# Monitoring of the Cracks on Bell Tower of ST. Anastasia Cathedral in Zadar Croatia

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# MONITORING OF CRACKS ON THE BELL TOWER OF ST. ANASTASIA CATHEDRAL IN ZADAR CROATIA

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## ABSTRACT

The bell tower of the cathedral of St. Anastasia in Zadar is a major landmark and an important cultural object which has been a subject of strong restoration and preservation efforts for many years. In order to determine the long term stability of the existing cracks, a monitoring system consisting of 8 fiber optic displacement sensors was installed in October 2012. This paper presents the previous structural assessment work as well as the results of the crack displacement measurements. Special attention is given to the analysis of correlation of crack displacements to the temperature and possible other outer disturbances.

**KEYWORDS :** *stone masonry structures, structural health monitoring, cracks, fiber optic sensors, time series analysis*

## INTRODUCTION

The bell tower of the cathedral in Zadar was built in two phases. The ground floor and first floor (height of 16.6 m) were built in the 15th century (Figure 1); while the rest (height 38.3 m - in total 54.9 m) was upgraded in 1885 and was designed by the English architect Thomas Graham Jackson (Figure 7). The bell tower was built with carved stones of limestone, the older part from the local quarries, while the newer part mainly from the quarry Vrnik near island of Korčula.

Five years after the construction completed, cracks appeared in the 15th century parts of the bell tower. Croatian conservator Ćiril Iveković analyzed the causes of damage and made restoration project in year 1900 [1], but since no trace of remediation exists, it is logical to assume that repairs were not performed.

During the 1991 the restoration works were carried out on the bell tower. Damaged floors and stairways were replaced; walls were grouted, inside faces of the walls were plastered and damage on the pyramid was repaired. Also the joints on external face of the walls were repointed and the damaged parts on the NW facade were replaced. The outer faces of the ground and first floor walls were not repaired at the time due to the specific defects. The primary intention was to first carry out preliminary tests to determine the cause of the damage and afterwards an optimal rehabilitation could be proposed. However, the war interrupted all activities on the bell tower.

Most damage is seen on the southeast façade of the bell tower, even more: there are almost no undamaged cut stone blocks on the ground floor and first floor (Figure 3). The longest continuous crack stretches from the ground floor to the cornice on the second floor. On the NW façade there are few cracks that extend from the ground floor to the cornice on the first floor and there are particularly prominent cracks along the eastern corner of the bell tower where some ashlars with broken off cants can be found (Figure 5). On the SW façade there are three cracks and the longer one stretches from the ground to the first floor (Figure 2). On the SE façade there is a crack that starts in the upper half of the ground floor and extends to the first floor.

Figure 1 : Aquarelle

Figure 6: Bell tower

Figure 2:  Southwest façade

Figure 3: Southeast façade

Figure 4: Trial pit

Figure 5: Eastern corner

Figure 7: Core

## STRUCTURAL ASSESMENT OF THE BELL TOWER STRUCTURE

In 2010 soil mechanic and geophysical investigations were done: excavation of trial pit 2.8 m depth along the SW wall of the bell tower (Figure 4), exploratory drilling to the 20m depth east of the bell tower, two MASW profile were taken and four profiles were recorded with Ground Penetrating Radar (total length of approximately 70 m), six profiles on the ground and first floor of the bell tower were recorded using GPR (total length of approximately 39 m). Soil mechanic and geophysical exploration activities established that the bell tower was founded on the limestone rock and damages on the bell tower were not caused by differential settlements or inadequate foundations. Georadar profiles of walls indicate a homogeneous and uniform masonry with no cavities.

The core was extracted from the foundation part of the bell tower (Figure 7). Drill hole to depth 2.5m was inspected by endoscopy. Endoscopic examination and examination of the extracted core revealed that the masonry of the bell tower in the foundation part is uniform, built of ashlar blocks in lime mortar. Tests of compressive and tensile (Brazilian test) strength of stone were performed on specimens made from cores[1][3][1][4].

Assessment of the natural oscillation frequencies was also performed, based on microtremors excitation recorded on the ground level, on the footing expansion and on bell tower floors [1][5][1][7].

In 2011 a detailed architectural survey with orthophoto of façades of the bell tower with marked damage in the mantle was done. The results of this survey served as a basis for a 3D FEM model of the structure which was employed for the static and dynamic analyses which took into account also the non-linear behavior of materials. Results of measurements of dynamic properties of the structure were compared to the results of 3D FEM model modal analysis and used to validate the 3D FEM model [1][8].

The basic purpose of the proposed monitoring campaign was to determine the following: (i) to estimate the stability of the cracks i.e. whether there is a trend of increasing crack opening and (ii) to establish the degree of correlation between the crack opening and external conditions such as temperature changes, wind speed and wind direction [1][6].

In September 2012 thus eight fiber optic displacement sensors were installed, two on characteristic cracks on each façade. At the same time the weather station was installed to monitor changes in weather conditions, temperature, humidity, air pressure, rainfall, wind speed and direction. The weather station is situated 170m northwest of the bell tower.

## MEASUREMENT SYSTEM

The crack displacement is measured via optical deformation sensors SOFO standard by SMARTEC SA [2,10]. Eight fiber optic displacement sensors were mounted at locations across the cracks at two elevations on each facade. Base length of all SOFO sensors is 500mm. The sensors measure the displacement between two metal anchors by measuring the elongation of optical fiber spanned between the anchors. The measurements of elongation are absolute and are performed using autonomous reading unit. The reading unit consists of optical multiplexer and the measurement part, which, by physical displacing a small movable mirror which reflects the incident laser light, determines the length difference between active and unstrained optical fiber. The accuracy of measurements is 1μm. The measurements are insensitive to temperature variations due to the temperature compensation achieved through the comparison with the unstrained fiber installed along the active fiber. The measurement principle is highly robust compared to standard measurement principles involving measurement of electrical quantities which are more prone to drift and to outer disturbances like thunderstorms and power failures.

The measurement system consists of SOFO reading unit connected via RS232 to the computer running SOFO SDB software and GPRS router, which enables remote control of the measurement campaign. To avoid power failures the system is equipped with UPS. An example of the installation of the SOFO sensor is shown in Figure 8. The sensor is secured to two standard aluminum L-brackets which are anchored to the stone using metal anchors. Each bracket is anchored with two steel anchors ϕ8mm.

The readings were taken continuously at the interval of 10minutes. Since reading of a single sensor takes approximately 10-12s, the readout of sensors is successive and is done in 80-100seconds.

Sensor locations are indicated in Figure 9 and Figure 10.

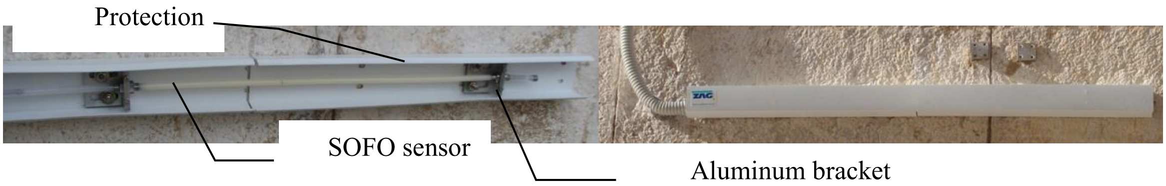
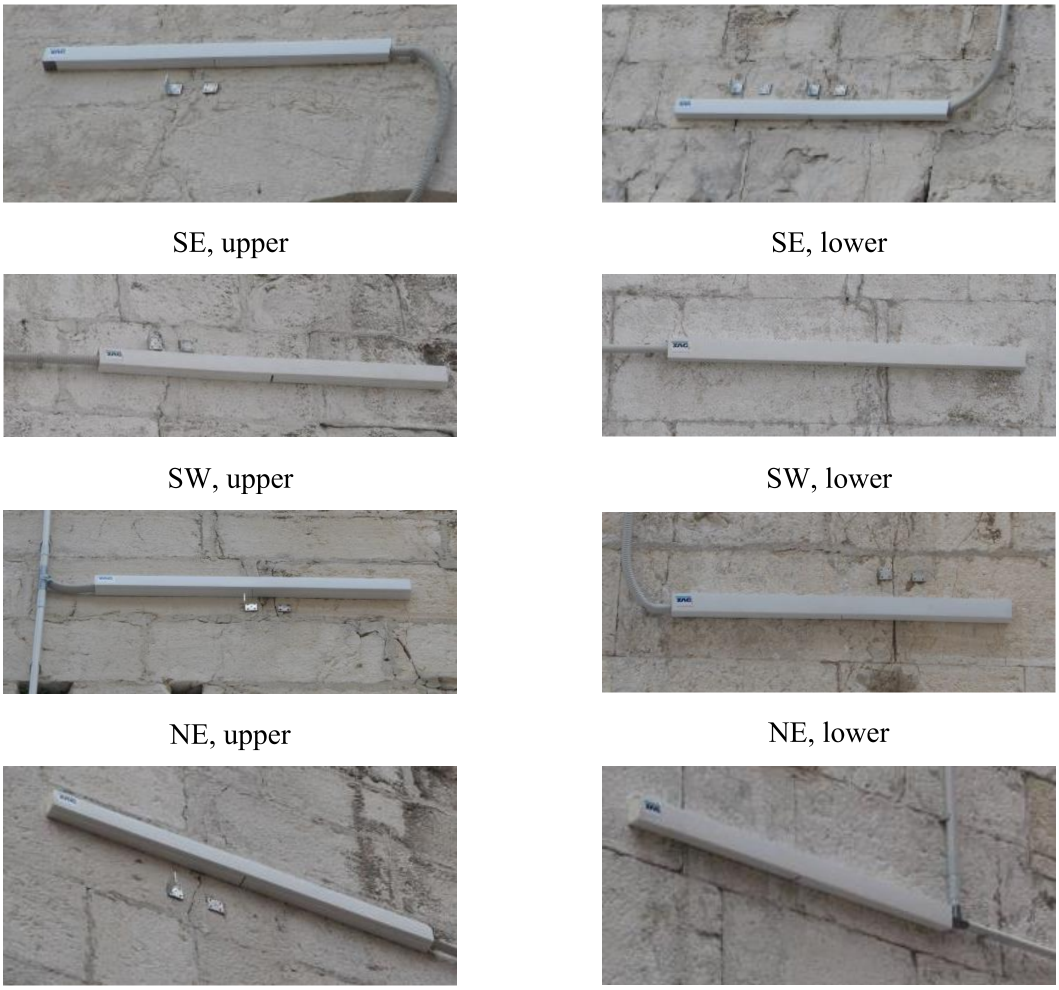



Figure 8: Example of standard SOFO sensor installation


Figure 9: Map of cracks and indicated sensor locations



SE, upper | SE, lower

SW, upper | SW, lower

NE, upper | NE, lower

NW, upper | NW, lower

Figure 10: Sensor designations and micro locations

**RESULTS OF CRACK DISPLACEMENT MONITORING**

The time variation of the displacements of all the sensors is shown in Figure 11 for the period of the monitoring from October 2012 to the end of February 2014. The time history of single sensors is shown in separate diagrams.

The crack displacements are first compared against temperature variation. The crack displacements are in accordance with the long term temperature variation. By filtering the original signal we can focus the daily variations and on seasonal variations separately. The air temperature can thus be written as the sum of seasonal and daily variation: $T=T_s+T_d$ and in the same manner the cracks displacement d can be decomposed into seasonal and daily variation: $d=d_s+d_{d.}$

The time analysis shows that the seasonal variation of crack displacements $d_s$ are proportional to the temperature and have a lag of 11.6days relative to the seasonal temperature variation. The amplitude of seasonal variation which is computed as $\Delta d_s=(d_{s,max}-d_{s,min})/2$ and is shown in Table 1. Comparison of $d_s$ for all sensor locations is shown in Figure 13.

Noticeable difference in crack displacement variation can be observed between north facing sides as opposed to the south facing ones. No abrupt changes of crack displacement are noticeable through the whole period of monitoring indicating there were no major disturbances present which would damage the structure permanently.

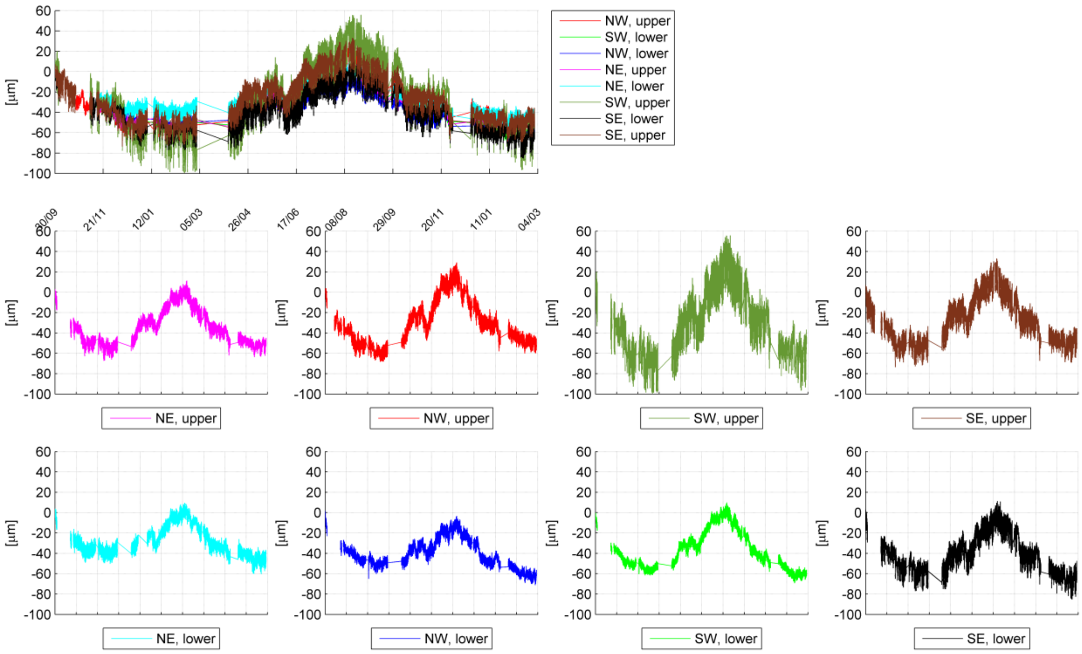



Figure 11: Measurements of crack displacements

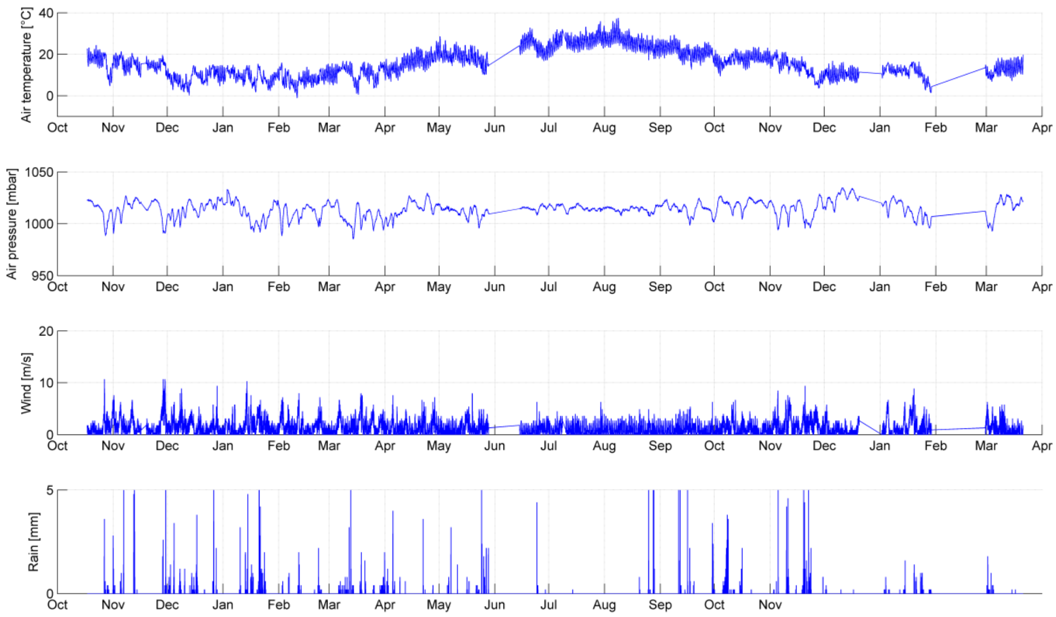



Figure 12: Weather data

Table 1: Amplitudes of crack displacements

| | **NW, upper** | **NW, lower** | **NE, upper** | **NE, lower** | **SW, upper** | **SW, lower** | **SE, upper** | **SE, lower** |
|---|---|---|---|---|---|---|---|---|
| **$\Delta d_s$ [μm]** | 40 | 29 | 29 | 26 | 54 | 33 | 37 | 34 |
| **$\alpha_d$ [μm/K]** | 1.6 | 1.6 | 1.1 | 1.1 | 3.7 | 0.9 | 3.2 | 3.0 |

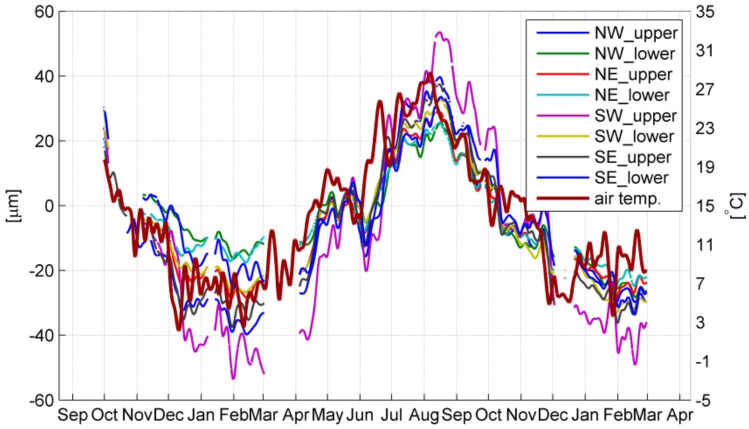



Figure 13: Seasonal variation of crack displacements

The daily variation of crack displacements $d_d$ is proportional to daily temperature variation $T_d$, but with a negative sign, meaning that the cracks are opening with the temperature decrease and vice-versa. Due to the finite dimension of the sensors, the measured crack displacement is a sum of the effect of temperature expansion of the wall as well as the crack opening itself.

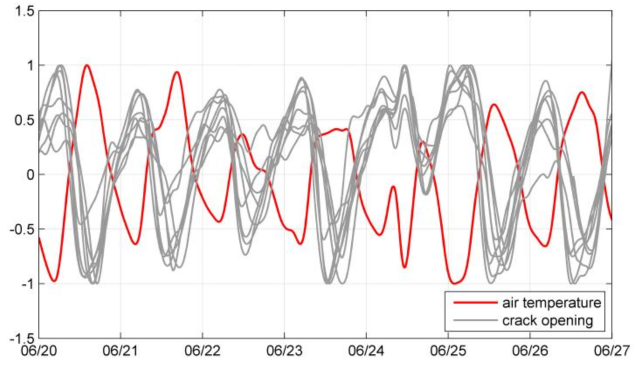



Figure 14: Normalized daily variations of temperature and crack displacements

The phenomena can be explained by observing the temperature distribution through the depth of the walls. While the part of the material close to the surface of the wall closely follows the temperature variation of the outside air temperature, the temperature of the inner parts responds with a substantial lag, which is a consequence of a large thermal mass of the wall. The temperature increase of the inner part causes the overall expansion of the wall while the temperature increase in the surface layer causes the closing of the crack. The measured crack displacement is thus proportional to the temperature difference between the surface and inner parts of the wall.

The time lag between crack displacements $d_d$ and daily temperature variation $T_d$ is approximately 40-60min, depending on the sensor location. Figure 14 depicts the comparison of normalized daily variations of air temperature to the normalized crack opening on all sensor locations. Since surface temperature of the wall was not measured, an approximation of surface temperature $T_{ds}$ was computed by integrating the differential equation $dT_{ds}/dt=\kappa(T_d-T_{ds})$, where the coefficient $\kappa=12.3$ was determined to match the mean measured time lag of crack displacement versus the air temperature T. The initial condition was set approximately to the air temperature 40min before the initial time of the integration.

Table 1 lists the mean value of the ratio of daily crack displacement amplitude to the amplitude of daily surface temperature variation $T_{ds}$ denoted by $\alpha_d$ for the observed period. The ratio $\alpha_d$ is not only directly proportional to the thermal expansion of the wall (≈5μm/K) but reflects also the inner structure of individual cracks. Thus the evolution of the ratio $\alpha_d$ can be used as the indication of possible changes in the crack inner structure.

The effect of wind on crack displacement is estimated to be less than 0.1μm/(m/s), thus the influence of wind cannot be observed directly.

**ACKNOWLEDGMENTS**

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