MEASUREMENTS OF LARGE-SPAN ROOFS – DIAGNOSTIC ASPECTS

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1. INTRODUCTION

In a building terminology a large span roof is a roof with a limited number of internal support posts and a large usable surface, free from supports. A suspended roof – where bands play a pivotal role - is widely considered to be particularly light, modern and efficient in its basic functions (Breger, 1996). An example of such a roof is that of the Koszalin open-air theatre, with an area of approximately 4460 sq m (Fig. 1). The structure of the roof is based on a prestressed cable network in the hyperbolic paraboloid shape (a saddle mould surface), attached to a steel rim girder (Filipkowski, 1977).

Fig. 1. Suspended roof of the open-air theatre in Koszalin
Sources: materials of the constructor of the roof.

Diagnostics of a suspended structural roof aims to assess both the technical condition of the roof and to examine and predict the behaviour of the structure under changing operating conditions (such as sunlight, wind force, snow load). For the purpose of diagnosis it is quite often necessary to register periodically its geometrical structure. In this context, assessing the relevance and effectiveness of different measurement methods is undoubtedly an important and current issue, where engineering surveying

and construction intersect, mainly due to the specifics of the roof in terms of its design, geometry and functionality. The result of this evaluation should be an indication of adequate methods and tools for measuring and their conditions of use, which ultimately may lead to the development of methodology for registration of a geometrical structure of sample building roofs for diagnostic purposes (Deska, 2010).

2. METHODOLOGY OF REGISTRATION OF THE GEOMETRICAL STRUCTURE OF THE ROOF

2.1. Scope of Measurement

In the diagnosis of a roof construction one can distinguish two different situations depending primarily on the moment when the registration of its geometrical structure begins (Deska, 2010; Deska and Pawłowski, 2010).
In the context of the expectations of designers and engineers, it is most appropriate to perform required measurements both before and after stressing the roof structure, covering all nodes of the construction grid. This would allow one to gauge changes in specific geometric features of the roof, caused by stress and its own weight, against assumptions of the design. In addition, registering geometry at point zero, correlated with predefined load, can serve as a geometrical and constructional basis for inference – by means of periodic measurements - of the current technical condition and physical forces within the structure.
Subsequent periodic measurements, starting with the post – compression measurement, may be limited to only those grid nodes which are used in calculations of the strength.
When measurements commence only after commissioning of the roof covering, the first diagnostic measurement will satisfy the builders' expectations if it provides data for establishing in full the geometry of the roof - even with certain approximation. Subsequent measurements can then cover selected nodes of the construction grid, mainly in the context of a regular registration of their vertical displacements under certain conditions such as snow loads. Measured displacements of selected nodes are specific geometrical feature, because their changes due to load and temperature best reflect the operation of the roof structure and the state of forces working within the structure, thus facilitating informed decisions regarding a safe usage of a roof.

2.2. Measurement Conditions

For a periodic registration of the geometrical structure of a roof construction, we can identify certain conditions which have significant influence on the selection of the most rational methods of measurement.
These conditions can be summarized in three thematic groups, including:

- **organisational conditions - ability to access the structure, signalling of control points, location of measuring stations, conditions of measurement,**
- **construction and design conditions - the type, condition and initial geometry of the structure, also design estimates and conditions of usage of the roof,**
- **measurement conditions - the required range of measurement and expected accuracy.**

The above mentioned factors should be subjected to analysis at the stage of planning the measurements for the specific roof construction. In addition, one may need to conduct test measurements in both the laboratory conditions and on the object itself, mainly in

the context of the capabilities and accuracy of observations of the structural roof construction grid nodes (also known as details) (Deska, 2010; Deska and Pawłowski, 2010). All the data thus obtained, both by analysis of conditions and test measurements, can be the basis for choosing the specific methodology of measuring tasks, usually involving periodic registration of the geometrical structure of the roof being diagnosed.

2.3. Procedure of Developing Measurement Methodology

Research conducted on-site (Deska, 2010) and long-term cooperation with the object's constructor, justify a detailed description of specific issues that can be presented as a multi-stage process of the development of methodology for measuring the specific roof, taking into account all the circumstances.

Stage I – "Define expectations of designers and obtain necessary information about the object", including:

1. **indication by the designers of the measurement range and accuracy of designation of certain geometrical features,**
2. **obtaining information about the roof (geometric design, construction and strength) and its immediate vicinity,**
3. **obtaining information about properties of roof construction, particularly when under the influence of external factors.**

The conclusion of Stage I - formulation of the measurement task, general reconnaissance of the object and conditions prevalent on site, gathering of data about the object obtained from the previous research.

Stage II - "Feasibility of meeting designers' expectations and verification of information about the object", including:

1. **test measurements in laboratory conditions using various methods and pieces of equipment for non-signalled details, corresponding in dimension and/or shape to the roof construction grid nodes,**
2. **test measurements on the object and assessment of the dynamics of the object and external conditions within the framework of the measurement task and planned measuring methods,**
3. **selecting details in the grid nodes as "points" to be observed or construction of universal signals appropriate for intended measurement methods and conditions in the facility.**

The conclusion of Stage II - evaluate capabilities and effectiveness of the use of different methods and measuring equipment against the accuracy expected by designers.

Stage III - "Choosing observed points, the method and equipment", including:

1. **selection of control points (details in the grid nodes and/or signals – targets),**
2. **determination of the location of reference points and controlled points,**
3. **choice of the method or methods for registration of the geometrical structure of the roof.**

The conclusion of Stage III – if one determines that the grid nodes are to be the controlled points as well, one has to decide whether it is desirable to introduce eccentric reductions in the results of linear and angular measurements, which allow to determine the location of the centre of each of the details within the adopted reference system; the

choice of methods and measuring equipment; determination of the way of performing measuring operations and calculations.

Stage IV - "Implementation of the measurement task - the registration of geometrical structure of structural roof", including:

1. **stabilising reference points and possible signalisation of controlled points of the roof,**
2. **measurement and allignment of the network formed by reference points and the measurement of selected points of the roof,**
3. **elaboration on final results, as required by constructors.**

The conclusion of stage IV - the registration of geometric structure adequate in scope and accuracy to constructors' needs, enabling the assessment of the roof's technical conditions and to take necessary preventive measures.

2.4. Measurement Methods

Experimental measurements, conducted on a sample facility, the open-air theatre in Koszalin, were made using the polar coordinates method, spatial intersections, digital photogrammetry and the laser scanning method, enabled verification of their effectiveness in the measurement task to determine the locations of selected nodes in construction grid of structural roofing.

2.4.1. Angular Space Intersections

The results of empirical research (Deska, 2010) clearly indicate that the space intersection method is inefficient when one observes a larger number of cylindrical details from only one measurement base. Observation of some dozen details would require a selection of multiple bases for measurement. Furthermore, it is clear that ambiguously identifiable structural detail is not an appropriate object for angular observations due to its image changing in a field of view of a telescope. It is therefore necessary to introduce reductions (in each case calculated as part of the eccentricity of the object), which, as labour-intensive, is not justifiable in diagnostic measurements.
The angular intersection method can be used in diagnostic measurements in cases where one signals only selected controlled points of the structure; it is recommended, however, that it should be used, when registering the location of selected points of the structure rather than the construction grid as a whole.

2.4.2. Method of Polar Coordinates and Free Stations

Based on test measurements (Deska and Pawłowski, 2006, 2009; Deska, 2010) it is reasonable to conclude that when using certain reflectorless total stations, it is possible to achieve accuracy of locating the position of individual construction details in the region of 3-5 cm, i.e. figure *a priori* assumed by the constructors.
Due to properties of the rangefinder and the structural detail, one can designate points on the surface of details as controlled points; and not necessarily enter adjustment of the distance to the centre of the object. Consequently, one will record a point located no more than 20 mm away from a specific point on the surface of a structural detail. Defining of eccentricities or geometric interpretation of the beam appearing on the

surface of the detail would be impractical. Not introducing reductions onto the results of measuring the distance and directions, due to properties of the cylindrical detail, equipment and methods, under the operating conditions, may actually result in the registration of a point that is located no farther than 27 mm from the centre of the detail.

The above conclusions are confirmed by results of research conducted on a test object, measuring of cylindrical details in nodes of a roof structure (Deska, 2010). As for other details, it is necessary to verify them, for example by using custom-built device (Deska and Pawłowski, 2006; Deska, 2010). This approach can be used only for emergency monitoring and only using a verified set, consisting of an instrument - a signal, that is a reflectorless total station and a detail. This set needs to be verified by previous research, conducted in appropriate conditions. In this case, one should primarily assess the convergence of the target axis and the axis of the infrared rangefinder beam and a laser rangefinder beam, as well as the size of the beam - through the impact of these elements on the measured distance to the detail.

Using the constructed targets (Deska and Pawłowski, 2007; Deska, 2010), which clearly indicate observed points and enable one to measure the distance to the reflective tape with an infrared rangefinder, it is possible to obtain the accuracy of the location of the selected signal within the margin of 1 cm in some situations, it is best to use a tacheometer equipped also with a laser rangefinder (if the signal is observed at an unfavourable angle) and a broken eyepiece. The use of robotic tacheometers with automatic targeting systems due to their limited precision of "tracing" the targets's centre with the reflective tape can only be used to accelerate the measuring procedure, through, for example, their use in a rough targetting of a signal.

The polar coordinates method using 5"-7" tacheometers and free stations allows to determine the location of controlled points (signal points) in adequate conditions (stable temperature, cloud cover limiting changes in sun exposure, no wind).

Studies performed allow to conclude that the polar coordinates method can be considered the most effective for the registration of some dozen to a few dozen selected points in each epoch of measurement. It is not, however, effective for the inventory measurements, primarily due to the properties of the structure and its dynamics.

2.4.3. Photogrammetric Method

Modern trends in close range photogrammetry in the field of engineering focus on using digital photogrammetry workstations and digital images, including non-metric ones, taken by amateur digital cameras.

An experiment carried out during the tests (Deska and Pawłowski, 2008b; Deska, 2010) justifies the conclusion that the method of digital photogrammetry using medium resolution amateur cameras is suitable for diagnostic recording of a geometrical structure of the roofs, particularly when it relates to the registration of geometry the first time and covers the entire roof structure. This conclusion concerns the band constructions for which the expected accuracy of determining the location of the node is 3 cm to 5 cm.

Application of photogrammetric method requires, in general, the determination of coordinates of reference points in an external reference system; in connection with this, one needs to designate, before or during the registration, a substantial number of points with known coordinates, in which custom-built target signals can be installed.

2.4.4. Laser Scanning and Terrestrial Laser Scanners

Conclusions drawn from the experiment of employing laser scanning techniques for the study of roof construction (Deska and Pawłowski 2008a; Deska, 2010) concern primarily the resolution of scanning . To precise modelling of elements of the roof in case of steel arches and their joining to the bands, it is sufficient to use the resolution of about 5 mm. However, for the proper modelling of grid nodes, which constitute the joints of support and tension bands (maximum number), it is necessary to scan with the resolution of at least 2 mm, from several stations; then make a joint analysis after combining several point clouds. In this way, blind spots are eliminated while registering points on a larger area of an object.

Due to the dynamics of the geometry of the roof construction (especially in its central part), resulting from changes in temperature, a registration of geometric structure for diagnostic purposes should be conducted when the temperature outside is stable, with no sunshine or strong wind. For these reasons, the measurement time should be as short as possible, and the scanner used – as fast as possible. For a full description of the geometry of a roof structure one can simultaneously use several (at least two) scanners and perform a scan from four different stations (the ideal solution would be the simultaneous use of four scanners, placed symmetrically under the roof. Each fragment of the structure should then be scanned from at least two stations with a resolution of at least 2 mm x 2 mm (it is preferable that two scanners simultaneously scan the same fragment of the structure from different stations).

A significant limitation in the use of a laser scanner for open roofs is its lower limit of operating temperatures, being 0º C. This virtually eliminates possibility of registration in winter conditions of snow and ice load. Another limitation, noticeable during the test, is significantly lower scan speed in case of so-called upper window scanning, i.e. scanning in the range above 32.5 degrees from instrument's horizon, as well as a limited choice of scanning range, in the form of scanning of rhombic segments spread on the surface of a sphere. In the case of placement of scanning stations under the scanned object, both a limited choice of scanning range and reduced scanning speed are very significant.

In view of these considerations it can be assumed that the application of a terrestrial laser scanner to record the geometrical structure of selected parts of suspended roof is significantly limited and in practice it can only refer to a few points, elements or details. In case of closed roofs and roofs with lesser dynamics and less susceptible to movements caused by wind pressure and temperature changes, laser scanning is undoubtedly the most effective method, despite of registration of a number of redundant observations, including points located beyond elements of the support structure on the cover of the roof (Deska, 2010).

3. CONCLUSIONS

The results of modelling simulations carried out by specialists in the field of structural mechanics (Filipkowski et al., 2006) confirm that the registration of a geometrical structure of a sample roof, the subject of our research, corresponds in scope and accuracy to the expectations of designers. In this situation it is therefore reasonable to say that a certain geometric state of the roof structure is directly linked to the state of the existing forces; by means of the periodic observation of selected points of roof construction it is possible to assess the viability and the strain of the roof, which is in turn directly related to the safety of its use.

The choice of a measurement method depends not only on the precision it offers, but mainly on the constructors' expectations. In changing operating conditions, predefined accuracy values for determining the grid node's location (3 to 5 cm) can be obtained using the photogrammetric and the polar coordinates method, as well as using a laser scanner, even if observing non – signalled points of the construction. When they are signalled, the precision capability of these methods is higher (even below 1 cm).

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