Application of Nondestructive Methods as Indicators of Damages on Historical Monuments (On Example of St. Lawrence Cathedral in Trogir)

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1. Introduction

In the original shape Cathedral of St. Lawrence in Trogir dates at the 13th century A.D. In the 15th century chapels St. John and St. Jerolimus were added. The cathedral is a cultural heritage monument protected by UNESCO.

As it was decided that the construction needs a major repair, the works were preceded by instrumental monitoring of the most obvious fissures notices on the walls and pillars. Monitoring was organized and conducted by regional office of the Croatian ministry of culture in Split. Positions of the monitoring devices are shown Fig. 1.

At the beginning an observations were recorded daily, but as it was found out that this was too frequent, this frequency was reduced. Initially, eleven sensors were used.

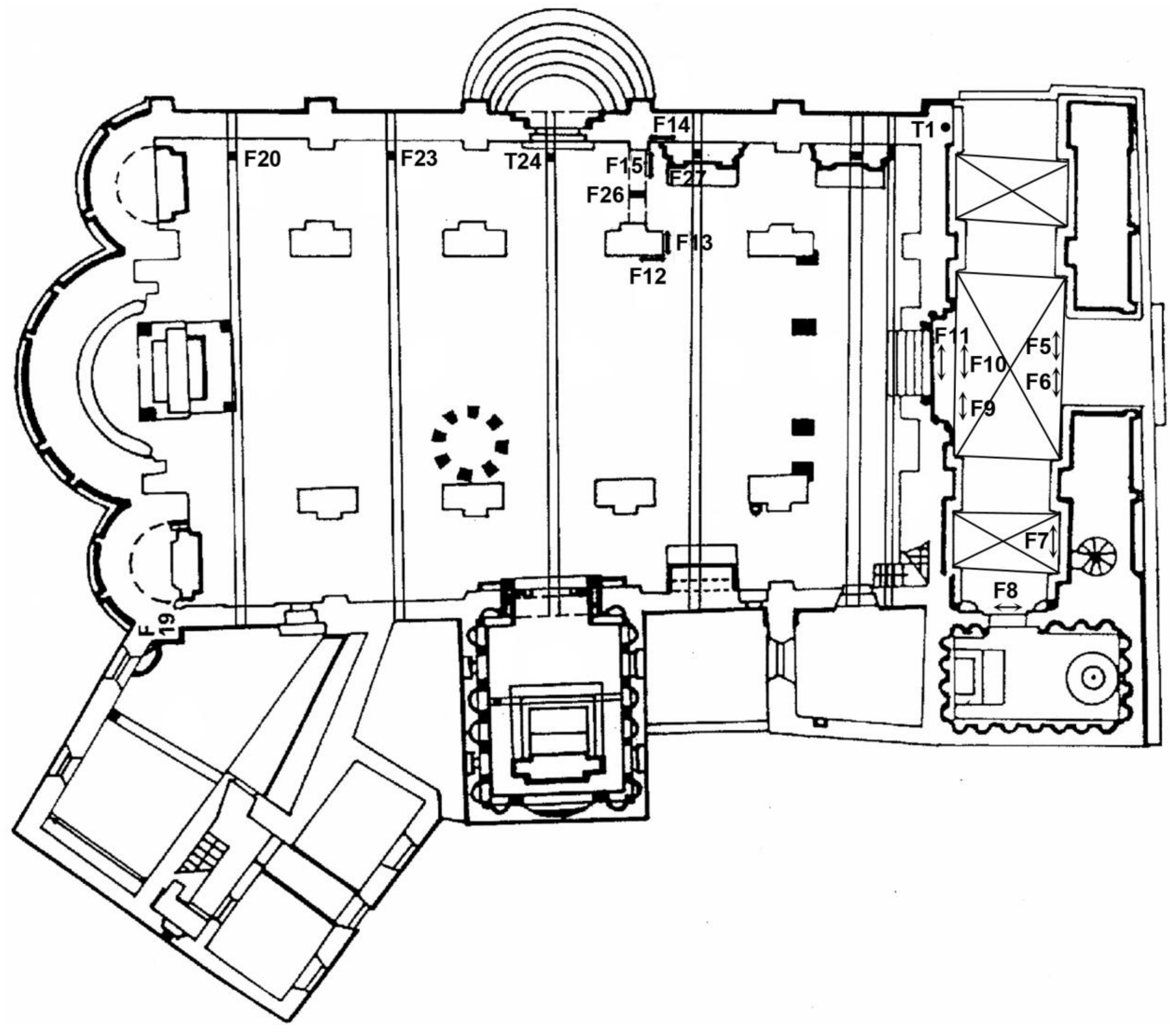

Figure 1. Locations of monitoring devices

2. Data Analysis

For the purpose of data collecting about the construction behaviour, following data were measured and recorded:

1. air temperature
2. air humidity
3. fissure displacement
4. stress changes in some construction elements
5. inclination of bell tower
6. ground water level

In this paper term fissure is used for the cracks in construction induced with stresses. All measurements were carried out with the non destructive methods. The aim of this paper is to present data of measured fissures displacements correlated with the air temperature changes.

Observations of data were run in three periods, first from 11. Mart 1997. to 09. February 1999. (altogether 727 days), second between 01. January 2002. and 03. January 2003., and third period between 27. January 2003. and 01. February 2004. Without interruption caused with an insufficient money resource, data from 8 years of continuous measuring should be available. Unfortunately in the meantime between the described monitoring periods, because some reconstruction measures has been carried out, on some monitoring positions measuring devices has been removed and restored again later. Consequences of these actions, for example, are different statistical correlations between temperature and displacements for the each period on the same monitoring point. Authors were not able to explain this effect, but it is obvious that method of the monitoring device installation have an important influence.

On the figures 2. and 3. measured data of displacements and temperature from all monitoring points are displayed. Positions of all monitoring points are shown on the figure 1., presenting a horizontal cross section of the cathedral.

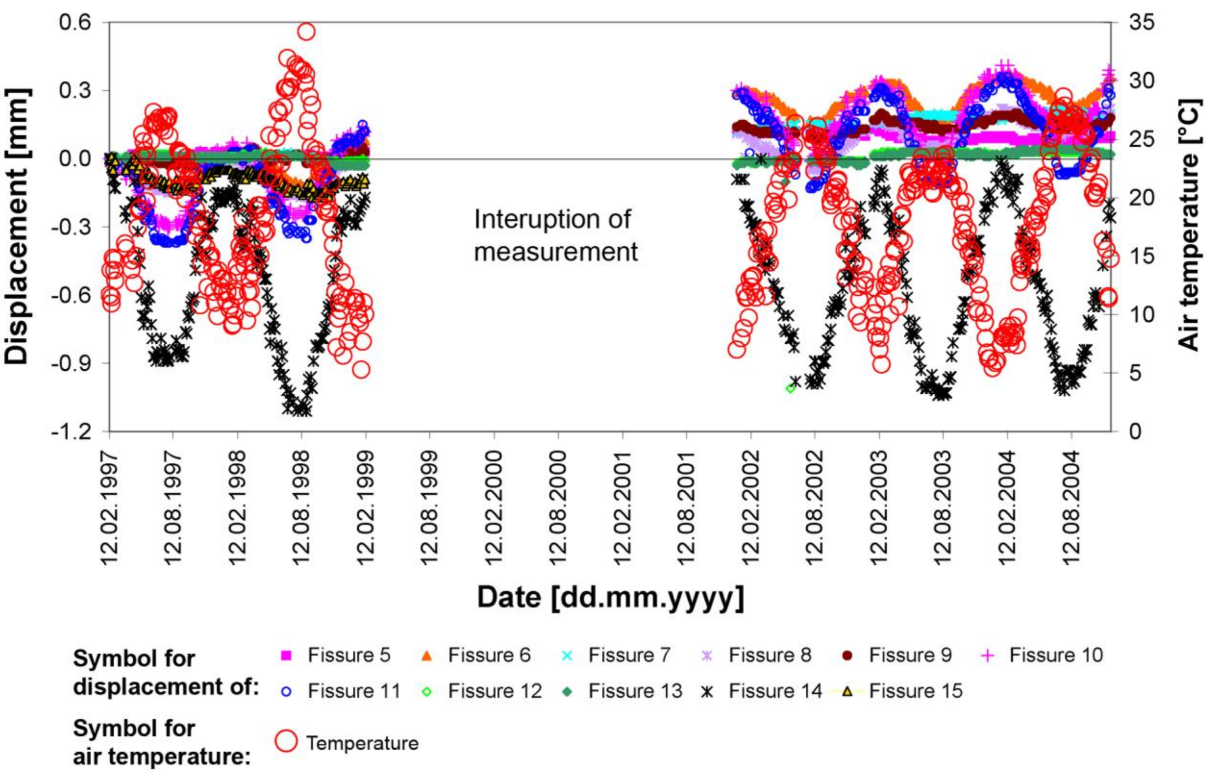

Figure 2. Fissures displacements in time, on monitoring points P5-P15, with air temperature (red circle)

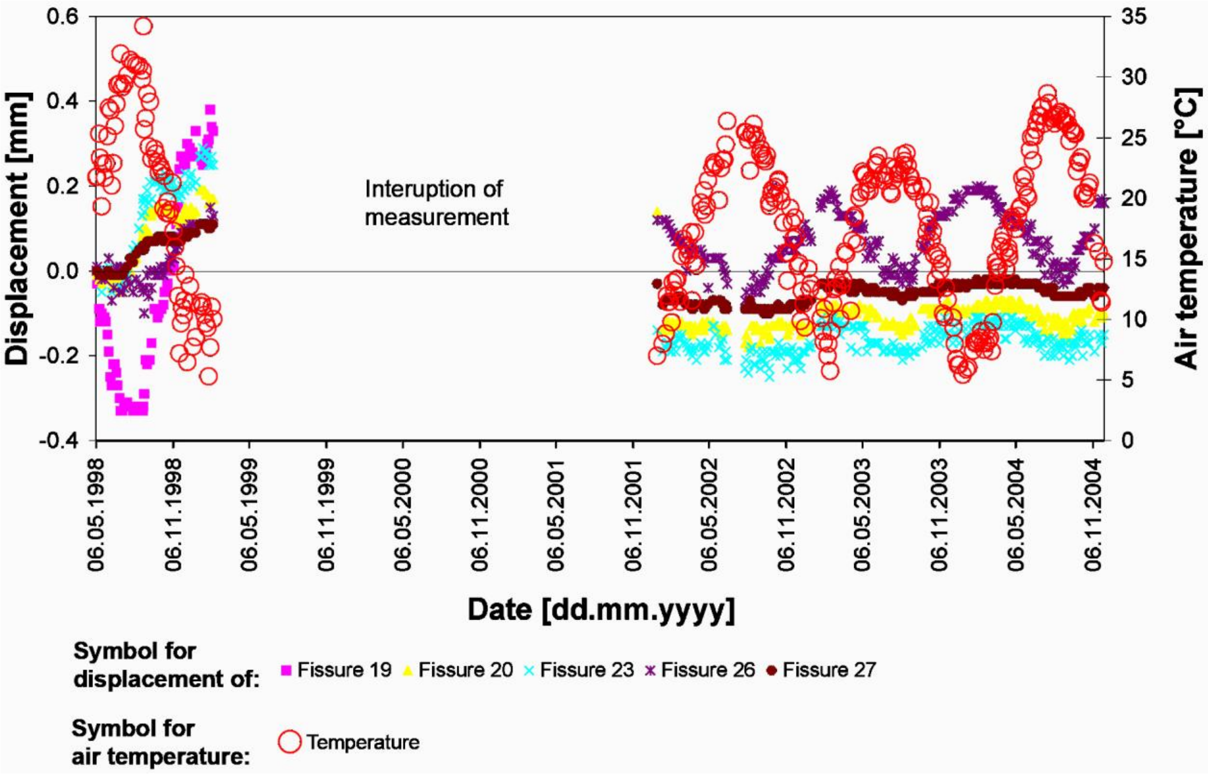

Figure 3. Fissures displacements in time, on monitoring points P19-P27, with air temperature (red circle)

As it can be seen from figures 2. and 3., oscillation of temperature is in accordance with annual periodical behaviour, as it is expected. Fissures displacements have the different order of magnitude on different monitoring points. The biggest range of displacement have fissure on the monitoring position number P14.

Table 1. Example of basic statistical data analyse for monitoring point P6

statistical characteristics	monitoring period		
	1997 - 1999	2003 - 2004	1997 - 2004
mean	-0.0315	0.270	0.141
standard error	0.00444	0.00369	0.00763
median	-0.01	0.27	0.19
mode	0.03	0.33	0.03
standard deviation	0.0612	0.0589	0.161
simple variance	0.0037	0.0035	0.0258
kurtosis	-1.18	-1.00	-1.44
skewness	-0.189	-0.221	-0.259
range	0.23	0.22	0.51
minimum	-0.14	0.15	-0.14
maximum	0.09	0.37	0.37
number of data	190	254	444
confidence level (95%)	0.00876	0.00727	0.0150

Data analyse shows that some of the fissures almost do not move, so they were excluded from the further investigation. All attention is focused on monitoring points: P6, P7, P8, P9, P10; P11, P14 and P26.

For neither of the fissures, a width at the beginning of the monitoring was not recorded. So all data are absolute values of displacements without any consideration of a width at the beginning of monitoring. Displacement of the some fissures extremely depends on the temperature changes, so it is very important in which period of the year measuring device was embedded. Depending on the season and temperature values, at the start of monitoring fissures could be in period of opening or closing. So only after multiannual observations the mean value of displacement around all results oscillate could be detected, as well as the trend of these displacements.

On the example of the monitoring point P6 will be demonstrate the basic statistical data analyse. This analyse was performed also for all measured data on all other monitoring points.

For all monitoring points trend of fissure displacements is calculated for the first period of monitoring, than for the second and third period of monitoring together, and finally for the total monitoring period. Graphical display of calculated trends is shown for the monitoring point number P6 on the Figure 4.

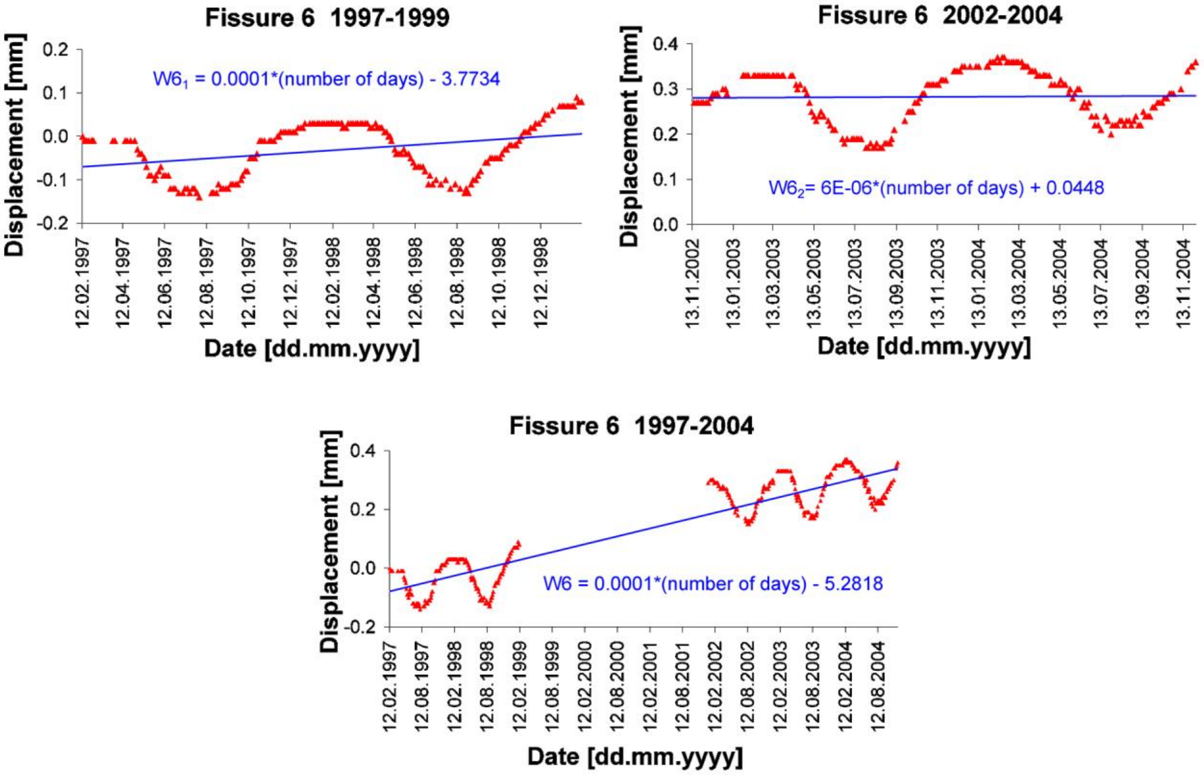

Figure 4. Graphical display of calculated displacement trends in time for monitoring point number P6, for different periods of monitoring

On the base of performed calculations a mathematical model of the fissure behaviour has been developed. Based on this model it is possible to extrapolate fissure behaviour in the time, and make a prediction of the fissure displacement in a future period. For all monitoring positions prediction of a fissure displacement has been calculated for periods of 1, 10, 100 and 1000 years. As an example, in the table 2. calculated displacement prediction is shown for a monitoring position P6.

Table 2. Predicted displacements of fissure on monitoring position P6, for periods of 1, 10, 100 and 1000 years

No. of monitoring position	period of observation	trend equation	predicted expansion of fissure width in **[mm] for [years]**			
			1	**10**	**100**	**1000**
P6	1997 - 1999	W6= 0.0001*(days) – 3.7734	0.0365	0.365	3.65	36.5
	2002 - 2004	W6 = 6E-06*(days) + 0.0448	0.0022	0.0219	0.219	2.19
	1997 - 2004	W6 = 0.0001*(days) – 5.2818	0.0365	0.365	3.65	36.5

Analyse of a predicted data for an expansion of fissures has shown illogical results for some monitoring positions. Predictions have shown very large expansion of these fissures in future, but in fact displacements in the some parts of the monument are restricted with the construction characteristics.

On the other side, analysed data have shown that in the most cases fissure displacements are in direct correlation with an air temperature changes. So a correlation between the temperature and magnitude of displacements has been compiled. Graphical display of the calculated correlation is shown on the figure 5. for a monitoring position number P6. Analyse has been performed separately for the each previously described monitoring period. Results of analyse for monitoring point P6 has been displayed in table 3. From the displayed data it can be concluded that for all periods when monitoring has been performed, fissure displacement has a linear thermal coefficient of the same order of magnitude. The same results have been observed for almost all other monitoring positions. Comparison of the results for linear thermal coefficients can be used for comparison of the fissures behaviour.

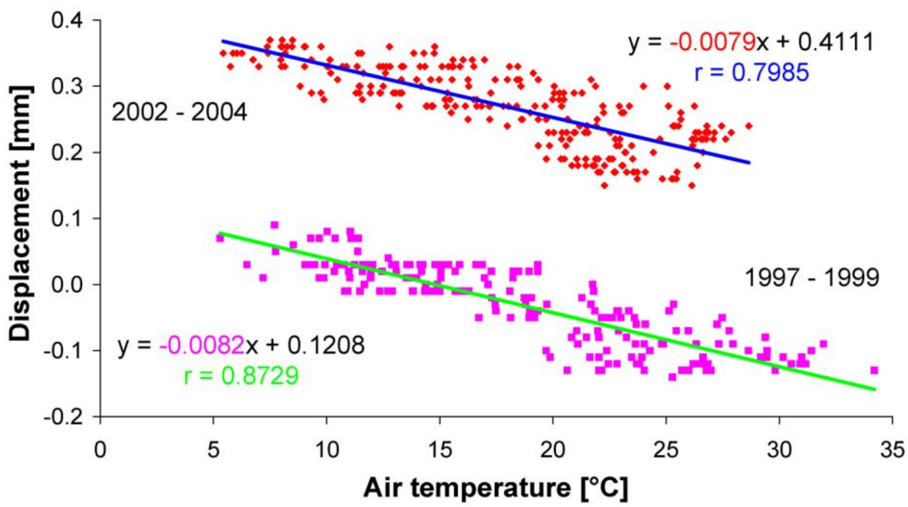

Figure 5. Graphical display of the calculated correlation between air temperature and displacements of fissure for a monitoring position number P6

For the analysed correlations the biggest correlation coefficient is for a linear thermal coefficient. For every data array mathematical model has been calculated. With these models the linear thermal expansion coefficients, α [mm/ °C], have been defined for each monitoring point.

Table 3. Statistical evaluation of data for monitoring position P6

monitoring position	displacement			predicted expansion of fissure width	correlation between air temperature and displacement		
	observation period	mean [mm]	range [mm]	for 10 years [mm]	observation period	correlation coefficient	linear thermal expansion coefficient α [mm/°C]
P6	1997 - 1999	-0.032	0.23	0.370	1997 - 1999	0.873	-0.0082
	2002 - 2004	0.27	0.22	0.022	2002 - 2003	0.799	-0.0079
	1997 - 2004	0.14	0.51	0.370	2003 - 2004	-	-

Analyse of the linear thermal expansion coefficients for monitoring positions P6, P7 and P8 has indicated some very interesting conclusions. Very high values of the correlation coefficients show that all of these three fissures extremely respond on the air temperature change. The liner thermal coefficients for each fissure, if different observation periods are compared, are of the same order of magnitude, approving the quality and reliability of the measured data. On the other side if the orders of magnitude for the liner thermal coefficients are compared for fissures P6 and P8, with coefficient for fissure P7, there is difference between them for one level. It is also interesting to observe that the width of fissures P6 and P8 increase with the increase of the air temperature, while a width of fissure P7 decrease, and vice versa. It is obvious that parts of a construction where these monitoring positions are located, behave as one zone in the sense of temperature changes.

Monitoring position P14 has shown the biggest range of the displacement and markedly matches with temperature changes. Statistical evaluation of data for the monitoring position P14 is shown in the table 5. On this position influence of temperature on fissure displacement is very high as well as the trend of a fissure width expansion.

Table 4. Liner thermal expansion coefficients for monitoring positions P6, P7 and P8

monitoring position	correlation between air temperature and displacement		
	observation period	correlation coefficient	linear thermal expansion coefficient α [mm/°C]
P6	1997 - 1999	0.873	-0.0082
	2002 - 2003	0.799	-0.0079
	2003 - 2004	-	-
P7	1997 - 1999	0.715	0.0015
	2002 - 2003	0.827	0.0014
	2003 - 2004	0.683	0.0015
P8	1997 - 1999	0.939	-0.0078
	2002 - 2003	0.898	-0.0093
	2003 - 2004	0.804	-0.0096

Table 5. Statistical evaluation of data for monitoring position P14

monitoring position	displacement			predicted expansion of fissure width	correlation between air temperature and displacement		
	observation period	mean [mm]	range [mm]	for 10 years [mm]	observation period	correlation coefficient	linear thermal expansion coefficient α [mm/°C]
P14	1997 - 1999	-0.532	1.11	-0.73			
	2002 - 2004	-0.566	1.03	-0.365			
	1997 - 2004	-0.552	1.11	-0.1095	1997 - 2004	0.933	-0.0458

On the figure 6. is shown a comparation of linear thermal expansion coefficients α for monitoring positions P6, P7, P8, P9, P10, P11, P14 and P26. Displayed values can be used to explain a thermal behaviour of the building parts. Monitoring positions P6, P7 and P8 are located on the outside west and north walls of building portal. These walls are not exposed to the heating of the sun, so magnitudes of the fissures displacements are small. The same order of the displacement magnitude have fissure on monitoring place P9, placed above an entrance door. This wall is also not exposed to the sun light. Fissures on positions P10 and P 11 have a greater reaction compared to previously described fissures, although this position is also protected from the direct insolation. Fissure on the position P26 have a very similar reaction on the temperature changes as fissures on positions P6 and P8, although this position is protected against heating from the sun. This monitoring position is placed on the column beside the southern entrance in the church. The most expressed reaction on the temperature changes has fissure on the monitoring position P14. This fissure is placed above entrance door on the southern wall, directly exposed to influence of the sun insolation, and the reaction is expected.

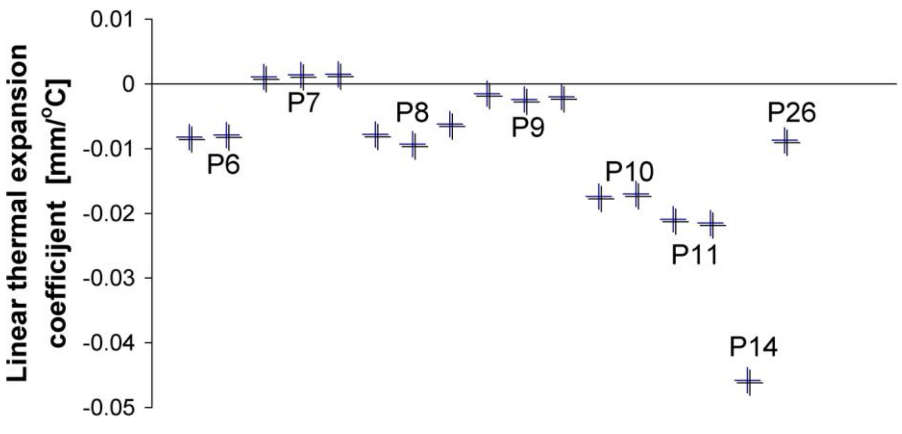

Figure 6. Values of the linear thermal expansion coefficient for monitoring positions P6, P7, P8, P9, P10, P11, P14 and P26

3. Conclusion

Implementation of the non destructive monitoring and measuring methods on the monuments of cultural heritage, brought in very important achievement in the field of reconstructions and restoration works on these buildings. From the presented monitoring results for the cathedral of St. Lawrence in

Trogir, it was concluded that there is no problem with the foundation or with the subsoil. Almost all fissures are induced with the stress changes that are consequence of the thermal behaviour of the construction. Expansion of the fissures widths is relatively small in time, so the stability of the construction is not endagered. Because the buliding is almost 800 years old, it is decided that existing stability should be meintained with a constant preservation.

References

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