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LONG-TERM MONITORING OF MECHANICAL DAMAGE ON THE HISTORICAL STRUCTURES

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Abstract: *Important information for the risk assessment of some damages on the historical structures represents data of failure development. Cracks in the load-bearing walls are one of the observed failures. This article focuses on remarkable method of damage measurement, their long-term monitoring and devices used for measurement.*

Keywords: ***Long-term monitoring, linear variable differential transformer, crack on the wall***

1. Introduction

Long-term monitoring of crack movement in load-bearing walls and arches is one of the methods for a diagnosis of historical structures. Decision about reconstruction or structural adjustment of walls, ceilings or even bases is based on the results from the monitoring of the damage development. Changes that have to be monitored are very slow and relatively small. So that the long-term crack monitoring and data recording is necessary for determination of the crack development.

The automatic measurement by the linear variable differential transformer has emerged as the most suitable method. High resolution, accuracy and measurement stability are the most important advantages of the method. The sensors requirements such as operation difficulty and price come from the fact that the measurement often goes on while the historical structure is in common use, e.g. sightseeing tours, cultural actions or restoration works take place there. There are several examples of testing and evaluation of the measurement that have been made on the historical structures in the Czech Republic in last years in the paper.

2. Analysis of requirements and choice of the method

A used device has to be able to measure the displacement in units of micrometers, because the change of the crack dimension in the walls is generally tens or hundreds of micrometers for a period of several months. Sensor has to be mechanically connectable to the measured structure in an easy way, so that the historical building is not damaged. It has to survive adverse effects of local climate such as wind or rain and also the presence of dust or vibration has to be taken into account. The measurements itself and data recording has to be in a motion unattended for a long time; potential power cuts can't stop them. Data have to be saved continuously throughout the monitoring of the structure without risk of loss. The monitoring device is placed on the historical building for a long time (up to several years), often in a hardly accessible location. In spite of that its price can't be extremely high. The chosen method can also allow measuring the temperature in an area of the crack, temperature outside and relative humidity of the air altogether because all the information is relevant while evaluating the damage development.

3. Reasons for use of LVDT

The linear variable differential transformers (LVDT) have certain significant features and benefits, most of which derive from their fundamental physical principles of operation or from the materials and techniques used in its construction. Following characteristics are decisive for choosing of the sensor for our objective.

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Fig. 1: *LVDT sensors*

Friction-Free Operation

Usually there is no mechanical contact between the LVDT's core and coil assembly therefore no rubbing, dragging or the other source of friction is there. This feature is particularly useful in displacement measurements and high resolution dimensional gaging systems.

Infinite Resolution

Since LVDT operates on electromagnetic coupling principles in a friction-free structure, it can measure infinitesimally small changes in the core position. This infinite resolution capability is limited only by the noise in LVDT signal conditioner and the output display's resolution. These same factors also give LVDT its outstanding repeatability.

Unlimited Mechanical Life

Because there is normally no contact between the LVDT's core and coil structure, no parts can rub together or wear out. This means that LVDT features unlimited mechanical life. This factor is especially important in high reliability in operation on places without longstanding supervision as in the case of monitoring of the historical objects.

Single Axis Sensitivity

LVDT responds to motion of the core along the coil's axis, but is generally insensitive to cross-axis motion of the core or to its radial position. Thus, LVDT can usually operate without adverse effect in applications involving misaligned or floating moving members and in cases where the core doesn't travel in a precisely straight line.

Environmentally Robust

The materials and construction techniques used in assembling LVDT result in a rugged, durable sensor that is robust to a variety of environmental conditions. Bonding of winding is followed by epoxy encapsulation into the case, resulting in superior moisture and humidity resistance, as well as the capability to take substantial shock loads and high vibration levels in all axes. And the internal high-permeability magnetic shield minimizes the effects of external AC fields.

Both the case and the core are made of corrosion resistant metals, with the case also acting as a supplemental magnetic shield. For those applications where the sensor must withstand exposure to flammable or corrosive vapours and liquids or operate in pressurized fluid, the case and coil assembly can be hermetically sealed using a variety of welding processes. Ordinary LVDTs can operate over a very wide temperature range, but if required, they can be produced to operate down to cryogenic temperatures.

Null Point Repeatability

The location of LVDT's intrinsic null point is extremely stable and repeatable, even over its very wide operating temperature range. This makes LVDT performing well as a null position sensor in closed-loop control systems and in high performance servo-balance instruments.

Absolute Output

LVDT is an absolute output device, as opposed to an incremental output device. This means that in the event of loss of power, the position data sent from LVDT will not be lost. When the measuring system is restarted, LVDT's output value will be the same as it was before the power failure occurred.

4. Working principle

The linear variable differential transformer (LVDT) is an excellent device for converting mechanical displacement into an electrical signal. It can be employed in a large variety of transducers, including strain, displacement, pressure, acceleration, force and temperature. In **Fig. 2** is shown a schematic illustration of a linear variable differential transformer employed as a displacement sensor suitable for our demand of a long time monitoring.

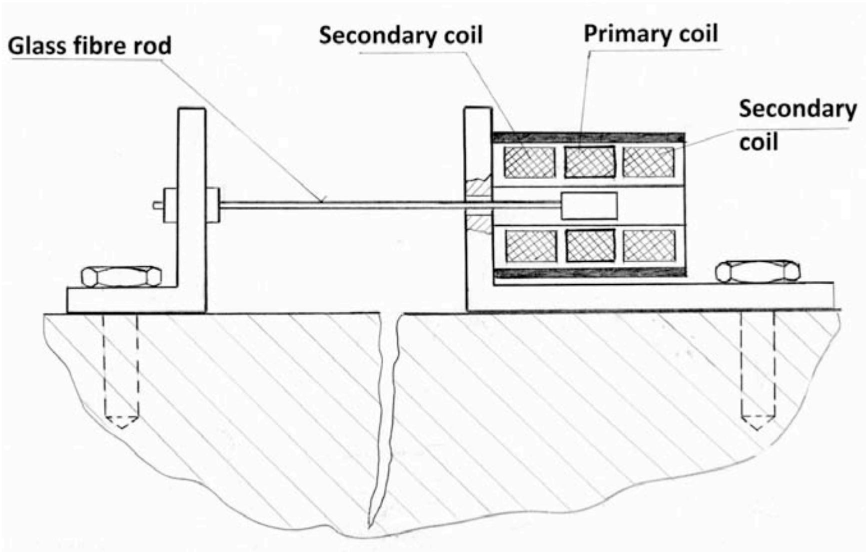

Fig. 2: Schematic illustration of linear variable differential transformer employed as a displacement sensor for monitoring of crack

In the figure we can see crack of the wall, whose movement we want to measure. The body of LVDT with coils is closely fixed to wall on one hand of the crack and glass fibre rod with ferrite core on the other hand. A linear differential transformer has three coils. Every position of the core in coils gives different electrical output. As the core moves within the coils, it varies the mutual inductance between the primary and each secondary winding, with one secondary becoming more tightly coupled to the primary and the other secondary becoming more loosely coupled. The two secondary coils are wired in series opposition, and consequently the output voltage E_{out} is the difference between the voltages developed in each secondary (that is, $E_{out}=E_1-E_2$, see **Fig. 3**). In a symmetrically constructed transformer a null output should occur when the core is at the center point between the two secondary coils.

The output low level voltage E0 is in special electronic integrated circuit (demodulator) transferred to high level DC voltage EDC. The output voltage EDC of the demodulator for typical linear variable differential transformer as a function of core position is given in **Fig. 4**.

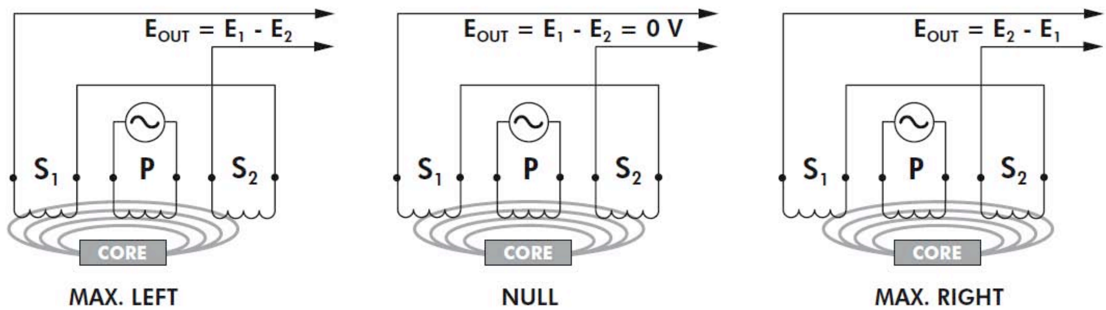

Fig. 3: Schematic diagram of the linear variable differential transformer circuit

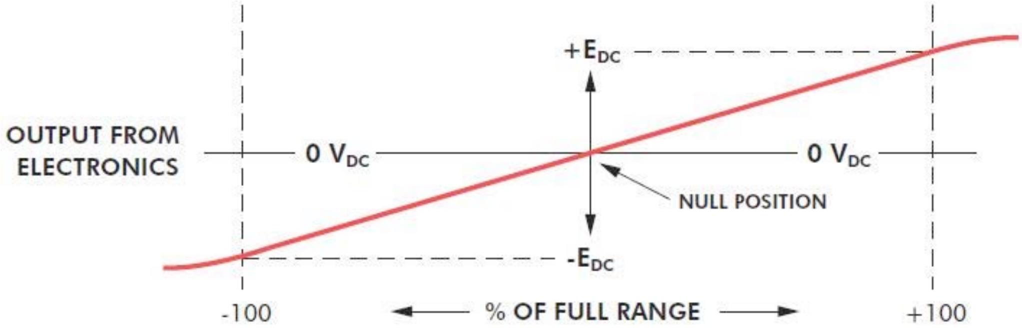

Fig. 4: DC output from electronics as a function of core position

5. Data acquisition system

Most of the data loggers available on the market fulfilling the requirements of the long-therm monitoring exceeds with its price level of 100 000 CZK. It would be uneconomic to use them for capturing date at hourly intervals, because they are designed for demanding measurements in laboratories or in situ. Therefore the DAM logger of price about 30 000 CZK was chosen. It was developed as a “low-cost” option of data logger for requirements of building geology workers. It is used for many years in situ for monitoring various physical parameters (temperature, relative humidity, pressure, displacements, etc.). It can be equipped with up to 6 modules for measuring those variables and it measures in 18-bit resolution. Resulting price of the system is determined by the number of channels required and therefore by the number of used modules.

This system was in recent years retrofitted with other optional auxiliary units, such as remote connection to computer via GSM module sending simple SMS messages to selected phone numbers, or charging system using solar cells. SMS messages send to mobile phones are used for reporting emergency situation on the monitored object (exceeding the limits of specified displacement or speed of increase of measuring variable, etc.). We can build sophisticated monitoring system that will withstand even in severe conditions.

6. Practical applications of LVDT in monitoring

The above mentioned system was already used in many projects related to reconstruction and preservation of historical monuments.

Examples of use:

- monitoring of cracks in Telč Castle during works on the sewer drain in the neighbourhood of the castle
- monitoring of Holy Trinity Column – Olomouc during its reconstruction
- monitoring of cracks in the walls of the pilgrimage church in Stříbrná Skalice during its reconstruction
- monitoring of cracks in the walls of the Pragues New Town Hall
- monitoring of failures in the vaults in the Franciscan monastery in Kadaň
- monitoring of the movement of the roof balustrade corner pillars of the southern façade of the National Museum in Prague
- study loading test of the arch above ground floor in Hvězda Summer Pavilion
- monitoring and warning system on the rock tower in Dolní Žleb u Děčína close to the railway line Děčín – Dresden
- monitoring in Hřensko

Two last examples do not belong among historical structures, but they are natural rocks whose erosion threatens objects in their neighborhood. Currently the monitoring of cracks takes place at two historical monuments, St. Jacob’s Church in Kutná Hora and Viceroy's Summerhouse in Stromovka Park in Prague.

7. Examples of monitoring results

7.1 Monitoring of failures in the vaults in the Franciscan monastery in Kadaň

Monitoring of the structure was going on from 2006 to 2008. The vaults in monastery chapter hall has been disrupted by a net of cracks, see **Fig. 5.** The positions of LVDT sensors 1, 2 and 3 are also marked in the picture. Diagrams were made using measured data and the movements of the cracks have been evaluated for the entire measurement, see **Fig. 6**, **Fig. 7** and **Fig. 8** where the crack opening and closing are shown. The temperature in the LVDT positions was measured, see **Fig. 9**.

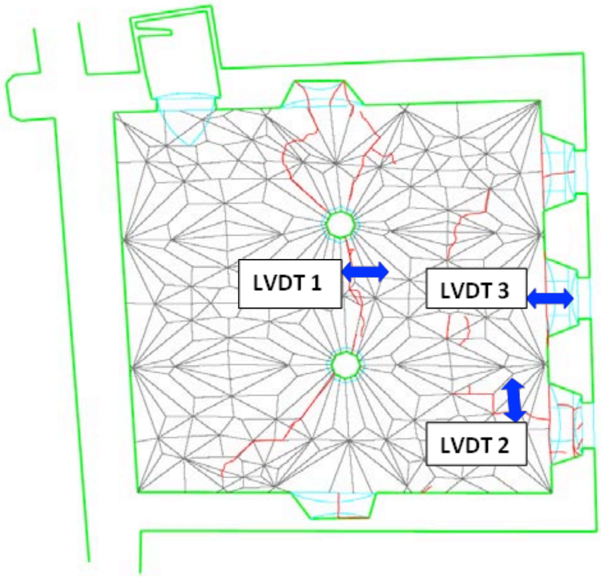

Fig. 5: Crack net and positioning of the sensors in the vaults

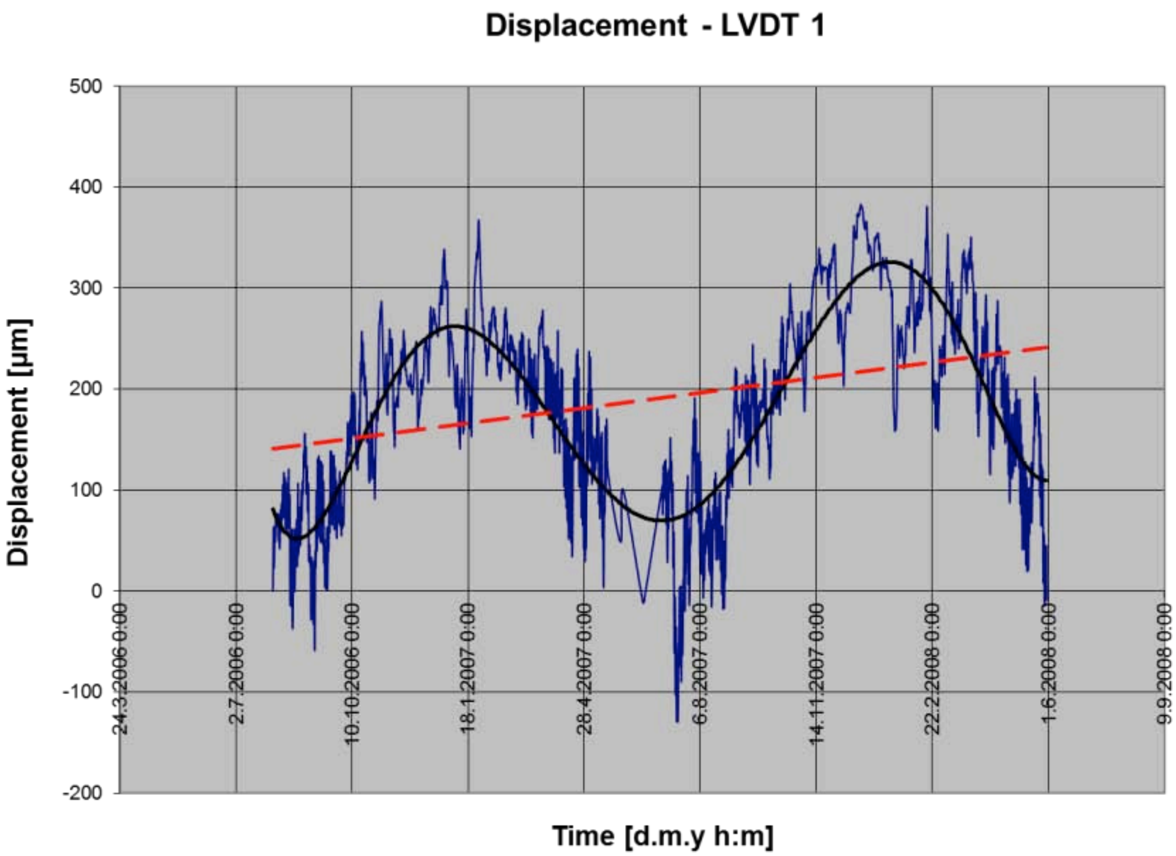

Fig. 6: Movements of the (LVDT 1)

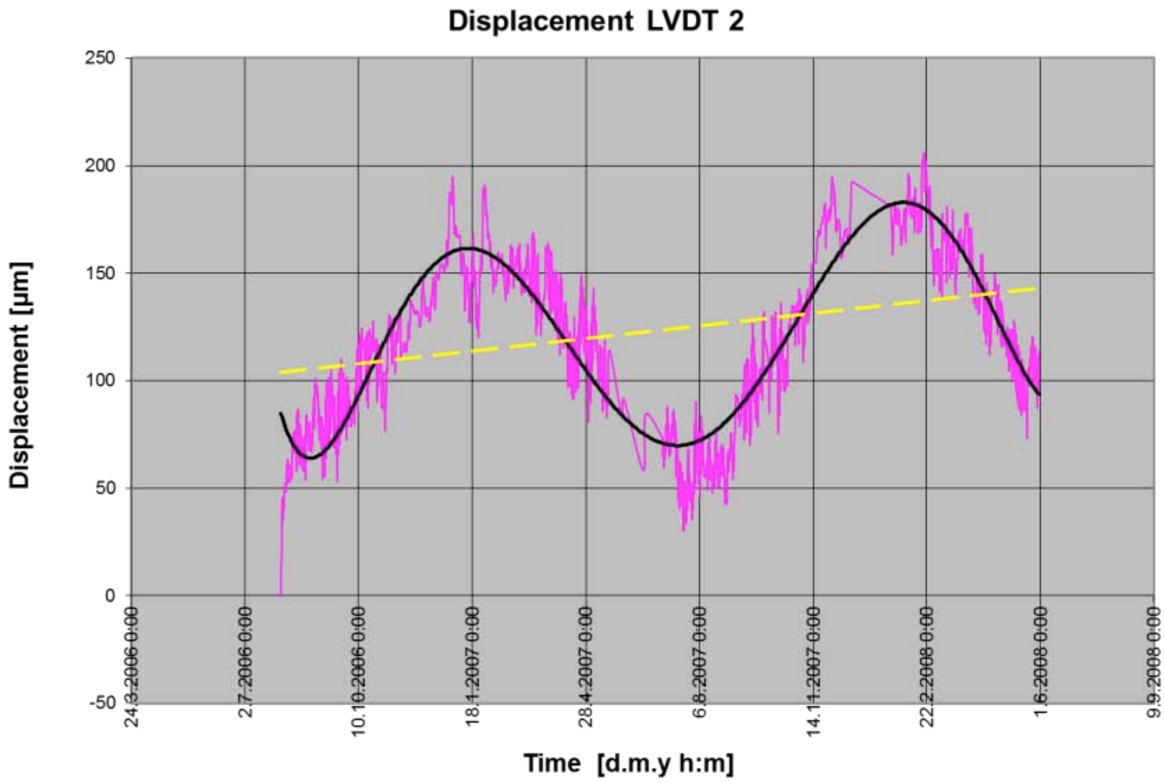

Fig. 7: Movements of crack (LVDT 2)

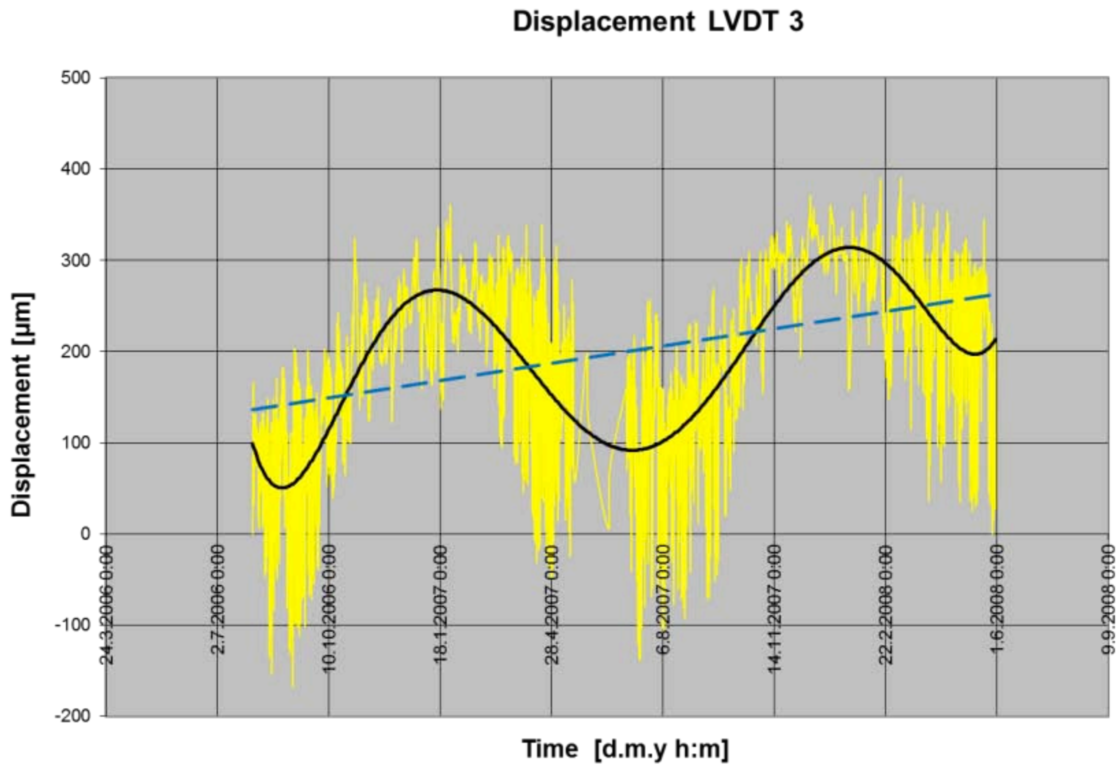

Fig. 8: Movements of crack (LVDT 3)

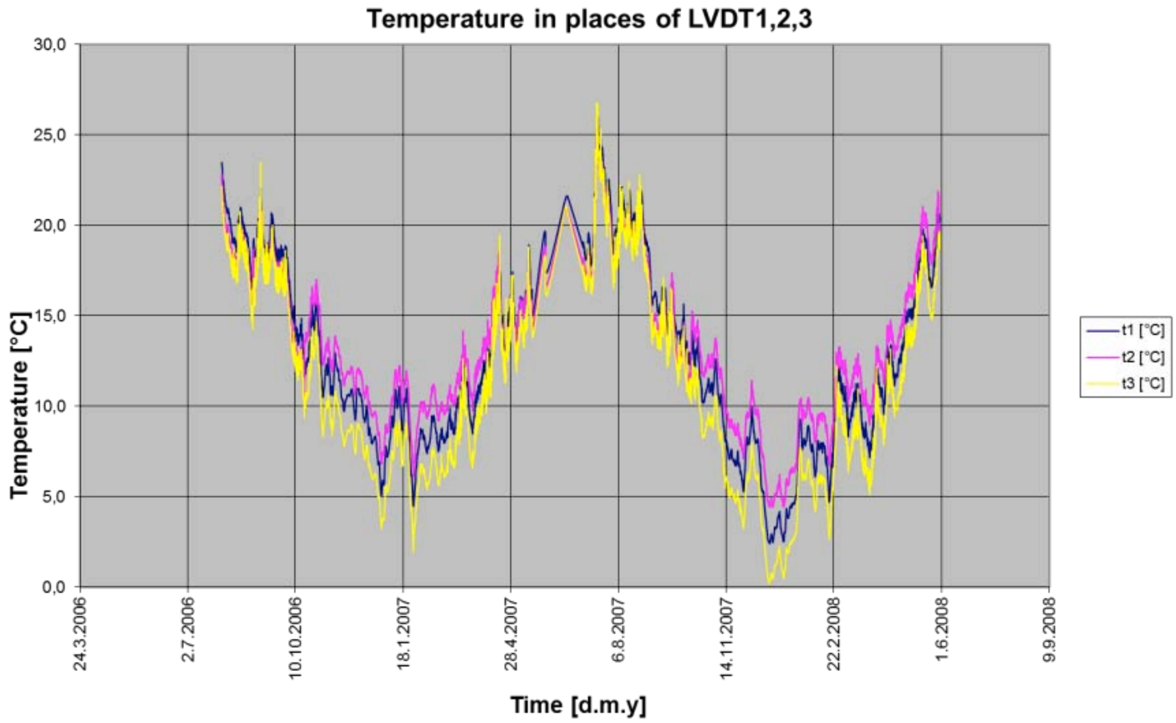

Fig. 9: Temperature in the positions of LVDT

7.2 Monitoring of cracks in the south wall of St. Jacob's Church in Kutná Hora

Monitoring in the structure is going on nowadays simultaneously with the reconstruction of the roof that started in 2011. There are large cracks in the south wall of the object, therefore monitoring of their development during the reconstruction has been suggested. Two positions for LVDT sensors at inner side of the wall, where the cables do not hinder works, were chosen in the first phase. As the next step the other place for sensors will be chosen. The sensor set up is shown in the **Fig. 10**.

The significant crack's movement was observed from the record of LVDT 2 when the roof was removed and the reconstruction started, see **Fig. 11** below. However, there is no obvious change on the record of LVDT 1 from this time. The following development of the cracks will be monitored to control condition of the wall.

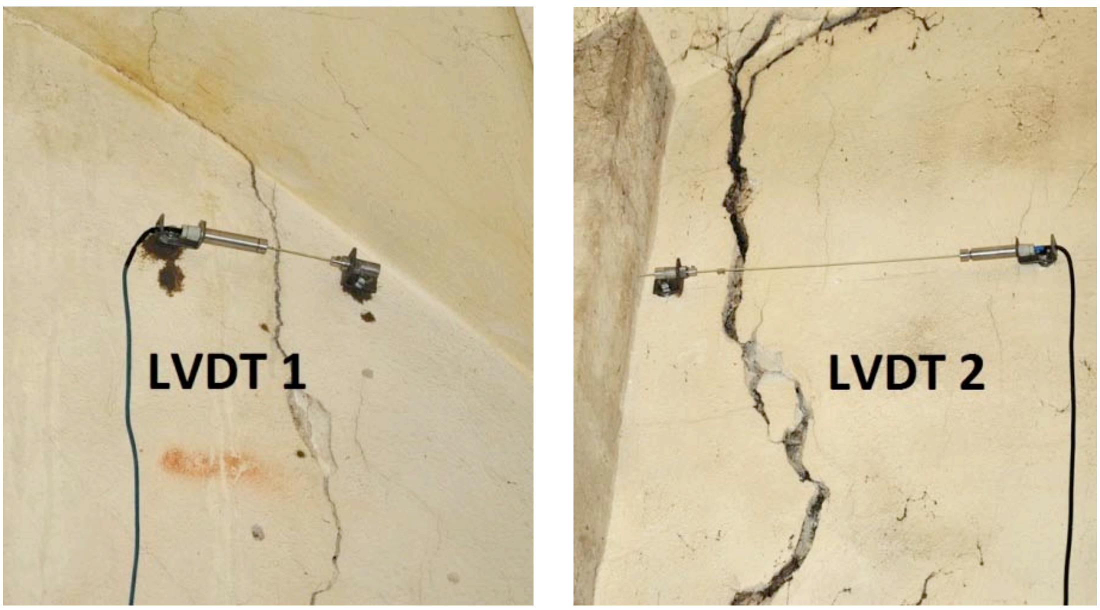

Fig. 10: LVDT set up, a) an inner side of the wall, b)an exterior side of the load-bearing wall

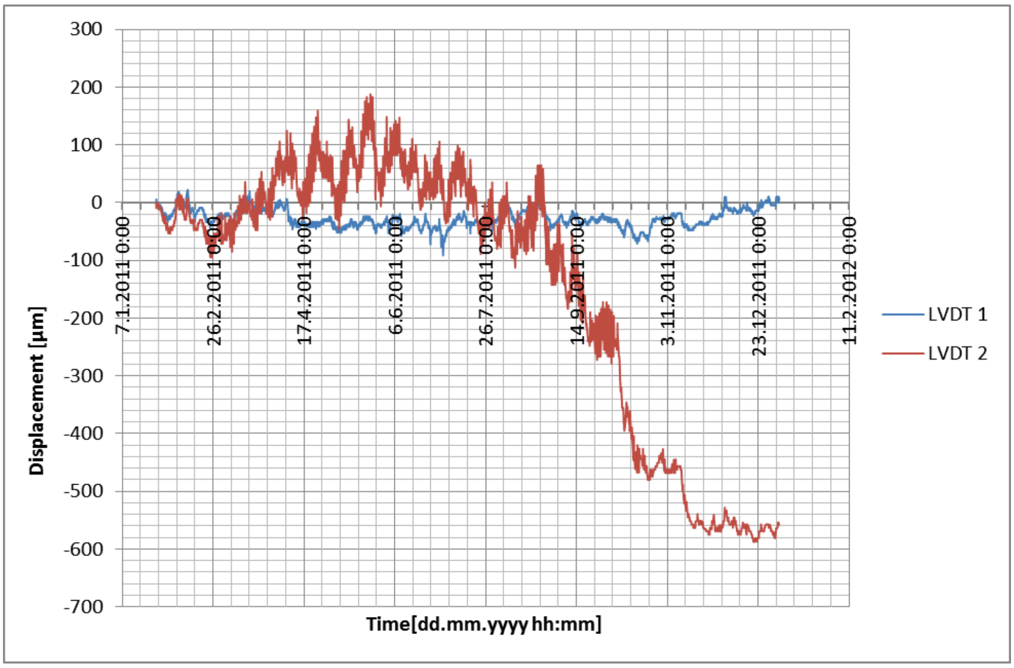

Fig. 11: Movements of cracks in St. Jacob's Church

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