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Structural analysis of monitoring results of long-span roof structures

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Key words: *displacement; method of joints; truss; load; geospatial monitoring*

ABSTRACT

The concept of analysis of geodetic monitoring results solely from a geometric point of view is recognized as an obsolete approach. A complex analysis of geodetic measurements (geometric approach) and the structure stress-strain analysis (mechanical approach) allows obtaining the whole picture of any engineering structure displacements. The detailed scheme of the structural analysis of geospatial monitoring results of the long-span roof structures has been given in the presented paper. The results of the geospatial monitoring of the large warehouse have been chosen as a study subject. The structure's roof consists of planar trusses, the main objects of external loads combined with dead loads. According to the complex analysis procedure, the trusses were analyzed using the method of joints with the determination of partial member forces. At the next step, these forces were leveraged in the following order member force–member deformation–node displacement. To obtain the actual displacements of the truss nodes, one has to account for the vertical displacements of the leaning points where the truss touched the column. That step is also being accomplished using the method of joints. Having the actual node displacements, one may compare them with geodetic monitoring results. The comparison results generally allow us to reveal the places with unacceptable displacements and estimate whether they are determined with the necessary accuracy. In this particular case, the final node's displacements were yielded as an output of combined analysis, both geometric and mechanical. That, in turn, lets to acquire the deformation process's genuine parameters. The study results have shown the high efficiency of the presented research methodology.

I. INTRODUCTION

The analysis of geospatial monitoring results is always a complex and multitask issue (Welsch and Heunecke, 2001; Eichhorn, 2017). Today, no one will object that only geometrical analysis is not enough to comprehend the reasons and aftermaths of the deformation of a structure. The times when it was sufficient to calculate the values of displacements and simulate the displacements using polynomial models or other ones have gone. Thanks to the powerful computational possibilities of modern equipment and software, it has become possible to apply highly complex mathematical models to simulate and analyze the deformation process. The mathematical models that were hard to use or time-consuming (Szostak-Chrzanowski and Chrzanowski, 2004; Szostak-Chrzanowski *et al.*, 2008) have come up accessible to anyone who is familiar with PC. Recent studies being explored the use of new models and methods in geospatial monitoring analysis, *e.g.*, neural networks, machine learning, etc. Among those methods, structural mechanics takes a particular place. The design, construction, and exploitation of any engineering structure obey the principles of structural mechanics. Civil engineers perform sophisticated calculations to provide the structure stability, durability, and safety requirements in general. These calculations are of importance for construction management and building deployment. At the same time, the results of these calculations serve as a base for building control and monitoring. However, the calculation results are given in a form that works well for builders but do not account needs of surveyors. To date, no study has explicitly looked at the role of structural mechanics in geospatial monitoring and their relationship. During building exploitation, especially when geospatial monitoring tasks come up, the surveyor cannot bind structural mechanics calculations' results with monitoring requirements. Moreover, the criteria for monitoring (accuracy, target emplacement, etc.) are frequently up to the surveyor. Under such circumstances, the surveyor's requirements are based on his experience or literature. It is evident that such an approach cannot be considered correct and reliable. The best way is to determine the requirements using a civil engineer's calculations. However, those calculations either do not fit the surveyor's requirements or even are not being done. But even having the requirements, the analysis of monitoring results all the more so needs the structure simulation using structural mechanics. The reason is that different loads and conditions may lead to unpredictable displacements and distort the analysis results. In such a case, the surveyor must have the necessary skills to analyze construction using modern software. It would not have been possible if the BIM had not come in handy. BIM contains all the required information concerning the structure and the calculation model of particularly. The primary calculation approach embedded into BIM is the finite element method (FEM) (Logan, 2012; Lee, 2015). The pros and cons of this method are given in (Shults, 2020). The calculation procedure is simple and may be repeated for different conditions. The surveyors actively use FEM in their studies (Taşçi, 2015; Alizadeh-Khameneh *et al.*, 2018). Therefore, today the surveyor may carry out structure simulation and facilitate the monitoring results analysis. Before implementing FEM, the primary method for structure calculation was the method of joints. It is worth mentioning that the method of joints gives the same results as FEM for simple structures. The long-span roof leaning on plane trusses is a sample of such simple structures. This study examines the relationship between structural mechanics and geospatial monitoring of long-span roof structures. The method of joints has been chosen as the main method of structural mechanics. The paper comprises five parts. Part one deals with the introduction, and part two presents the study object. The third part outlines some of the critical principles of the method of joints and its liaison with geospatial monitoring results. Part four details the findings of monitoring results analysis. The fifth part is dedicated to conclusions.

II. STUDY OBJECT AND MONITORING DESIGN

The study object is the large warehouse in Kyiv, Ukraine (Figure 1). Geospatial monitoring was organized due to periodic damages that the warehouse owner observed during a year. The spatial geodetic network inside the warehouse with external referencing has been created to embark on the monitoring (Figure 2). The accuracy of the created network is presented in Table 1.

Figure 1. General view of the warehouse.

After the preliminary analysis of the structure's geometry and design scheme, it was decided that the major concern and possible reason for the periodic damages is the deformation of the roof construction and vertical displacements of columns. The roof structure is made up of planar steel trusses that are leaned onto the cantilevers of the concrete columns. Therefore, the primary goal of geospatial monitoring was to determine the vertical displacements of the system "truss-columns" and the probable inclination of the columns. According to these demands, at the belt of each truss, three targets for reflectorless measurements were installed (Figure 3).

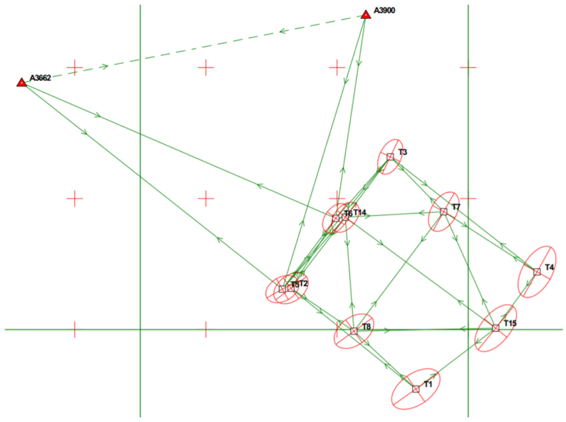

Figure 2. Horizontal view of the spatial geodetic network for monitoring with error ellipses.

Table 1. Network accuracy

Point	m_{XY} [m]	m_Z [m]
T1	0.0024	0.0014
T2	0.0018	0.0009
T3	0.0016	0.0008
T4	0.0024	0.0013
T5	0.0016	0.0010
T6	0.0015	0.0010
T7	0.0019	0.0010
T8	0.0020	0.0010
T14	0.0016	0.0009
T15	0.0024	0.0012

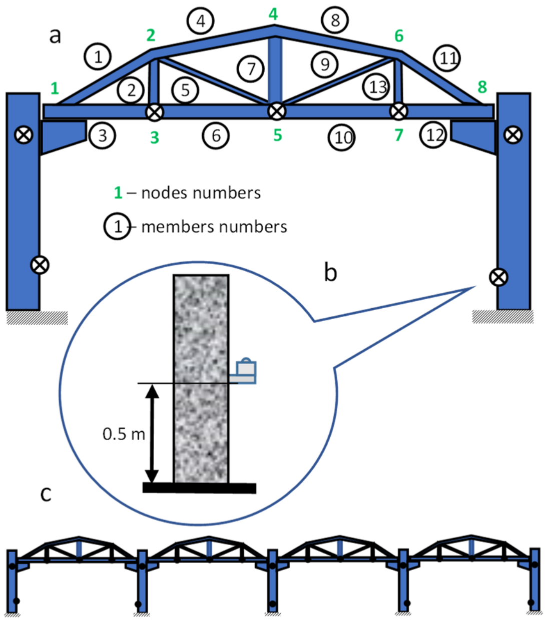

Figure 3. System "truss-columns" and the emplacement of targets: a - system "truss-columns" with the marks emplacement and numbers of joints and members; b – deformation benchmark emplacement at the bottom of a column; c – the warehouse cross-section that shows the order of columns and trusses.

In addition, each column was marked by one reflectorless target at the top and one benchmark near the floor to afford prism installation (Figure 3). Two hundred and forty targets and seventy benchmarks were installed in total. The observations for each epoch were accomplished by a precise total station using the free-station method. The first observation epoch was conducted in June 2016. Twelve observation cycles were carried out in total. The geometrical analysis of the obtained results has revealed unpredictable relationships. As a result, the necessity of structural analysis has become evident. It has been decided to apply the structural mechanics approach, namely the method of joints, for the complex analysis of monitoring results.

III. Method of joints

Before analyzing monitoring results, let's briefly consider the idea of the method of joints and how it can be related to geospatial monitoring tasks. It is generally known that the spatial displacement ΔS of any structure is considered in three dimensions with the corresponding constituents ΔS_x, ΔS_y, and ΔS_z. These values are the sum of particular displacements due to the displacement of the structure under its weight (dead load) Δl_x, Δl_y, Δl_z; temperature loads, and other external influences (wind, snow, etc.) or loads (live load, equipment load, etc.) Δt_x, Δt_y, Δt_z; the displacement due to the structure elements manufacturing errors Δm_x, Δm_y, Δm_z; the ground displacements of the structure as a function of the structure weight pressure on the base Δg_x, Δg_y, Δg_z. So we may write down the following expressions (Shults *et al.*, 2020) (Eq. 1):

$$\begin{gathered}\Delta S_x = \Delta l_x + \Delta t_x + \Delta m_x + \Delta g_x \\ \Delta S_y = \Delta l_y + \Delta t_y + \Delta m_y + \Delta g_y \\ \Delta S_z = \Delta l_z + \Delta t_z + \Delta m_z + \Delta g_z \\ \Delta S = \sqrt{\Delta S_x^2 + \Delta S_y^2 + \Delta S_z^2}\end{gathered} \tag{1}$$

The values in Equation 1 are typically calculated during structural analysis performed by a designer or civil engineer. As mentioned, there are different approaches to carrying out such an analysis. In structural mechanics for simple structures (frames, trusses, etc.) and their combinations, there is a well-known relationship (Connor and Faraji, 2016) (Eq. 2):

$$e = e_{load} + e_{temperature} + e_{manufactoring} \tag{2}$$

where e_{load} = structure element deformation due to various loads, including its own weight
$e_{temperature}$ = structure element deformation due to temperature variation
$e_{manufactoring}$ = structure element deformation due to manufacturing error

If one considers the planar truss, then the Equation 2 describes the extension of each member as a sum of partial extensions due to loads (dead load), temperature, and member's manufacturing error. The relationship between extensions and displacements is being presented in the form of deformation–displacement relations for the structure (Connor and Faraji, 2016) (Eq.3):

$$\mathbf{e} = \mathbf{\acute{B}}^T \mathbf{\acute{U}} \tag{3}$$

where $\mathbf{e}$ = vector of members' deformation
$\mathbf{\acute{B}}$ = extended matrix of members' cosines of direction
$\mathbf{\acute{U}}$ = extended vector of nodes displacements

The Equation 3 describes a well-known relationship between applied forces, extension or contraction of each member, and node displacements. In Equation 3, the ground displacements or support movements are also included. The given study treats the columns' vertical displacements as support movements. If the structure is statically determinate, one may estimate the reactions from equilibrium equations and then find the effect of supports' movements. The equations of the method of joints in matrix form (Eq. 4):

$$\begin{gathered}\mathbf{F} = \mathbf{B}^{-1}\mathbf{P} \\ \mathbf{e} = \left(\frac{L_i}{A_i E_i}\right)\mathbf{F} + (\alpha_i \Delta T_i L_i)\delta\mathbf{F} + e_{manufactoring}\delta\mathbf{F} \\ \mathbf{U} = (\mathbf{B}^{-1})^T \mathbf{e}\end{gathered} \tag{4}$$

where $\mathbf{P}$ = vector of applied forces
$\mathbf{F}$ = vector of member forces
$\mathbf{B}$ = matrix of members' cosines of direction
A = area of i^{th} member cross-section (different values for different members)
L = the i^{th} member length
E = modulus of elasticity for the i^{th} member
ΔT = temperature change
α = coefficient of thermal expansion for the i^{th} member (for this case, the coefficient of armed concrete)
$\delta\mathbf{F}$ = vector of virtual unit force (force equals one and applied to each node consequently)

In Equations 3 and 4, the designator $\mathbf{U}$ for the displacements vector has been taken from structural mechanics.

Therefore, if one knows the above-listed parameters, it is possible to calculate the structure displacements $\mathbf{U}$ under specific loads $\mathbf{P}$ in the model (Eq. 4). During the structure design, these parameters are defined in such a way that does not lead to the failure of the structure. In turn, it means that the allowable errors in geospatial monitoring should not lead to additional forces $\mathbf{F}$ in structure members that exceed 20%. This requirement is typical for structural mechanics.

So, having the displacements $\mathbf{U}$ from the simulation, we may treat any measured displacement ΔS that exceeds the value (Eq. 5):

$$\Delta S \geq 0.2U \qquad (5)$$

as significant.

In what follows, we will analyze just the vertical displacements as those which take the foremost concern; then, we may write down (Eq. 6):

$$\Delta S_z \geq 0.2U_z. \qquad (6)$$

To find the vector $\mathbf{U}$, the simulation of the roof truss has been accomplished. The truss was considered statically determinate, subjected to the loads from the roof cover and dead weight. The simulation results are presented in Figure 4.

It is clear that the truss deformed almost uniformly for the given loads. A random simulation has been carried out to calculate the effect of manufacturing error. The root mean square error of truss members manufacturing was accepted 4 mm. The output of the joined impact of loads and manufacturing error for one particular simulation is given in Figure 5. The largest displacements were observed in the middle. The calculation results have shown that maximum displacements have reached the value U_z = - 8.6 mm for the vertical component. According to Equation 6, any measured vertical displacement ΔS_z, which will be more than 1.7 mm considered significant. This value will be used for further analysis. However, the given computation does not account for the displacements due to temperature, environment (snow), and support movements. These displacements are unique for each span and observation epoch. That is why these displacements were calculated separately during the further structural analysis of monitoring results.

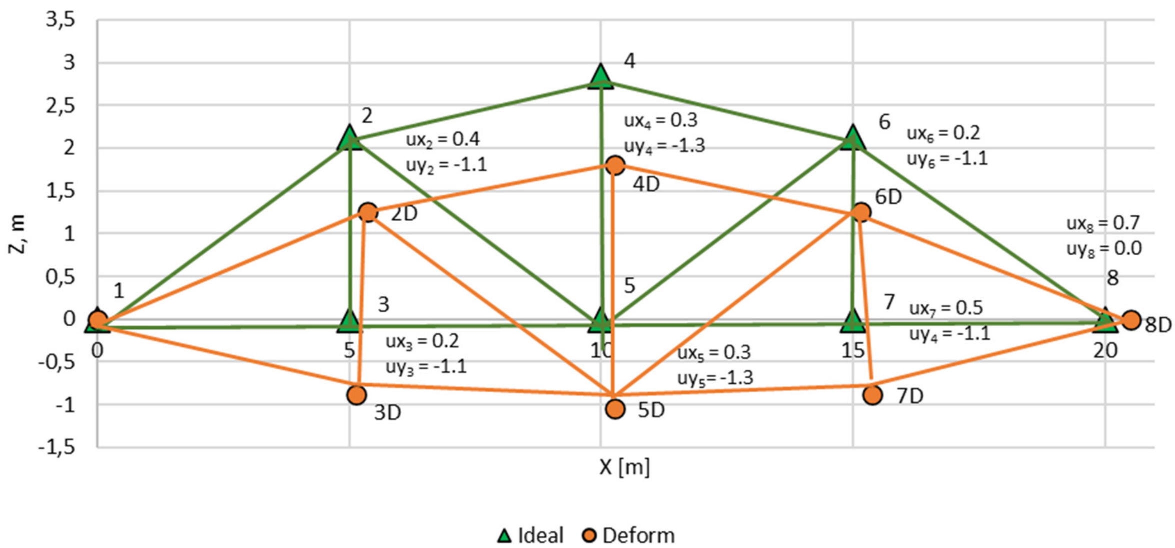

Figure 4. The picture of geometrically ideal truss and deformed truss (displacements are given in mm and have been scaled for visibility).

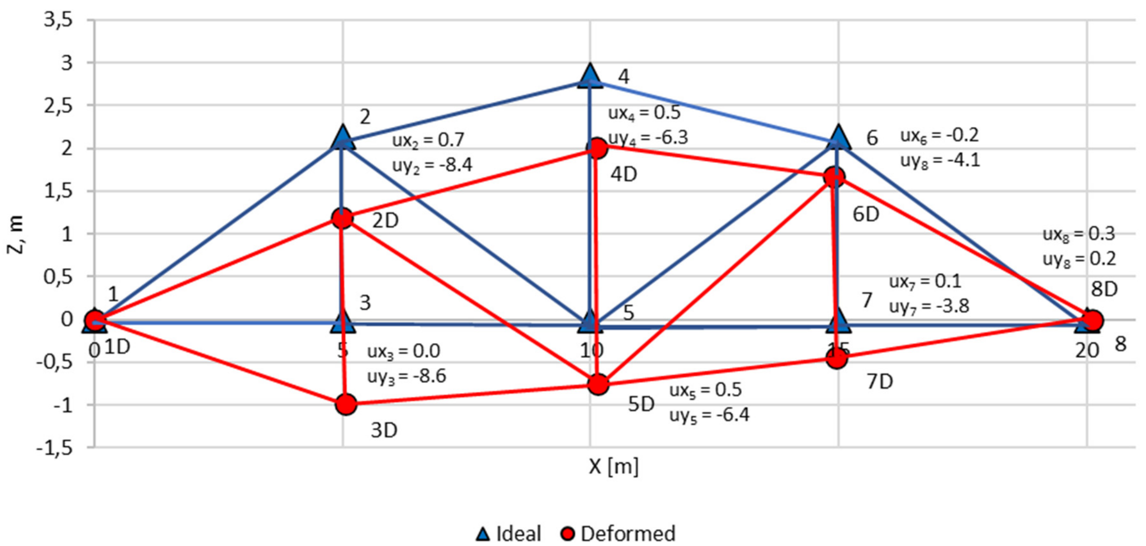

Figure 5. The picture of the combined impact of the loads and manufacturing errors (displacements are given in mm and have been scaled for visibility).

IV. Structural Analysis of Monitoring Results

The observation period lasted from June 2016 to August 2017. Thus the observation time included the snowy months with a significant temperature change. Therefore, some loads are time-dependent and act periodically. But, first of all, it is necessary to demonstrate the results of actual measurements that have been gathered during the monitoring period. Due to the vast set of measurements, it is impossible to present all the results. Below are the charts (Figure 6 – Figure 11) of vertical displacements for two trusses from different roof parts.

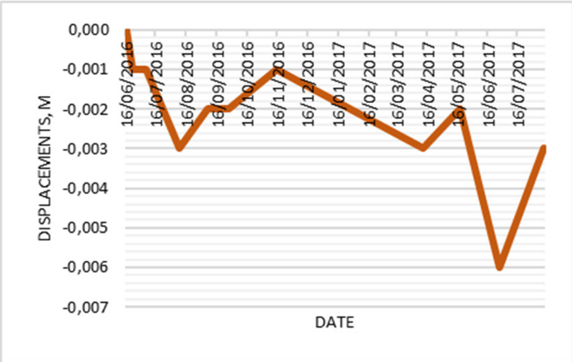

Figure 6. The vertical displacements chart for truss A3/B1 (point 3).

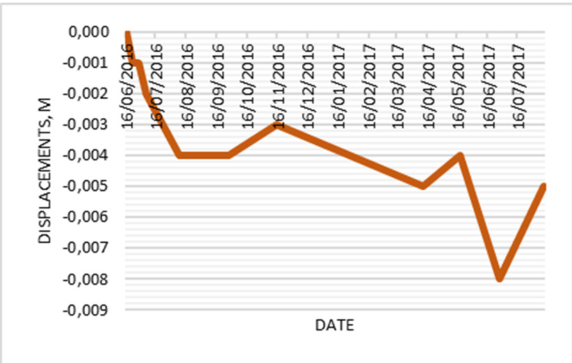

Figure 7. The vertical displacements chart for truss A3/B1 (point 5).

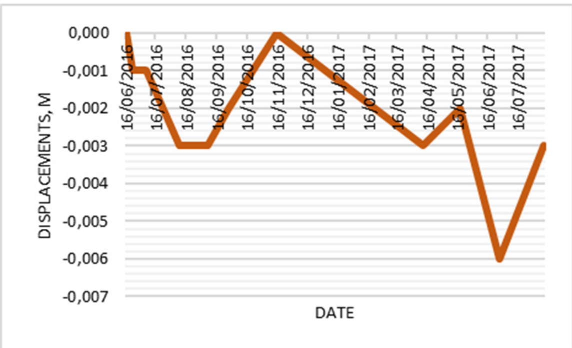

Figure 8. The vertical displacements chart for truss A3/B1 (point 7).

The charts visualize the vertical displacements of each truss at points 3, 5, and 7 (see Figure 4). These charts show the final values bigger than 1.7 mm, so the displacements are significant and need further analysis.

It is evident that the displacements have, unlike nature, even for Figure 6 – Figure 11. The given cases provide preliminary evidence that the deformation process is non-uniform and cannot be comprehended just from displacement analysis. A possible reason for these discrepancies might be various loads and their combination. Therefore, the only way to figure out whether the displacements are really exceeding allowable values or not is to carry out structural analysis. For the sake of the study, the following geometrical and physical parameters have been used (Table 2).

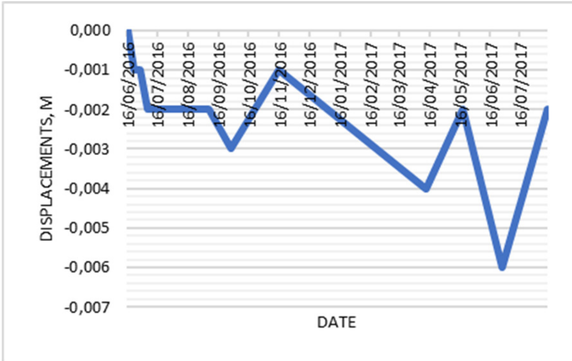

Figure 9. The vertical displacements chart for truss A5L/B4 (point 3).

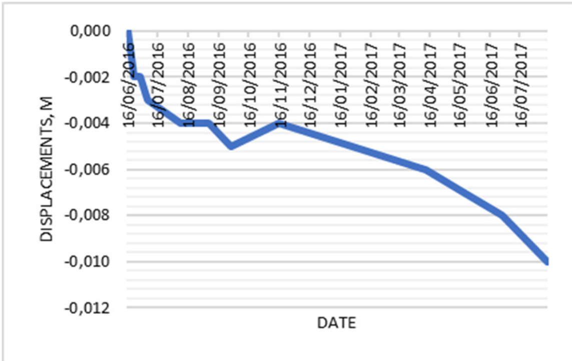

Figure 10. The vertical displacements chart for truss A5L/B4 (point 5).

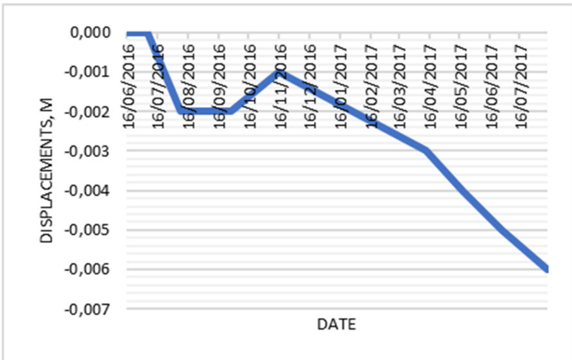

Figure 11. The vertical displacements chart for truss A5L/B4 (point 7).

In Table 2, the temperature deformation had been accepted according to the results of actual observations. It was determined that for the truss members, the temperature variation has the following view (Figure 12).

Table 2. The initial geometrical and physical parameters of truss members for simulation

Member	L_i [m]	ΔT_i [°]	L_i/A_iE_i	$\alpha_i \Delta T L_i$
1	5.439	12	6.53691E-06	0.000979
2	2.140	4	1.11458E-05	0.000128
3	5.000	4	6.51042E-06	0.000300
4	5.050	12	6.0699E-06	0.000909
5	5.439	4	9.44221E-06	0.000326
6	5.000	4	6.51042E-06	0.000300
7	2.850	4	1.48438E-05	0.000171
8	5.050	12	6.0699E-06	0.000909
9	5.439	4	9.44221E-06	0.000326
10	5.000	4	6.51042E-06	0.000300
11	5.439	12	6.53691E-06	0.000979
12	5.000	4	6.51042E-06	0.000300
13	2.140	4	1.11458E-05	0.000128

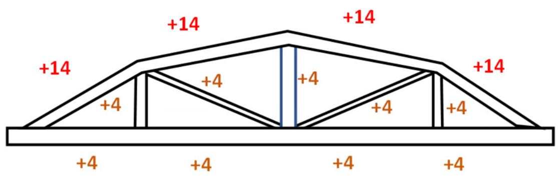

Figure 12. Truss temperature variation regarding the design temperature.

Figure 12 shows the summertime temperature variation from +4 C° up to +14 C° for members adjoining the roof.

The combinations of different displacements invoked by different loads are presented in Figure 13.

There are different causes of roof displacement. For the case in Figure 13a, the roof's truss is deforming under the additional loads (snow in our case) and temperature difference for the upper and bottom parts of the truss. The case in Figure 13b demonstrates the opposite process when a non-deformed truss is just inclined due to supports' movements or columns' vertical displacements, in other words. The case in Figure 13c combines both previous ones. It is obvious that only pure vertical displacements of truss points make sense for analysis. To find the pure vertical displacements, one needs to eliminate the displacements due to mentioned reasons. The study involved the calculation of the displacements from temperature change, columns' displacements, and additional loads for each monitoring epoch. These displacements have been ruled out from actually measured displacements at the next step. So the pure vertical displacements of the roof's trusses for the whole structure were determined. As a case study, below are the simulation results for the same truss for wintertime (Table 3) and summertime (Table 4) are given when environmental parameters were significantly changed.

Table 3. The simulation results for the system "truss-columns" for the specific loads for wintertime

Nodes	Nodes displacements due to loads [mm]				
	Δl_z	Δt_z	Δg_z [-6]	Δg_z [-2]	ΔS_z
u_1	0.0	0.0	0.0	0	0.0
v_1	0.0	0.0	-6.0	0	-6.0
u_2	0.4	0.2	0.0	0	0.2
v_2	-1.1	-2.2	-4.5	-0.5	-3.8
u_3	0.2	-0.3	0.0	0	0.2
v_3	-1.1	-2.0	-4.5	-0.5	-3.8
u_4	0.3	-0.6	0.0	0	0.3
v_4	-1.3	-3.0	-3.0	-1	-1.5
u_5	0.3	-0.6	0.0	0	0.3
v_5	-1.3	-2.8	-3.0	-1	-1.5
u_6	0.2	-1.4	0.0	0	0.5
v_6	-1.1	-2.2	-1.5	-1.5	0.2
u_7	0.5	-0.9	0.0	0	0.5
v_7	-1.1	-2.0	-1.5	-1.5	0.2
u_8	0.7	-1.2	0.0	0	0.7
v_8	0.0	0.0	0.0	0.0	-2.0

Table 4. The simulation results for the system "truss-columns" for the specific loads for summertime

Nodes	Nodes displacements due to loads [mm]				
	Δl_z	Δt_z	Δg_z [-9]	Δg_z [-3]	ΔS_z
u_1	0.0	0.0	0.0	0	0.0
v_1	0.0	0.0	-9.0	0	-9.0
u_2	0.0	0.3	0.0	0	0.3
v_2	0.0	-2.8	-6.8	-0.75	-8.8
u_3	0.0	-0.3	0.0	0	-0.3
v_3	0.0	-2.7	-6.8	-0.75	-8.7
u_4	0.0	-0.1	0.0	0	-0.1
v_4	0.0	-2.3	-4.5	-1.5	-5.3
u_5	0.0	-0.6	0.0	0	-0.6
v_5	0.0	-2.2	-4.5	-1.5	-5.2
u_6	0.0	-1.1	0.0	0	-1.1
v_6	0.0	-2.0	-2.3	-2.25	-2.0
u_7	0.0	-0.9	0.0	0	-0.9
v_7	0.0	-1.9	-2.3	-2.25	-1.9
u_8	0.0	-1.2	0.0	0	-1.2
v_8	0.0	0.0	0.0	-3	-3.0

As one may notice, the vertical displacements are entirely due to the supports' movements or columns' vertical displacements for the chosen truss. In turn, it means that there are no actual displacements of the truss and roof consequently. The only reason for roof displacements is the columns' vertical displacements. The map with vertical displacements' distribution has been created (Figure 14) to figure out the actual deformation of the roof. This map has been constructed for the last observation epoch. The distribution in Figure 14 is not applicable for analysis since it seems that the whole roof is being deformed. However, after structural analysis, the picture has changed substantially. In Figure 15, the map of the roof's vertical displacements after structural analysis is presented.

The map provides convincing evidence that the columns' vertical displacements cause the roof deformation.

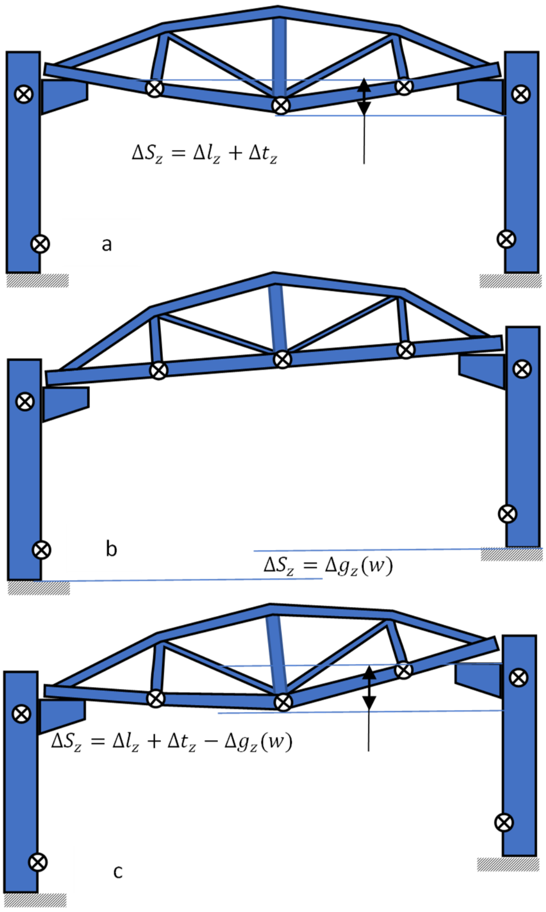

Figure 13. The various cases of the deformation of the system "truss-columns": a – pure truss displacement; b – columns' displacements; c – combined displacement.

The roof deformation occurs only in regions with considerable vertical displacements of columns. Therefore, the structural analysis has proved its high efficiency and allowed avoiding the wrong decisions by the results of geospatial monitoring.

V. Conclusions

The presented study examines the results of geospatial monitoring of the long-span roof structures using the structural analysis approach. A combined analysis based on geometrical and mechanical methods has been suggested in the paper. In light of the study, few conclusions can be drawn from the achieved results. The general picture emerging from the study is that the application of the structural analysis allows avoiding the wrong decisions concerning the structure deformation. The deformation picture becomes clear and reveals the true reason for displacements and their values. In the presented study, the suggested approach has let to eliminate the displacements, which had periodic nature.

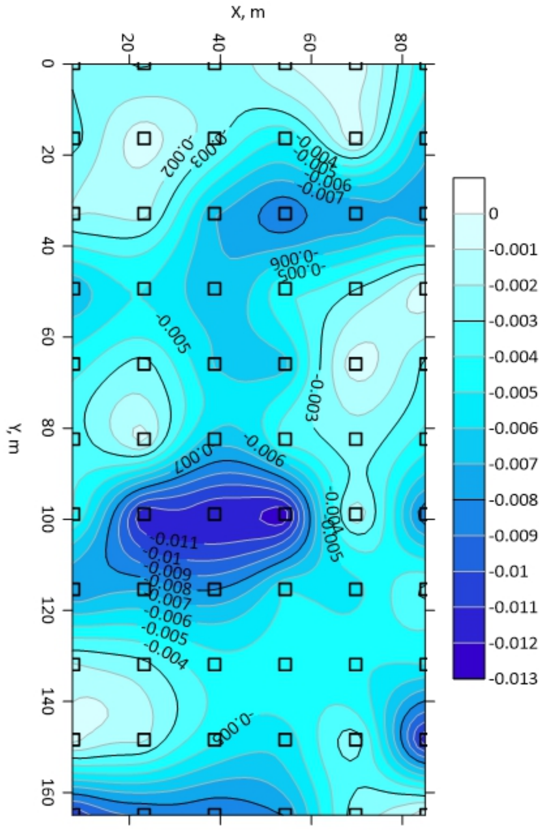

Figure 14. Map of the vertical displacements of the roof before structural analysis (columns depicted as rectangular).

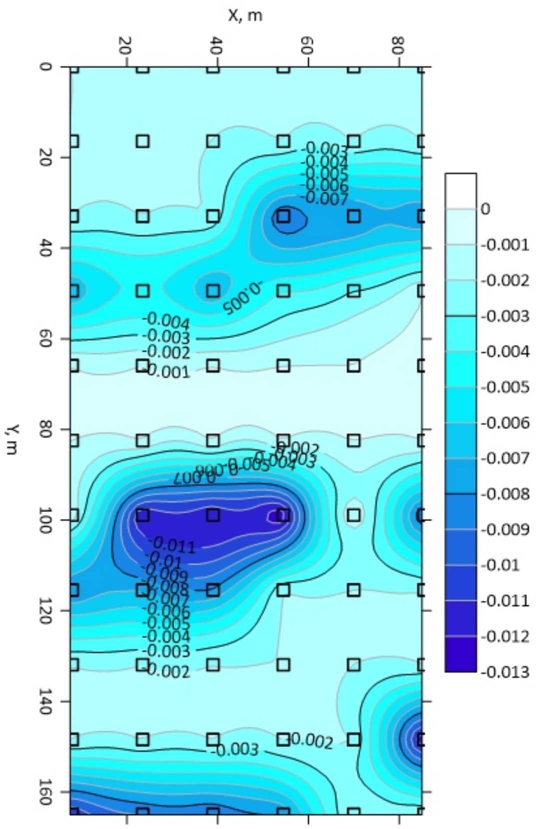

Figure 15. Map of the vertical displacements of the roof after structural analysis (columns depicted as rectangular).

Although the allowable displacements for the roof's trusses should have been in a range + 1.7 mm, the measurement results have shown values exceeding 12 mm. However, thanks to the structural analysis, it is become possible to rule out the additional displacements and find the source and reason for the roof deformation. Future research will have to address the offered approach in more detail. The study region has to be extended to more complicated structures. Of course, if the structures for analysis get complicated, a more robust method is needed. In what follows, for complex structures, FEM is preferable to use. Keeping in mind that current BIMs contain FEM since the design stage, the new branches of analysis become open for surveyors, particularly those dealing with geospatial monitoring analysis.

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