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The importance of structural monitoring as a diagnosis and control tool in the restoration process of heritage structures: a case-study in Portugal

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Abstract

The paper discusses the monitoring-based approach unfolded to evaluate the health condition of a heritage structure in Portugal. An extensive experimental campaign, including geometric survey, visual inspections, damage diagnosis, monitoring and control, is carried out to support and evaluate the actions undertaken to re-establish the structural strength. The paper focuses on the analysis of case-specific static and dynamic parameters deemed representative of the structural behaviour and highlights the benefits associated with the implementation of a monitoring-weighted methodology in terms of diagnostics of the system's vulnerabilities as well as control of the effectiveness of the adopted consolidation measures. The results

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demonstrate the feasibility and suitability of this systematic experimental approach for the non-invasive assessment of the structural fitness of built cultural heritage.

KEYWORDS: cultural heritage conservation, structural monitoring, diagnosis and control, masonry buildings.

1. Introduction and research aim

The systematic process of observing, tracking and logging data over a period of time in order to characterize the health state of structures and to detect any possible change due to damage occurrence is referred to as Structural Health Monitoring (SHM). Over years, this tool has become very popular in the engineering practice as it helps to improve safety, maintainability and lifetime management of structures by combining a variety of sensing technologies that enable to perform condition screenings in nearly real-time. Lots of attention has been devoted to the dynamic monitoring of structures which allows the estimation of modal features by just measuring a few nodal response processes at strategic locations and using wind, traffic and micro-tremors as operational conditions. One of the major benefits of dynamic monitoring is the possibility to exploit the recorded data for the application of vibration-based damage identification techniques which are extremely helpful for early-stage damage identification [1]-[4]. The monitoring of static parameters, such as strains, deformations, tilts and displacements, is another valuable tool for assessing the long-term structural performance and for tracking changes in behaviour that are often difficult to spot only with dynamic monitoring. However, since system's properties may change not only because of damage outset, but also because of the influence of varying ambient parameters [5], the continuous acquisition and analysis of data from the structure becomes fundamental to distinguish and filter out changes caused by exogenous factors (e.g. environmental conditions) from changes associated with endogenous phenomena (i.e. increasing structural damage) [6]. Unlike the static counterpart, the significant

amount of events that can be collected through dynamic monitoring is unwieldy, thereby calling for automated procedures to speed up the processing time for the modal parameters estimation [7]. Most of these procedures are based on the Stochastic Subspace Identification (SSI) method [8]-[9], either covariance-driven (SSI-cov) or data-driven (SSI-data), as this approach is apt to accurately identify closely spaced modes and is suited to be automated [10]. Being a non-destructive tool, SHM is particularly recommended when dealing with cultural heritage assets, where the need to respect the historical value of the constructions often limits the range of applicable techniques for the system characterization [11]. In this case, SHM may be employed with a twofold aim, i.e. as both diagnosis and control tool, holding a fundamental role throughout the preservation process [12]-[15]. As a diagnosis tool, SHM permits to characterize the system fitness, to detect the onset of damage and to study the effect of ambient variables on the structural behaviour. As a control tool, SHM is mainly used to follow the evolution of structural conditions during/after the execution of consolidation works in order to assess the global impact of the intervention and to assist in the evaluation of the effectiveness of the adopted remedial measures.

This paper aims at showing how a systematic monitoring-based approach can truly add a value to the investigation on cultural heritage assets, playing a vital role for both diagnosis and control purposes and providing a sound basis for any further evaluation of the structural health. The relevance of such a methodology is demonstrated taking profit of a real complex example belonging to the Portuguese architectural heritage. The presented case-study structure is a masonry church which was affected by a serious cracking pattern that could compromise the long-term structural stability. Based on accurate investigations and analyses, the building pathology was diagnosed and adequate consolidation measures were executed to reinstate the sound condition of the system. During and after the works, the structural response was monitored to keep under control undesired movements, to discern potential correlations

between damage and environmental changes and to evaluate the effectiveness of the intervention. The sections of the paper are organised so as to follow the entire process of ‘knowledge accumulation’ that has led to the screening of the structural health, in a progressive understanding of the building and its pathology. This process is based on the methodology proposed by ICOMOS [16] and consists of four main steps: anamnesis, diagnosis, therapy and control. Herein, special attention is given to the diagnostic and control phases, for which the structural monitoring represents the mainstay. More in detail, Section 2 gives a brief description of the church and its geometrical features; Section 3 describes the damage affecting the fabric and its root causes; and Section 4 is devoted to the discussion of the results from the monitoring task. The conclusions drawn from the study are reported in Section 5.

2. Description of the church

Saint Torcato church (Figure 1) is a *Neo-Manueline* temple located in a small village in the North of Portugal. The church is characterized by a Latin cross longitudinal plan with a central nave of nearly 58 m length and 11 m width ending into an apse. Opposite the apse and above the main entrance, the choir overlooks the holy space. A transept of about 37 m length and 11.5 m width intersects the nave at two third of its development. Either limb is covered with a barrel vault that leans upon a series of semi-circular arches resting on side bearing columns. A roof consisting of wooden trusses protects the vaults beneath. The crossing between longitudinal nave and transept is capped with a dome that lays on an octagonal tambour supported by four semi-circular arches. Main features of the façade are the splayed portal, the central rose window and the top balustrade that bounds the gallery accessible from the gable roof. Two spired towers with a rectangular plan of 7.5 m × 6.3 m and a total height of 58 m symmetrically frame the façade. Either tower has an inner stone staircase running along the walls up to the level of the bells, present only in the western tower.

The construction of the church started in 1825 and stretched over nearly two centuries, involving several building phases [17]. Hence, different materials can be distinguished in the fabric. Towers and nave are made of three-leaf walls consisting of outer regular granite masonry blocks with thin mortar joints and inner rubble core, whereas apse and main altar are built by reinforced concrete walls covered with granite veneer, revealing the recent replacement of this part. The thickness of the walls ranges from 1.1 m of the apse to 1.3 m of the nave and 1.4 m of the towers, while the thickness of the façade tapers upwards varying from 2.3 m to 1.4 m.

3. Damage survey and building pathology

The church exhibited moderate to severe structural damage (Figure 2). The most affected part was the façade where a V-cracking pattern arising from the keystone of the portal was observed. The major of the two cracks split the façade into two macro-blocks, being as deep as the thickness of the wall and reaching over 50 mm width at the tympanum level. Five vertical cracks of about 5 mm width were also present on the outer wall of the left side of the gallery. Inside the building, beyond the major crack crossing the façade, several cracks were visible in the vault beneath the choir and additional cracks were detectable along the weakest links of the sidewalls of nave and transept. Besides the cracking pattern, the last laser scanning [18] highlighted that the towers of the church were leaning forward in longitudinal direction and moving apart in transversal direction. Little hair cracks, probably due to the high compressive stresses caused by the load eccentricity associated with the tilting, were observed at the base of each tower.

It is not known when the cracks appeared, but the gypsum marks from 1976 found in the cracks prove that the damage originated long time before. In order to investigate the building pathology and assess the structural condition of the church, an extensive experimental campaign consisting of visual inspections, crack mapping, topographic and geotechnical

surveys was carried out in 1998 [19]. A simple static monitoring system was also installed to check the progress of damage over time: crack meters and demec strain gauges were used to monitor the cracks, whereas an optical theodolite and a heavy plummet were used to measure displacements and tilting of the towers. The first monitoring results reported a crack opening rate of 0.1 mm per year, pointing to the façade as the most active part of the church. In addition, the results from optical theodolite and plummet revealed that both towers were leaning towards west but with different inclination ratios. Merging this information with the outcome of the geotechnical survey, it was concluded that the main cause triggering the cracks and the separation movements of the towers was the differential soil settlement in the strata underneath towers and façade. Although the digging of two pits uncovered the presence of good quality foundation made of large-size granite blocks under the towers, the soil profile surveyed during the investigations showed heterogeneity and variability of the layers along the longitudinal section of the church [19]. The temple stands on a slope which is levelled by a landfills bank, thus the steady bedrock layer is very close to the foundation in the apsis and transept areas, but it goes deeper and deeper while proceeding towards the front of the temple. Here the soil is mostly composed of sands and non-cohesive layers, whose poor mechanical characteristics get worse when approaching the western area. This explains why the floor of the church was sinking from the transept towards the front façade and why this phenomenon was accentuated under the western tower.

4. Monitoring and control

Once the analysis of the ‘symptoms’ shed light on the root causes of the damage affecting the church, *ad hoc* strengthening measures were planned and executed (04/2014 – 07/2015) [20]. The strengthening design focused on three main aspects, viz.: (1) elimination of differential soil settlements; (2) restraint of towers leaning and attenuation of tensile stresses responsible for the cracking of the façade; and (3) restore of material continuity. To this end,

the consolidation measures involved the installation of micro-piles along the foundation sides of both towers, the placement of post-stressed tie rods to link the towers, and the injection of cracks. The works schedule is summarized in Table 1. Given the importance to evaluate the effects of the works on the global behaviour of the system, a continuous dynamic monitoring was carried out during and after the structural intervention. The outcome of the dynamic monitoring task is discussed next, after the results from the static monitoring system which is following the evolution of cracks opening and towers tilting since April 2009.

4.1 Description of the monitoring systems

A systematic monitoring-based approach requires an *a priori* planning of the key features to extract, the type and location of sensors to use, the number of events to record and the duration of the signal acquisition. For this study, based on the results of the experimental campaign, cracks opening rate, towers tilting and natural frequencies were identified as key parameters to monitor for assessing the structural health. Thus, two long-term monitoring systems were installed in the church, one static and the other dynamic.

The equipment of the static monitoring system was composed of:

- Two crack meters (CR1 and CR2), with a measurement range of $\pm 12.5\text{mm}$ and a resolution of 0.01mm , installed to monitor the V-cracking pattern of the façade. CR1 monitored the crack on the inner side of the wall, whereas CR2 monitored the crack on the outer side;
- Four uniaxial tilt meters (TL1 to TL4), with a measurement range of $\pm 1.5^\circ$ and a resolution of 0.03° , located on top of the towers at the bells level and positively oriented to North and East. The out of plumbs towards East-West and North-South were respectively measured by TL1 and TL2 for the eastern tower and by TL3 and TL4 for the western tower;

- Two surface temperature sensors (TS1 and TS2), with a measurement range varying from -20°C to $+100^{\circ}\text{C}$ and a resolution of 0.2°C , installed in the front façade. TS1 registered the temperature of the inner side of the wall (nearby CR1) and TS2 registered the temperature of the outer side of the wall (nearby CR2). Such a distribution allowed to evaluate the effect of the temperature gradient on the cracks;
- One combined sensor to measure air temperature (AT) and relative humidity (RH). The temperature range was between -20°C and $+70^{\circ}\text{C}$ with a resolution of 0.2°C , whereas the relative humidity range varied from 0% to 100% with a resolution of 2%;
- One data logger (D) for data acquisition provided with Global System for Mobile (GSM) communications to enable data remote downloading by phone line and located inside a protection box at the truss level (vault extrados).

The location of the devices is schematized in Figure 3a. To catch daily temperature variations, all records were taken with a sampling rate of one per hour (24 events per day).

The dynamic monitoring system consisted of:

- One strong motion recorder (R) with 16-bit ADC analyser provided with batteries and installed on top of the western tower (Figure 3b);
- One tri-axial force balance accelerometer (A) with a bandwidth from DC to 100 Hz, a dynamic range ± 1 g, a sensitivity of 10 V/g and an operating temperature range of -20°C – 70°C . Accelerometer and strong motion recorder were connected by cable. The final resolution of both sensor and analyser was $8\ \mu\text{g}$.

As the force balance accelerometer was not enough to monitor the dynamic behaviour of the church in terms of mode shapes, only the global modal parameters (frequencies and damping coefficients) are analysed in this study. According to the results of a former OMA [21], the mode shapes of interest of the church are those associated with the towers movements, whose frequencies fall within the range 2 - 3 Hz. Thus, the signals were acquired with a sampling rate

of 100 Hz every two hours. In detail, the first two modes are associated with in-phase bending modes of the towers in transversal and longitudinal directions, while the third and fourth frequencies correspond to out-of-phase bending modes [21]. To comply with the time window length requirements (i.e. acquisition time not less than 1000 - 2000 times the structure's fundamental period), the total duration for the dynamic acquisition was fixed to 600 s. Moreover, to avoid undesirable harmonics in the signals, the recorder was set to start registering data after the hourly bells ring.

4.2 Static monitoring: results and discussion

The analysis of the static monitoring data embraces a period of 6 years (29/04/2009 – 28/04/2016), involving a total number of 58993 events. This tool was employed to monitor the evolution of damage over years; to control the occurrence of unstable phenomena or further damage mechanisms before and during the structural intervention; and to understand whether ambient variables affect the statics of the system. The outcome is presented in two parts: the first part shows the results relevant to the period preceding the structural intervention, whereas the second part discusses the results obtained during and after the works.

4.2.1. Static monitoring before the structural intervention

Figure 4 shows the evolution of cracks opening and towers tilting before the works execution (04/2009 – 04/2014). As it can be seen, the cracks behaviour features a positive linear trend over years, meaning that the cracking pattern has not recovered but worsened with time, pointing out the need for corrective measures. The cracks width keeps increasing with an average opening rate of 0.1 mm/year, reading a higher growth rate for the exterior crack (CR2). Regarding the tilt data, it is noticed that both towers feature in-phase cyclic oscillations either in longitudinal (N/S) and transversal (E/W) directions with a common trend in leaning towards West-South. Greater oscillation amplitudes (responsible for the separation movements of the façade) are found for the western tower, reading maximum tilting values of 0.94 mm/m in West

direction and 0.75 mm/m in South direction. These values describe relative displacements as the original inclination of the tower is unknown, but, assuming that the towers had no initial imperfection in verticality, the actual displacements can be derived from the 3D laser scanning conducted in 2014 [18]. Based on the surveyed points cloud, the tower featuring greater inclinations is always the western one, with tilting values of 5 mm/m in West direction and 3 mm/m in South direction. Considering the towers as rigid bodies undergoing pure rotation about a fixed axis at the bottom of the foundation, the top displacements result equal to 0.26 m and 0.15 m in transversal and longitudinal directions, respectively, with rotation angles of 0.29° and 0.17° . Being these values within the threshold limits identified through the stability analysis of the tower [22], no alarm was issued but the visual appearance of the monument resulted compromised, calling for remedial measures.

It is stressed that the structural performance of historic buildings can also be adversely affected by environmental conditions [23], [24]. As a rule, masonry expands when temperature rises and contracts when temperature falls. Thermal contraction on the material surface without a corresponding change in its interior temperature can cause a thermal differential and potentially lead to cracking. If cracks already exist, temperature fluctuations cause the cracks to open and close accordingly. In order to comprehend whether ambient variables may influence the damage scenario of the church, crack and tilt data are plotted along with temperature and relative humidity. The results are displayed in Figure 5, where the relationship between monitored quantities is expressed through the coefficient of correlation r . Unlike crack CR1, crack CR2 shows a higher environmental variability (Figure 5a-b), being located on the exterior side of the façade and therefore directly exposed to seasonal fluctuations of temperature and relative humidity. As the temperature goes down (warm-cold cycles), the crack width increases; as the temperature goes up (cold-warm cycles), the crack width decreases. From a physical viewpoint, this phenomenon is due to the cracks closure/opening associated with the

thermal expansion/contraction of the masonry material with rising/decreasing temperature. Owing to the thermal inertia of the masonry walls, small phase shifts are also observed between temperature variation and CR2 trend. On the contrary, no correlation is found between crack growth rate and relative humidity. Concerning the towers oscillation (Figure 5c-f), a direct relationship with temperature fluctuations is remarked. The towers rotate towards North/East when temperature decreases and lean towards South/West when temperature increases. This phenomenon affects both towers, but the western tower is the one featuring a stronger temperature influence, reading values of r nearly equal to the unit. Although less strong ($r < 0.50$), a direct correlation between towers tilting and relative humidity is found as well.

4.2.2. Static monitoring during and after the structural intervention

The evolution of cracks opening during and after the strengthening works is illustrated in Figure 6. It is highlighted that in the period ranging between the micro piling (June/July) and the beam underpinning (November/December) the crack meters record abrupt jumps, reading an increase of crack width of about 1.7 mm for CR2 and of nearly 1.4 mm for CR1. Although modern drilling techniques used for micro piling are very neat and do not produce any harm to structures, excessive vibrations in cohesionless soils can induce overall ground movements and propagate to the surface and adjacent areas. In the present case, the substantial cracks opening monitored during drilling operations is ascribed to the soil loosening originated from excessive ground disturbance. In fact, as the piling works stop and both towers and foundation anchoring systems become operating through the tie rods activation, the trend stabilises and the crack growth is arrested (Figure 6a).

In what concerns the environmental effects on the damage pattern associated with the cracks, no relation is found with respect to seasonal variations of ambient parameters (Figure 6b-c). Yet, quite a strong correlation is registered between cracks opening and daily variations of environmental conditions (Figure 6d-e), especially in terms of temperature ($r \approx -0.81$): when

the temperature drops off, the material shrinks and the cracks width increases, whereas when the temperature rises, the material expands and the cracks width decreases. As expected, the ambient fluctuations sensibly affect the damage pattern of the church during the works, being the cracks still active. On the contrary, after the activation of the anchoring systems and the injections of cracks, no further influence of ambient conditions on the cracking pattern is found. Analysing the tilt data (Figure 7), it is deduced that the towers movements do not feature any significant change of trend during the works execution, being the tilting rate steady throughout the intervention. Although the monitored time span was likely not enough to catch the tilting turnabout expected after the activation of the anchoring system, it is plausible that towers oscillations suffered much more from varying environmental conditions rather than other phenomena. This is confirmed by the plots in Figure 7 which show a significant correlation between towers tilting and air temperature ($r > -0.95$), much stronger than the one with relative humidity ($r < 0.45$).

4.3 Dynamic monitoring: results and discussion

The dynamic monitoring of Saint Torcato church was carried out in three campaigns performed between 11/02/2014 and 23/08/2015, collecting a total number of 4743 events (Table 2). Main objectives of the dynamic monitoring are the evaluation of the efficiency of the strengthening works and the analysis of the environmental effects on the system's dynamics.

The extraction of modal parameters is carried out through an automatic processing algorithm implemented in MATLAB [25] and based on the data-driven Stochastic Subspace Identification method (SSI-data) [8]. Particular attention is given to the choice of the model order since the selection of small system orders can hinder the identification of weakly excited modes, but the choice of inappropriate large system orders can result in the appearance of many spurious modes. For the present application, after testing different values of model order in the range 20-100, a maximum model order of 50 is chosen. To sort out stable poles (physical

modes) characterized by nearly identical frequencies, damping coefficients and mode shapes, from mathematical poles (spurious modes) which tend to exhibit lack of coherence between these quantities, a clustering analysis is adopted [26]-[27]. The final physical modes are selected based on the fulfilment of two clustering criteria, i.e. the Frequency Assurance Criterion (FAC) and the Modal Assurance Criterion (MAC):

$$FAC = \left| \frac{f_{i+1} - f_i}{f_i} \right|_k \leq FAC_{thr}, \quad k=[1,2,\dots,n] \quad (1)$$

$$\min(MAC_{i,i+1})_k \geq MAC_{thr}, \quad k=[1,2,\dots,n] \quad (2)$$

As only one measurement position is used for the dynamic monitoring, the MAC criterion is adopted as a relative modal amplitude comparison of the pole-weighted mode shape component identified in each iteration. Before starting the automatic estimation process, a pre-processing stage is carried out: first, signals are decimated with factor 5 and resampled at 20 Hz; then, a linear 7 sample leading and 10 sample lagging moving average is applied to remove spikes and drop-outs; lastly, the signals are de-trended and the undesired frequency components are filtered out through a 4th-order high-pass butterworth filter with cutoff frequency of 1Hz, followed by a 4th-order low-pass butterworth filter with cutoff frequency of 25Hz. This operation reduced the number of data points to 11800 and made the identification more accurate in the frequency range of interest (0-5 Hz). Although the total number of output channels recorded by the single force balance accelerometer was 3 (one per direction), the output signal in vertical direction is not considered due to low-amplitude acceleration response. The acquisition and data processing parameters adopted for the modal features extraction are summarized in Table 3. Note that control parameters and threshold values are established according to the results of a few events manually analysed via traditional Frequency Domain Decomposition (FDD) [28] and in compliance with the results of the previous OMA [21].

The datasets not matching the sorting criteria imposed by the control values are automatically discarded during the process. Notwithstanding this, a success rate of 93% is reached.

The automated dynamic identification allowed to track the first four vibration modes of the church, which are the most important for the scope of the paper since they are associated with the towers movements (see Section 4.1). The statistics of the estimated modal parameters are given in Table 4 together with the ones concerning the environmental variables monitored during the same time span. The table includes mean value, standard deviation, coefficient of variation (CV) and extreme values (min, max) of each quantity. The magnitude of the ambient noise level is expressed by the Root Mean Square (RMS) of the two in-plane acceleration channels and is found to be rather low throughout the monitoring period ($RMS_{avg} = 0.004$ mg), reading only a few peaks during the drilling execution ($RMS_{max} = 0.045$ mg). Unlike damping values, natural frequencies are much better estimated, being the corresponding standard deviations and coefficients of variation very low ($\sigma = 0.01$ Hz; $CV < 0.6\%$).

Figure 8a presents the evolution of the four identified natural frequencies from February 2014, two months before the works began, till August 2015, one month after the works were over. Although all data were pre-processed to improve the outcome of the modal estimation, the frequencies result quite scattered. In the authors' opinion this might be the consequence of a low SNR due to the inadequacy of some of the dynamic system's components, which unfortunately could not be upgraded. Notwithstanding that, there are a few aspects that can still be caught in the chart and are worth exposing. To help the interpretation of the results, the chart is repeated by overlapping both frequency and crack evolution and marking the main phases of the structural intervention (Figure 8b). It is observed that during the first monitoring campaign, which lasts till the casting of the reinforced concrete beams for the foundation underpinning (11/02/2014 – 21/11/2014), all natural frequencies feature a decreasing trend. As the structure was damaged and the cracks width was increasing, frequency downshifts are evident at this

stage. But, when the anchoring system becomes operational, the structural stiffness begins to increase leading in turn to an increase of the frequency values, as evidenced by the results from the second (09/01/2015–15/04/2015) and third (21/07/2015–23/08/2015) monitoring campaigns. This outcome visibly reflects the structural improvement obtained with the adopted strengthening measures. Table 5 summarizes the average frequency values estimated before and after the activation of the anchoring system. The most significant changes concern the first two modes, whose frequencies increase up to 3.3% and 1.7%, respectively, after the intervention. A sample of two-month evolution of the natural frequencies relevant to these two modes is presented in Figure 9, together with the variations of ambient noise, temperature and relative humidity for the same period. Both modal frequencies show a moderate correlation with the daily variations of temperature and humidity, whereas no direct relationship is found with ambient noise during the works execution. Still, it cannot be excluded that the dependence of natural frequencies on air humidity is only apparent and mainly originates from the inverse correlation between humidity and temperature, which turns out to be the main driver behind the changes in the structural features. As cracks tend to close with rising temperature, the system results stiffer and this is ultimately reflected into the increase of the frequency values, being modal and physical parameters directly related.

As mentioned before, the high level of background noise in the dynamic data combined with the low amplitude of the signals led to scattered frequencies, thus an accurate analysis of the ambient variability of the system's frequencies over the entire monitoring period could not be performed but for the first frequency, being the one with the highest percentage upshift. Indeed, the plot of the frequency-temperature relationship for the first mode (Figure 10a) exhibits a clear variation of the regression line following the activation of the anchoring system, with the range of temperature variation being almost the same. Analogous considerations can be made concerning the frequency-humidity relationship (Figure 10b), even though the correlation

between the two quantities is lower. Despite the scatter in the modal parameters estimation caused by the low SNR, the distinction between frequency values associated with damage and no-damage scenarios is appreciable. Both the arrangement of the frequency–temperature and frequency-humidity points before and after the anchors activation and the variation of the regression lines indicate that the observed frequency shifts are permanent, confirming that the adopted strengthening measures have been effective in restoring the sound condition of the church.

5. Conclusions

The paper has shown the importance of a monitored-based approach to the evaluation of the structural fitness of built cultural heritage. The added value that this key tool can bring to the investigation process on historic assets is exemplified through a real case-study structure, a masonry church in Portugal. Because of differential soil settlements, the building was affected by severe structural damage which needed to be contained. Thus, ad hoc strengthening measures were designed and put into practice. Before, during and after the intervention, the system's response was tracked through structural monitoring. The static monitoring enabled to control the damage evolution over years, to check the occurrence of unstable phenomena during the consolidation works and to analyse the environmental variability of the structural behaviour. Complementary, the dynamic monitoring allowed to supervise the progress of damage and appraise the effectiveness of the structural intervention. It is evinced that, when efficiently implemented, monitoring-weighted approaches can unlock a great potential and play a leading role in terms of preventive conservation and maintenance of heritage structures.

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Table 1 – Works schedule of the structural intervention in Saint Torcato church.

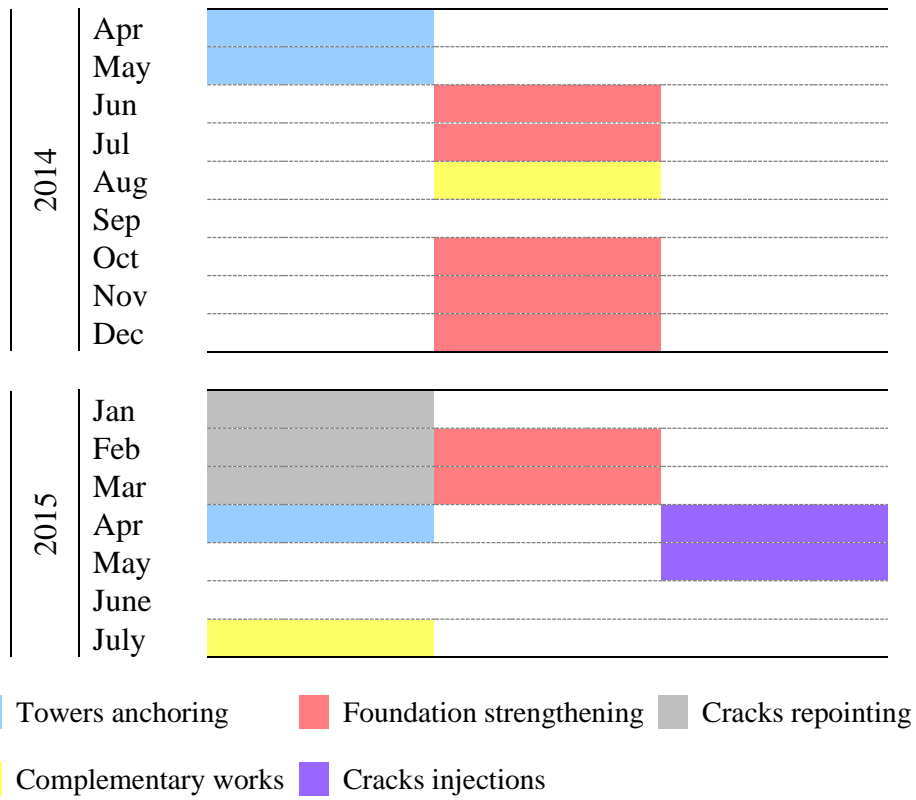


Table 2 – Data collection campaigns of the continuous dynamic monitoring.

Description	Time Span	Number of recorded events
1 st Campaign	11/02/2014 – 21/11/2014	3317
2 nd Campaign	09/01/2015 – 15/04/2015	1029
3 rd Campaign	21/07/2015 – 23/08/2015	397
Total		4743

Table 3 – Acquisition and data processing parameters for the automated modal identification.

Parameters	Description	Value
Acquisition parameters	Sampling rate [Hz]	100
	Signal duration [s]	600
	Sampling interval [h]	2
Processing parameters	State-space model order	50
	Decimation factor	5
	Frequency range [Hz]	2.0 – 3.0
	Damping range [%]	0.1 – 5.0
	FAC threshold	0.05 / 0.05 / 0.03 / 0.02
	MAC threshold	0.90
	Frequency control vector	[2.13 2.58 2.82 2.95]

Table 4 – Statistics of ambient variables and global modal parameters monitored from 11/02/2014 to 23/08/2015.

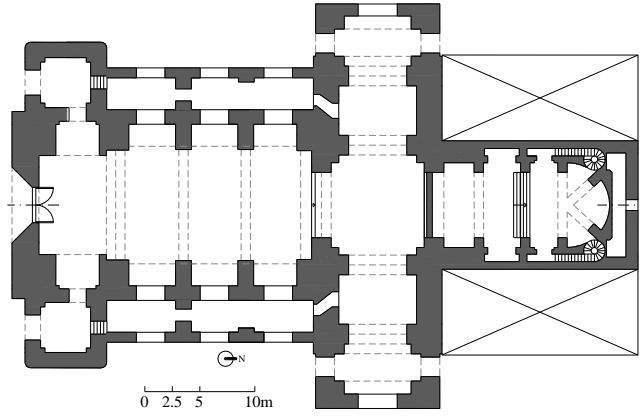
Results	AT [°C]	RH [%]	RMS [mg]	ω_1 [Hz]	ξ_1 [%]	ω_2 [Hz]	ξ_2 [%]	ω_3 [Hz]	ξ_3 [%]	ω_4 [Hz]	ξ_4 [%]
Average	16.55	68.22	0.004	2.15	1.47	2.61	1.55	2.84	1.46	2.94	1.38
St. Dev.	5.25	15.69	0.003	0.012	0.48	0.013	0.47	0.012	0.46	0.01	0.42
CV [%]	31.75	23.00	73.20	0.55	32.95	0.48	30.08	0.42	31.76	0.31	30.20
Maximum	28.78	101.09	0.045	2.26	4.63	2.71	4.28	2.96	4.14	3.00	4.08
Minimum	5.58	17.48	0.002	2.03	0.14	2.46	0.17	2.70	0.14	2.70	0.30

Table 5 – Average frequency values before and after activating the tie rods of the foundation strengthening system.

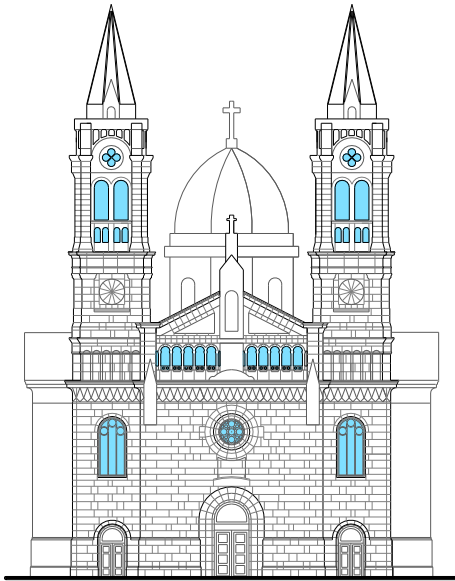
Mode	Average Frequency [Hz]		$\Delta\omega$ [%]
	Before tie rods activation	After tie rods activation	
1 st Mode	2.12	2.19	+ 3.3
2 nd Mode	2.59	2.64	+ 1.7
3 rd Mode	2.83	2.85	+ 0.9
4 th Mode	2.93	2.95	+ 0.7



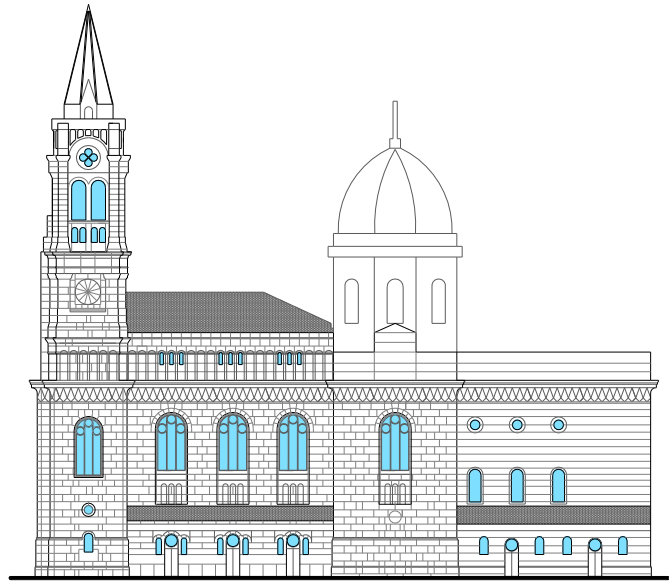
(a)



(b)

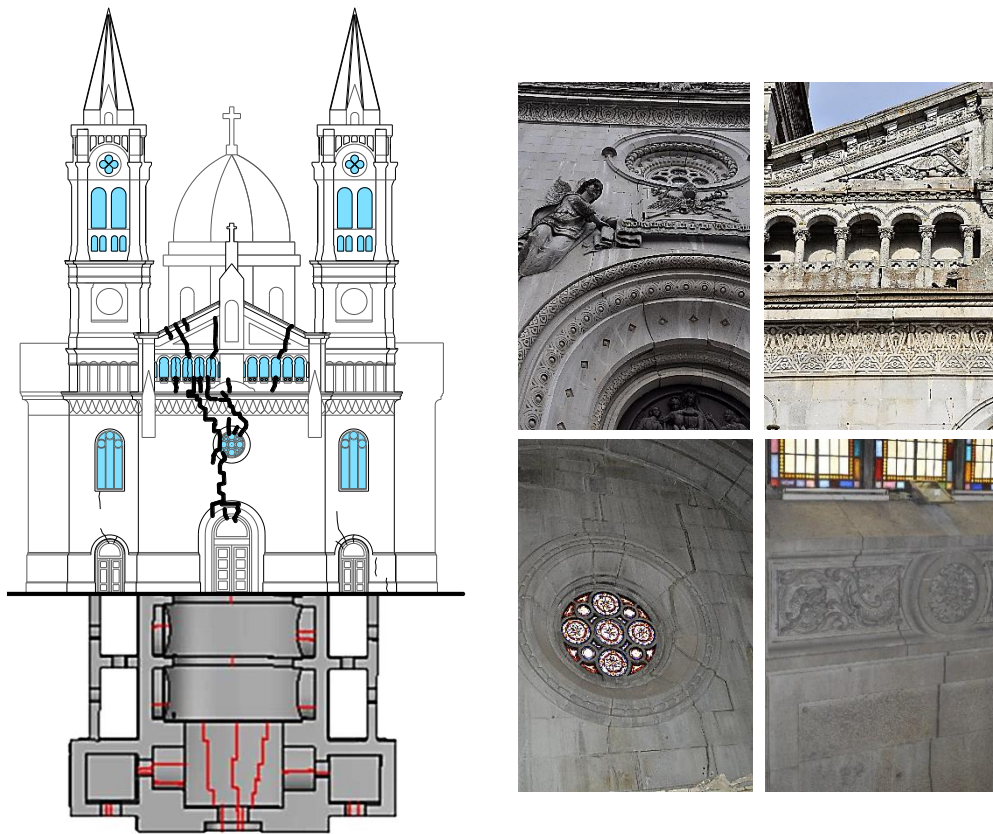


(c)



(d)

Figure 1 – Church of Saint Torcato: (a) general view; (b) plan; (c) façade; and (d) East front.



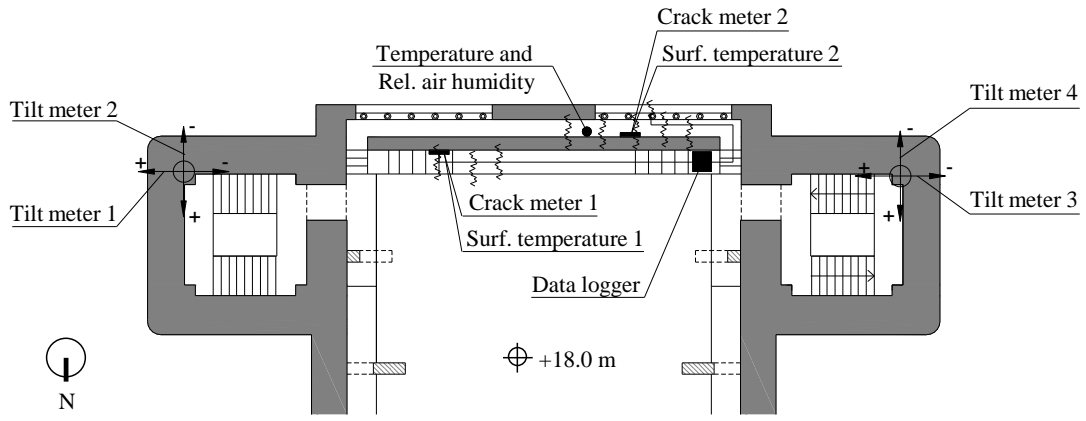
(a)

(b)

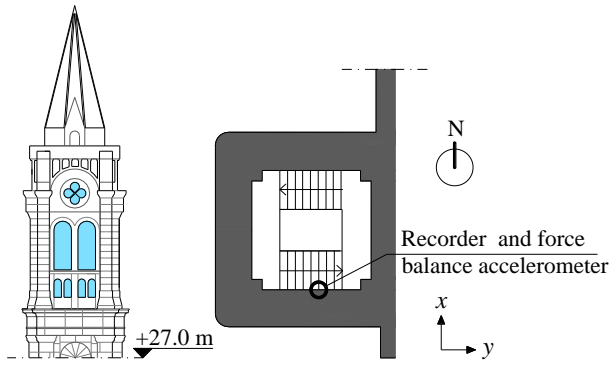


(c)

Figure 2 – Structural damage in the church: (a) crack pattern of the façade and choir vault; (b) details of the cracks; and (c) possible collapse mechanism [18].



(a)



(b)

Figure 3 – Distribution of the monitoring systems: (a) static and (b) dynamic equipment.

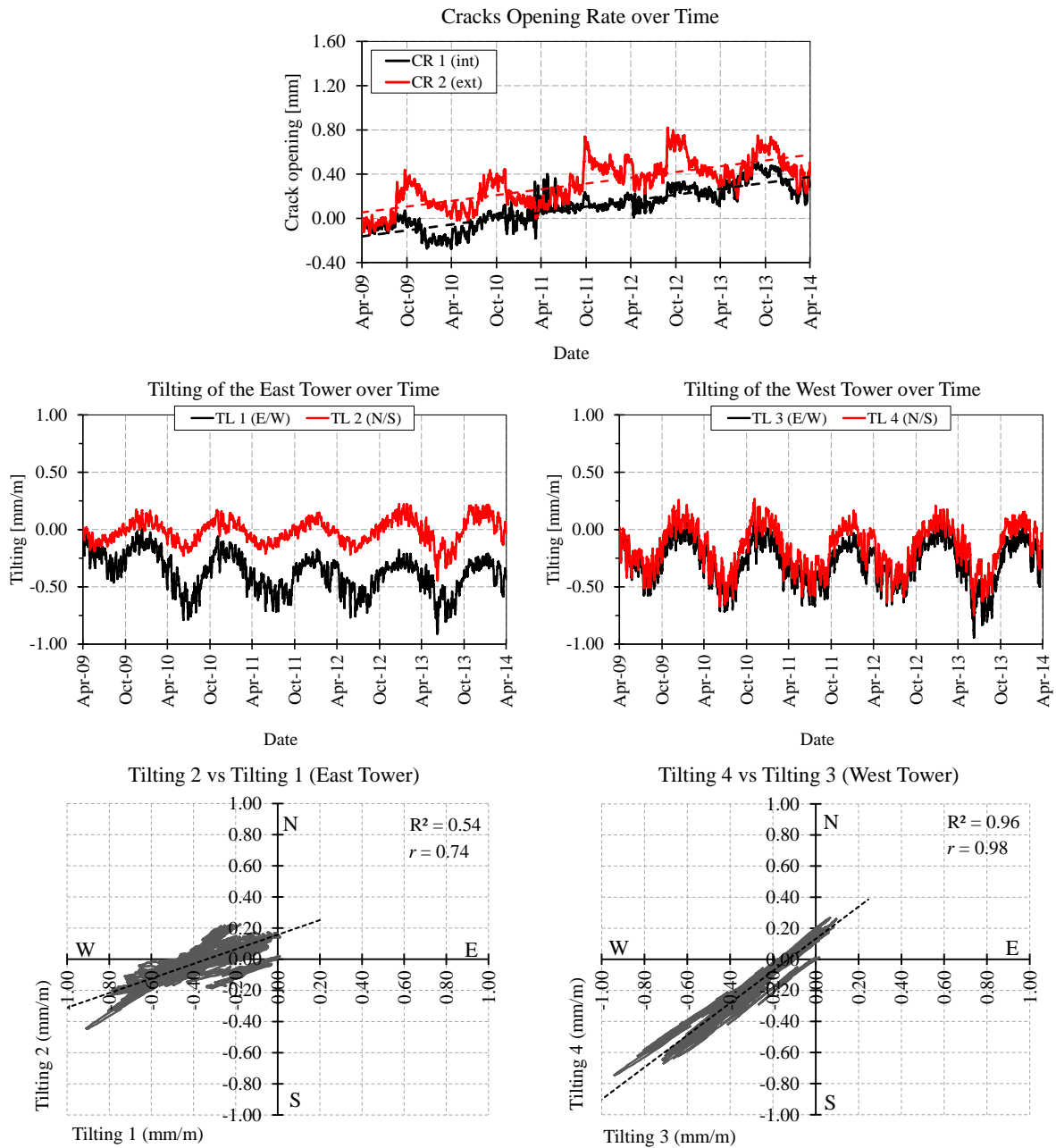
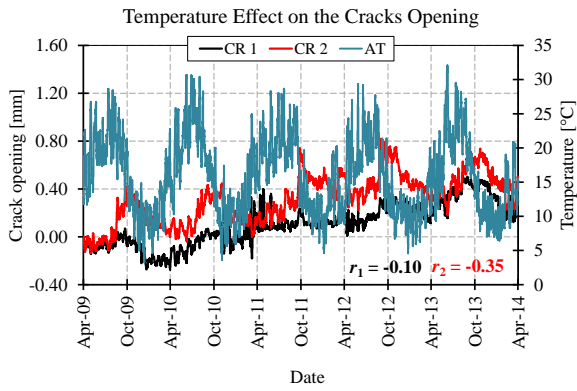
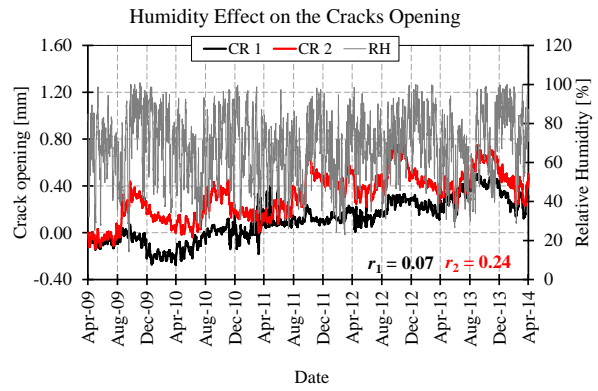


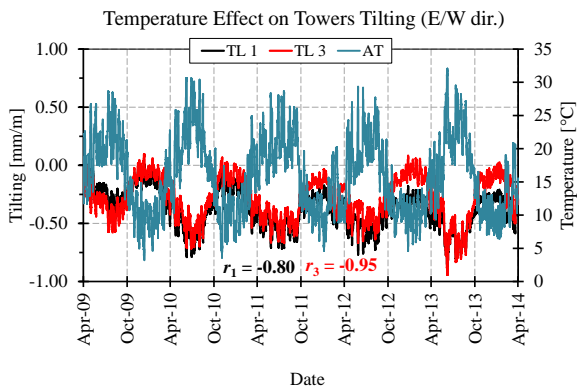
Figure 4 – Static monitoring of cracks opening and towers tilting before the works execution (r and R^2 indicate the coefficients of correlation and determination, respectively).



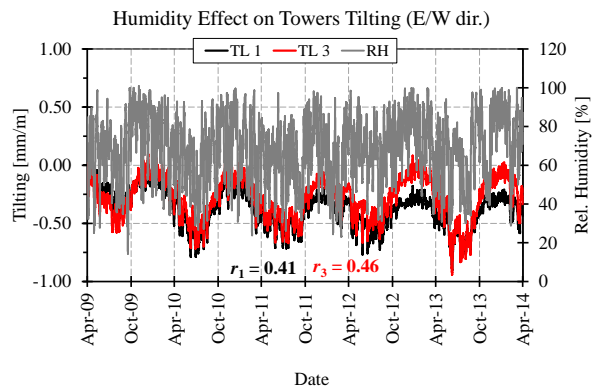
(a)



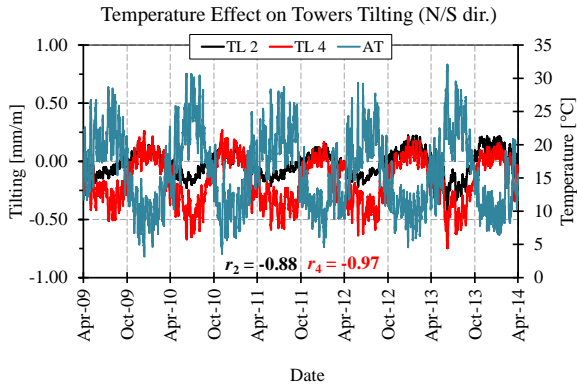
(b)



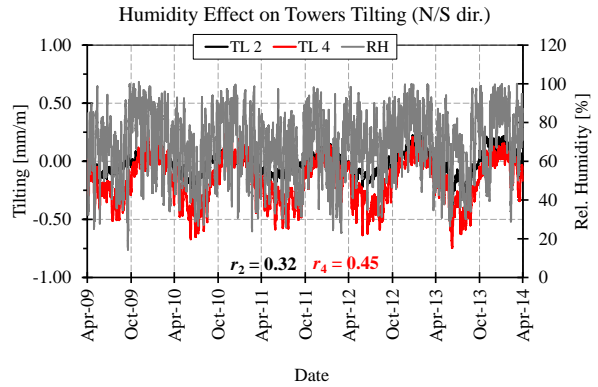
(c)



(d)



(e)



(f)

Figure 5 – Variation of cracks opening and towers tilting versus temperature (AT) and relative humidity (RH) before the works execution (the coefficient r indicates the correlation between crack or tilt data and ambient variables).

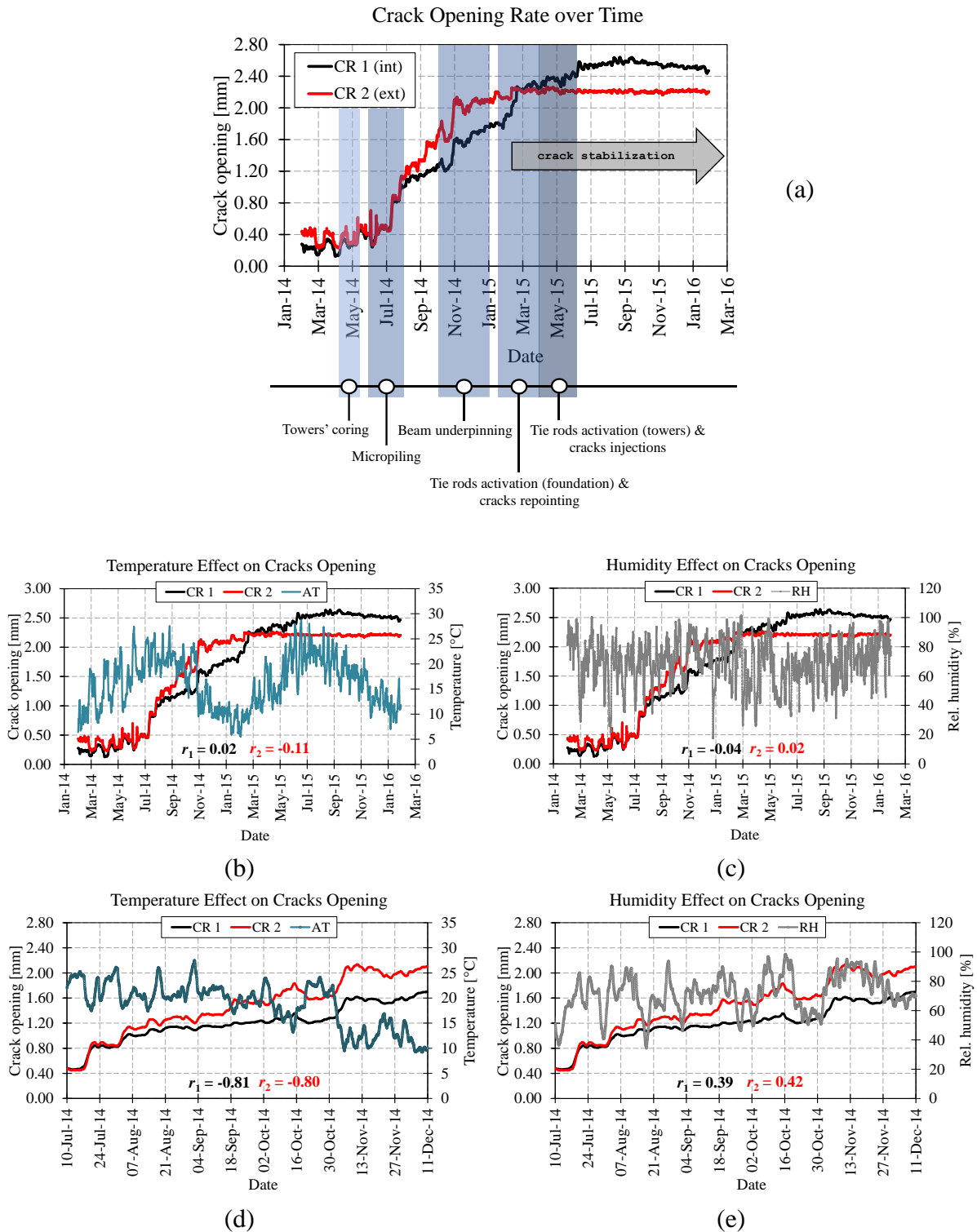


Figure 6 – Static monitoring during and after the structural intervention: (a) evolution of cracks opening rate; variation of cracks width with respect to (b-c) seasonal and (d-e) daily fluctuations of temperature and relative humidity.

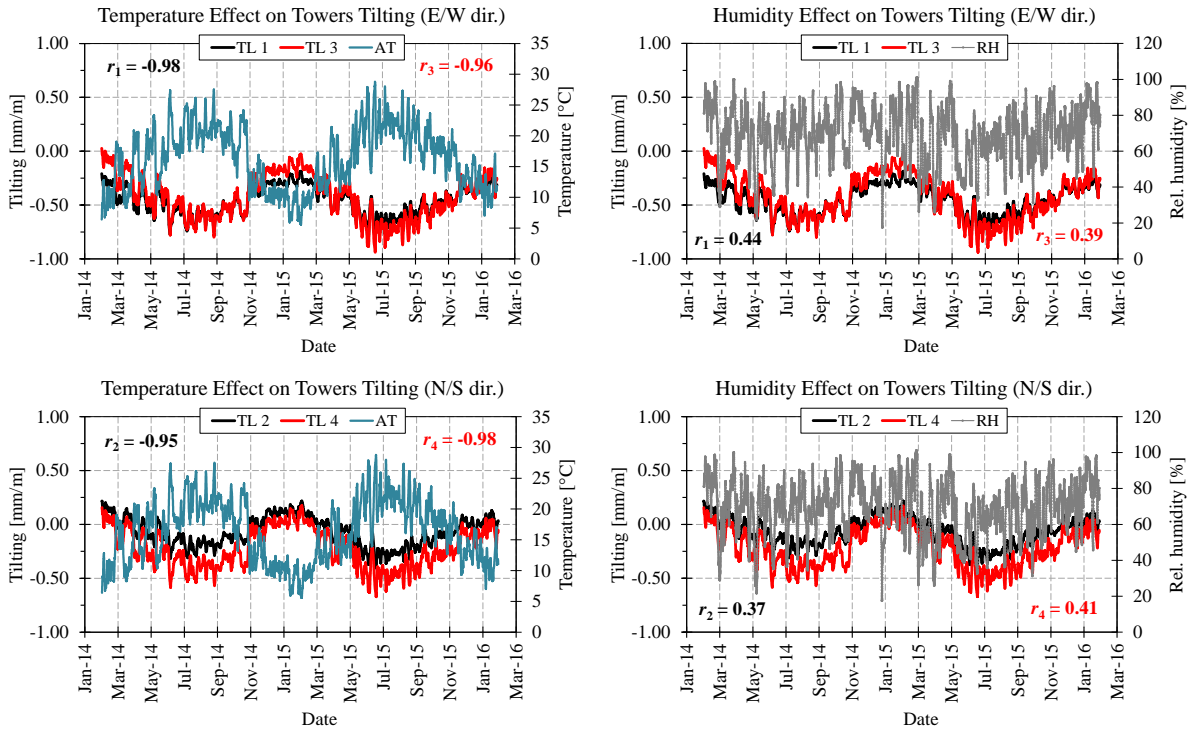
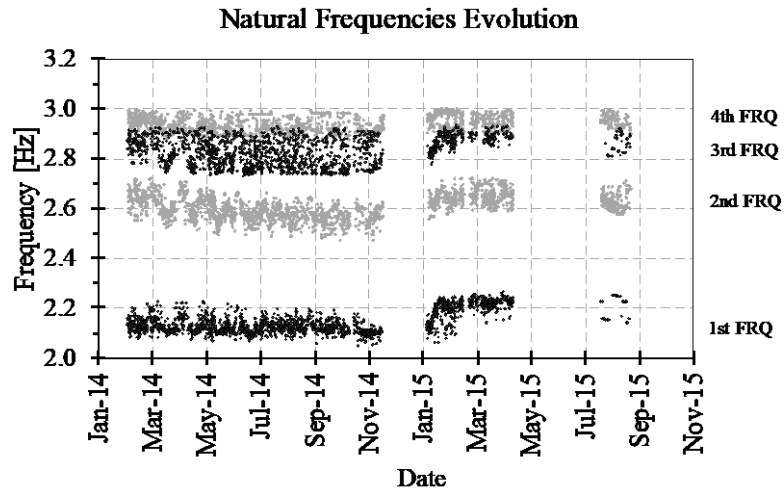
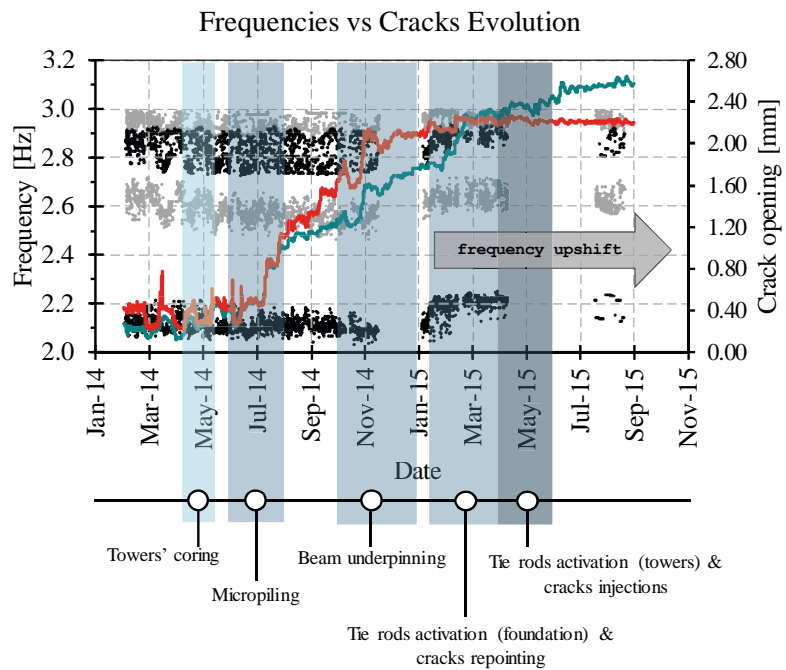


Figure 7 – Variation of towers tilting versus temperature (AT) and relative humidity (RH) during and after the works execution (the coefficient r indicates the correlation between tilt data and ambient variables).



(a)



(b)

Figure 8 – Evolution of (a) the identified natural frequencies during the structural intervention and (b) comparison with the cracks evolution.

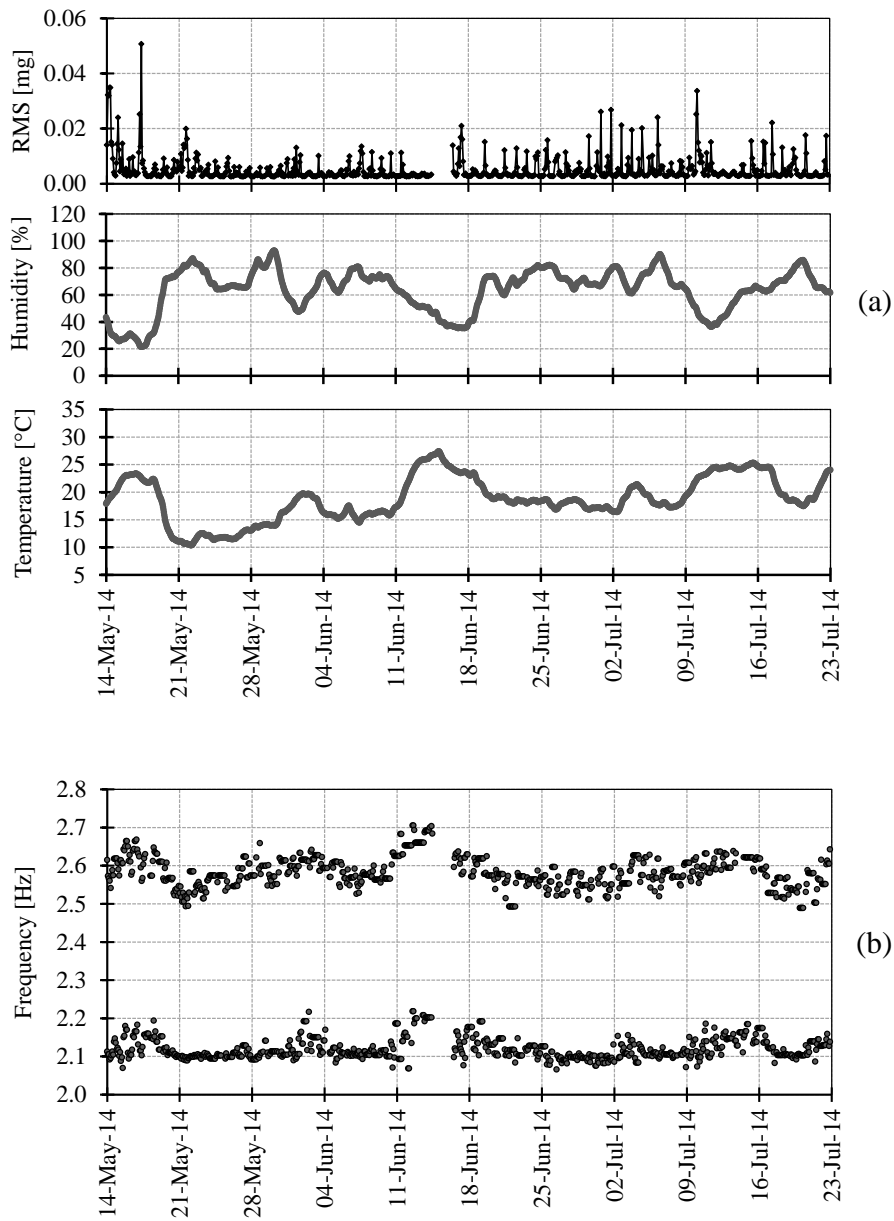


Figure 9 – Close-up of the time evolution of (a) ambient noise, relative humidity and air temperature with respect to (b) the natural frequencies of the first two modes of the church from 12/05/2014 till 23/07/2014.

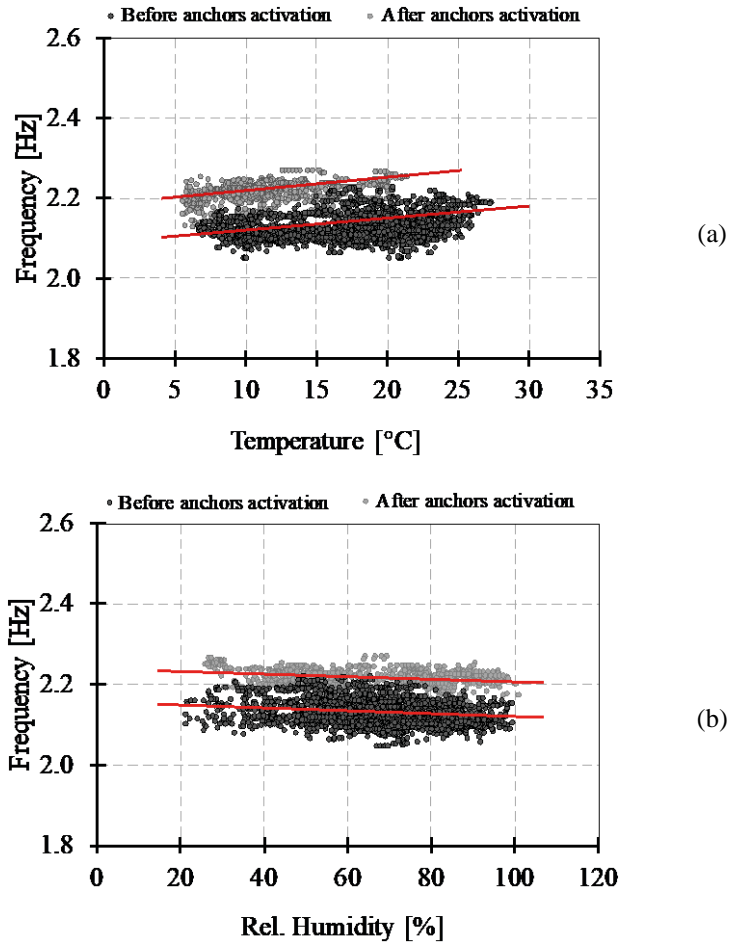


Figure 10 – Variation of (a) frequency-temperature correlation and (b) frequency-humidity correlation for the first mode before and after the activation of the anchoring system.