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Historic Buildings: Long Term Stability Evaluation Using Wireless Sensor Networks

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Abstract An automatic diagnostic monitoring system can guarantee the safety and integrity of a historic building. In this paper, we describe the long term application of a wireless sensor network (WSN) for permanent health monitoring in the Torre Aquila, a historic tower in Trento, Italy. The system consists of accelerometers, thermometers and fiber optic sensors (FOS) with customized wireless modules and dedicated software designed for wireless communication. The whole system was completed and started operation in September 2008, and data from the various sensor nodes are collected continuously, save during periods of system maintenance and update. Based on the first 1.5 years of operation in assessing the stability of the tower, the WSN is seen to be an effective tool. Modal analysis indicates that the tower has two independent structural parts. A comparison between the acquired long term deformation measurements and simulated numerical results shows good agreement. Monitoring of ambient vibration suggests that such vibration is not now a source of concern for the stability of the tower.

Keywords: Wireless sensor network, System identification, Structural health monitoring, Long term evaluation, Heritage buildings

Introduction

Monitoring historic buildings becomes more and more important, not only due to material deterioration in time, but also as a response to significant changes in the surrounding environment and to human action on the building since it was first built. Examples of historic structure monitoring can be found in the literature, while ever more conferences on historic buildings dedicate special sessions to this topic (D'Ayala and Fodde 2008). With the emergence of WSN technology, we now have a good solution for low cost and high efficiency structural health monitoring applications (Lynch and Loh 2006). Recently WSN technology has progressed from an initial hub-spoke architecture to a decentralized large scale multi-hop intelligent network, with hardware development (Polastre et al. 2005) providing long term monitoring capability in large structures.

In this paper we introduce the application of a dedicated WSN to an historic building, Torre Aquila, for its permanent health monitoring (Fig. 1). The tower was built in the 13th century, located in the city of Trento, Italy, and today attracts many tourists every year from all over the world, thanks to the valuable historic artwork in the building: a series of frescos, called "the Cycle of the Months". Torre Aquila was once a gate, later elevated with an additional floor and closed by adding another part, with a structural joint between the two parts (Fig. 1(a)). The joint passes through the wall in the middle of the frescos. To know if the two parts are structurally connected or not is of prime importance for future tower monitoring and management. What's more, the asymmetric connection to the city wall and to adjacent buildings makes the tower exhibit strongly asymmetric mechanical behavior, which could cause the joint between the two parts to open. With the increase of tourist influx to the tower and of traffic flow nearby, plus possible future tunneling work below, a permanent monitoring system was needed to provide the owner with a quantitative assessment of the tower stability.

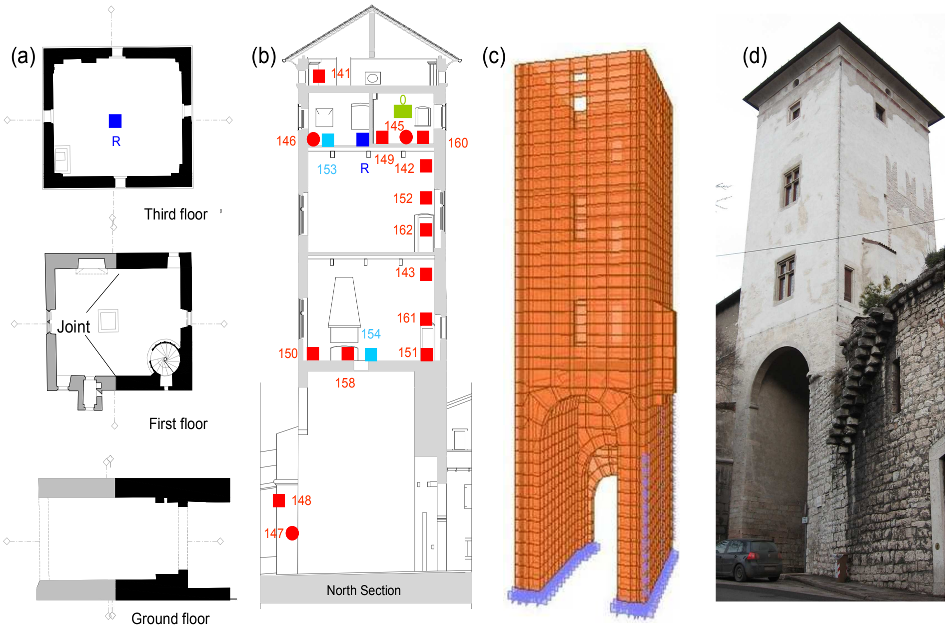

Figure 1: Schematic illustration of Tower and system installation

Preliminary Investigation and Modal Analysis

Endoscopic test Before application of the monitoring scheme, a set of endoscopic tests were carried out to study the mechanical properties of the materials, together with the non-destructive test methods including geognostic surveys, thermographic tests and chronological dating. The endoscopies were conducted with an 8-mm diameter flexible probe inserted into a hole with a diameter of 12 mm. The maximum insertion length can be up to 90 cm. Totally 16 endoscopic tests were implemented throughout the different floors. Endoscopic tests showed that the two parts of the masonry body exhibit completely different stratigraphic and mechanical properties (Zonta et al. 2008). In detail, the lower level walls are 40 cm thick, made of stone blocks and with an incoherent wall filling. At the upper levels, the older portion of masonry is thick stone blocks, while the more recent part is brick and stone blocks of different sizes.

Operational modal analysis A series of ambient vibration monitoring sessions were carried out to investigate the dynamic characteristics of the tower, which is quite necessary for the further application of WSN. Three piezoelectric accelerometers (model: PCB 393B12) were used to record the ambient vibration in three orthogonal directions at a sampling rate of 200 Hz. The tests were conducted at the place of R on the top floor (Fig. 1(a-b)). Based on the free ambient vibration records, the frequency spectrum is analyzed to extract the modal frequencies of the tower. In Fig. 2 four original independent free vibration sessions are adopted. Hann window is applied to improve the frequency spectrum before the use of FFT algorithm. By using peak picking method, the first 6 modal frequencies are identified from the spectrum: 2.8, 3.8, 4.7, 5.5, 7.1 and 8.3Hz.

Table 1: Comparison of modal frequencies between FEM and test results

Mode order	*FEM model A (Hz)*	*FEM model B (Hz)*	*Test results (Hz)*	Δ_A *(%)*	Δ_B *(%)*
1	3.08	2.75	2.8	-10	1.79
2	3.94	3.74	3.8	-3.68	1.58
3	5.51	4.91	4.7	-17.23	-4.47
4	6.82	5.82	5.5	-24	-5.8
5	7.48	6.94	7.1	-5.4	2.3
6	10.12	7.78	8.3	-21.92	6.27

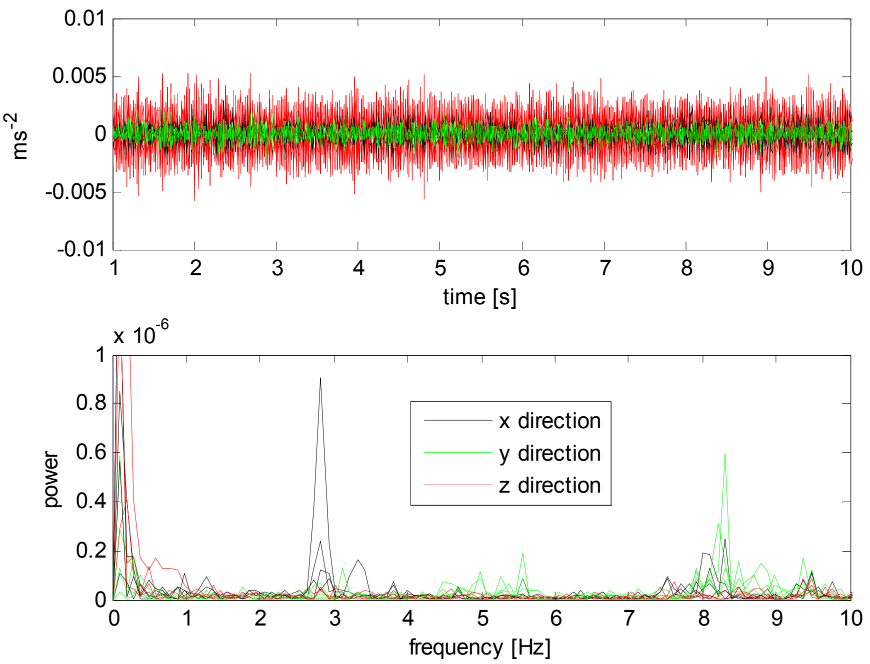

Figure 2: Power spectrum at node #145

On the other hand, a three-dimensional finite element model (FEM) was developed in the paper by Zonta et al. (2008) based on the geognostic investigation and endoscopic tests (Fig 1(c)). The main uncertainty still lies in the degree of connection between the two masonry parts of the tower. To deal with this uncertainty, two versions of FEM were developed, where model A considers the two parts as structurally connected and model B takes the two parts to be completely separate. The first six estimated eigenfrequencies with respect to each FEM are compared with experimental results in Table 1, where the Δ is the percentage difference between the estimated and experimental values. The comparison shows that model B matches the experimental results much better than model A. The estimated frequencies based on mode A usually being higher than the measured values indicates that total connection between two parts overestimates tower stiffness. Thus it is reasonable to regard that the two tower parts are structurally separate based on the current observations. In future, deeper studies will be carried out, including the identification of mode shapes, to further understand the tower behavior. Based on the updated model, more interesting results could be obtained under various external action and damage scenarios. For more information, the reader can refer to the paper by Zonta et al. (2008).

Motivation and Challenges to WSN in the Tower

To limit the invasiveness of the system in the tower, WSN technology was adopted in this project to eliminate the extensive cabling needed for a traditional tethered monitoring system. The motivation and requirements of monitoring set many challenges to WSN technology. First, to collect enough information, and to give warning of any potential risk to the fresco in real time, we needed the whole system to operate continuously for a long time span (e.g. one year) without battery maintenance. This is a challenge since power is always the scarcest resource (Lynch and Loh 2006) in a wireless network. Such a challenge can only be met by using customized hardware and dedicated software to achieve optimum system operation. Second, the system has both accelerometers and deformation sensors, to evaluate the dynamic and static behavior of the tower, as well as environmental nodes to compensate for temperature effects. To reconcile the different kinds of sensor nodes within the same network, an effective and flexible topology algorithm is needed to optimize the wireless communication system. Further, the use of multiple accelerometers within a network requires that the time synchronization issue be properly addressed. Last, the ability to remotely task the network will be very useful in adjusting system configuration as necessary.

Design of Monitoring System Scheme

To meet these challenges, the 3MATE! WSN module was selected as the core platform, given its low power consumption and low cost (www.3tec.it). At the vibration nodes, an additional FRAM chip was used in the WSN module to allow for its high sampling rate. As to software, a high level architecture was designed atop the middleware called TeenyLIME, accommodating the demands of heterogeneity, time synchronization and remote task functionalities. On this topic, the reader can find detailed information in the paper by Ceriotti et al. (2009).

With the selected WSN module, 3 accelerometers, 2 FOSs and 12 environmental nodes were deployed in the tower (Fig. 1(b)), to cover static and dynamic evaluation of structural integrity, from local to global scale. Customized interfaces were designed with respect to the differing sensing requirements. The two FOSs (#153 and #154) are a new type of fiber optic strain sensor, coupled with a low cost interrogation unit, which were designed by Tretec and the University of Trento and systematically tested and calibrated in our laboratory. They are used to record joint behavior and wall inclination with a long measurement base. The accelerometers (#145, #146 and #147) are used to monitor the dynamic behavior of the tower, and were installed on the top floor and in the foundations respectively (Wu et al. 2009).

In the current configuration, the FOS and environmental nodes gather one sample per minute and all the vibration nodes are set to work at a sampling rate of 200 Hz for 30 seconds each session. All the nodes are powered by two pairs of batteries (C or D type according to the sampling rate), except the two fiber optic sensors, where the wireless modules are powered directly by the interrogation unit. The whole system can work continuously for around a year without changing the batteries.

Long term Evaluation of the Tower

The system was first started in September 2008, and has worked continually save during system maintenance and update (Fig. 3). Further analysis based on the updated FEM shows that thermal gradients always produce the largest absolute strain in the tower, compared to other effects such as wind and snow, although only a minor part of this is stress-induced.

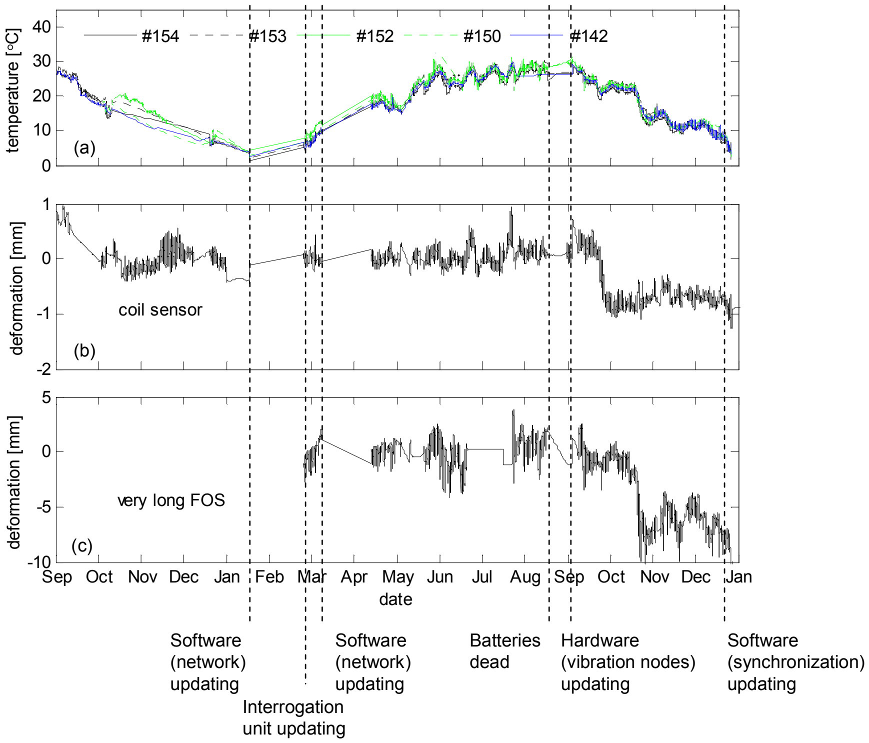

Figure 3: Temperature records from different nodes (a); Deformation time history recorded by coil FOS (b) and long FOS (c)

Static analysis of the Tower Fig. 3 shows the deformation records from the two FOS with their corresponding temperature records. Fig. 3(a) presents the temperatures measured by different environmental nodes. All temperature records from each node show similar trends. Looking at the temperature records shows a clear daily variation related to sunrise and sunset each day, and an obvious seasonal trend with maximum temperature in summer and minimum in winter. Influenced by the temperature, the tower, including the width of the joint and the length of the wall, exhibits a similar trend (Fig. 3(b, c)). The amplitude, as recorded by the coil sensor (Fig. 3(b)) in a daily cycle, is between 0.05mm and 0.30mm, in good agreement with the numerical results of the FEM model B discussed in (Zonta et al. 2008). Fig. 3(c) shows the wall corner deformation measurements acquired by the very long FOS (node #153) from February 2009 to January 2010. Comparison between the real measurements from #153 and predicted results shows that they are of the same magnitude.

Since damage to the frescos is caused by stress-induced strain, compensation is important to remove any temperature related effects, whether daily or seasonal. Based on the compensated deformation, we can further update the joint evolution conditions by using a Bayesian updating algorithm, with the newly acquired data, day by day. The estimated probability of a trend in joint deformation, based on data available now, is very close to zero, so there is no special concern for the safety of the tower nor for the integrity of the frescos. For detailed procedures of temperature compensation and model updating, the reader can refer to the paper by Zonta et al. (2010).

Vibration limit analysis Every day, we record a series of vibration sessions at intervals of 45 minutes. In our design, a low cost compact tri-axial accelerometer based on Micro Electro Mechanical Systems (MEMS) technology is adopted to monitor tower vibration. Each sensor was carefully calibrated in the laboratory and the results were discussed in the paper by Wu et al. (2010). The RMS resolution of the vibration node is estimated to be around 0.07 m/s^2. This resolution level is not sensitive enough for a modal analysis with ambient vibration, but good enough for risk warning under critical vibration.

In order to monitor the day to day vibration level on the ground and top floors of the tower, every day a number of sampling sessions were acquired, each lasting 30 seconds. As an example Fig. 4(a) shows part of one typical signal acquired, under normal environmental conditions: on the horizontal axis, recorded at node #146 at 11:38 AM; and under similar conditions with jump nearby at node #145, vertical axis, at 11:31 AM. We see that the normal ambient acceleration is very low, less than 0.2 ms^{-2}. Although this vibration level is of the same order as the sensor noise, this is sensitive enough to detect critical vibration such as the jump at node #145 in Fig. 4(a). We can see that even in the

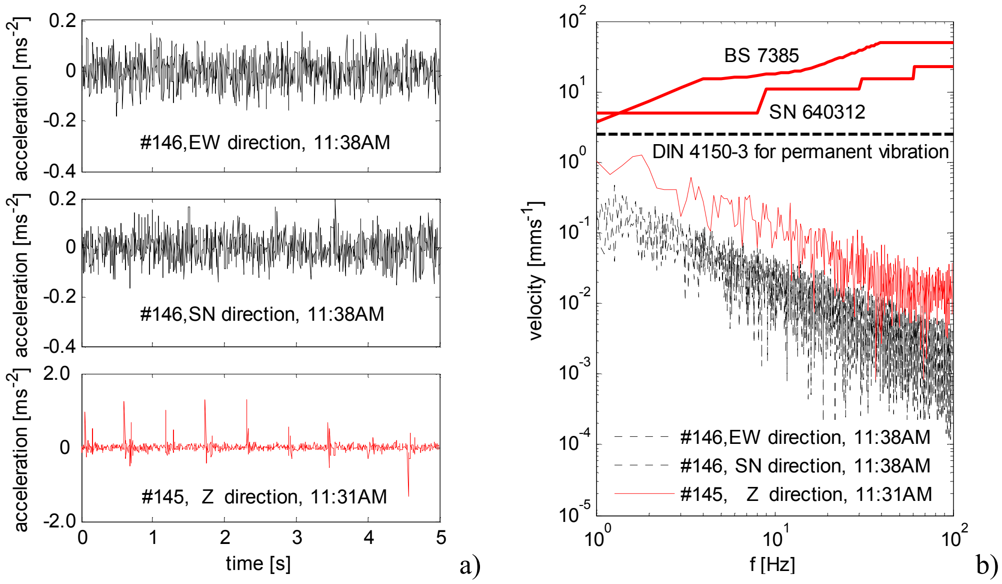

Figure 4: Typical time history recorded by node #146 and #145(a);Fourier spectrum of typical acceleration records, compared with vibration limits (b)

‘jump case’, the vibration level is still much lower than the vibration limits (Fig. 4(b)), including both permanent and temporary vibration conditions, as suggested by BS 7385-2, DIN 4150-3 and SN 640312 standards (BSI 1993, DIN 1999, SNV 1992). It provides a more quantitative estimate of vibration, and shows that ambient vibration is currently not a source of concern for the tower stability. The result also justifies the use of this low cost vibration node in our case.

Conclusion

A wireless structural health monitoring technology was applied in Torre Aquila to monitor its structural integrity. To address correctly the challenges set by the monitoring target, we designed customized hardware and dedicated software to form a reliable, flexible and long term stable WSN. Based on wireless sensor technology, the tower is under overall evaluation. Endoscopic test showed that the two parts of the masonry body have completely different stratigraphic and mechanical properties, and modal analysis further indicates that the tower has two independent structural parts. However, the long term joint deformation trend is monitored by investigating the real trend after removing temperature effects. Based on current monitoring data, there is no evidence that the joint is opening. Using the updated FEM, good agreement can be obtained between estimated and experimental values. Ambient vibration monitoring suggests that such vibration is not now a source of concern for the stability of the tower. This application proves that WSN is an effective tool for long term monitoring and will be a useful addition to project management resources in the case of future tunneling work.

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