability of stand-alone scaffolding for formwork.

The article deals with the issues of elastic-plastic second-order analysis in relation to the working anchored scaffolds and it is focused on the standardization of computational models for engineering calculations. Including in calculations the plastic bearing capacity reserve and using objective calculation procedures, allows optimal designing of the scaffolding and evaluating of the load capacity.

In this work, the starting point for developing computational models and their behaviour under the load was the study of the actual construction of the scaffold. Structural model analyses were carried out in terms of their conformity with the actual construction. The above involve the identification of static equilibrium paths (MSR) for individual models, i.e. the "load – displacement" of representative points of construction and their comparison with the MSR of the tested scaffolding structure.

The shape of the static equilibrium paths of the MSR rods and nodes depends on:
– rigidity of components,
– geometric imperfections,
– elasticity of knuckles in knots,
– load type (static, dynamic),
– kind of stress (compression, stretching, bending, compression with bending).

In the case of computational models, the shape of the static equilibrium paths of the MSR rods and nodes will depend on the type of analysis used (first or second order analysis).

Figure 1 provides an overview of the currently used structural analysis models. These models use two methods of analysis (according to first-order theory and second-order theory) and three material models (elastic, elastic-plastic and rigid-plastic).

Based on model calculations, the values of internal forces and displacement are determined. Based on them can be determined by using the appropriate interaction patterns, a degree of strain of the components of the structure.

Three models of analysis were used in this article:
– elastic model, first-order analysis with respect to stability ratings of load capacity,
– elastic model, second-order analysis with respect to strength ratings of load capacity,
– elastic-plastic model, second-order analysis with respect to strength ratings of load capacity.

For comparative purposes, the results of the analyses of individual models were evaluated according to different verification formulas to determine the extent of their applicability.
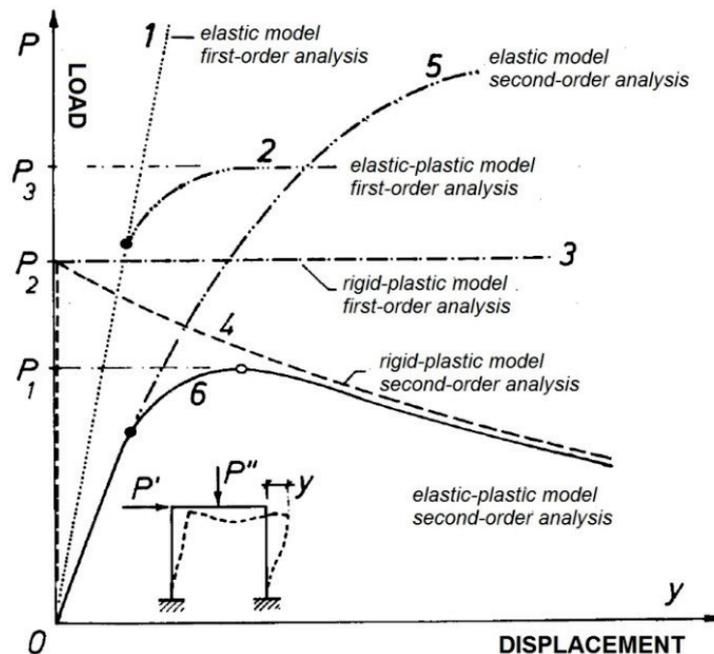
Fig. 1. Static equilibrium paths of structure [1]

2. Experimental study of stability and strength of scaffolding

The experimental study of the basic system configuration was the starting point and benchmark for constructing and evaluating computational models.

The purpose of the study was to test the behaviour of the system under the influence of constant horizontal forces reflecting the influence of wind and rising from zero until destruction due to the vertical load Fv. The result of the study was the equilibrium pathway (MSR) of the representative points of the structure and the value of the destructive load.

The research was carried out at SP Technical Research Institute of Sweden in Boras, Sweden. SP and IMBiGS staff participated in the study. The results of the study were documented in the study report [12].

Parameters of tested scaffolding design:
– width of the frame: 0.74 m,
– construction of bolt connection of upper frame with platforms: bolt connection,
– number of fields per one storey: 3,
– length of field: 3.0 m,
– number of storeys: 4,
– height of the storey: 2 m,
– height of scaffolding: 8.5 m,
– grid anchor every 4 m vertically and every 3 m horizontally,
– types of anchors: in one row of the extreme frameworks with anchorage V, the remaining anchors are single. Connections of anchors with stands by rotary joints,
– types of platforms: in one vertical layout aluminum-gluing platforms 0.64 m, others – steel platforms 0.32 m,
– height of unscrewing nuts of screw stand: 0.45 m,
– construction materials of tested scaffolding elements:
  – racks – pipe $\varnothing 48.3 \times 2.7$ steel S235JR o fy, k > 320 MPa,
  – upper bolts – rectangular pipe SHS $35 \times 50 \times 2$, steel S235JR,
  – lower bolt – pipe $\varnothing 33.7 \times 2.6$; Steel S235JR,
  – shank pins – pipe $\varnothing 38.0$-600 steel 355JR.

Figure 2 shows a diagram of the structure of the scaffold submitted to the study, showing the characteristic dimensions and points of the displacement measurements.

2.1. Method of applying load and load values of scaffolding construction

The structure was loaded in three phases:
– first step – applying permanent horizontal loads H3 + H4 = 0.65 kN (Fig. 2) on the second level parallel to the facade. After the displacement measurement, the structure has been unloaded,
– second stage – application of constant horizontal loads H1 = 0.65 kN and H2 = 0.65 kN (Fig. 2) on the second level in a direction perpendicular to the facade. After the displacement measurement, the structure has been unloaded,
– third stage – application of 1 kN load on each stand, then applying the load H1 = 0.45 kN and H2 = 0.75 kN in the direction perpendicular to the facade, then applying the load H3 + H4 = 0.45 kN. The values of horizontal loads remained unchanged throughout this phase.

After applying the horizontal loads, the main phase was the attempt to exert increasing vertical loads F1, F2, F3, F4 until destruction. During the test, the load on the extreme frames was twice as low as on the centre frames. As a result of the tests, it was found that the breaking load of the crane structure was 33.6 kN/rack. Fig. 3 shows a view of the tested structure on a test bench.

Figure 4. graphically shows the results of experimental studies in the form of static equilibrium paths for measurement points in which displacement measurements were taken.
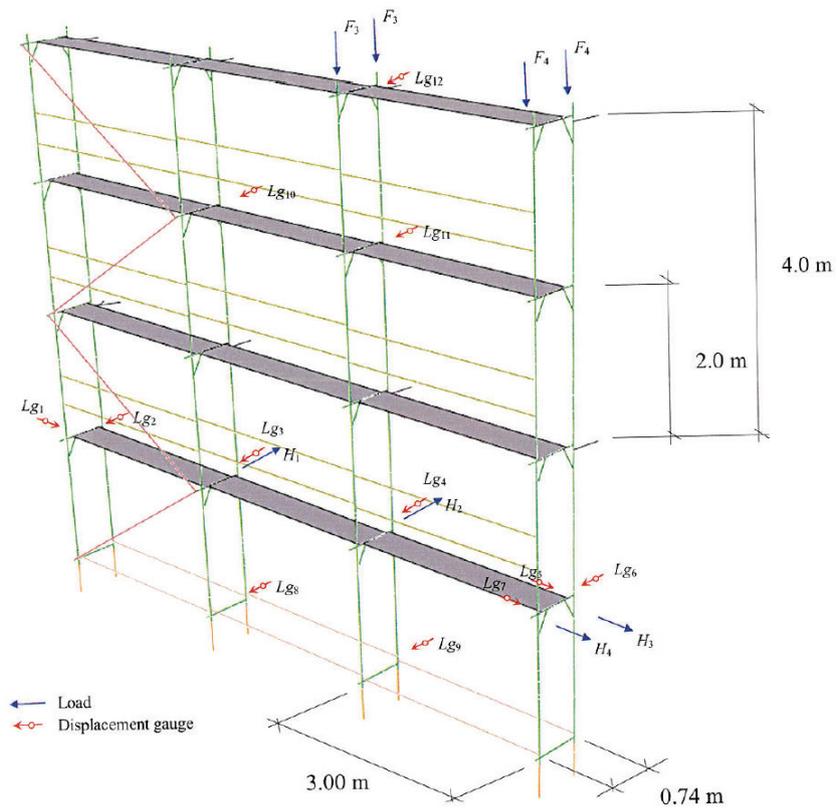
Fig. 2. Diagram of tested construction with the points in which the displacement was measured

Fig. 3. View of tested construction on the test bench
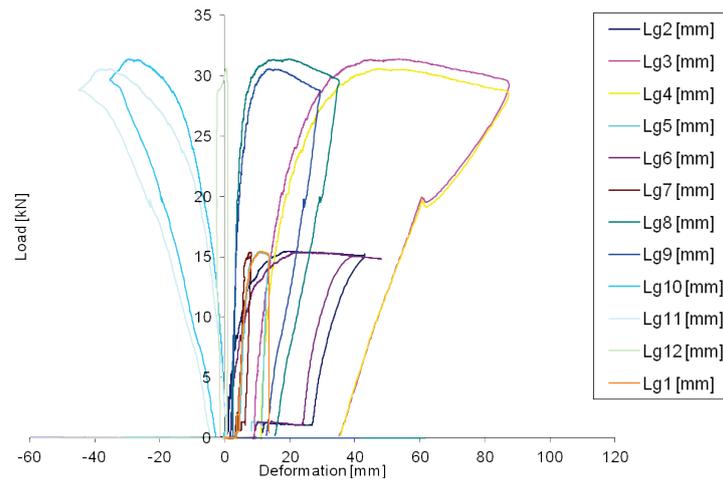
Fig. 4. Results of the scaffold construction studies (static equilibrium paths for measuring points in which displacement measurements were taken)

3. Computational models of empirically tested scaffolding construction

3.1. General assumptions used in scaffolding models

a) Computational models have been developed in Autodesk Robot Structural Analysis Professional 2011.
b) The computational model should accurately represent the actual construction of the scaffold. Model parameters were grouped into two groups: fixed parameter and variable parameters.
c) Fixed parameters are:
   – geometrical dimensions of structural grid (width, length, height of the area) the length and height of the scaffolding,
   – cross-sections and type of material declared in the construction bar,
   – types and values of loads and how they are applied. The load values assumed in the models were in line with the load values of the structure in the experimental studies,
   – support conditions (supports and anchors),
   – constant variation of the static frame pattern (the connections in the frame surface are rigid connections).
d) Variable parameters are:
   – computational methods (first order elastic analysis, second order elastic analysis and second order elastic-plastic analysis),
   – material nonlinearity – model of material declared in structural bars (no nonlinearity – elastic model, nonlinearity declaration – model of elastic material with reinforcement),
   – geometric nonlinearity including:
   – type of connection "upper frame bolt – replacement joint": rigid, articulated or flexible,
   – imperfections in construction (no imperfections, local imperfections, tilt imperfections or equivalent loading).

3.2. Detailed assumptions taken into account in scaffolding models

a) The models assume a spatial static scheme of scaffolding.
b) It was adopted according to PN-EN 112811-1, that the connection of the stands is rigid.
c) The calculations include the factor $\gamma_m = 1.15$, standing for the material durability, calculated according to $f_d = R_e/1.15$.
d) Stringers with upper bolts of frames brackets declared in the model are equivalent to plate concentration systems. Alternatively, 3 types of stringers were combined with upper frame

bolts: perfectly rigid, articulated and flexible. The starting point for determining the suscepti-bility of the "stringer – upper bolt" was the horizontal rigidity determined for a two-pillar structural module with 3.0 m long steel platforms, perpendicular to the wall. Based on this rigidity, the rigidity of the "longitudinal – upper bolt" connection was determined. For this purpose, the experimentally determined by IMBiGS characteristics of the horizontal system, previously tested in the SP, were used. In the calculation model, the horizontal stiffness characteristics were taken into account, replacing the actual plate concentration system with a representative bar system with malleable nodes.

In this model, the stringers were flexibly connected to the upper bolt. The rigidity of the knots was determined from the dependence:

$$K_w = \frac{K_\perp \cdot l^2}{8},$$

(1)

where:
K_w – knot rigidity of replacement system,
$K_\perp$ – horizontal rigidity determined experimentally,
l – surface length.

The characteristics for the platforms of 3.0 m in length for the perpendicular direction have been assumed according to the data contained in the report [13]:

a) The calculations include tilting imperfections: pre-chamfering of the frame stands due to the clearance on the frame joints, adopting the imperfection model shown in Fig. 5.
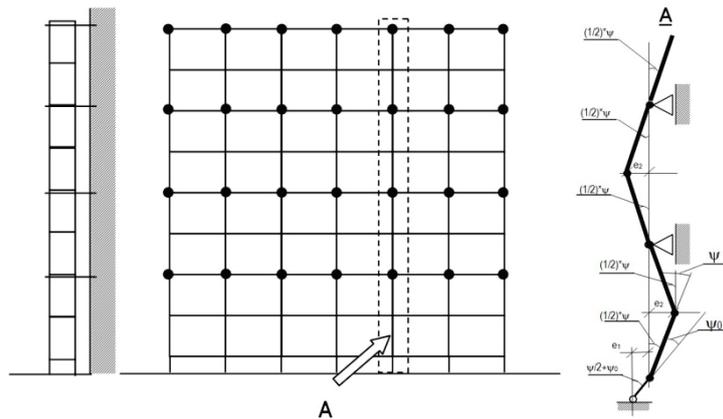
Fig. 5. Tilt imperfections according to EN 12811

b) Dummy load H_i was calculated according to the HD 1000 of the formula:

$$H_i = \frac{V_{iw} + V_{iz}}{100\sqrt{2}},$$

(2)

where:
V_{iw} – internal rack load on a given tier,
V_{iz} – external rack load on a given tier.

c) Local imperfections, such as the initial bending of the racks, were declared according to EN 1993-1-1.

d) Calculations were made for load combinations: vertical loads + horizontal loads determined by SP + dummy loads acc. to HD 1000 or tilting imperfections.

e) Elastic analysis was based on a linear-elastic model of the material, whereas in the elastic-plastic analysis a model of the elastic-plastic material with the E1 / E gain = 0.04 was adopted. Two cases of elastic-plastic behaviour of the structural elements were considered. In the first case it was assumed that the plastic deformations could occur in to the upper and lower bolts of

the vertical frames. In the second case, it was assumed that plastic deformations would involve both bolts and racks.

f) Analysis has been conducted on two static scheme "perfect" and "imperfect" (Fig. 6). "Perfect" was used in the models (Tab. 1): 1, 2, 5, 6, 7, 10, 11, 12. "Imperfect" was used in the models (Tab. 1): 3, 4, 8, 9.
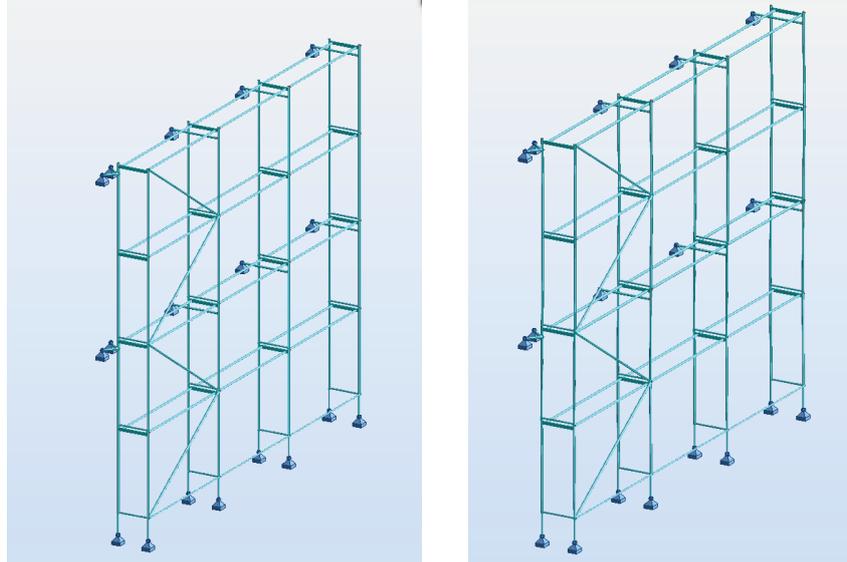
Fig. 6. Design models under the analysis. On the left side the „perfect" construction, on the right side „imperfect" construction with visible tilt-ups

Tab. 1. List of calculation models and their marking

Type of analysis	Type of analysis symbol	Calculation models					
		1	2	3	4	5	6
		Model perfectly rigid without imperfection	Model perfectly rigid without imperfection with articulated joints	Model perfectly rigid with tilt imperfections	Model perfectly rigid with tilt imperfections with articulated joints	Model perfectly rigid with dummy loads	Model perfectly rigid with articulated joints and dummy loads
First-order elastic analysis	A	01-A-MS-P	02-A-MSR-P	03-A-MS-IMP	04-A-MSR-IMP	05-A-MS-OZ	06-A-MSR-OZ
Second-order elastic analysis	B	01-B-MS-P	02-B-MSR-P	03-B-MS-IMP	04-B-MSR-IMP	05-B-MS-OZ	06-B-MSR-OZ
Second-order elastic-plastic analysis	C	01-C-MS-P					06-C-MSR-OZ 06a-C-MSR-OZ

Type of analysis	Type of analysis symbol	Calculation models					
		7	8	9	10	11	12
		Models with flexible joints without tilt imperfections	Models with flexible joints with tilt imperfections	Models with flexible joints with local tilt imperfections	Models with flexible joints with dummy loads	Models with flexible joints with dummy loads and local imperfections	Models with flexible joints with bidirectional dummy loads
First-order elastic analysis	A						
Second-order elastic analysis	B	07-B-MP-P	08-B-MP-IMP	09-B-MP-IMPL	10-B-MP-OZ	11-B-MP-OZL	12-B-MP-OZ2
Second-order elastic-plastic analysis	C			09-C-MP-IMPL 09a-C-MP-IMPL	10-C-MP-OZL	11-C-MP-OZL	

3.3. Construction model loads

Variable vertical loads

The vertical loads are the dominant loads. During the calculation of each model, the load was changed from 0 until reaching the difference in the iteration process or 34.5 kN per rack. Variation of the load allowed to designate the MSR (vertical force – displacement of a specific point of the structural model).

Fixed horizontal loads

Places of application of constant horizontal loads and their value corresponded to the load values of the scaffold structures in the course of experimental research. The values of these forces were constant and independent of the vertical load.

Horizontal dummy load

In the case of imperfect models, when the initial model was not declared in the calculation model, the model was loaded with a dummy load where values were strictly dependent on the vertical loads and increased along with the increase of vertical loads.

Combination of loads

Calculations were made for load combinations: vertical loads + horizontal loads determined by SP + dummy loads acc. to HD 1000 or tilting imperfections.

3.4. Verification criteria

Each structural model rod was checked for compliance with five dimensioning criteria to verify the degree of cross-sectional strength of the rod.

Criterion 1

Formula for racks according to PN-90/B-03200:

$$\frac{N}{\varphi_i N_{Rc}} + \frac{\beta_x M_{x\,\max}}{\varphi_L M_{Rx}} + \frac{\beta_y M_{y\,\max}}{M_{Ry}} \leq 1 - \Delta_i . \tag{3}$$

Formula for bars according to PN-90/B-03200:

$$\frac{N}{N_{Rc}} + \frac{M_{x\,\max}}{M_{Rx}} + \frac{M_{y\,\max}}{M_{Ry}} \leq 1 . \tag{4}$$

Application: First-order analysis, perfect elastic model, stability and endurance criterion of the elastic dimension. For comparative purposes, this criterion was also used in nonlinear analyses.

Criterion 2

Formula for racks and bolts according to EC3:

$$\frac{N}{N_{Rc}} + \frac{M_{x\,\max}}{M_{Rx}} + \frac{M_{y\,\max}}{M_{Ry}} \leq 1 . \tag{5}$$

Application: Second-order analysis, imperfect elastic model, endurance criterion of the elastic dimension. For comparative purposes, this criterion was also used in linear analyses.

Criterion 3

Formula for racks and bolts:

$$\frac{M_x}{M_{x,pl}} + \frac{M_y}{M_{y,pl}} + \cos\left(\frac{\pi}{2} \cdot \frac{N}{N_{pl}}\right) \leq 1 . \tag{6}$$

Application: Second-order analysis, imperfect elastic and elastic-plastic model endurance dimensioning criterion using the plastic reserve cross-section.

Criterion 4
Formula for racks and bolts:

$$\frac{N}{N_{pl}} + \left(\frac{M_x}{M_{x,pl}}\right)^2 + \left(\frac{M_y}{M_{y,pl}}\right)^2 \leq 1. \tag{7}$$

Application: Second-order analysis, imperfect elastic and elastic-plastic model endurance dimensioning criterion using the plastic reserve cross-section.

Criterion 5
Formula for racks and bolts:

$$\frac{N}{N_{pl}} + \frac{M_x}{M_{x,pl}} + \frac{M_y}{M_{y,pl}} \leq 1. \tag{8}$$

Application: Second-order analysis, imperfect elastic and elastic-plastic model endurance dimensioning criterion using the plastic reserve cross-section.

4. Results of calculations

The results of the calculations used to analyze the work of the construction model were the values of displacement and internal forces in the construction rods. These results allowed to determine the static equilibrium paths and the degree of strain on the individual components of the structure models.

The static equilibrium paths for 25 models were defined for all 12 points corresponding to the points in which the measurements of the actual construction were measured during the test. Fig. 7-10 illustrates the MSR models and the actual construction for the most distinctive point of construction. In contrast, Tab. 2 lists the maximum design loads per 1st load according to different load capacity criteria, taking into account the maximum stress of the individual components for selected representative models.

5. Conclusions

Based on the studies and calculations of 25 scaffold calculation models, the following conclusions can be drawn:
a) As part of this work, we have developed computational models that faithfully reflect the behaviour of the scaffolding tested by SP.
b) Linear models according to the first-order theory are not useful for static analysis of scaffolding structures. The stability criteria of the load capacity evaluation can be used to estimate the limit of the load capacity, but this process requires defining the factor of general inefficiency. In practice, this factor is often arbitrarily accepted, without doing buckling analysis. Such an approach may lead to incorrect assessment of the deadweight. The value of the stability factor may determine if the load capacity will be significantly understated or overstated.
c) Nonlinear models according to the theory of the second-order in the elastic range allow to set the MSR with a high degree of conformity with the actual MSR. This applies to models with imperfections declared as dummy loads. Imperfections taken in the form of preliminary tilt cause that the MSR are below the pathways identified in the experimental studies. This means that the value of the declared acc. to EN 12811-1 imperfections are much higher than in real construction. Estimation of the load capacity can be made on the basis of the strength

condition, provided that the dummy loads are taken into account and that the rigid connections of the bolts with the stringer replacement are not present. Failure to meet these conditions will cause the carrying capacity of the structure to be overstated relative to the actual one. Taking into account the horizontal stiffness of the structural model, the results of the calculations are very close to those of the actual construction. It is possible to declare articulated joints, but it is possible in most cases to expect that the design load capacity will be understated.
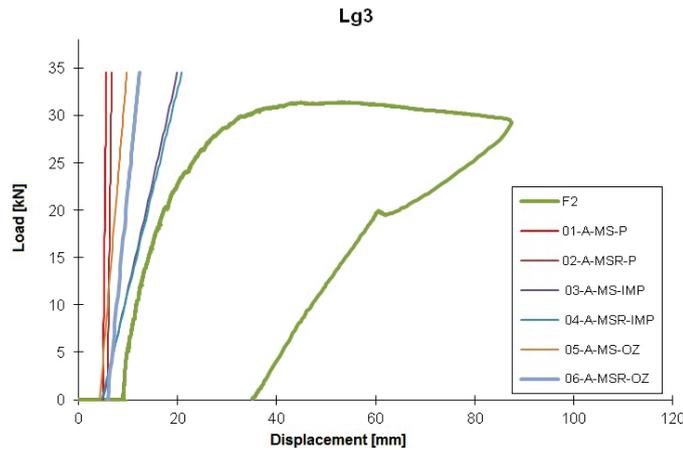
Fig. 7. MSR measuring point 3 – First-order elastic models
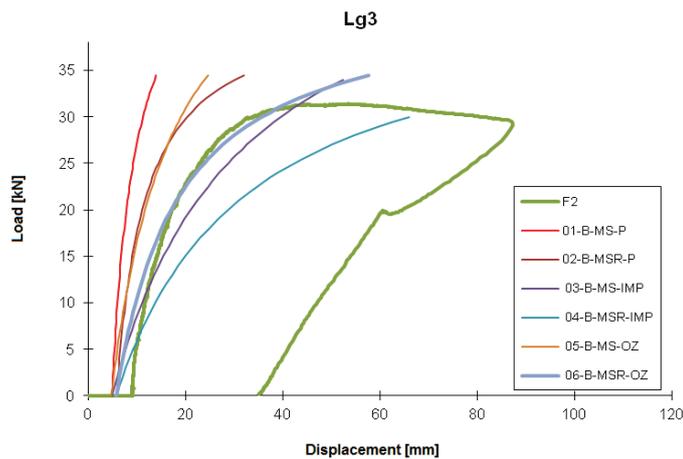
Fig. 8. MSR measuring point 3 – Second-order elastic models; model with rigid and flexible joints
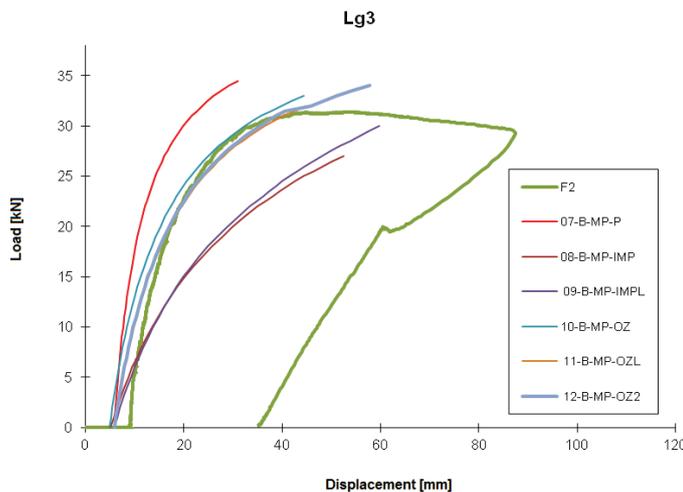
Fig. 9. MSR measuring point 3 – Second-order elastic models; model with flexible joints
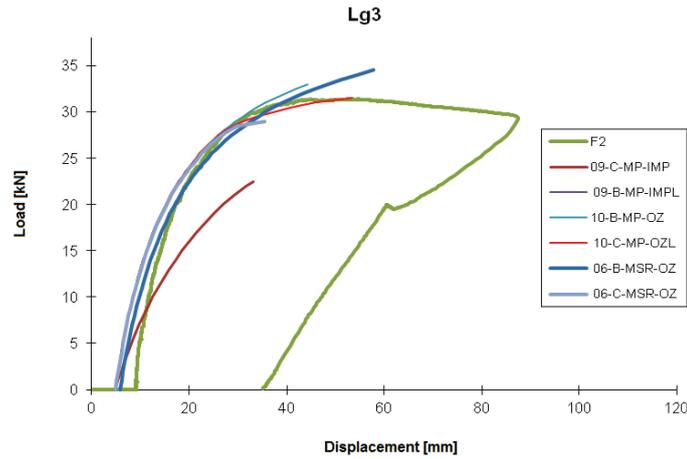
Fig. 10. MSR measuring point 3 – Second-order elastic-plastic models; model with flexible joints

Tab. 2. Maximum design load [kN] per first load according to various load capacity criteria, taking into account the maximum stress of individual components

Model 01-B-MS-P	Criterion				
	1	2	3	4	5
rack	27.0	34.5			
upper bolt		34.5			
bottom bolt		34.5			
screw stand	23.5	34.5			
load-bearing capacity defined by process convergence	none				
design load capacity of construction	23.5	34.5			
Model 06-B-MSR-OZ	Criterion				
	1	2	3	4	5
rack	20.0	30.5	34.0	34.5	32.5
upper bolt		29.5	30.0	30.0	30.0
bottom bolt		16.0	20.0	26.5	20.0
screw stand	20.0	34.5	34.5	34.5	34.5
load-bearing capacity defined by process convergence	over 34.5				
design load capacity of construction	20.0	16.0	20.0	26.5	20.0
Model 11-B-MP-OZL	Criterion				
	1	2	3	4	5
rack		30.5	32.0	32.0	32.0
upper bolt		31.0	30.0	30.0	30.0
bottom bolt		16.0	20.0	26.5	20.0
screw stand		30.0	32.0	32.0	32.0
load-bearing capacity defined by process convergence	32.0				
design load capacity of construction		16.0	20.0	26.5	20.0
Model 10a-C-MP-OZ	Criterion				
	1	2	3	4	5
rack		28.0	28.0	28.0	28.0
upper bolt		28.0	28.0	28.0	28.0
bottom bolt		18.0	23.0	28.0	23.0
screw stand		28.0	28.0	28.0	28.0
load-bearing capacity defined by process convergence	28.0				
design load capacity of construction		18.0	23.0	28.0	23.0

d) The elastic-plastic analysis gives a very high accordance of computational analysis results with the actual results of the experimental studies. One of the basic values of these models is the ability to estimate the limit capacity based on the analysis of the convergence of the computational iteration process. In most cases, the load at which the convergence of the iteration process was not reached was very close to that of the destructive load.

e) In most cases, in the nonlinear analysis, the load capacity of the model was limited by the load capacity of the lower frame bolts. The load was about 7-10 kN less than the load at which the calculation process was not convergent. This means that despite the 2 times oversize load of the bolt, the scaffolding structure remained stable. This raises the question of the reasonableness of the application of the current validation standards in relation to the construction of scaffolding. The article suggests criterion 4. The analyses carried out indicate that this criterion could be successfully used to evaluate the bar strength of a structural model using second-order elastic-plastic analysis.

Acknowledgements

References

[1] Biegus, A., *Nośność graniczna stalowych konstrukcji prętowych*, Wydawnictwo Naukowe PWN, 1997.
[2] Gutkowski, W., *Regularne konstrukcje prętowe*, Państwowe Wydawnictwo Naukowe, 1973.
[3] Wojewódzki, W., *Nośność graniczna konstrukcji prętowych*, Oficyna Wydawnicza Politechniki Warszawskiej, 2005.
[4] Weiss, S., Giżejowski, M., *Stateczność konstrukcji metalowych. Układy prętowe*, Arkady, 1991.
[5] Peng, J., Yen, T., Kuo, C., Chan, S., *Analytical and experimental bearing capacities of system scaffolds*, Journal of Zhejiang University Science, A, Vol. 10 (1), pp. 82-92, 2009.
[6] Peng, J. L., Chan, S. L., Wu, C. L., *Effects of geometrical shape and incremental loads on scaffold systems*, Journal of Constructional Steel Research, Vol. 63, pp. 448-459, 2007.
[7] Weesner, L. B., Jones, H.L., *Experimental and analytical capacity of frame scaffolding*, Engineering Structures, Vol. 23, pp. 592-599, 2001.
[8] Peng, J.-L., Chen, K.-H., Chan, S.-L., Chen, W. T., *Experimental and analytical studies on steel scaffolds under eccentric loads*, Journal of Constructional Steel Research, Vol. 65, pp. 422-435, 2009.
[9] Liu, H., Zhao, Q., Wang, X., Zhou, T., Wang, D., Liu, J., Chen, Z., *Experimental and analytical studies on the stability of structural steel tube and coupler scaffolds without X-bracing*, Engineering Structures, Vol. 32, pp. 1003-1015, 2010.
[10] Peng, J.-L., Wu, C.-W., Chan, S.-L., Huang, C.-H., *Experimental and numerical studies of practical system scaffolds*, Journal of Constructional Steel Research, Vol. 91, pp. 64-75, 2013.
[11] Chandrangsu, T., Rasmussen, K. J. R., *Structural modeling of support scaffold systems*, Journal of Constructional Steel Research, Vol. 67, pp. 866-875, 2011.
[12] Raport SP-Technical Research Institute of Sweden, Nr 3P07913, *RAM2 Scaffolding system – Global test*, 05-03-2014.
[13] Ekspertyza – sprawozdanie IMBiGS, Nr 13304/MZ, *Badania wytrzymałościowe elementów konstrukcyjnych oraz poziomych układów stężających rusztowań ramowych RAM*, maj 2013.
[14] PN-EN 12811-1:2007, *Tymczasowe konstrukcje stosowane na placu budowy, Część 1: Rusztowania. Warunki wykonania i ogólne zasady projektowania,* 2013.
[15] PN-EN 1993-1-1:2006, *Eurokod 3: Projektowanie konstrukcji stalowych. Część 1-1: Reguły ogólne i reguły dla budynków,* 2006.
[16] HD 1000:1988, *Rusztowania robocze i ochronne z prefabrykowanych elementów konstrukcyjnych, projektowane obciążenia i wymagania bezpieczeństwa,* 1988.