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INTEGRATED DYNAMIC AND THERMOGRAPHY INVESTIGATION OF MALLORCA CATHEDRAL

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ABSTRACT

An integrated investigation of engineering archaeometry was carried out using dynamic identification, dynamic monitoring and Infra-Red (IR) thermography for the study of the dynamic behavior of Mallorca cathedral in Spain. The cathedral is a large historical masonry structure built during 14-16th c. Dynamic identification and monitoring allowed the capturing of eight natural frequencies of the cathedral. IR thermography was used as a complementary inspection technique in the context of a continuous monitoring. Usually, IR thermography is used punctually for the inspection of a part of an inspected structure. Here an alternative was tried as the IR camera was installed for two two-weeks periods in the winter and in the summer of 2011 to monitor the stone surface temperature of a large portion of the cathedral. The correlation between the cathedral natural frequencies and the stone surface temperature of some selected structural elements was investigated and compared with the correlation with the external and the internal temperatures. It was found that the correlation with stone surface temperature was lower than that with external temperature. The study allowed a better understanding of the influence of temperature changes on the structure's dynamic behavior.

KEYWORDS: Mallorca Cathedral, Historical Structures, In-situ Investigation, Dynamic Identification, Dynamic Monitoring, IR Thermography, Air Temperature, Stone Temperature

1. INTRODUCTION

Historical structures are very important assets of the world heritage as cultural resources involving important artistic, spiritual, technical and scientific merits. They contribute to the identity of cultures and countries and provide valuable documents on the great achievements from the past. Moreover, they represent important economic resources. For these reasons and many others, modern societies allocate great technical and economical effort to the conservation of their architectural heritage. European researchers, in particular, have carried out a number of research projects on the subject (PERPETUATE, 2010-2012, SEVERES, 2010-2012, PROHITECH, 2004-2008, EU-INDIA, 2004-2006, RISK-UE, 2001-2004, CHIME, 2000-2003).

In fact, the preservation of the architectural heritage faces significant challenges ranging from the difficulty in understanding the historical construction materials to the complexity of possible actions influencing on it. Due to these difficulties, often faced when assessing the structural safety of a historic structure, the assessment of heritage structures requires combining different approaches such as historical investigation, inspection, experiments, static monitoring, dynamic monitoring and structural analysis. The aim is to respect the authenticity of the historic structure, to the extent possible, by designing an efficient solution which, while attaining the required safety level, minimizes the impact in terms of material and structural alteration. In the study here presented, dynamic identification, dynamic monitoring and Infra-Red (IR) thermography were employed for studying the dynamic behavior of Mallorca cathedral, one of the largest worldwide masonry historical structures, and its dependency on external temperature, internal temperature and stone surface temperature.

Two different but interconnected activities, namely dynamic identification and dynamic monitoring, can be envisaged for the study of the dynamic response of historical structures. While dynamic identification is based on punctual measurements of the dynamic response by means of tests performed in a discrete way, dynamic monitoring involves the continuous measurement of the dynamic properties.

Dynamic identification is carried out to obtain information on the global dynamic behavior of the structure, including natural frequencies, mode shapes and damping coefficients. It is also an efficient tool to validate and update structural numerical models by comparing experimental and numerical natural frequencies and mode shapes (Elyamani and Roca, 2018a,b). Some of the early applications of dynamic identification in studying historic structures can be found in (Chiostrini et al., 1992; Erdik et al., 1993; Modena et al., 1997). For recent applications, the reader is referred to (Diaferio et al., 2015; Foti et al., 2014; Ceroni et al., 2014; Cagnan et al., 2015; Votsis et al., 2015; Votsis et al., 2012).

Dynamic monitoring can be carried out to confirm the obtained information from the dynamic identification. Additionally, it aims at studying the evolution of modal parameters in time, studying the influence of environmental climatic effects (temperature, humidity, etc.) on the dynamic parameters and capturing the dynamic response in the occasion of possible seismic events, among other possible purposes (Elyamani and Roca, 2018a,b). Some recent applications have been presented by (Masciotta et al., 2016; Basto et al., 2016; Lorenzoni et al., 2013; Rivera et al., 2008; Cabboi et al., 2014).

Most materials absorb Infrared Radiation (IR) over a wide range of wavelengths which results in an increase in their temperature. When an object has a temperature greater than absolute zero it emits IR energy. IR thermography is a nondestructive inspection technique which converts the emitted IR radiation pattern into a visual image by the usage of an IR camera. An IR camera measures, calculates and displays the emitted IR radiation from an object (Clark et al., 2003).

IR thermography has been applied to several emblematic historical structures for inspection purposes. For instance, the IR thermography was used extensively in the inspection activities carried out on the church of Nativity in Bethlehem (Faella et al., 2012). The IR thermography showed: 1) moisture problems due to rainwater seepage and re-climbing moisture presence in several masonry walls; 2) the plugging of some openings; 3) nearly homogenous materials used in the roof except one area in which different materials were used; and 4) great seepages of rainwater in the narthex roof caused by the lack of an efficient waste disposal system for drainage. Binda et al. (Binda et al., 2011) used IR thermography as one of the inspection techniques applied to the Spanish Fortress damaged by L'Aquila earthquake. Because the masonry was hidden by thick plaster, the IR thermography was used to reveal its texture, which helped in identifying the most representative areas where to execute minor destructive tests like flat-jack. Tavukçuoğlu et al. (2010) used the IR thermography in the inspection of a 16th century historical mosque. The aim was to discover the activeness of observed structural cracks. Other studies involving the use of thermography in ancient structures can be found in (Jo and Lee, 2014; Alves et al., 2014; Bagavathiappan et al., 2013; Martinez et al., 2013).

This research was carried out within the research project NIKER (NIKER, 2010-2012) aimed at investigating the effects of earthquakes on historical constructions via extensive experimental and numerical studies applied to several case studies. Mallorca cathedral was chosen as one of the selected case studies. A comprehensive review on the restoration of the cathedral is given in Elyamani and Roca (2018c).

The experimental investigation activities employed for the study of the cathedral included Ambient Vibration Testing (AVT) and dynamic monitoring. An IR thermography was used as a complementary system for the measurement of temperature. Usually, the IR thermography is used punctually for inspecting a certain part of a structure. Here, an alternative application was tried. The IR camera was used to continuously monitor the temperature during two two-weeks periods within summer and winter of 2011. This allowed a detailed investigation of the correlation between the natural frequencies of the cathedral and the stone surface temperature of different structural elements of the cathedral like columns, vaults and arches.

2. MALLORCA CATHEDRAL

Mallorca cathedral is a Cultural Heritage of National Interest in Spain since 1931 (Figs.1 and 2). It is located in the city of Palma, in Mallorca Island. When compared with other worldwide Gothic cathedrals, it is found that its piers show an unusually large slenderness ratio, while its main nave span is the second longest span among Gothic cathedrals after Girona cathedral. Its main nave is among the highest ones after those of Beauvais and Milan cathedrals.

The construction started in the beginning of the 14th century and continued to the beginning of the 17th century. The first built part was the Trinity Chapel (part I in Figure 3) in year 1311. About 60 years later the Royal Chapel (part II in Figure 3) was finished. It was then decided to modify the design from that of a single nave building to a three-nave one. No documented justifications behind this decision were revealed by any historical research carried so far about the cathedral construction. The imposing main large nave and the west facade (part III in Figure 3) were completed by the year 1601.

Figure 1. Mallorca Cathedral from outside: apse area (left), south façade (centre) and main façade (right).

Regarding the geometrical configuration of the cathedral (Figure 3), it is found that the main nave has a length of 77 m distributed over eight bays and the width covered by the naves is 35.3 m. The lateral nave and the central nave spans are 8.75 m and 17.8 m, respectively. The lateral naves are covered by pointed vaults of simple square plan. The central nave is covered by vaults of double square plan. This scheme is repeated in all the bays of the naves except in the 5th one (from the choir), due to the presence of lateral doors. In this bay, the longitudinal span of the vaults is slightly longer. The height reached by the vaults at their highest point (the key of the transverse arches) is about 44 m. The cathedral is also unique in being the Gothic cathedral with the highest lateral naves (29.4 m). All of the octagonal columns have a circumscribed diameter of 1.7 m except those of the first three bays from the choir that have a slightly lesser value of 1.6 m. More information on the cathedral can be found at (Caselles et al., 2012; Elyamani et al., 2017a; Gonzalez et al., 2008; Elyamani et al., 2017b; Pela et al., 2014; Elyamani, 2015; Caselles et al., 2015; Elyamani et al., 2012; Roca et al., 2013).

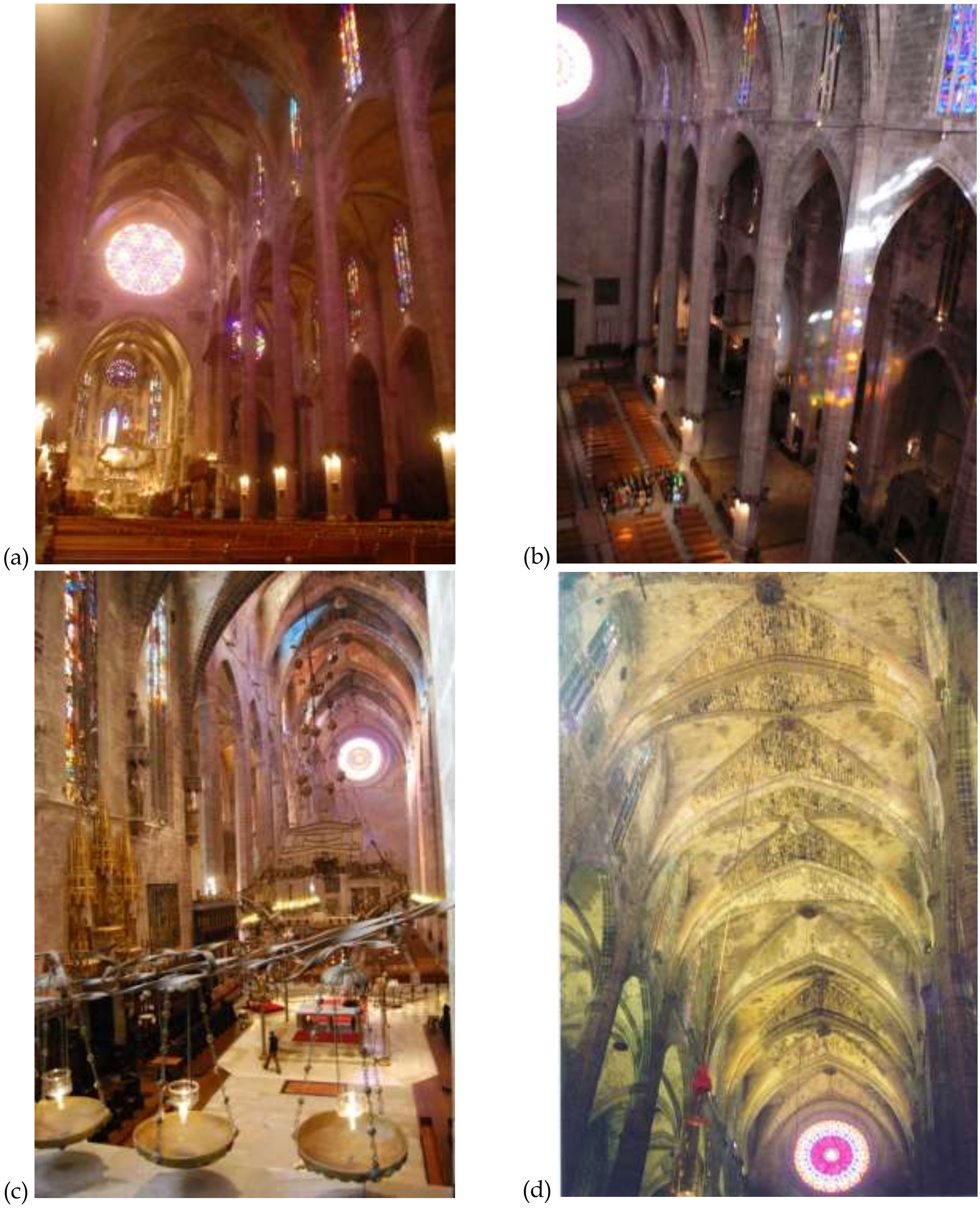

Figure 2. Internal views of Mallorca cathedral: (a) view of the choir, central nave and south lateral nave; (b) view of the west façade and north nave showing the slenderness of columns and the upper and lower clerestory walls; (c) view of the central nave from the choir; and (d) central nave vaults .

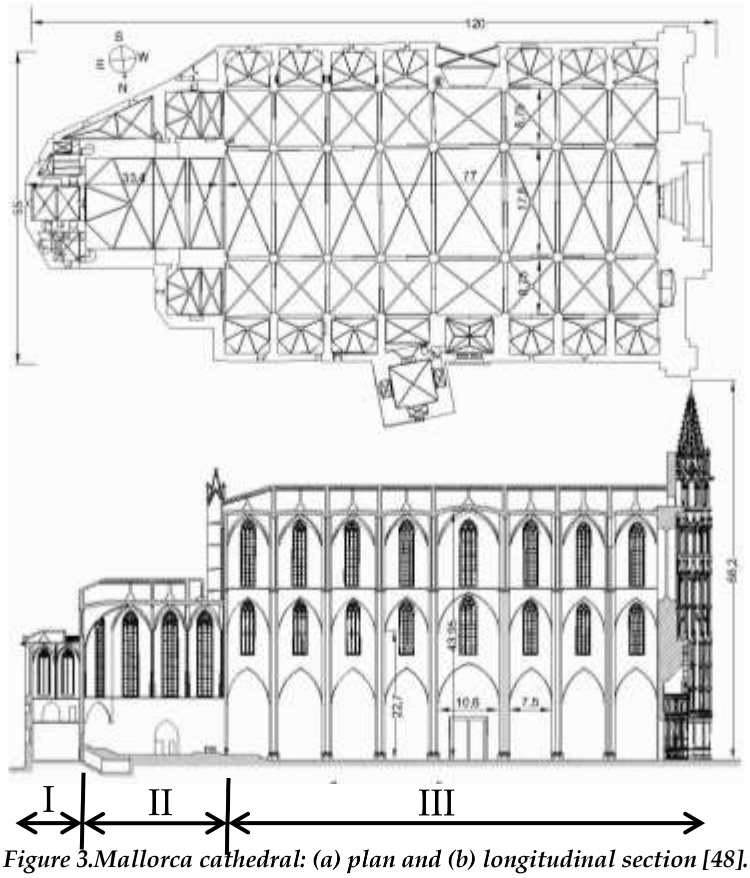

Figure 3.Mallorca cathedral: (a) plan and (b) longitudinal section [48].

2. DYNAMIC INVESTIGATION OF THE CATHEDRAL

2.1 Ambient vibration testing (AVT)

The objective of AVT was to identify the natural frequencies, mode shapes and damping ratios of the cathedral. The natural frequencies and modes shapes were used to update the numerical model of the cathedral which was then used in the seismic analysis of it (Elyamani et al., 2017a). A brief about AVT is given here and full details can be consulted at (Elyamani et al., 2017b; Elyamani, 2015).

The tests configuration was based on a preliminary modal analysis carried out using an initial FE model of the cathedral. It was noticed that only the first and the second modes were global ones with considerable mass participation and characterized by predominant movement of the main and lateral naves of the cathedral. Consequently, the used accelerometers were organized in different setups so that capturing these two modes would be achievable. Three tri-axial force balance accelerometers were used in AVT and the sampling rate was 100 samples per second.

The obtained signals during AVT were processed for dynamic identification using MACEC software (MACEC, 2011). Four different methods were employed: the Frequency Domain Decomposition (FDD) (Brincker et al., 2001); reference-based covariance-driven Stochastic Subspace Identification (SSI-cov/ref) (Peeters and De Roeck, 1999); reference-based data-driven Stochastic Subspace Identification (SSI-data/ref) (Peetres and De Roeck, 1999) and poly-reference Least Squares Complex Frequency domain identification (pLSCF) (Peetres and Van der Auweraer, 2005). Eight modes were identified. The natural frequencies of all of them were satisfactory identified (Table 1), whereas, the mode shapes and the damping ratios of only three of them were satisfactory identified.

Table 1. Identified natural frequencies (Hz) using different methods.

Identification	Mode ID.							
method	1	2	3	4	5	6	7	8
FDD	1.143	1.431	1.503	1.569	1.942	2.232	2.406	2.649
SSI-cov/ref	1.162	1.433	1.511	1.576	1.939	2.214	2.421	2.656
SSI-data/ref	1.166	1.445	1.514	1.576	1.942	2.241	2.434	2.662
pLSCF	1.145	1.430	1.509	1.576	1.943	2.234	2.432	2.666

2.2 Dynamic monitoring

The use of AVT was followed by a continuous dynamic monitoring system. A brief is given here and more details can be referred to at (Elyamani et al., 2017b; Elyamani, 2015). The system was composed of a digitizer, a Data Acquisition system (DAQ), a Global Positioning System (GPS) antenna, an internet router and the three tri-axial accelerometers previously used in the dynamic identification tests, Figure 4. The system worked properly for two periods: from 17/12/2010 to 13/9/2011and from 18/5/2012 to 29/12/2012. Within this second period, the system was interrupted from 30/7/2012 to 4/9/2012. The system was programmed to continuously measure, record, and wirelessly transfer the records of the accelerations on a 24 h basis. The natural frequencies were determined manually using the Peak Picking (PP) method four times per day: at 6 a.m. (06:00), 2 p.m. (14:00), 8 p.m. (20:00) and 12 a.m. (24:00) during the entire monitored periods.

The eight natural frequencies identified from AVT were identified continuously by the system. The identified natural frequencies were plotted versus the time as presented in Figure 5. The gap in the second period corresponds to the dates previously mentioned during which the system was out of service due to technical problems.

Figure 4.The dynamic system in operation: accelerometer S1, DAQ, router and GPS antenna (left); accelerometer 145-Station and digitizer (middle); and accelerometer Soil-station (right).

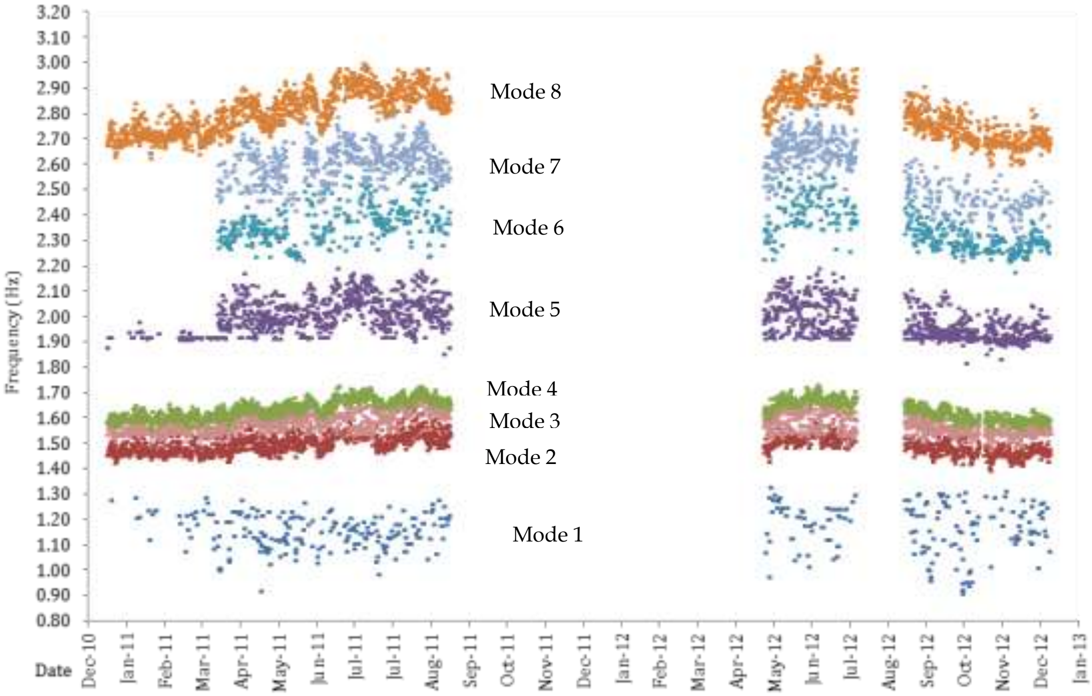

Figure 5. Evolution of the natural frequencies of the cathedral over time.

In the first monitoring period, the cathedral natural frequencies showed an increasing trend that can be attributed to the raising of the temperature, since the monitoring started in winter and ended in summer. The contrary was found for the second monitoring period during which a decreasing trend was noticed, also attributed to the temperature variations as the monitoring started in summer and ended in winter.

Table 2. Comparing natural frequencies (Hz) from AVT and dynamic monitoring, and amount of changes of the natural frequencies over the monitoring period.

Mode number	1	2	3	4	5	6	7	8
AVT (SSI-cov/ref)	1.162	1.433	1.511	1.576	1.939	2.214	2.421	2.656
Dynamic monitoring	1.158	1.496	1.576	1.631	1.988	2.353	2.593	2.797
Coefficient of Variation (CV) (%)	7.1	2.57	2.49	2.29	3.51	3.48	3.74	3.18
(Max.-Min.)/Max. (%)	31.8	14.9	13.9	10.4	17.0	16.6	18.5	14.3

Table 3. Correlation coefficients between temperature and cathedral frequencies.

	Mode ID.							
Regression model	1	2	3	4	5	6	7	8
Linear	0.197	0.766	0.544	0.834	0.618	0.640	0.602	0.806
Quadratic	0.241	0.802	0.544	0.854	0.643	0.660	0.603	0.819

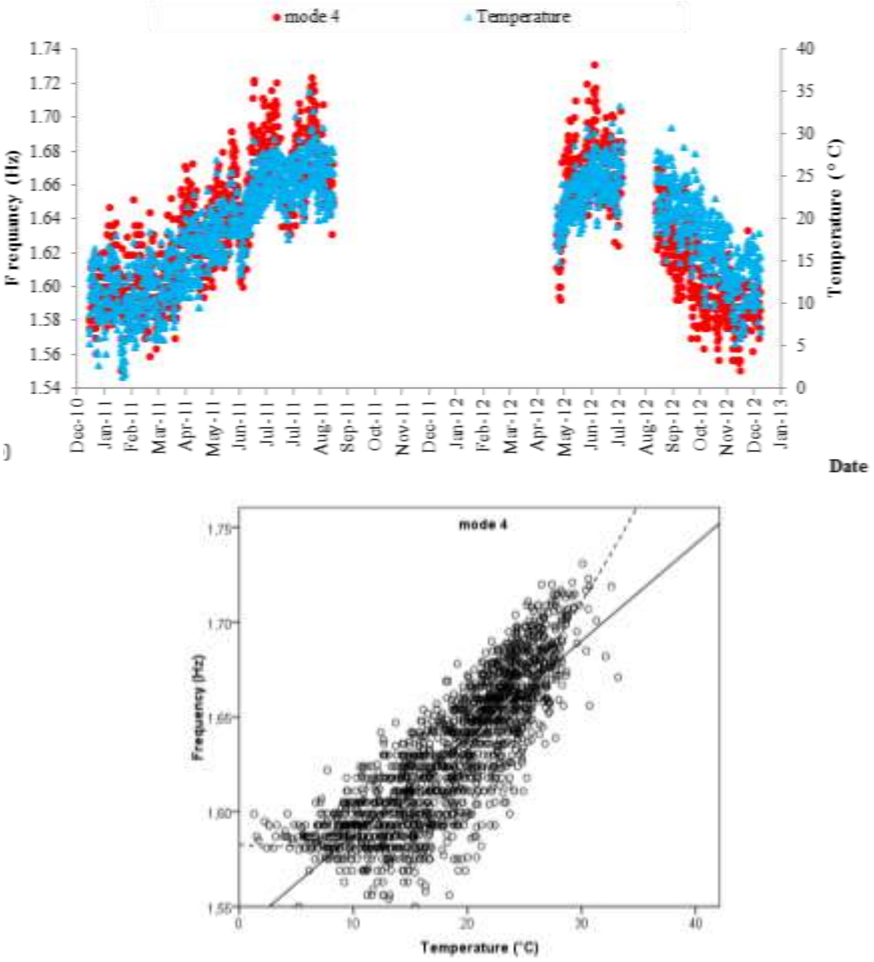

Figure 6. Changes of the natural frequency of mode 4 with external temperature (top) and correlation with external temperature (bottom). Linear and quadratic regression models are in solid and dashed lines, respectively.

It can be observed that modes 2, 3, 4 and 8 showed curves characterized by more continuous and intensive readings when compared to the curves of the other modes 1, 5, 6 and 7, that showed less continuity and intensity of readings. In addition, the curves of modes 2, 3, 4 and 8 showed a lesser scattering in comparison with the curves of other modes. The increasing and decreasing trends observed over time were clearer in the case of the continuously detected modes 2, 3, 4 and 8, whereas no distinguishable trends were observed for the remaining modes.

The frequencies detected in the dynamic tests were lesser than the mean values found by the dynamic monitoring system, Table 2. This difference can be attributed to the fact that the tests were performed in winter, whereas the monitoring system covered several summer months. The months from May to July and also half of the month of September were repeated two times in the entire monitoring period, thus resulting in an average temperature about 18.4 °C, whereas in the tests it was about 7.4 °C.

Table 2 also reports the changes of the natural frequencies over the whole monitoring period. In terms of coefficient of variation (CV), the modes 2, 3, 4, and 8 showed the lowest values. These modes were more centralized and manifested less variability when compared with the rest of the modes which had higher CV values. The same note can be stated when relating the range (maximum–minimum) with the maximum value as shown in the last row of the table. The Modes 2, 3, 4, and 8 had less variability than other modes. The very high value of Mode 1 could be related to the difficulty of detection rather than to changes in environmental conditions.

The change of the frequencies with temperature was plotted for the eight detected modes (Figure 6 for mode 4 as an example). It was noticed that the relation was clearer and the in-phase oscillation was more evident for modes 2, 4 and 8 than for modes 3, 5, 6 and 7. The frequency variations under changes of exterior temperature were investigated and both the correlation and the regression were studied, Figure 6. It can be noticed in Figure 6 that the trend is not exactly linear. Therefore, both of linear regression and quadratic regression were considered to investigate into more detail the type of the relation between temperature and frequencies. The obtained correlation coefficients are summarized in Table 3. As can be seen from the comparison among all models, a linear relation between temperature and natural frequencies provided a good approximation. No significant increase in the coefficients of correlation was obtained when considering a higher degree model. The correlation coefficient of the quadratic model was only slightly higher than that of the linear one. The highest correlation value was around 0.80 to 0.86 for modes 2, 4 and 8, followed by the correlation coefficients ranging from 0.55 to 0.66 for modes 3, 5, 6, and 7.

3. THERMOGRAPHIC INVESTIGATION

3.1 Description of the thermographic monitoring System

An infrared (IR) camera of type "Thermo GEAR G120" produced by NEC Company was used. Its main characteristics are: 1) measuring range from -40° C to 500° C with accuracy of ±2°C or ±2% of reading, whichever is greater; 2) thermal image of 320 pixels (horizontal) X 240 pixels (vertical); 3) spectral range from 8 to 14 µm; 4) frame rate of 60 frames/sec; 5) automatic focusing with focal distance from 10 cm to infinity; and 6) automatic recording of images with interval from 3s to 60 min.

It worked at the same location in two periods: 1) in the winter of 2011 for 14 days from 27/1 (at 11:15) to 9/2 (at 23:45), and 2) in the summer of the same year for 16 days from 28/6 (at 8:16) to 13/7 (at 22:46).

The IR camera position and its coverage area are shown in Figure 7. As shown, it was located inside the north pulpit and directed to the arches, the vaults, the upper clerestory and the columns of the main nave. This place allowed the IR camera to cover a large portion of the first five bays of the main nave. The IR camera recorded photos each half an hour. A sample of the monitoring photos in the summer and the winter periods is shown in Figure 8.

(a) (b) (c)

Figure 7. Mallorca cathedral thermography monitoring: (a) the red circle shows the IR camera position; (b) the IR camera during operation (inside the pulpit); and (c) the area covered by the IR camera.

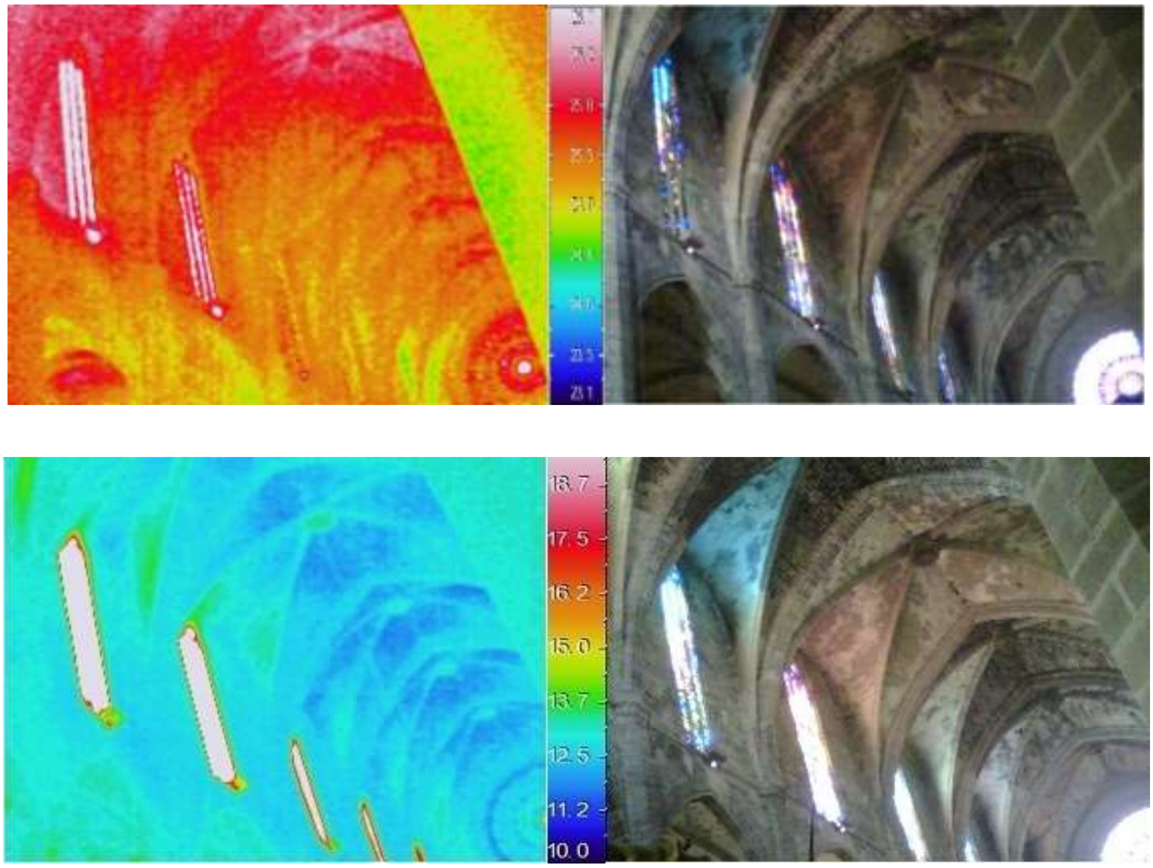

Figure 8. Two examples of the thermography monitoring: 1) summer period on 2nd of July 2011 at 9:46 a.m. (top); and 2) winter period on 2nd of February 2011 at 13:15 (bottom). Temperature scale in (°C).

3.2 Comparisons between different temperatures

For each day of the two monitoring periods, four IR photos were processed at the same times of the dynamic monitoring data, i.e., at 6 a.m., 2 p.m., 8 p.m. and 12 a.m. Using the software "Inf ReC Analyzer NS9500 Standard" which was provided with the IR camera, the stone surface temperature was determined for two samples from the considered structural elements (the columns, the clerestory walls, the arches and the vaults) as shown in Figure 9. In the figure also the places of the three temperature sensors used in the summer period are shown.

The stone surface temperature recorded is influenced by the distance from the IR camera, the ambient relative humidity, the ambient temperature and the stone emissivity. The available geometrical survey of the cathedral provided the distance from the IR camera to each of the considered structural elements samples. An average ambient relative humidity and temperature of 65% and 27.9 °c, respectively, were used for the summer period and 83% and 13.5 °c for the winter period. These approximate values were estimated from the previous static monitoring system that worked for five years (from 2003 to 2008) and showed clearly the repeated cycles experienced by these parameters. More details about this monitoring are available in (Gonzalez et al., 2008). Regarding, the stone emissivity, the cathedral was built mainly from limestone which has an emissivity of 0.95 according to the references on the subject (Gosse, 1986; Adler, 1969).

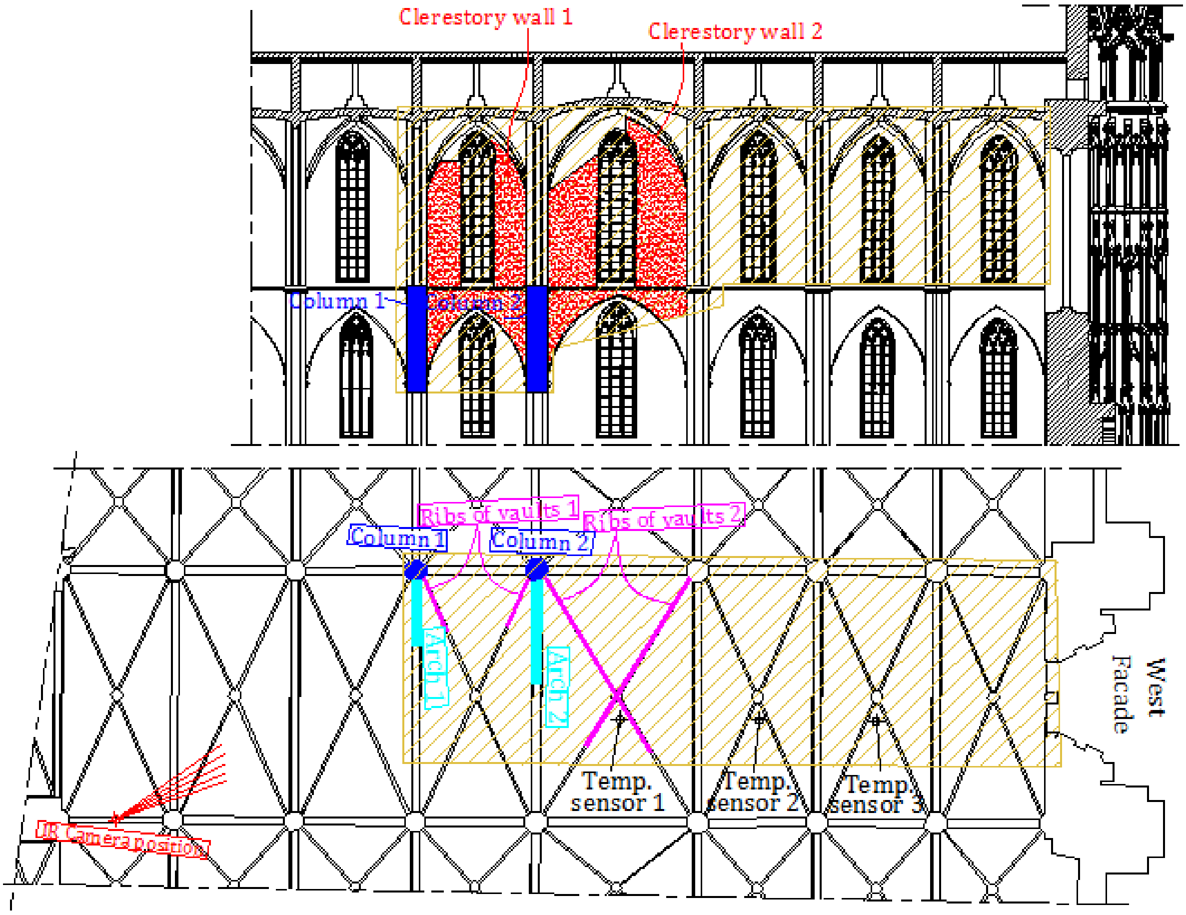

Figure 9. Selected samples from structural elements within the IR camera coverage area: clerestory walls and columns (top), arches, columns and vaults (bottom). Coverage area hatched in light brown.

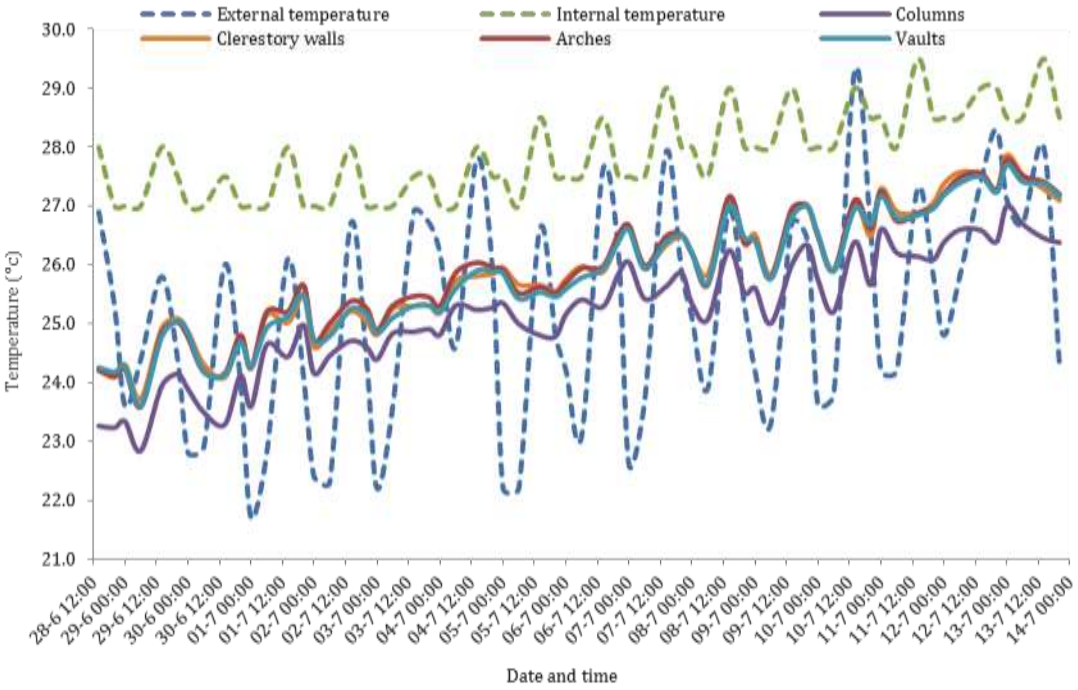

Figure 10. Comparison between external, internal and stone surface temperatures in the summer period from 28/6/2011 to 13/7/2011.

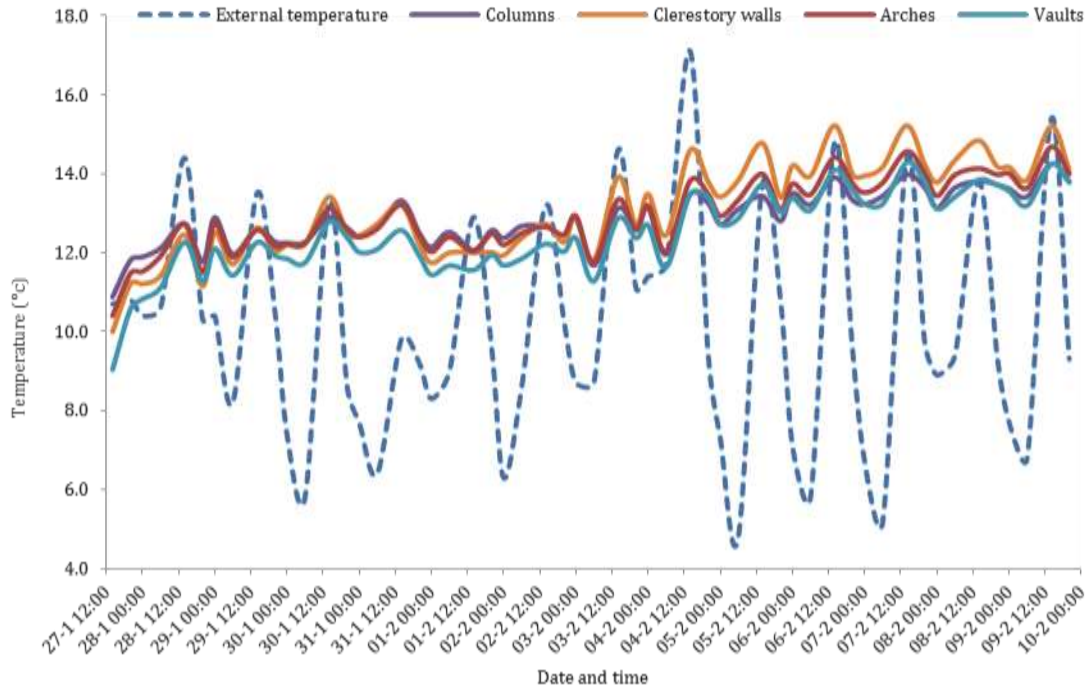

Figure 11. Comparison between external and stone surface temperatures in the winter period from 27/1/2011 to 9/2/2011.

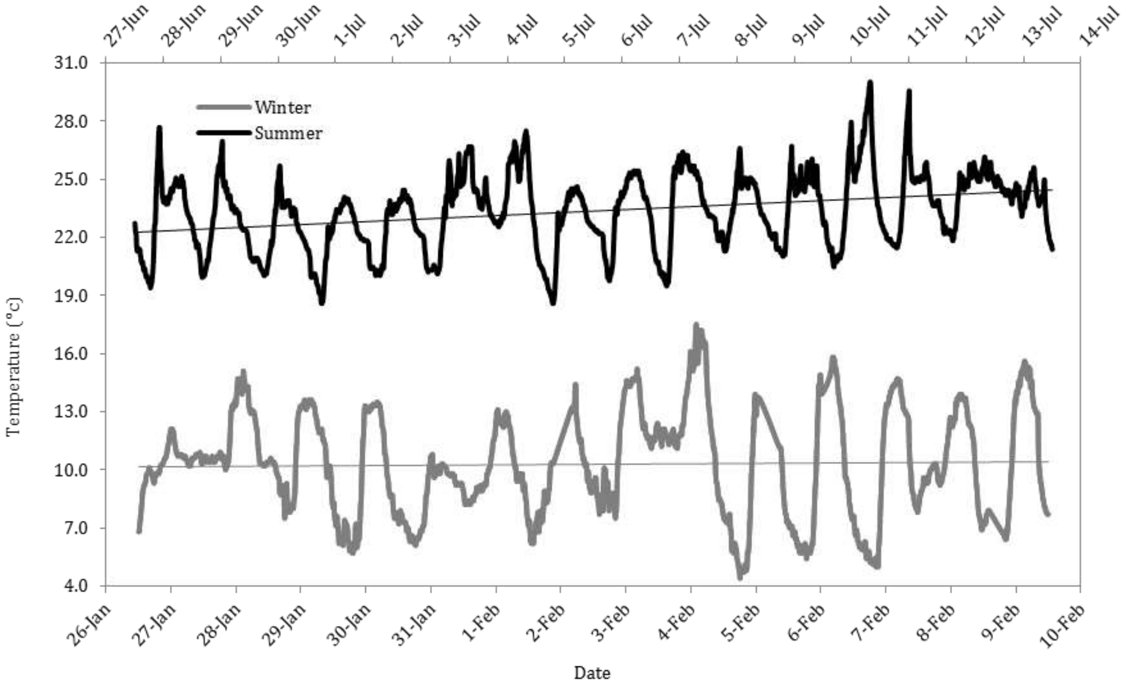

Figure 12. Comparison between external temperatures for the summer and winter periods. The trend lines are also shown.

A comparison was made between the external temperature (measured from a near meteorological station), the internal temperature (measured in summer only using temperature sensors) and the stone surface temperature of the considered structural elements for the summer period (Figure 10) and the winter period (Figure 11). It can be seen that the stone surface temperatures of the different structural elements were in phase and very near to each other for the two monitoring periods. For the summer period, the internal and the external temperatures were in phase, whereas, the stone surface temperature was sometimes delayed with respect to the external and the internal temperatures. In the winter period, the stone surface temperature was in phase with the external temperature.

To explain the reason of the delay of the stone surface temperature in the summer period, a comparison between the external temperature of the summer and the winter periods is shown in Figure 12. It can be noticed that an increasing trend was observed during the summer period, whereas a constant trend was obtained during winter. It can be assumed that, in the summer period, the stone was not able to radiate the stored heat as fast as the rapidly increasing external temperature, therefore producing a delay in the variation of surface temperature with respect to the external one. This phenomenon disappeared in the winter period during which the stone could radiate the heat in phase with the almost constant rate of change of the external temperature.

3.3 Correlation between natural frequencies and different temperatures

An acceptable qualitative correlation was found between the natural frequencies of the cathedral and the stone temperature changes. Figure 13 shows this correlation for mode 4 as an example. The stone surface temperature indicated in Figure 13 corresponds to the average temperature of the columns, the vaults, the arches and the clerestory walls.

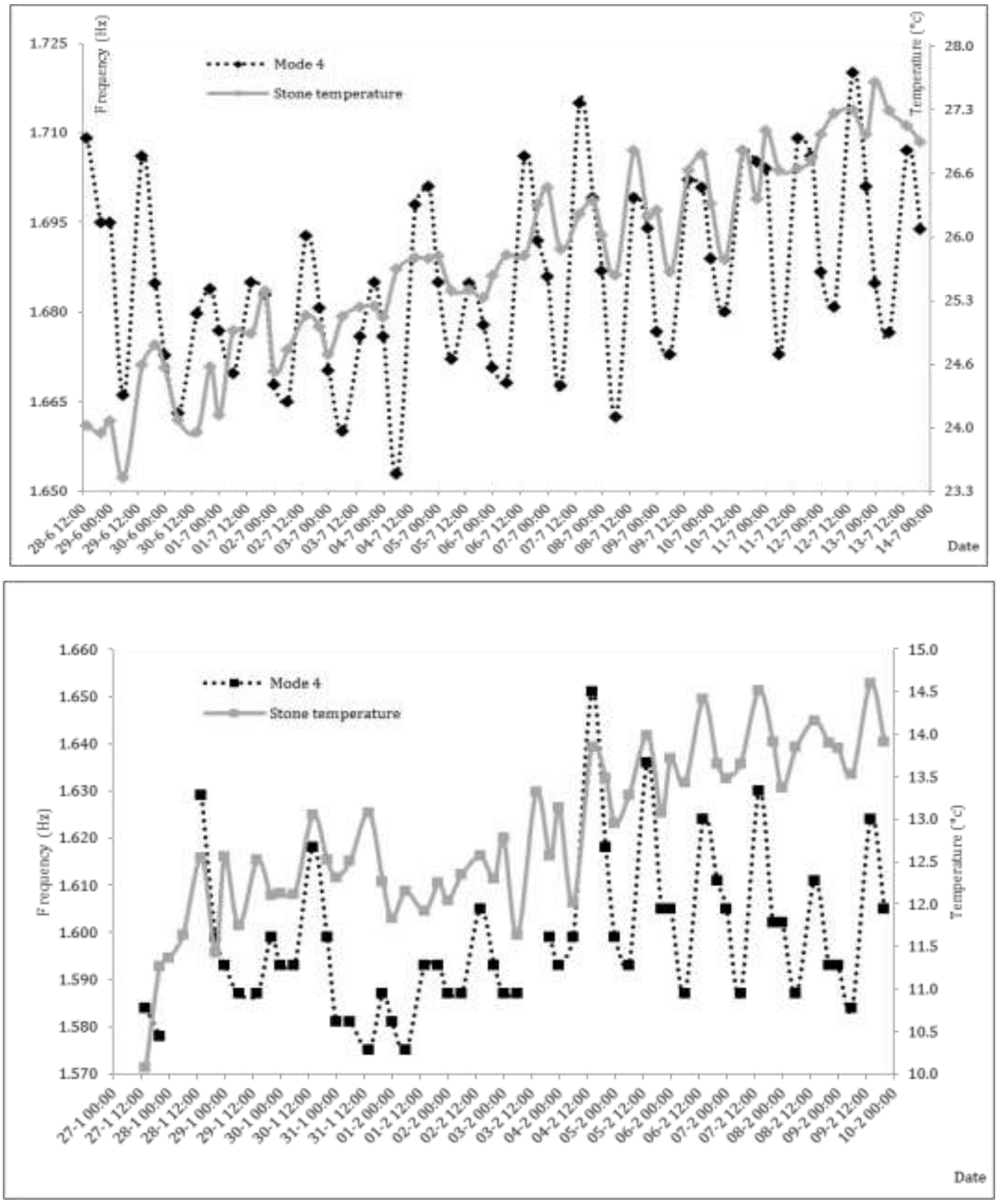

Figure 13. Changes of mode 4 with stone temperature: summer period (top); and winter period (bottom).

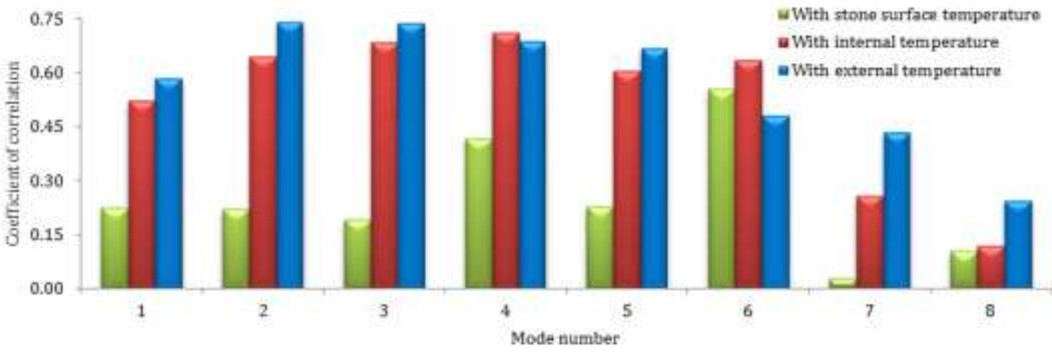

Figure 14. Summer period: comparison between coefficients of correlation of different temperatures with the first eight modes of the cathedral.

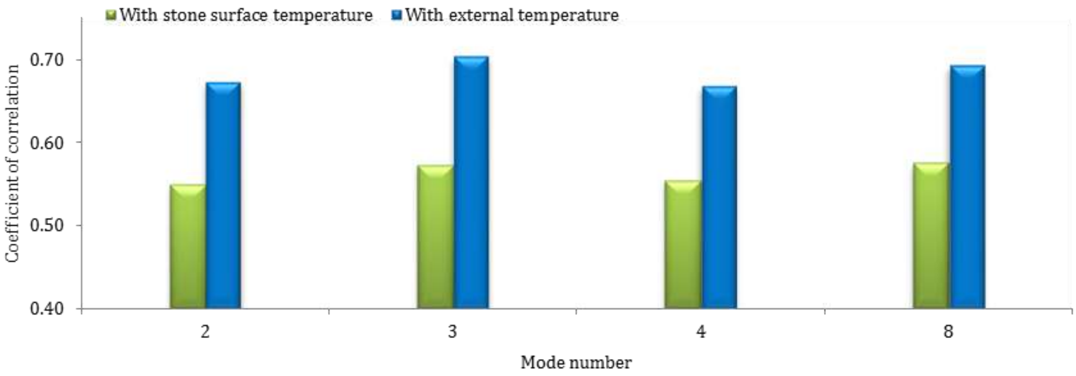

Figure 15. Winter period: comparison between coefficients of correlation of different temperatures with four of the cathedral modes.

Table 4. Statistical variations in the cathedral frequencies in the summer and winter periods.

Monitored period	Parameter	Mode no.							
		1	2	3	4	5	6	7	8
Summer 28/6-13/7/2011	CV (%)	2,79	1,59	2,38	0,91	2,19	3,49	2,42	1,21
	$\frac{(\text{Max.}-\text{Min.})\%}{\text{Max.}}$	9,2	6,1	8,5	3,9	9,1	10,5	9,9	5,7
Winter 27/1-9/2/2011	CV (%)	–	1,59	1,68	1,02	–	–	–	1,48
	$\frac{(\text{Max.}-\text{Min.})\%}{\text{Max.}}$	–	6,4	7,1	4,6	–	–	–	6,0

In Figures 14 and 15 the coefficients of correlation between the natural frequencies of the cathedral and the different temperatures are presented. For the summer period and during the period of thermography monitoring, the eight modes were identified, whereas, for the winter period only the modes number 2, 3, 4 and 8 were identified. The other modes were local ones; therefore, their identification was not always attainable as can be noticed in Figure 5. It can be noticed for the summer and the winter periods that the coefficients of correlation with the stone surface temperature were less than those with the external and the internal temperature. In the summer period, the coefficients of correlation with the external temperature were in average 0.57 and were clearly higher than those with the stone surface temperature which were in average 0.25.

On the contrary, in the winter period the coefficients of correlation with the stone surface temperature were in average 0.56 and were not so far from those with the external temperature which were 0.68 in average. The discussion given in the previous section (3.2) may explain this finding. The statistical variations in the identified modes during the summer and winter monitored periods are reported in Table 4.

For modes 2, 4 and 8 slightly higher changes could be noticed in winter period than in summer period. For mode 3 the contrary was found.

Table 4. Statistical variations in the cathedral frequencies in the summer and winter periods.

Monitored period	Parameter	Mode no.							
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Summer 28/6-13/7/2011	CV (%)	2,79	1,59	2,38	0,91	2,19	3,49	2,42	1,21
	$\frac{(\text{Max.} - \text{Min.})\%}{\text{Max.}}$	9,2	6,1	8,5	3,9	9,1	10,5	9,9	5,7
Winter 27/1-9/2/2011	CV (%)	–	1,59	1,68	1,02	–	–	–	1,48
	$\frac{(\text{Max.} - \text{Min.})\%}{\text{Max.}}$	–	6,4	7,1	4,6	–	–	–	6,0

4. CONCLUSIONS

An integrated inspection and monitoring program, encompassing different activities, has been applied to Mallorca cathedral a large masonry historical structure built during the 14th – 16th c. The AVT allowed for a good identification of the natural frequencies of eight modes. The AVT was followed by a continuous dynamic monitoring that worked for about 15 months on a 24 h base. It confirmed the results of the AVT by allowing the monitoring of the evolution of the eight natural frequencies over time. It was found that the changes in the natural frequencies of the cathedral, in terms of CV, were between 2.3 and 3.7%, and their percentual variation was between 10.4 and 18.5%.

A seasonal thermography monitoring (as a complementary study for the dynamic monitoring) was used. An IR camera was installed in the winter and the summer of 2011 for two weeks to monitor the internal stone surface temperature of a large portion of the cathedral. The correlation between the cathedral natural frequencies and the internal stone surface temperature of some selected structural elements was investigated. The correlation of the natural frequencies with the external and internal temperatures was also analyzed.

Concerning the correlation among the different temperatures measure, the main conclusions are: I) The internal stone surface temperature of the columns, vaults, arches and walls was in phase and very near to each other; II) In summer, it was observed that the internal stone surface temperature did not always vary according to the external temperature because the stone was not able to radiate the stored heat as fast as the rapidly increasing external temperature; III) in winter, the stone surface temperature was in phase with the external temperature.

Regarding the correlation between the natural frequencies and the different measured temperatures, the thermography monitoring revealed an acceptable correlation between the stone internal surface temperature and the cathedral frequencies. In the winter period higher correlation coefficients than in the summer period were found. It was observed also that the natural frequencies were more correlated with the external temperature then the internal temperature and finally with the internal stone surface temperature.

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