REGISTRATION OF GEOMETRICAL STRUCTURE OF A LARGE-SPAN SUSPENDED ROOF FOR DIAGNOSTIC PURPOSES

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The following paper uses the example of the open-air theatre roof in Koszalin to present the results of empirical research covering collection and interpretation of data concerning the geometric structure of a suspended roof for the purpose of its diagnostics. The conducted study covers direct surveying by the polar coordinates method with the use of reflectorless total station, close range photogrammetry, laser scanning, and thermovision, mainly in the context of their effectiveness with regard to specific expectations on the part of the constructors.

1. GENERAL CHARACTERISTICS OF SUSPENDED ROOFS AND THEIR DIAGNOSTICS

Presently, suspended roofs are considered exceptionally light, modern, and effective (Breger, 1996). An important construction feature of suspended roofs is the usage of suspension ability to stretch properly prepared ropes (cables). Depending on the type of support, arrangement of cables, their anchorage, and functional requirements, the suspended roofs can be constructed as flat or spatial structures of considerable span (Borusiewicz, 1978). Transition of loads by the suspended roof is possible after a proper prestressing of its construction, which ensures stiffness so that it keeps the required shape under various conditions, including such factors as the dead load, snow load, temperature changes, and the wind pressure.

Fig. 1. Suspended roof of the open-air theatre in Koszalin.

One example of a suspended roof is the roof of the open-air theatre in Koszalin (Fig. 1), whose construction consists of a prestressed cable network in the hyperbolic paraboloid shape, attached to a steel rim girder. The basic supporting structure consists of two flat two-hinge steel arches. The horizontal projection is a lens of 101.80 x 58.60 m and surface of 4460 square meters (Filipkowski, 1977).

The proper registration of construction geometry after realization of the object (post realization documentation), is most important for the general diagnostic purposes. In case of suspended roofs, introduction of additional compressive forces during assembly usually causes considerable deviation from project assumptions. In such a case, it is very important for the constructors to be able to repeat the strength calculations, relating to the geometry of existing structure, whose registration may be limited to the connections of the construction network. In the above mentioned situation, the aim of surveying for diagnostic purposes is to determine the spatial location, in a constant reference system, of selected roof points, which can be the details of the construction network, constituting its connections (Fig. 2).

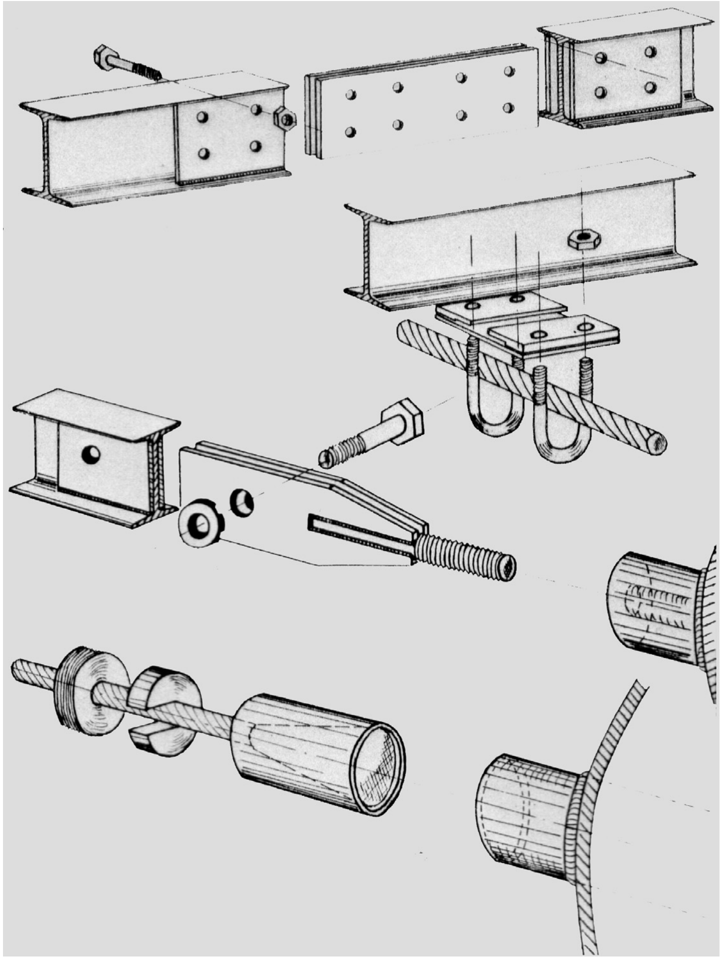


Fig. 2. Details of the construction network – connections
Sources: genuine materials of the constructor of the roof.

2. REGISTRATION METHODOLOGY OF THE SUSPENDED ROOF GEOMETRICAL STRUCTURE

2.1. Conditions and Scope of Study

The basic conditions influencing the choice of registration methodology of the suspended roof geometrical structure are:

- outside factors causing changes in size and shape of the roof, as well as the location of construction network connections in comparison to the project assumptions,
- scope and speed of the above changes,
- dimension and shape of connections (details) of the roof construction network,
- construction and project properties of the roof ,
- required scope and accuracy of registration of the details' location, determined a' priori by the constructors at the level of ± 3 cm to ± 5 cm,
- registration epoch, (e.g. prior to and after prestressing of the construction roof, periodically at the utility stage, in case of snow load or pre-emergency state.

Taking into consideration the above conditions, the scope of study conducted on the testing object was the following:

- direct surveying by traversing at free stations (Leica TCR407 Power and Topcon GPT 3007 tacheometers),
- close-range photogrammetry method with the application of medium resolution digital cameras (Olympus E300 camera with ZUIKO DIGITAL 14-45 mm lens, and software Topcon Image Surveying Station PI-3000 and PI- Calib) (Deska and Pawłowski, 2008b),
- laser scanning (laser scanner HDS Leica ScanStation and Leica Cyclone v. 5.8 software) (Deska and Pawłowski, 2008a).

The above survey has been extended to include thermovision, more specifically the registration efficiency of temperature distribution on the surface of the roof. The temperature changes are considered by the constructors as a specific type of cable network load. In the conducted survey, a thermovision camera AGEMA LWB 880, colour camera CCD for picture orientation, and Thermoscope v. 2.03 software (Deska and Pawłowski, 2008c) have been used.

2.2. Method of Polar Coordinates

The results of subsequent observations by the polar coordinates method of selected roof construction points, in the form of coordinates in an assumed coordinates system (Fig. 3), were each time the basis for conducting the simulation of construction strength and preparing periodical expert appraisement regarding its safety - for instance (Filipkowski et al., 2006).

Based on the comparison of the point coordinates, referring to respective surveying epochs, the constructors obtained significant data, including the following:

- occurrence of largest vertical displacement of 51 cm downwards in the middle part of the roof and along its shorter symmetry axis with simultaneous uplift of 17 to 21 cm

in construction connections located near supports, while the construction was loaded with snow weighting around 51 kg/ m^2,

correspondence of changes in coordinates of points distributed symmetrically in relation to the construction axis, which showed, to a considerable degree, proper work of the construction under load,

comparability of the vertical displacements difference in selected construction points, being the result of two observations conducted under varying temperature conditions (30° C temperature difference) under the roof, with vertical displacements of the construction under snow load of about 15 kg/m^2.

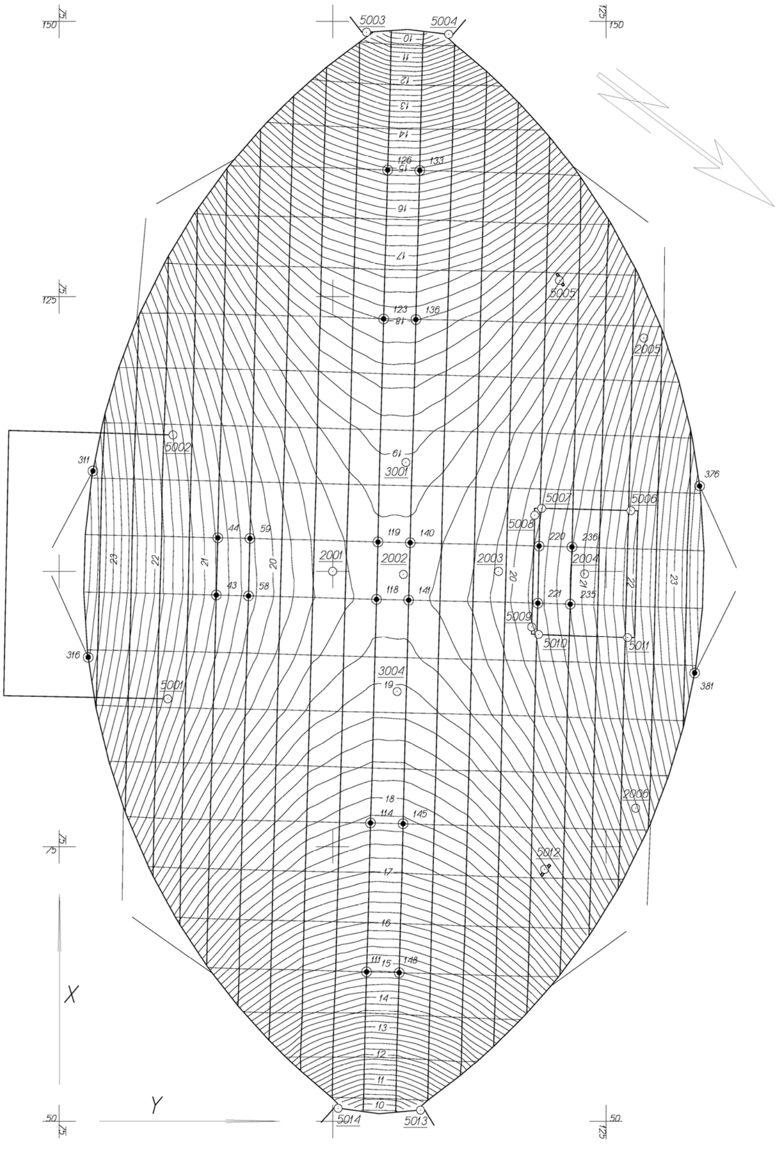


Fig. 3. Horizontal projection of the construction network.

The result of study conducted under laboratory conditions and on the testing object, namely surveys to cylinder details constituting the construction connections of the suspended roof, indicates that it is possible to observe a point on the surface of a detail, corresponding in each case to the centre of its picture in a tacheometer telescope. In case of polar coordinates surveying method, the consequence of the above approach, will always be the registration of a point located no further than 27 mm from the centre of the detail. Taking into consideration the required accuracy, on the part of the constructors, ranging from ± 3 cm to ± 5 cm, the determination of the eccentric, and reduction to the result of distance and direction survey, as well as additional premarking of observed points of the roof, may be considered unnecessary (Deska and Pawłowski, 2006; Deska and Pawłowski, 2007).

2.3. Photogrammetry Method

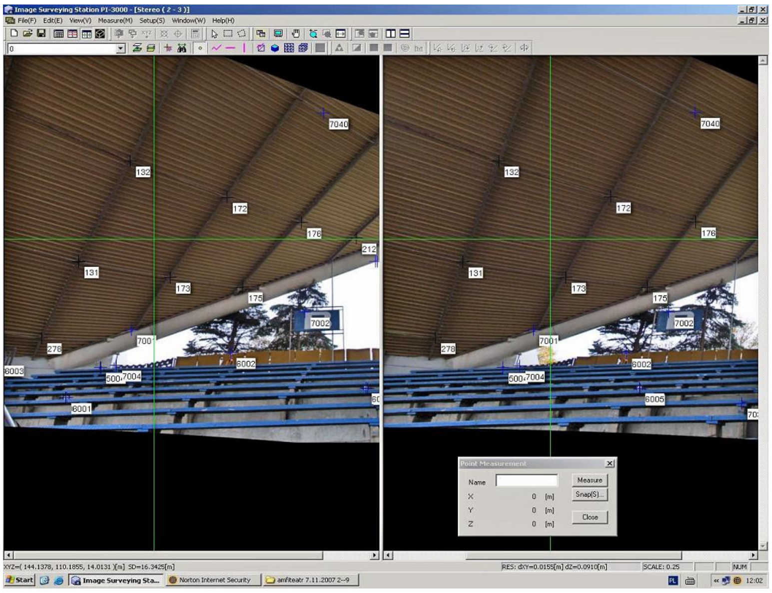
The model of the chosen roof construction fragment covering 1/10 of its surface was created on the basis of 8 pictures making up 7 stereoscopic pairs, and 15 points with coordinates determined by the polar coordinates method, and 24 turning points, which as common points, had the function of connecting points on the subsequent pictures.

For the points of known coordinates, the parameters determining the so-called basic accuracy of stereoscopic measurement (stereorestitution) are as follows:

Field Resolution: PlaneRes 5 mm and DepthRes ranging from 2 to 3 cm,

Standard Deviation $_x$ =0.0171m, $_y$ =0.0253m, $_z$ = 0.0109 m,

Maximum Residuals DX = -0.0481 m, DY = -0.0521 m, DZ= -0.0226 m.



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X    0  [m]
Y    0  [m]
Z    0  [m]
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XYZ=( 144.1378, 110.1855, 14.0131 )[m]  SD=16.3425[m]
RES: dXY=0.0155[m] dZ=0.0910[m]   SCALE: 0.25
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Fig. 4. Measurement of coordinates of points using.

The survey of chosen construction connections (details) was conducted on one of the chosen stereogram (Fig. 4), with the aim of determining their coordinates *X,Y*, and *Z*. These coordinates, together with ones obtained by the application of polar coordinates method with the reflectorless tacheometer Topcon GPT 3007 are presented in Table 1.

Table 1. Comparison of the Coordinates of Chosen Suspended Roof Construction Details, Determined by Photogrammetry and Polar Coordinates Method

	Photogrammetry Method (Topcon PI-3000) [m]			Polar Coordinates Method (Topcon GPT 3007) [m]			Difference in Coordinates [m]		
No. of Observed Point (Detail)	X	Y	Z	X	Y	Z	ΔX	ΔY	ΔZ
131	144.19	108.12	12.26	144.17	108.14	12.23	0.02	-0.02	0.03
132	140.18	108.02	13.87	140.18	108.04	13.85	0.00	- 0.02	0.02
172	140.17	110.95	14.13	140.20	110.99	14.10	- 0.03	-0.04	0.03
173	144.13	111.05	12.62	144.15	111.07	12.60	- 0.02	-0.02	0.02
175	144.14	114.07	13.11	144.18	114.08	13.12	-0.04	-0.01	-0.01
176	140.10	113.92	14.42	140.14	113.95	14.45	-0.04	-0.03	-0.03
212	140.16	116.88	14.96	140.13	116.89	14.98	0.03	-0.01	-0.02
278	147.76	108.21	10.48	147.78	108.24	10.48	-0.02	-0.03	0.01

Taking into consideration different observation epoch of the suspended roof construction with the above methods, and different air and suspended roof temperatures at that time, the correspondence of obtained coordinates within the range of -0.04 m to 0.03 m shows comparable accuracy of both methods as to the registration of the geometrical structure of the suspended roof.

2.4. Laser Scanning

The scope of study regarding the use of laser scanner to register the geometrical structure of the suspended roof was as follows:

- scanning with resolution of 2 cm vertically and horizontally of the whole construction at one scanning station from the distance of about 50 m,
- additional scanning with 2 mm resolution limited to chosen construction elements at the above station (impulse laser scanner HDS Leica ScanStation),
- scanning with resolution of 5 mm vertically and horizontally, of half of the construction at one scanning station located within the distance of 35 m from the eastern pediment (HDS ScanStation 2 scanner),
- determination of roof elements registered as point clouds (Fig. 5, Fig. 6).

The results of the survey conducted indicate that:

- the sufficient resolution to model the connections of the construction network equals approximately 5 mm in case of steel arches and their cable and I section anchoring (Fig. 5), and the necessary resolution in case of the connections of load and tension cables is 2 mm,

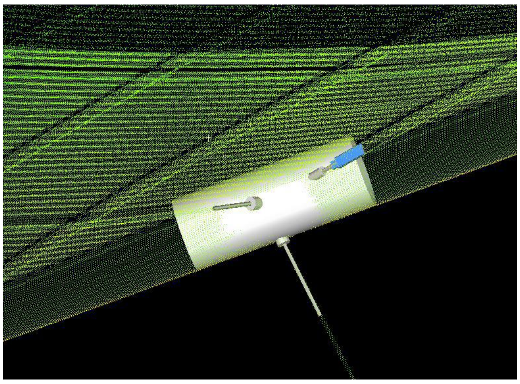

Fig. 5. Modelled parts steel arch, cables – suspension member and guy, and the I section tension member with joining parts.

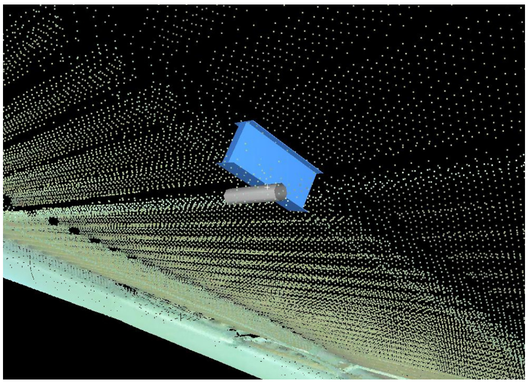

Fig. 6. Modelled parts cable – the suspension member and the I section - sension member near the knot of the construction.

due to the dynamic changes of the geometrical structure of the roof (especially in its middle part), resulting from temperature changes, the scanning should take place in stable temperature conditions, lack of sunlight or strong wind, with a scanner of possibly highest scanning speed; it is registered on two scans of the same suspended roof element conducted within a few hours interval under different temperature (Fig. 7 – in the form of two clouds of points, and Fig. 8 – after separate modelling of a load cable fragment – suspension member),

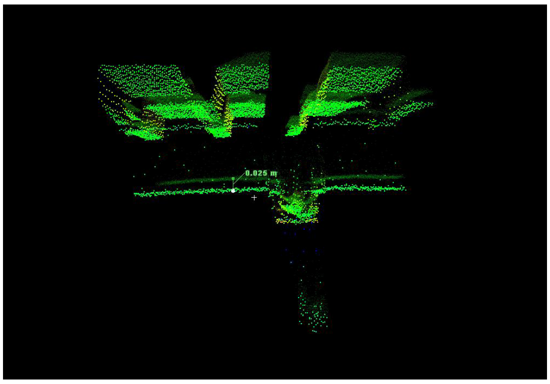

Fig. 7. Two scans made within a few hours (seen as two images of the same elements moved vertically).

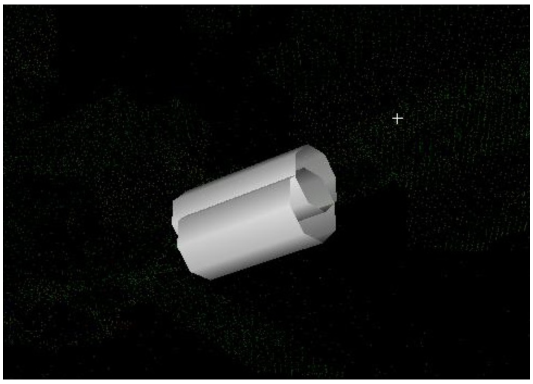

Fig. 8. A modelled part of the suspension member from two clouds of points.

the optimal solution to register fully the geometrical structure of the roof, is to use simultaneously two or four scanners located symmetrically under the construction roof and scanning with the resolution of 2 mm (if possible two scanners should scan the same construction fragment simultaneously).

The conclusion resulting from the structure strength examination and the survey of the testing object of prestressed cable network construction, justifies the indication of two different situations in diagnostics of the roof, depending primarily on the geometrical structure's registration beginning epoch.

It is most proper to begin the above registration already at the roof realization stage and conduct appropriate surveys prior to, as well as, after prestressing of the construction, covering all connections of the construction network. This will enable the assessment of changes of the selected geometrical features of the roof, resulting from prestressing and dead load. Subsequent surveys, taking place during the utility of the roof, should provide data regarding the location of all connections of the construction network at times determined by the constructor, as well as, data regarding only selected connections in case of snow load.

If the survey is conducted in such a manner, it is possible to assess the geometrical changes of the suspended roof structure in time, as well as relate them to the changing forces affecting the construction, determined on the basis of specific structural strength calculations. The geometrical state of the suspended roof construction, determined as a result of the survey, relates directly to the current state of operating forces. In this context, the results of periodical observation of the suspended roof's geometric structure can constitute the basis for assessment of the load carrying capacity, and tension relevant to the safe utilization of the suspended roof.

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