

# Long-term Deformation Measurements of atypical Roof Timber Structures

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## Abstract

The paper includes conclusions from evaluation of results obtained from long-term measuring of innovative atypical roof timber structures. Based on the results of measurements of vertical and horizontal deformation components it is possible to analyze the real behaviour of structures in given conditions. By assessing deformations in various stages, including particularly external and internal environment temperatures, relative air humidity and moisture content of wood, decisive parameters for real structure behaviour can be established. The data are processed from period 2001 – 2013.

**Key words:** geodetic deformation measurement, atypical roof timber constructions

## 1 INTRODUCTION

Timber is a traditional natural material from which a roof structures are built, characterized by strength, low weight and good workability. Wooden structures further have an aesthetic appearance, and therefore the market is still very much in demand of them.



Figure 1 Tennis hall in Frýdlant nad Ostravicí, 1997, span 40,4 m

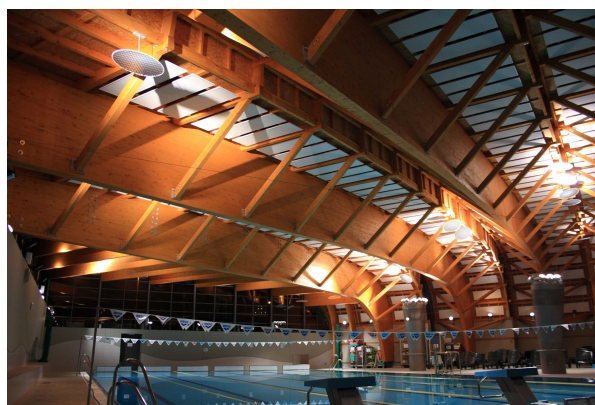


Figure 2 Swimming pool in Brno, 2010, span 35 m

Today, the building industry increasingly use wood or wood-based materials mostly in roofing of smaller objects but more frequent is the use of wood in the construction of large

span structures of complex geometric shapes (straka, 2004). This trend will most likely continue which is proved by the number of structures built in the Czech Republic and especially abroad.

In Fig. 1 is a sample of the roof structure in the tennis hall of Frýdlant nad Ostravicí, made from solid wood and put into operation in 1997 (span 40,4 m). In Fig. 2 is a sample of the roof structure of swimming pool in Brno, made of glued solid beams with span of 35 m, placed in service in 2010 (Pexová, 2009). Usage of new technologies raises the need for the design feedback in the form of monitoring during construction and after commissioning to verify their actual behavior in given conditions, while this information is used to refine the static models and to optimize the material design of new structures of a similar nature. To monitor effectively the actual performance of roof structures the geodetic measuring methods are used (Bureš, 2002 and Bureš, 2004).

Technical regulations for construction and operation of buildings require partially the systematic measurement of displacements and deformations. The influence of environment leads to gradual changes in the mutual spatial relationship of different parts of structures (sinking and creep), which is reflected in measurable distortions of geometric parameters. It is purposeful to measure regularly these deformation phenomena in appropriate intervals (measurement epochs). The following text presents the results of long-term measurement of large span roof of the multi-purpose sports hall in Bílovec monitored since 2001.

## 2 BASIC INFORMATION ABOUT THE MEASURED STRUCTURE

Sporty multi-purpose hall in Bílovec was implemented in 2001. Fig. 3 gives a view of the completed structure inside the hall. Hall ground is rectangular measuring 60 x 30 m. The main structure supporting the roof system is made up from three-hinged arches with a span of 59 m (Fig. 4).



Figure 3 Roof after its completion

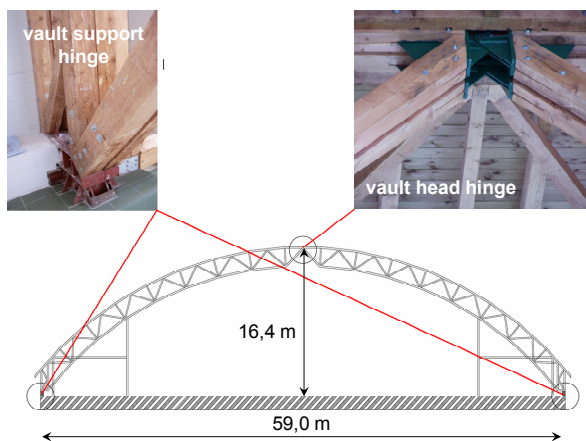


Figure 4 Three-hinged arch

The arches are in the transverse direction stiffened by longitudinal and lateral bracing, and the entire framework creates the spatial carrying system (Bureš, 2004). Bar connections in the joints are designed using thin steel plates inserted in the slots and steel nails (Hradil, 2008). The roof structure supporting is attached to the concrete foundation footings by hinge bearings. Installation of the roof structure was realized with high accuracy (actual radial deviation of the roundness of the structure did not exceed 16 mm) (Bureš, 2004).

After completion of the structure the geometric parameters of the construction are changing gradually due to touch down and creeping of the various components in joints.

Other important factors affecting the deformation are weather conditions, especially the effects of temperature and humidity, and seasonal influences. Due to insolation the roof deck is warming which is reflected by expansion effects. In winter, the hall is from outside exposed to frost and snow load. Inside the temperature is maintained by the air conditioning on  $+15^{\circ}\text{C}$ . The roof structure of the hall is systematically geodetically monitored since its commissioning in 2001. For the period 2001-2013, data are available from 8 epochs of measurement in different seasons.

### 3 MEASURING SYSTEM AND MEASUREMENT TECHNOLOGY

The behavior of the observed roof structure is evaluated on base of measurement results of surveying markers system mounted on the lower bands of arch construction. The entire structure is composed of nine arches, measuring markers are mounted on five of them. Site network consists of 36 surveying markers, their positioning in the section and plan is shown in Fig. 5. The control system consists of 4 surveying marks 9011-9014 set up on the supporting pillars of the structure side walls. Surveying marks are in the shape of 30 mm targets with concentric circles.

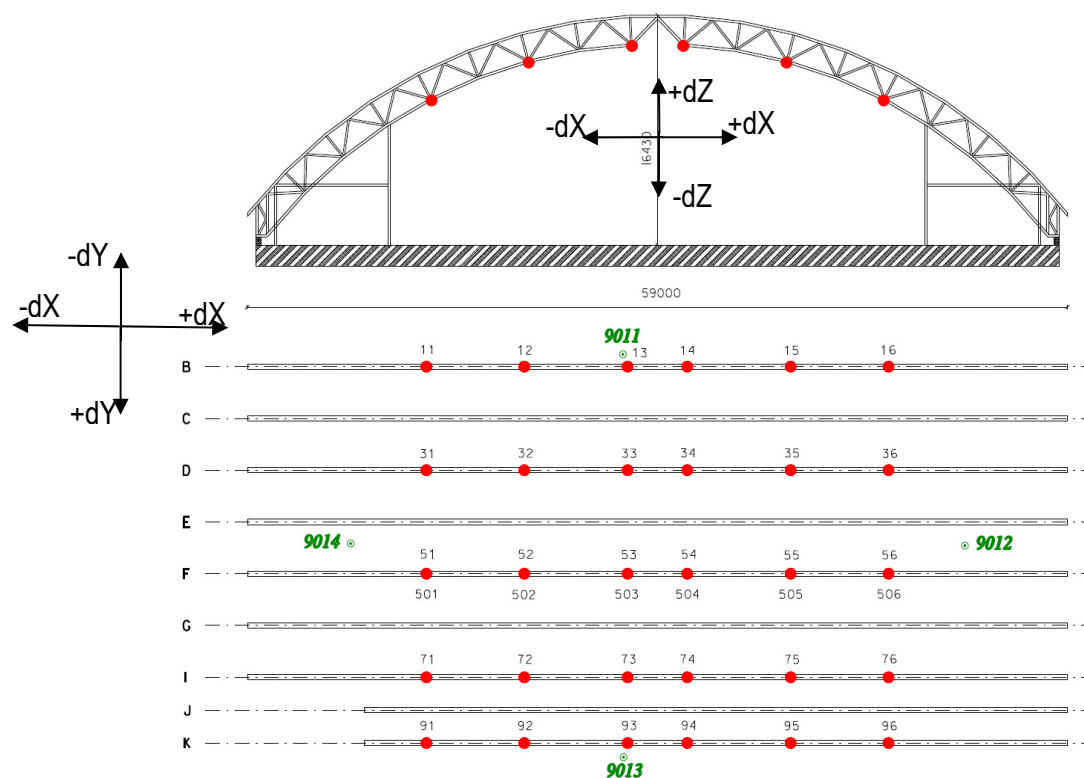


Figure 5 Layout of the construction surveying markers

The measurement technology is based on the method of the spatial intersection of the angles measured by total station with an angular accuracy of 0.5 mgon from four free stations configured as quadrangle points geodetic positions in the transitional form stabilized during surveys by geodetic tripods. During the measurements the values of air temperature, surface temperature structure and relative humidity are recorded by data loggers Comet.

From the data in each stage the spatial coordinates are calculated using least squares adjustment (LSA). Cartesian coordinate system X, Y, Z is oriented in the direction of main axes of the construction (Fig. 5). From the differences of the coordinates in various epochs the

deformations can be evaluated in the longitudinal, transverse and vertical direction. Characteristics of the accuracy of coordinates derived from the LSA can be directly used to calculate the uncertainties in deformations and their interpretation. An analysis of the accuracy of the single measurement epochs, the mean expanded uncertainty for an epoch deformation is  $\Delta\delta = 1.4 \text{ mm}$  ( for  $K = 2$ ,  $P = 0.95$ ,  $\alpha=5\%$ ).

#### 4 RESULTS OF EVOLUTION OF DEFORMATIONS

In Fig. 6 is shown in plan in form of isolines and color hypsometry the state of longitudinal deformation, in Fig. 7 the state of transverse imperfections. In terms of distribution of the longitudinal strain it is evident that half the roof structure is deformed more strongly than the other, due to the structural arrangement of trusses which is different in both halves of the structure.

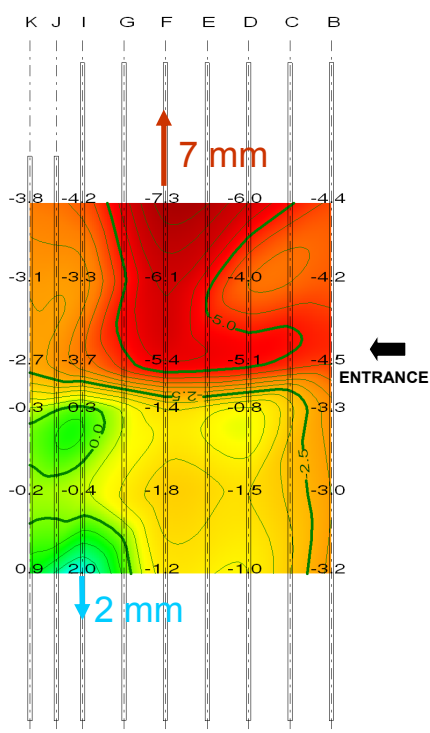


Figure 6 Longitudinal deformation

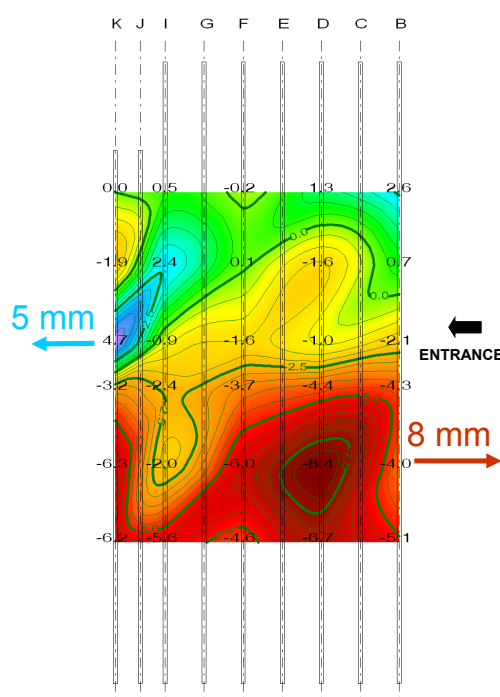


Figure 7 Transverse imperfections

Maximum longitudinal deformations are as high as 7 mm, and maximum values of transverse imperfections are up to 8 mm, while the isolines with support of color hypsometry can help to identify the most-stressed particular structural components joints.

In Fig. 8 the state of vertical deformations of the roof structure after 12 years of its commissioning. In vertical direction of the monitored roof construction the greatest distortions were in the tops of arches, considerably smaller vertical deformations were in arch quarters. Over the years, the hall vertical deformations gradually slightly increased. The values of deformation are strongly influenced by exposure to ambient temperature. In winter there is a vertical downward movement - the deflection of the roof, and in the summer months there is a vertical shift upwards (Kalina, 2010 a Kalina, 2011). The vertical deformations are manifested mostly by decrease amounting to 18 mm at the top of the arch, and shrinking toward the arch  $\frac{1}{4}$ , where are smaller than 5 mm. Deformations are partially compensated by movements in the underlying spherical bearings and in the top hinge. Mechanics of motion of the arch construction is in a section shown in Fig. 9.

Fig. 10 shows the evolution of the vertical deformation at the top of the arc in time given in calendar months from the beginning of the surveying, and the temperature in intermediate epochs of measurement. At higher temperatures in summer there is an uplift in the top of the arc, and vice versa at low temperatures in winter is the top to decrease. In particular, the vertical deformation are strongly influenced by ambient temperature. The effect of temperature shows in the vertical change of about 4 mm over 10°C temperature changes.

Fig. 11 shows the evolution of the vertical deformation at the top of the arc in time given in calendar months from the beginning of the surveying with correcting temperature influence in intermediate epochs of measurement.

It is evident from the development of vertical deformation that during approximately the first 15 months after the commissioning proceeded the gradual fitting together with the creeping yield of the construction joints.

After one or two years the construction has settled, what was demonstrated by permanent vertical deformation at arc top 16,4 mm, and after 10 years of commissioning the vertical deformations have not changed within accuracy limits and therefore the construction is stable.

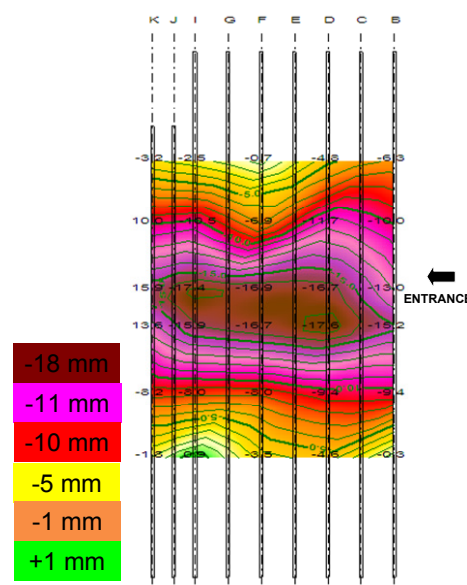


Figure 8 Isolines and hypsometry of vertical deformations

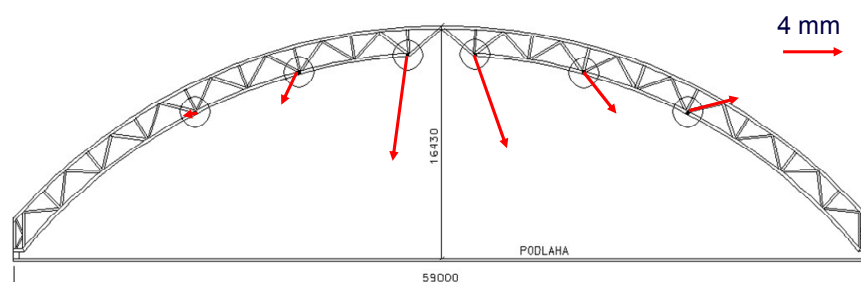


Figure 9 Mechanics of arc movements

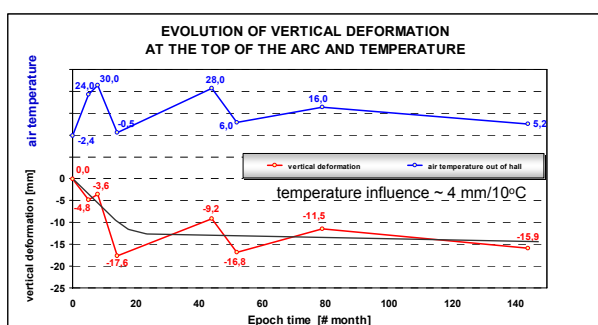


Figure 10 Vertical deformations and temperature

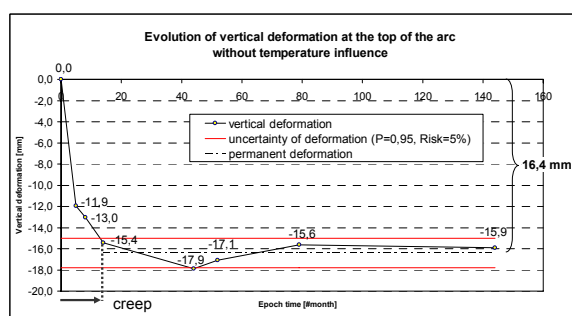


Figure 11 Vertical deformations without temperature influence

## 5 CONCLUSION

The evaluation of results of geodetic measurements roof for the period 2001 to 2013 showed the effectiveness of the use of geodetic methods for monitoring the constructions of

similar type. In compliance with the technology of measurement the changes and deformations greater than 1.5 mm can be reliably detected. Geodetic measurements showed that the actual values of deformations are small and correspond well with the theoretical deformation model in terms of the structure static model. Based on this model, for the static behavior of the structure the critical value in the transverse direction for this structure type of given span is considered 50 mm. In the vertical direction the critical value of deformation is considered 120 mm. At present the vertical deformation components are reaching up to 20 mm. The construction is securely stable. The trends of variations can be assessed at this stage to infer the potentially weak points in construction, where in future we can expect the emergence of possible failures. Measured values of deformations are small and thus deep under the critical construction reliability values. The wooden roof structure during its service life is constantly in the process of aging and drying, and the result is very slow accretion of permanent deformations. The largest share of the seasonal changes in the shape of the structure have the temperature changes of the external environment - the construction is "seasonally breathing". By repeated measurements further informations are obtained on the structure's behavior during its operation. Knowledge learned from the measurements results are used to refine the structure static behavior model, its diagnostics and for designing of new load-bearing timber structures of similar type. Theoretical models have to be constantly verified by physical measurement, and the surveying methods for this purpose are very effective.

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