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# AUTONOMOUS MONITORING SYSTEM OF GIRDERS' DEFLECTION IN LARGE HALL BUILDINGS

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**Summary**

Systematic climate change can may bring about abnormally heavy snowfall in wintertime, which means that roofs in exposition, municipal, industrial halls and sports arenas may be excessively and destructively loaded [Kłosek and Prószyński 2008]. Ten years have passed since the greatest construction disasters in the EU countries happened, when a whole series of grave accidents took place due to snow and ice overload of roofs in large halls. These events emphasize the need to introduce an early warning system to prevent that kind of risk. A geodetic system that monitors selected parts of structure can warn about a danger related to accumulation of masses of snow and about a degree of deflections in a building structure.
The article presents the newest original measuring Multi-Disto Monitoring System (MDMS) for collecting information on current state of geometric deformation of steel or ferroconcrete girders supporting large hall roofs.

**Keywords**

large hall roofs • snow load • girder • defection • autonomus measurement system

## 1. Tragic outcome of catastrophes caused by the collapse of large hall roofs

Winter between 2005 and 2006 in Europe was marked by heavy snowfall reaching even 65 cm a day, in places like Ostholstein, Münsterland, Bavaria, Poprad, Kvetnica, Riga and many others. The resulting overload of roof constructions in large scale establishments caused three great catastrophes in just 53 days [Bryś et al. 2013]. On 2 January 2006 in Bad Reichenhall, Bavaria, a wooden roof construction of the ice rink collapsed. 15 young sportsmen lost their life in the accident and 34 were seriously injured or maimed. On 29 January in Chorzów a roof of Katowice International Fair trade hall collapsed under the load of heavy snow during the National Exhibition of Carrier Pigeons, killing 65 people and leaving 120 others with life-long injuries. In that accident the load of ice and snow reached $1.44\ kN \cdot m^{-2} = 147\ kg \cdot m^{-2}$ [Mendera 2007]. On 23 February of the same year in Moscow a city Basmanny market hall roof fell down. 66 people died as a result and many others were severely injured.

These are just the most spectacular disasters during that untypical, snowy winter. Many other roofs of larger industrial halls in Europe collapsed at that time. Within the European Union alone 160 people were killed in these accidents and more than 160 would struggle with life-long injuries. Due to the series of tragedies a DIN 1055 standard has been modified in the EU countries, taking into account diverse precipitation and wind loads in critical climate zones of the EU. A layer of ice 10 cm thick can weigh up to 0.88 kN · $m^{-2}$, while 1 kN · $m^{-2}$ is equivalent to around 100 kg · $m^{-2}$ of fresh snow. 70 cm cover of lingering, wet snow can weigh up to 2.75 kN · $m^{-2}$, or 280 kg · $m^{-2}$.

On 11 and 12 January 1997 in Montague, New York, in 24 hours the snowfall amounted to 1.956 m. And during the snow storm in 1981, in Mount Shasta Ski Park, western coast of the US, the snowfall within a few hours reached 4.8 m! In that case a layer of wet snow could weigh more than 1900 kg · $m^{-2}$.

Approximately the specific gravity of snow [Alpicon] according to PN = 80-B-02010-A21 with regard to load of snow is:

- fresh snow – 1 kN · $m^{-2}$,
- settled snow – 2 kN · $m^{-2}$,
- wet snow – 4 kN · $m^{-2}$,
- old snow lingering for a few months – 4.4–3.5 kN · $m^{-2}$,
- frozen snow – 6.0–7.0 kN · $m^{-2}$,
- ice – 9.0 kN · $m^{-2}$.

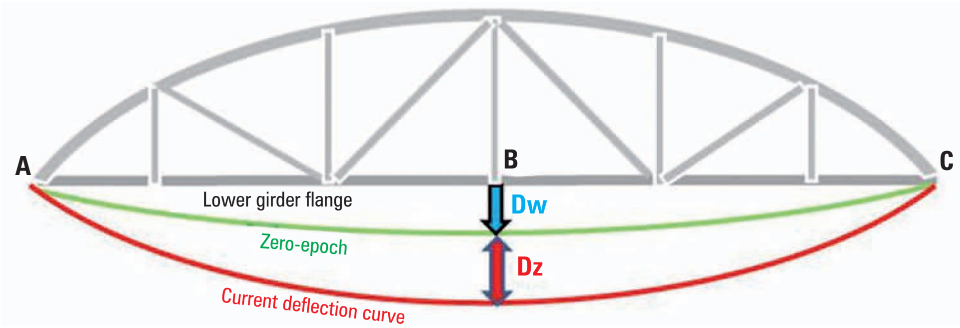
The above data show that specific gravity of snow is not a constant value, because it changes with time of its lingering. Shape and slope of roofs also play a significant role in this respect, as well as location of a building, including its proximity to water reservoirs (lakes, seas, gulfs) and its height above sea level. In any of the collapsed buildings there was no systematic geodetic monitoring which would certainly allow to prevent the catastrophic events. For geodetic monitoring and data collection are essential measures for assessment of geometric condition and safety of roof construction, especially in large halls. The constructive elements of industrial and public service halls are subject to permanent, accidental and seasonal deformations, expressed in changes of distance of control points between subsequent measurements, mainly of roofs. Elastic deflections (reversible) and plastic (permanent) and absolute dislocations are caused by rheological, geotechnical, geophysical, meteorological factors, by current movements of the earth's crust, impact of mining, dead load or/and anomalies in snowfall and icing during exceptional weather conditions. Destruction of building component is proceeded by a phase of elastic strain and a building construction damage is proceeded by increasing dislocation of the building's components: deflection or deviation [Witakowski 2008].

Geodetic calculation of scope of changes, geometrical identification and distinguishing between permanent and temporary deformations play a significant role when geodesists and industrial construction specialists in geotechnics, statics of buildings and resistance of materials are drawing up a report and carrying out an evaluation of geometrical condition of buildings. Of special importance in evaluation of buildings' safety are deformations, vertical dislocations and deflections of steel and reinforced concrete girders in large hall roof constructions.

## 2. Construction and functioning of autonomous measuring Multi-Disto Monitoring System (MDMS)

Numerous construction disasters in winter of 2005/2006 proved conclusively that installing automatic, remote monitoring system in buildings is essential [Wójtowicz 2009]. The modern, dynamic development of electronics, information technology and telematics has inspired the authors to construct a simple and reliable measuring system combining electronic DISTO laser distance meter with the system's control room.

Infallible evaluation criterion of structural durability and safety of building structures are the results of space-time deformations and deflections of steel and reinforced concrete girders in large halls roofs. Thanks to latest information techniques and technologies, communications satellite and wireless communications – radiocommunications, GSM, Internet, WiFi, Bluetooth and automated geodesic tools of latest generation – it is possible to wholly automatize the measuring and telemetric process of transmitting information about geometric deformations of particular construction components at risk of being affected by changeable temperature, load of snow, ice, wind, etc.




Source: authors' study

**Fig. 1.** Deflection values of deformed lower girder flange, noted in the middle of a steel or ferroconcrete girder ($D_W$ – deflection value under constant dead load of a hall's roof construction, $D_Z$ – increase of deflection value under variable load of ice or snow layer. Control points A, B, C are situated symmetrically on a girder and are stabilized by magnetic plates glued by an epoxy adhesive to lower surface of the girder flange

Data in the MDMS (Multi-Disto Monitoring System) can be transmitted by a wireless local area network (WLAN) up to 500 m or by a radio modem network up to several dozen meters. Vertical distances $L_A$, $L_B$ and $L_C$ to the floor level or to any other immovable element (Figure 1), measured at any established intervals (even every few seconds), will be used for calculating current increase of a girder deflection value ($D_z$) set by a simple formula:

$$D_z = 0.5\ (L_A + L_C) - L_B \tag{1}$$

A single measuring set used in a MDMS in large halls and arenas consists of three distance meters Leica DISTO Pro (or equivalent) connected online by a brand-name standard interface RS-232C connectors with a Satel radio modem (or similar), depending on distance to a control computer (Figure 2). Radio modems can function as transceivers and they do not rely on services and infrastructure of network operators.


Photo by authors

**Fig. 2.** Buckled reinforced concrete girder (white) with a measuring and transmitting equipment: 1 – DISTO Pro, 2 – radio modem, 3 – cable and connector RS-232C, 4 – curve of momentary deflection of a lower girder flange

DISTO distance meters are attached in a vertical position to a lower flange of a girder by means of magnetic plates joined by an epoxy adhesive. Standard deviation of increase of a girder deflection value – calculated in comparative laboratory measurements tests by means of a precision level and a DISTO distance meter – was 0.7 mm in case of girders situated at a height of 6 m.

## 3. Data transmission system with radio modems and WLAN

The innovative character of the presented monitoring system consists in a remote coordinating of control measurements from many rangefinder units, in data processing in real-time and signalling when critical values are exceeded. Radio modem systems can be configured in a variety of ways, which allows adopting autonomous solutions that meet the requirements related to monitoring a construction component of buildings (Figure 3). All radio modems and distance meters are adjusted to transmitting a signal both ways even over a distance of several dozen meters [Woźniak 2007].

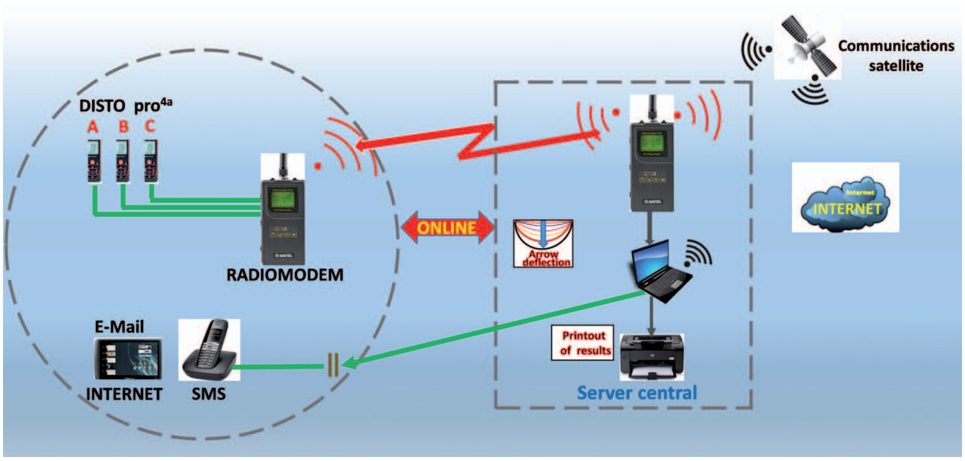



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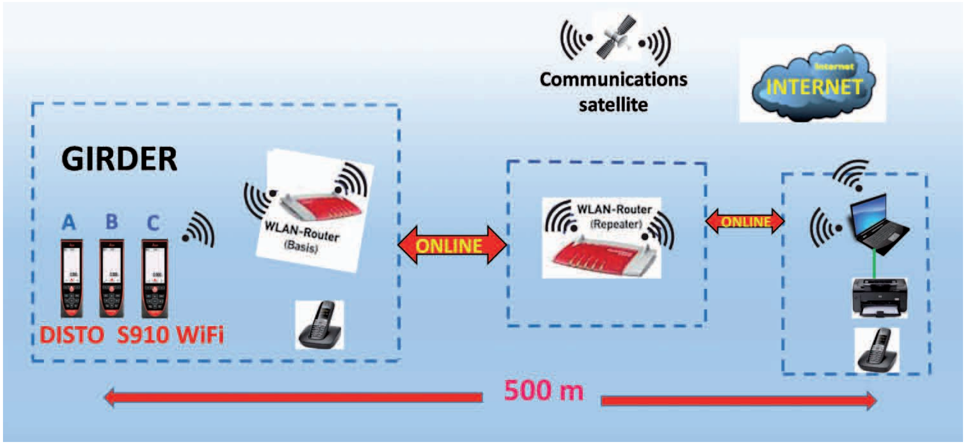
**Fig. 3.** Architecture of bilateral communication between a DISTO distance meter and a computer/computational control room and transmission of alarm messages




Source: authors' study

**Fig. 4.** Architecture of wireless monitoring of girders, with the use of WLAN (WiFi)

The transmission distance depends mainly on the strength of a radio modem and current weather conditions, topography and radio waves propagation (rain and snowfall, time of day, air humidity, fog, wooded hills). In Poland a free data transmission bandwidth falls within the range 868–870 MHz according to the regulation of the Minister of Infrastructure and guidelines of the European Union. Since a radio modem can work as a repeater station, distances between end units can be increased at will. Devices for radio data transmission can work both in very simple as well as extensive systems of transmission of binary signals. Such systems, based on the latest generation sensors, are generally used in monitoring industry, communication, environment, hydro engineering facilities, electric traction, water and sewage networks, heating substations, water level at reservoirs, etc. Devices like that are made for example by SATEL.

DISTO S910 of the latest generation with a WiFi module automatically creates WLAN, which transmits measurement data to an end receivers (PC, tablet, smartphone, etc.) for further analytical and graphical study (Excel, Word, NotePad). DISTO is automatically connected with an external computer by an application DISTO Transfer (DISTO Apps & Compatible Software: Setup DISTO5-506, version 5 or newer).

The particular advantage of the system lies in fast data transmission of measurement data online and sending alarm messages in case set limits for girder deflection are exceeded: N – normal, A – alert, E – emergency, D – disastrous. These limits are established every time by designers or experts in building structure and/or construction supervisors, depending on a type of a building structure and intensity as well as character of critical loads (snowfalls etc.) or when periodic measurements are carried out [Der nächste Winter... 2012, DIN 1055-5 2007].

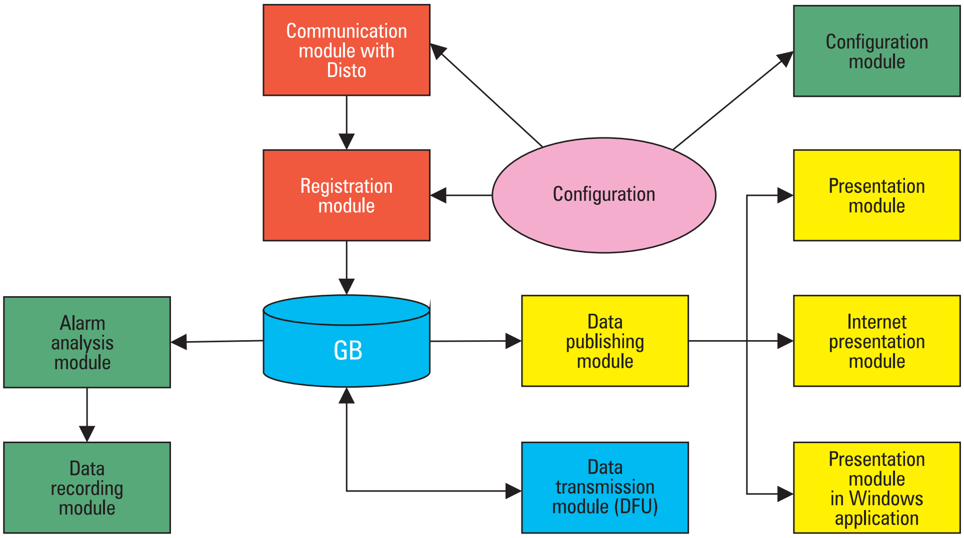
## 4. Functional idea of GeoSurvey system

The presented MDMS that uses autonomous GeoSurvey software developed by M. Woźniak and R. Rybus [Woźniak 2007] allows to control the process of measurement, collects observational data, visualises their values on any configured graphical chart, processes continuously observational data, visualises and archives results of any chosen interval of geodetic survey. The system analyses the results and initiates a reaction of sending an alarm note by email or SMS to registered receivers/decision-makers (Figures 3–5).

GeoSurvey system operates as entirely autonomous. Thanks to using standard formats for saving numerical, vector, raster data the system works with other analytical and graphical tools. Among its basic functions are continuous measurements together with a possibility of ongoing presentation of results in flexibly defined graphs. One of the functional programmes of the software is a module designed to control from a station the process of repeated measurements, according to established measurement schedule (of object's monitoring). It is possible to control all observations or their functions according to a defined algorithm of monitoring a building. The software, thanks to its multithreaded character, allows for simultaneous operation of many elements of the measurement and for processing data in many of its tools at the same time.

The presented system can be applied without further modifications to carry out other surveying tasks related to measurement of rooms and deflection of construction elements. These tasks include:

- defining the geometry of construction elements' deformation caused by seasonal or/and daily changes,
- measuring deflections of load-bearing structures of bridges and overpasses during static loads,
- observation of elastic deflections of overhead cranes,
- monitoring of deformations – especially in the form of epoch measurements – of buildings and technical facilities in mining areas.




Source: [Woźniak 2007]

**Fig. 5.** Flowchart of modules in the GeoSurvey software with a Multi-Disto Monitoring System structure

It should be stressed that systematically improved laser reflectorless distance meters in the coming years would be used more and more extensively in surveying engineering and in servicing and control of industrial construction.

## 5. Conclusions

- Defining progressive, elastic deformations of girders in halls' roofs under the load of heavy and prolonged snowfall has a particular significance in the estimation of safety of roof construction and in early warning about a possible damage or construction disaster [Bryś et al. 2013].
- Global climate change can lead to exceptionally heavy snowfall in wintertime together with simultaneous forming of thick layers of ice, which can excessively load

large scale roofs of industrial, municipal, exposition halls, sport arenas, hangars, multi-storey garages, etc.

- The presented autonomous measuring Multi-Disto Monitoring System operates under control of GeoSurvey software and it allows for acquisition and transmission of data, their ongoing processing, calculation of deflection parameters, graphic visualisation of results and their archiving with freely set intervals (measurement epochs) of control observation.
- Reflectorless laser distance meters, connected by radio modem to wireless global telecommunication systems are an element of constant control of high risk buildings. Local networks have numerous advantages: they work independently of any network operators, can connect large number of devices, simplicity of radio network diagnostics, two-way communication allowing precise control of online devices.
- Low purchase and exploitation costs are yet another advantage of the presented system. But the financial aspect, though important, is less significant if we take into account that only in the EU countries there are tens of thousands large scale halls in operation, with rooftops of more than 2500 $m^2$, posing potential risk to their users.
- During laboratory tests high precision and repeatability of results with standard deviation below ±0.7 mm have been confirmed. Accuracy of the results meets the requirements imposed by designers and experts assessing stability of building structures. Since in wintertime meteorological conditions inside halls are stable, the results of control measurements and assessment parameters of changes in structure deformations are hardly distorted by atmospheric conditions.
- Accuracy and reliability of geodetic measurements and low costs of set of devices in the presented Multi-Disto Monitoring System underpin its use in planned and intervention monitoring, when checking the performance of large halls construction under abnormal loads.

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