Demountable Rod Structures with Flexible Connections
Ensuring the Reliability and Safety of Construction Objects

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Abstract. Individual walls of structures based on wedge-type scaffolding can be different in height and are often used as enclosing structures for different cultural and sporting events. Usually, such structures are covered in the longitudinal direction with an awning cloth on both sides, which is why they take on the full wind load from the entire area of the awning. When calculating such structures, the wind load is the determining load. In practice, these structures are built according to the recommendations of the manufacturer's catalog of scaffolding, and they are repeatedly statically indeterminate systems with a large number of unloaded elements. This increases the material consumption of the structure and increases the cost of transport and installation work. In structures made of modular scaffolding, diagonal elements are used to give spatial rigidity to the structure, to reduce the calculated length of vertical elements, and to perceive the shift movements of the cell caused by uneven vertical movements of adjacent posts and horizontal loads. A structure with a full set of diagonal elements has a large number of weakly loaded elements. In this regard, it is possible to perform the so-called «discharged» construction scheme for more efficient use, replacing rigid diagonal elements with cable ties and reducing the number of diagonal elements in the longitudinal direction. The main task of the work is to analyze the stress-strain states of both the original system with rigid diagonal elements and systems obtained by partially replacing standard diagonals with flexible connections in the form of pre-stressed and non-pre-stressed cable ties. In order to study the actual operation of elements of rod collapsible structures and improve their design solutions, an experimental study of a fragment of the Layher system with cable ties was performed. Based on the experiment, it was determined that the actual movements when using flexible connections differ significantly from the calculated ones. The reason for the discrepancy is the deformation of the elements in the attachment points. To increase the rigidity, the design of the attachment unit needs to be changed.

1. Introduction
Currently, rod demountable structures, in particular, structural solutions based on modular wedge-type scaffolding, are increasingly used in the field of cultural and entertainment sports events.

Usage the modular scaffolding system allows to create structures of completely different types, such as scaffolding, stands, stages, podiums, and platforms.
In structures made of modular scaffolding, diagonal elements are used to give spatial rigidity to the structure, to reduce the calculated length of vertical elements, and to perceive the shift movements of the cell caused by uneven vertical movements of adjacent posts and horizontal loads. A structure with a full set of diagonal elements has a large number of weakly loaded elements. In this regard, it is possible to perform the so-called «discharged» construction scheme for more efficient use, replacing rigid diagonal elements with cable ties and reducing the number of diagonal elements in the longitudinal direction.

The purpose of the work is to study of the actual operation of the elements of rod demountable structures, to search and improve their design solutions.

2. Numerical study
The main task of the work is to analyze the stress-strain states of both the original system with rigid diagonal elements and systems obtained by partially replacing standard diagonals with flexible connections in the form of pre-stressed and non-pre-stressed cable ties.

![Figure 1. The initial scheme](image)

The initial scheme was calculated in the LIRA – CAD 2013 PC R3. The system is loaded with its own weight, additional load and wind load. The pulsation component of the wind load is taken into account by means of the LIRA – CAD PC. The calculation was made in conjunction with an elastic base, counted as folded sandy soil. The distribution of longitudinal forces N in the elements of the initial scheme is shown in figure 2.

From the results obtained, the conclusion follows:
- the most loaded are the diagonals of the cross frames of the lower tier of the wall and the counterfort Nmax=12.3 which exceeds the limit force N = 1.264 t.
- the diagonals of the longitudinal frames are loaded at 19% (Kmax = 201/1040 = 0.19);
- in crossbars, the forces are Nmax = 4.78 t, which exceeds the limit force N = 3.1 t.
- movements along the Y axis are equal to 1320 mm and exceed N / 75=25500/75=340.
- there are 1182 crossbars (horizontal elements);
- there are 2412 diagonal elements;
- there are 1719 posts (vertical elements);
the total weight of the elements is 46999.2 kg.
The diagonal elements of the cross frames were replaced with flexible pre-tensioned cables made of steel cable with a total diameter of 6 mm of the 1x7 (1+6) construction according to DIN 3052 (analogous to GOST 3062-80) of the 1570 MPa marking group. Pre-tensioning of cables is created using lanyards.

Due to the need to take into account dynamic loads (wind pulsation), the pre-tension simulation in the LIRA-CAD PC was performed by setting the temperature loads on the cable ties according to the law of linear thermal expansion. A conditional coefficient of linear temperature expansion is introduced ($\alpha = 3,08386091 \times 10^{-4}$), which allows to change the tension force in the rod by 100 kg when it is cooled by 1°C. The general view of the scheme with tightening is shown in figure 3. The pre-tensioning force of the cable ties is 50 kg.

Figure 2. Longitudinal forces N in the initial scheme

Figure 3. The installation of cable ties scheme
From the results obtained:
- movements along the Y axis are equal to 119 mm;
- the forces in the tightening cables are equal to 2600 kg, which is 83% of the breaking force;
- the weight of the elements for the system assembly was 3333.2 + 2544.75 = 27353.55 kg (standard Layher elements + the weight of the tightening cable without taking into account the nodal fastening elements).
- after replacing the standard diagonal elements with cable extensions the horizontal movements along the Ye axis were reduced from 1322 mm to 204 mm which does not exceed $H/75 = 25500/75 = 340$.
- the busiest posts are the lower tier $N_{\text{max}} = 3.76$ t, which does not exceed the limit force of $N = 4.6$ t.
- in crossbars, the force is $N_{\text{max}} = 1.78$ t, which does not exceed the limit force of $N = 3.1$ t

3. Experimental study
The tested design is a system of Layher core elements that has 2x2 cells in the plan and 1 cell in height (the cell has dimensions of 2x2x2).
Tests are performed on a vertical load that is concentrated on the middle post (vertical element). To transfer the load to the central post, an improvised mast with a traverse is assembled. Loading is performed using a hydraulic jack, which in turn is connected to a hydraulic compressor. The load transferred to the rack is fixed by the force meter, which is loaded using a second hydraulic Jack connected in parallel with the working jack (this decision was made due to the inability to install the force meter to the working jack). During the test loading of the structure is carried out step by step. The step is $N = 1/10$ – $1/20$ from the design load. The voltages are recorded using strain gauges installed on the structural elements, and the readings from them are transmitted to the computer using an automated hardware and software unit.
Figure 5. Testing scheme (scheme with standard elements)

1. Power mast;
2. Working jack;
3. Standard diagonal;
4. Second jack with power meter;
5. Compressor;

The load application step is 250 kg, and the deflection meter readings are recorded at each step;

- deflection meter 6PAO, mounted on the middle post, it estimates movements along the vertical axis;
- deflection meter CHEES, it is set directly along the control diagonal and shows the curve of the diagonal from the plane. The data processing unit takes readings (analog signal) of strain gauges with a frequency of 10 Hz (10 times per second) and transmits them to a personal computer, where a special software “National instruments” is registered in digital and graphical form.

Figure 6. Longitudinal forces in the diagonal D1
Figure 7. Longitudinal forces in the diagonal D2

Figure 8. Longitudinal forces in the diagonal D3

Figure 9. Longitudinal forces in the diagonal D4
Process and results of an experimental study of an installation with flexible connections:

The tested design is a system of Layher core elements that has 2x2 cells in the plan and 1 cell in height (the cell has dimensions of 2x2x2). Pre-prepared cable ties with steel plates installed in them, to which strain gauges are glued to measure the forces in the puffs, are installed instead of standard diagonal elements in the original scheme. The tests are carried out in the same way as the tests of scheme with standard elements.

Figure 10. Movements of the central post along the Z axis

Figure 11. Horizontal curvature of the diagonal

Figure 12. Testing scheme (scheme with flexible connections)
1. Power mast, 2. Working jack, 3. Diagonal with compensator, 4. Second jack with power meter, 5. Compressor;

Figure 13. Graph of the dependence of the longitudinal forces in the cable tightening 1 on the load

Figure 14. Graph of the dependence of the longitudinal forces in the cable tightening 2 on the load

Figure 15. Graph of the dependence of the longitudinal forces in the cable tightening 3 on the load
Based on the results of an experimental study, it was determined that the replacement of standard diagonal elements with cable ties leads to a significant increase in vertical movements. There is also a discrepancy between the values of displacements obtained from the results of the calculation of the installation with flexible connections and the experimental study. The calculated vertical displacements at the maximum applied load were: 9.66 mm, and the experimental vertical displacements were: 22.48 mm. The average values of the longitudinal design forces in the cables differ by 6.1%.

4. Conclusions
An experimental study of a system with flexible connections shows a slight difference from the results of a numerical study of longitudinal forces in cable ties. The main reason for the discrepancy in displacement values is the deformation of the cable attachment elements. Replacing rigid diagonal elements with cable ties increases the rigidity of the structure by 4 times, reduces the longitudinal forces in the elements, and reduces the material consumption.

References
[1] Liu C, He L, Wu Z and Yuan J 2018 Experimental and numerical study on lateral stability of temporary structures Archives of civil and mechanical engineering 18 (Elsevier) p 1478-90
[2] Peng J -L, Ho C -M, Chan S -L and Chen W -F 2017 Stability study on structural systems assembled by system scaffolds Journal of Constructional Steel Research 137 (Elsevier) p 135–51
[3] Yuan X, Anumba C J and Parfitt M K 2016 Cyber-physical systems for temporary structure monitoring Automation in Construction 66 (Elsevier) p 1–14
[4] Chandrangsu T and Rasmussen K J R J 2011 Structural modelling of support scaffold systems Journal of Constructional Steel Research 67 (Elsevier) p 866–75
[5] Prabhakaran U, Beale R G and Godley M H R 2011 Analysis of scaffolds with connections containing looseness Computers and Structures 89 (Elsevier) 1944–55
[6] Crick D and Grondin G Y 2008 Monitoring and Analysis of a Temporary Grandstand Structural Engineering Report No.275 (Edmonton: Department of Civil & Environmental Engineering of University of Alberta) 48-98
[7] E. Błazik-Borowa*, J. Gontarz1. The influence of the dimension and configuration of geometric imperfections on the static strength of a typical façade scaffolding. 2015
[8] Bryan, E.R. The stressed skin design of steel buildings / E.R. Bryan. – London, 1973.
[9] Dr.-Ing. Robert Hertle. Gerustbau – Stabilität und statischkonstruktive Aspekte / Dr.-Ing. Robert Hertle // STAHLBAU KALENDER. - Ernst & Sohn Verlag für Architektur und technische Wissenschaften GmbH & Co. KG, Berlin. - 2009.
[10] General Building Authority Approval Z-8.22-64 "Layher Allround Scaffolding Modular System Allround Steel". - German Civil Engineering Institute. - Berlin, 2012.
[11] Cristiano Loss and Andrea Frangi. Experimental investigation on in-plane stiffness and strength of innovative steel-timber hybrid floor diaphragms. Engineering Structures, 2017.
[12] E. Li, J. B. Ferreiro, "A note on the global stability of generalized difference equations", Appl. Math. Lett., vol. 15, pp. 655-659, 2002.
[13] E. Liz, A. F. Ivanov, J. B. Ferreiro, "Discrete Halanay-type inequalities and applications", Nonlinear Anal., vol. 55, pp. 669-678, 2003.
[14] Y. N. Raffoul, Y. M. Dib, "Boundedness and stability in nonlinear discrete systems with nonlinear perturbation", J. Differ. Equat. Appl., vol. 9, no. 9, pp. 853-862, 2003.
[15] S. Udpin, P. Niamsup, "New discrete type inequalities and global stability of nonlinear difference equations", Appl. Math. Lett., vol. 22, pp. 856-859, 2009.
[16] E. Kazkurewicz, A. Bhaya, Matrix Diagonal Stability in Systems and Computation, Boston: Birkhauser, 1999.
[17] A. Y. Aleksandrov, A. P. Zhabko, "Preservation of stability under discretization of systems of ordinary differential equations", Siberian Math. J., vol. 51, no. 3, pp. 383-395, 2010.
[18] K. Brayton, C. H. Tong, "Stability of dynamical systems: a constructive approach", IEEE Trans. Circuits and Systems, vol. CAS-26, no. 4, pp. 224-234, 1979.
[19] R. K. Brayton, C. H. Tong, "Constructive stability and asymptotic stability of dynamical systems", IEEE Trans. Circuits and Systems, vol. CAS-27, no. 11, pp. 1121-1130, 1980.
[20] T. Yoshizawa, "Stability Theory by Liapunov Second Method", The Mathematical Society of Japan, 1966.
[21] V.A. Kuzkin, "Unsteady ballistic heat transport in harmonic crystals with polyatomic unit cell", Continuum Mechanics and Thermodynamics, 2019.