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Dynamic testing and health monitoring of historic and modern civil structures in Italy

Vincenzo Gattulli[*1], Marco Lepidi[2a] and Francesco Potenza[1b]

[1]Department of Civil Architectural and Environmental Engineering, University of L'Aquila, Nucleo Industriale di Pile, 67100, L'Aquila, Italy
[2]Department of Civil, Chemical and Environmental Engineering, University of Genoa, Via Montallegro 1, 16145, Genoa, Italy

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Abstract. The paper reports a wide overview of the scientific activities on Structural Health Monitoring (SHM) in Italy. They are classified on three different conceptual scales: national territory (macro); regional area (medium); single structure (small). In the latter case differences have been pointed out between permanent installation and short-term experimental campaigns. A particular focus has been dedicated to applications devoted to cultural heritage which have an important historic, strategic and economic value for Italy. Two specific cases, the first related to the permanent monitoring of an historical Basilica and the second regarding the dynamic testing of a modern structure, have been presented as a basis for a general discussion.

Keywords: structural health monitoring; system identification; cultural heritage; dynamics

1. Introduction

Public and private administrators currently have to address the issue of safeguarding the Cultural Heritage (CH), the modern buildings and the infrastructures – and finally cities as a whole – due to their strategic and economic significance. In this regard, Structural Health Monitoring (SHM) has emerged as an interesting tool for its capability to assess the real conditions of a structure, Amezquita-Sanchez and Adeli (2014), Goyal and Pabla (2015).

In Italy, the most promising application fields of SHM include the continuous evaluation of the performance of damaged structure and eventually of the protection efficiency of not-permanent reinforcing in the case of earthquake, Foti *et al*. (2014), Potenza *et al*. (2015), Russo (2013a), the constant observation of ambient vibrations due to traffic or wind, Zonta *et al*. (2010), Jang *et al* (2010), Saisi *et al*. (2015), the registration of corrosion, high temperature, cumulative crack growth, Lorenzoni *et al*. (2016), the realistic assessment and monitoring of the enhanced dynamic response of controlled or isolated structures, Basu *et al*. (2014).

Furthermore, a strong augmentation of SHM activities followed the recent catastrophic 6.3 Mw

∗Corresponding author, Professor, E-mail: vincenzo.gattulli@univaq.it
[a] Assistant Professor, , E-mail: marco.lepidi@unige.it
[b] Research fellow, E-mail: francesco.potenza@univaq.it

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earthquake occurred in the small city of L'Aquila in Italy, causing considerable damage to the existing structures, Özerdem and Rufini (2013), Ceci *et al*. (2010, 2013). In particular, a large portion of the cultural heritage suffered considerable damage, Brandonisio *et al*. (2013), D'Ayala and Paganoni (2011). Consequently, numerous scientific activities have accompanied both the immediate recovery and the long-term reconstruction program in different fields of earthquake science and engineering. For example, after the installation of all the scaffolding systems, which were necessary to prevent damage increases or even structural collapses, SHM methods were used to understand the actual structural behaviour, and moreover to assess the effectiveness and quality of these emergency solutions. To this purpose, in some cases the permanent monitoring has been lasting from a limited number of hours up to several months. In other cases, the monitoring system has been permanently installed on the structure, and it can be used also to determine the change that will occur in the structural behavior during the reconstruction phase, Russo (2012a), Potenza *et al*. (2015). In particular, several monitoring systems have been installed in the emergency phase, to understand the occurred behavior in damaged building, Rainieri *et al*. (2012), or during the construction of temporary scaffolding, in order to verify the efficacy of the added structural system especially in the case of monumental building, Cimellaro *et al*. (2012). Moreover, a series of accelerometric monitoring systems of buildings have been deployed and managed by the Italian Department of Civil Protection (DPC) during the seismic aftershock sequence, Spina *et al*. (2011).

Recently, structural monitoring activities have been deemed a qualifying element of the city towards integration of this function with latest generation communication networks that use optic fibers, Ye *et al*. (2014), and area served by wireless systems with high efficiency, Gattulli *et al*. (2014). These actions are consistent within of the emerging concept of development of a Smart City (SC) in which the pervasive use of Information and Communication Technologies (ICT) can actively improve the life quality of citizens of an urban area. The concept of SC is accompanied by a new model for smart urban development and sustainable socio-economic growth, Neirotti *et al*. (2014). ICT-based solutions have to be considered as tools able to help the urban and living planning that have the aim of improving the economic, social and environmental tasks. Indeed, the application of ICT-based advanced services can bring improvements in multiple applicative domains, from advanced transport and mobility management to ambient assisted living and e-government.

Finally, the specific area of CH should be mentioned for Italy, where there are, for example, a large number of historical masonry towers. In this case, it is difficult to realize surveys, invasive flat jacks tests, removal of plaster and endoscopic tests, therefore vibration-based monitoring or dynamic tests have been often applied to investigate dynamic behaviour and hidden damages, Foti *et al*. (2012a), Foti *et al*. (2012b), D'Ambrisi *et al*. (2012), Saisi *et al*. (2015). Moreover another use of the dynamic tests is related to the investigation on the effectiveness of specific interventions as in the case of stiffening for resonance cancellation as illustrated in Lepidi *et al*. (2009).

The paper summarizes first the state-of-art of SHM in Italy and then it delineates the main steps of SHM system design illustrating a hierarchical path for reaching the full system operability. In the last part of the paper, two cases studies are presented: the long-term monitoring of a seismically damaged historic monumental church and the dynamic testing of a seismically damaged strategic modern building.

2. Rapid development of SHM in Italy

In Italy, SHM activities are developed at three different scale levels: macro, i.e., a monitoring system network widespread on the whole Italian territory, medium, i.e., a monitoring system network limited to an area of a single city or historical center and small, i.e., a SHM system installed on a single structure such as a monumental building, a bridge, etc.

In the first case, the Italian Department of Civil Protection (DPC) has developed and currently manages a network of permanently vibration-based monitoring systems installed in public buildings, bridges and dams spread in all Italian territory, Dolce *et al*. (2015), Spina *et al*. (2011). This network is called Seismic Observatory of Structures (OSS, acronym of the Italian name "Osservatorio Sismico delle Strutture"). The 65% of the buildings that belong to this network are made in reinforced concrete, while the remaining 35% are masonry structures. Naturally, the highest percentage of buildings is located in the areas with high risk of seismic hazards: 39% in zone I, 55% in zone II, 4% in zone III and 2% in zone IV, according to the Italian Standard classification. Moreover, among the various typologies of the buildings, there are about 50% of schools, 14% of hospital, 22% of city halls and 14% of other types. The monitoring systems are composed by force-balance accelerometers operating in both modes, wireless or wired. For each system there is a triaxial accelerometer placed at ground level needed for acquisition of the input. A local unit in each building manages the acquisitions of the recorded sensor accelerations induced by both micro-tremors having a Peak Ground Acceleration (PGA) of 10-4g and strong-motion earthquakes. The data are recorded when a pre-fixed threshold (usually ±0.01 g for the ground and ±0.02 g for the structures in elevation) with a sample time of 200 Hz is overcome. Then, data are automatically sent to a central server at DPC headquarters in Rome and processed in case of earthquake. The OSS monitored structures are currently 129, yearly increasing in number. The first setup was installed in the 1992 while the permanent complete monitoring system started in the 1998. One of the most important tool implemented in the network is related to a post-earthquake automatic analysis. The aim is to furnish a rapid damage scenario of the buildings. The algorithm implemented by the DPC is made run in Matlab and it calculates the following parameter: the peak ground acceleration (PGA) in X and Y main directions of the buildings, the peak structural acceleration (PSA), i.e., the max acceleration of the structure in X and Y main directions, the corresponding dynamic amplification factor given by the ratio between PSA and PGA, and the max inter-story drift provided by the displacements calculated with a double integration of the accelerations. These parameters are then compared with the threshold values connected to the different damage levels.

Regarding the medium scale, SHM at urban scale is considered one of the possible key-point within the more general concept of Smart City (SC). This concept was introduced to characterize a wide area of activities that aim to improve the quality of life of citizens through the widespread use of Information and Communication Technologies (ICT). The latter are seen as a tool to help the planning of all the actions to improve the economic and social aspects of a city. Various cities around the world have started to provide advanced services and support the SC framework such as the case of the Smart Santander project in the city of Santander or the development of the Sino-Singapore Tianjin Eco-City. Notwithstanding the vast number of application domains it is difficult yet to establish a unique definition of SC. In Neirotti *et al.* (2014), 70 different case studies of smart cities in different countries of the world are reviewed and compared to each other, defining an index able to take into account the relationship between the number of provided services and the economic, social, geographic, demographic and environmental characteristics, in order to obtain an understanding of the current state of smart cities framework evolution. Even in the city of L'Aquila, deeply damaged in the L'Aquila earthquake of 2009, SC themes are currently addressed by the public authorities ad institutions, by leveraging on all those actions planned for the reconstruction. An example is the INCIPICT project, acronym of "*INnovating City Planning through Information and Communication Technologies*" (Fig. 1). The project will take advantage of the-depth reorganization and revision at which the network of services (water supply, electric and telecommunications networks) is submitted. In particular, possible connectivity solutions for the city of L'Aquila will be indicated, in particular for its historic center, to provide access to the ultra-wide-band for public institutions and for supporting their research initiatives. It is expected the construction of an experimental optical network, available to the scientific community, with dedicated wireless access points, useful for the development of new networking technologies and new services. The project will realize the implementation of permanent monitoring services in buildings easily accessible from the network. The main goal is to create a distributed monitoring system network, based on sustainable, innovative, minimally invasive technologies. Today the INCIPICT project expectation is to create a network of 31 buildings (21 in reinforced concrete, 9 in masonry and 1 in steel).

Throughout the whole Italian territory there are several case studies of modern and historic structures such as: towers, churches and old bridges in which a permanent SHM system has been installed. This large number of activities are conducted by private companies, universities and research centers even if the obtained results are not fully reported in an adequate scientific manner. A certain number of contribution can be found in Cavalagli *et al*. (2015), Gentile and Saisi (2015), Lorenzoni *et al*. (2016), Modena *et al*. (2015), Saisi *et al*. (2015), Pau and Vestroni (2013), Potenza *et al*. (2015), Russo (2013b), Zonta *et al*. (2010). A set of single permanently monitored structures are reported in the upper part of the Table 1 while in the lower rows single cases of dynamic testing are delineate. In the following, the motivations that lead to the decision to install a permanent SHM system, as reported in the cited references, are summarized.

Fig. 1 Map of L'Aquila with evidence, in yellow line, of the experimental optical network connecting the different SHM systems for strategic and monumental buildings

The general motivation, for almost all cases, is linked to the structures' aging, as for example, in the case of the Iron arch bridge in which the main objective of the monitoring regarded the evaluation of the actual condition after many years of service, Gentile and Saisi (2015). In other case the CH safeguarding is devoted to what is supported and contained by the monitored structure as in the case of the frescoes in the "Sala dei Berrutti" (Conegliano Cathedral). Other typical historic constructions, very widespread in all Italian territory, are the masonry towers. In the literature the assessment of the structural condition of these constructions is pursed by rapid dynamical test, Foti *et al*. (2012a), Foti *et al*. (2012b). However, in Zonta *et al*. (2010), is showed a whole path regarding the design and implementation of a permanent SHM system for an ancient tower. In this case a principal motivation concerns a control of the structure against whatever external perturbation due to the important frescoes here also present.

After a catastrophic event, such as an earthquake, SHM systems have been applied to follow the interactions between the structure and the installed non-permanent seismic protection systems and the potential increase of damage due to aftershocks. Permanent systems have been designed, in most of the cases reported in Table 1, for capture the h24 structural response. One of the main reason of this choice is to have the possibility to purge the effect of the temperature on the identified results, as in the case of Lorenzoni *et al*. (2016). In other cases only a monitoring during seismic actions is pursued due to the selected target which is to assess the structural condition after an earthquake or merely because the installation of more sensible sensors, able to perform the OMA procedures, have been considered expensive. In a few cases other techniques as the Acoustic Emission (AE) are applied whose results are combined with those coming from the Non-Destructive Tests (NDTs). Regarding the dynamic tests the most performed ones are the Ambient Vibration Tests (AVTs). The easy deployment of the experimental setup and the avoiding of energy consumption to create the artificial input make these tests very appealing.

In general, the final aim of the dynamic tests is to enhance numerical model useful to perform accurate analysis of structural assessment.

Table 1 Selected examples of monitoring systems and dynamic testing recently conducted in Italy

C	Name	Typology / Date	Structure	Notes	Location / references
			Permanent Monitoring		
1	Basilica di S.M. di Collemaggio	Church 1287 A.C.	Masonry	Seismic monitoring	L'Aquila Potenza *et al*. (2015)
2	San Michele bridge	Bridge 1889 A.C.	Iron arch bridge	Dynamic monitoring	Milan Gentile and Saisi (2015)
3	Roman Amphitheatre	Amphitheatre I century B.C.	Masonry	Dynamic and static monitoring	Verona Lorenzoni *et al*. (2016)
4	Torre Aquila	Tower XVII century	Masonry	Dynamic and static monitoring	Trento Zonta *et al*. (2010)
5	Torrazzo	Tower 754 A.C.	Masonry	Dynamic and static monitoring	Cremona Zasso *et al*. (2004)
6	Chiesa delle Anime Sante	Church 1713 A.C.	Masonry	Dynamic monitoring	L'Aquila Russo (2013a)

Continued-

7	Torre Gabbia	Tower XIII century	Masonry	Dynamic monitoring	Mantua Saisi *et al*. (2015)
8	Campanile di San Giorgio	Tower XIV century A.C.	Masonry	Seismic monitoring	Trignano (Reggio Emilia) Clemente and Buffarini (2009)
9	Chiesa dell'Immacolata	Church 1726 A.C.	Masonry	Static monitoring	Masnago (Varese) Marazzi (2011)
10	Torre degli Asinelli	Tower XII century A.C.	Masonry	AE	Bologna Carpinteri *et al*. (2015)
11	Palazzo Ducale	Palace 1350 A.C.	Masonry	Dynamic and static monitoring	Venezia Russo (2013b)
12	Guglia Maggiore del Duomo	Church 1769 A.C.	Masonry	Dynamic and static monitoring	Milano Cigada *et al*. (2013)
13	Torre Sineo	Tower XII century A.C.	Masonry	NDTs and AE	Alba (CN) Carpinteri and Lacidogna (2006)
14	Torre Astesiano	Tower XII century A.C.	Masonry	NDTs and AE	Alba (CN) Carpinteri and Lacidogna (2006)
15	Conegliano Cathedral	Church 1345 A.C.	Masonry	Static monitoring	Conegliano Lorenzoni *et al*. (2016)
			Dynamic testing		
16	Sanctuary of Vicoforte	Church 1596 A.C.	Masonry	AVTs and bell tests	Vicoforte (Milan) Chiorino *et al*. (2011)
17	Cappella della Sindone	Church 1667 A.C.	Masonry	AVTs	Turin De Stefano (2009)
18	Torre di Matilde	Tower 1200 A.C.	Masonry	Bell tests	San Miniato (Pisa) Bennati *et al*. (2005)
19	Torre Grossa	Church 1300 A.C.	Masonry	Dynamic and static tests	San Gimignano (Siena) Bartoli *et al*. (2013)
20	Cattedrale di Siracusa	Church V century B.C.	Masonry	NDTs	Siracura Binda *et al*. (2007)
21	Campanile di S. M. in Aracoeli	Tower/Belfry 1537 A.C.	Masonry	AVTs and bell tests	Roma Nisticò *et al*. (2015)
22	Campanile della Chiesa Collegiata	Tower Late Roman age	Masonry	AVTs	Varese Gentile *et al*. (2015)
23	Morca footbridge	Footbridge 1850 A.C.	Wood	AVTs	Varallo (Vercelli) Gentile and Gallino (2008)
24	Anfiteatro Flavio (Colosseum)	Amphitheatre 80 B.C.	Masonry	AVTs and dynamic tests	Rome Pau and Vestroni (2008)
25	Basilica of Maxentius	Church IV century A.C.	Masonry	AVTs	Rome Pau and Vestroni (2013)
26	Torre della Cattedrale	Tower XVII century A.C.	Masonry	AVTs	Monza Gentile and Saisi (2007)
27	Public Administration	Tower 1930 A.C.	Masonry	AVTs	Bari Foti *et al*. (2012b)
28	Chiesa di S. Caterina	Church 1700 A.C.	Masonry	AVTs	Casale Monferrato (Alessandria) Ceravolo et *al*. (2015)
29	Engineering Faculty Building	Modern building Last 90's	Reinforced Concrete	AVTs	L'Aquila Foti *et al*. (2014)

2. Design of SHM systems for cultural heritage

SHM constitutes for the historical and architectural heritage a good tool to enhance the management of the assets. The purpose of SHM may differ case by case, however main possible objectives can be synthetized as follows:

- measure the vibrations induced by environmental actions, traffic, wind or by rare events such as earthquakes;
- evaluate the effects coming from foundation settlements or from soil-structure interaction with dynamic local amplifications;
- measure the evolution of existing cracks (opening or closure);
- determine the actual structural behaviour to assess seismic vulnerability and effectiveness of restoration interventions used to repair the damage caused by catastrophic events;
- evaluate the enhancement of the structural response to dynamic (wind, earthquake) actions as result of relevant structural modifications after the adoption of invasive protection strategies (e.g., base isolation or passive control systems);
- make a long-term analysis of the structural dynamic response and its modification after final retrofitting and reconstruction;
- observe the damage produced by the degradation of the material along its physical (dissolution, hydration, frost), chemical (acids and salts dissolved that produce corrosive solutions) or biological nature (engraftment of lichen and weeds).

Naturally, once determined the target, it is possible to organize a reasonable path to develop the SHM system. In should be noted that in the "Guidelines for the assessment and mitigation of seismic risk of cultural heritage with reference to the technical standards for construction of the decree of the Ministry of Infrastructure and Transport, January 14, 2008" the structural health monitoring is indicated only as the last step of a general set of activities aiming to reach "the building knowledge". In this respect the fundamentals steps are:

- identification of construction: location in relation to particular risk areas,
- geometric relief of the building: full description of stereometry of the structure, including any cracking phenomena and deformation,
- identification of the building historic evolution: sequence of the transformation phases, from the hypothetical original configuration to the actual one,
- identification of the elements constituting the structure: construction techniques, construction details and interconnections between components,
- identification of materials: state of degradation and evaluation of mechanical properties,
- knowledge of subsoil and foundation structures: changes that occurred over time and relative instability.

Each point, listed above, contributes for a reliable analysis of the structural behaviour simulated by numerical models (e.g., finite element models). At the final stage, the analysis and the design of the hypothetical planned monitoring system begins on the basis of previous short-term dynamic or static tests. Consequently, especially in this case, that is also called vibration-based monitoring, the optimal allocation of the sensors is suggested by the information coming from the predictive numerical models looking, for instance, to the points in which the maximum values occur in the modes mainly involved in the dynamic response. Surely, the sensor locations should avoid the zero-modal points because in such case it is practically impossible to identify the main dynamic characteristics, such as frequencies, modal shapes and damping.

2.1 Signal acquisition

The set of tools and instrumentation used for the SHM is called data acquisition system. The variables to monitor can be kinematics (as displacements, velocities or accelerations), mechanics (as forces, stress, flow rate) or also physics (temperature and humidity). At each variables correspond a specific sensor able to capture also very small variations of the measured variable. Obviously, prior to the sensor type selection, the objective of the monitoring system should be clearly defined. The signal is an electrical magnitude proportional to the monitored variable.

In the SHM field the most used sensors are the accelerometers and the displacement transducers (Fig. 2). In the last years the vibration based monitoring has had a rapid and extensive development also due to the performance provided by the accelerometers. Indeed an important observation is that the displacement oscillations make evident the modal components at low frequency (below 1 Hz) while acceleration ones are amplified at higher frequencies above 1 Hz. Often, the main modes that describe the structural dynamics, for modern or monumental buildings, appear in the range between 1 and 10 Hz. Moreover, the vibrational measurements can be used to detect hidden or invisible damages. As well known, the structural dynamics is described by modal characteristic (as modal frequencies and shapes) that are functions of the physical and geometric variables which compose the structure to be monitored. Instead, the displacement transducers are applied for a static monitoring concerning both the opening or closing of cracks and also a measure of the deformation. Among the most utilized accelerometers there are the piezoelectric, servo and force-balance accelerometers and MEMS (Micro Electric Mechanical System). The piezoelectric accelerometers take advantage of the piezoelectric material proprieties able to generate an electric charge when they are subjected to a variable force. Indeed, when a force is applied to the sensor, an inertial force will be imposed to the seismic mass, collocated inside the sensor's involucre, that will press the piezo-material producing a voltage proportional to the applied acceleration. They are robust and reliable sensors, having stable characteristics over the time, but they have drawbacks in the measurement at the low frequencies (below 1 Hz). Instead, in the servo-accelerometers the voltage generated is proportional to the force needed to eliminate the movement induced by the acceleration of the seismic mass. The latter is linked to the sensor box by springs and generally it is present also a viscous fluid that dampen the motion of the seismic mass. In general, the servo-accelerometers have an high cost, an high precision but they are bulky and heavy. The MEMS are sensors of different nature (mechanical, electrical and electronic) whose principle is based on the variations of the electrical capacity that are produced by the acceleration imposed to the sensor. The microincision processes allow to realize configurations able to measure capacitive microvariations enhancing the MEMS accelerometer performance.

Regarding the static SHM, alternatively to the traditional measurement technique based on mechanical or electrical devices, a fast development has been achieved by innovative sensing systems based on optical fiber sensing, Li and Ansari (2001), Jacobs *et al*. (2007). Important advantages respect to the typical strain gauges, is that the optical sensors are of small size and very light weight, moreover they are immune to electromagnetic interference and corrosion and in particular they possess embedding capability, Gattulli *et al*. (2015). In Ansari (2007) and Ye *et al*. (2014) is illustrated the basic principles regarding the monitoring of civil engineering structures using optical fiber sensors. A general system needed for release a network of fiber optical sensors is composed by a light transmitter, a receiver, an optical fiber, a modular element and a signal processing unit. One of the most widely used optical sensors is the Fiber Bragg Grating (FBG), especially for the civil SHM, Todd *et al*. (2001), Betz *et al*. (2003), Moyo *et al*. (2005), Valvona *et* *al*. (2015). A rough manner to describe the mechanism of an FBG sensor is the following: when a broadband light, coming from a light transmitter, pass through the grating of the sensor, a specific wavelength (called Bragg wavelength) is reflected and to this wave corresponds a grating period. If the grating is subjected to some deformation, the period of the reflected wavelength will change and so it is possible to connect the deformation with the variation of the Bragg wavelength. It worth to notice that the total strain is given by the sum of the mechanical and thermal strain. For this reason the optical measurements have to be purged by thermal effect.

The complete set of the SHM sensors can communicate and be connected to the central acquisition and the signal processing unit in two ways: wired or wireless. Thanks to the rapid and growing development of the Information and Communication Technologies (ICT) based solution, there has been in the last years an important attempt of the Wireless Sensors Networks (WSNs), Federici *et al* (2012) and Gattulli *et al*. (2014). A typical sensor node contains a microcontroller unit, a radio unit, some kind of long-term stable storage (Flash memory, SD card etc.), and I/O capabilities to support sensors. Generally, in comparison with the traditional wired acquisition systems there are both advantages and drawbacks. The first ones regard the reduced cost of the installation and equipment, more flexibility (in particular in the choice of the positioning of the sensors) and the possibility to use smart sensors. The disadvantages are the time synchronization and the communication reliability.

2.2 Signal processing and system identification

Signal processing is an important step of the whole monitoring process, because from the sensed data is possible to extract relevant information useful to determine the structural damage level. Regarding the handling of the acquired data, one of the important problems to solve is the treatment of the noise present in the signals. For this reason, over the years, different processing techniques operating in the time, frequency and time-frequency domain have been developed and compared, Antonacci *et al*. (2012).

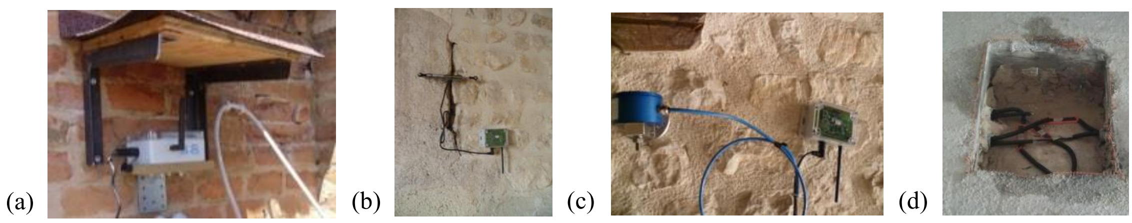
The first class contains procedures capable of developing approximate and statistical models from the monitoring system data. In general, signals are recorded from sensors dedicated to capture the input (excitations to the structure) or the output (response of the structure). The most important time domain procedure used are the following: autoregressive (AR), moving-average (MA) and autoregressive moving average (ARMA) model. A variations of the parameter describing the model can be exploited to detect and to locate the damage (these methods are also called model-based). An example of the application of these procedure for the structural health monitoring can be found in Carden and Brownnjohn (2008). One of the most popular time domain system identification tools, used by the civil and mechanical engineering communities for the extraction of the modal properties is the Stochastic Subspace Identification (SSI) introduced by Peeters and De Roeck (1999). This is a particular member of a more general Subspace State-Space System Identification (4SID) family of time-domain algorithms. The application of these input-ouput (4SID) or output-only (SSI) methods produces a black-box state-space model. A rigorous mathematical mapping from the state-space model parameters to the physical parameters (i.e., the transition from a black to a grey or white model) has yet to be undertaken. An attempt to realize this relationship can be found in Kim *et al*. (2012a), Kim *et al*. (2012b).

The simplest and oldest technique applied in the frequency domain is based on the Fast Fourier Transform (FFT), employed to rapidly convert a discretized time series in a frequency domain representation. Indeed, the main peak of a FFT could be associated to the principal frequencies that characterize the structural dynamics. It is therefore clear that a frequency change, determined by the FFTs of the signals acquired at the same sensor, could be used as a tool to detect the damage. Since the FFT is applied to a discretized signal, there will be a maximum frequency value that can be identified depending on the sampling time or frequency that, based on the Nyquist theorem, should be equal to twice the maximum frequency to be identified. Different authors have used this technique to detect the structural damage as reported in Bandara *et al*. (2014). A recent procedure working in the frequency domain, used also for damage identification, is the Enhanced Frequency Domain Decomposition. This is a stochastic method that operates on the spectral matrix and, under some assumptions, the procedure permits the system identification, see Brinker *et al*. (2001).

In general the structural response due to an environmental excitation (e.g., an earthquake in the more critical cases) is non-stationary, i.e. the dynamic parameters are functions of the time. For this reason the time and frequency domain techniques are unable to indicate how this time-dependent modification occurs. In recent years several time-frequency analysis techniques have demonstrated a good efficiency in the evaluation of these characteristics. Among them the Short Time Fourier Transform (STFT) and the Wavelets Analysis (WA) are two techniques which have the advantages of being very easy to use and providing useful information, Tarinejad and Damadipour (2014). The STFT divides the entire signal into small time intervals and then performs the Fourier Transform in all short intervals. Logically, the larger the windowing is, the better the frequency resolution will be, but also the worse the time resolution is, and vice versa. An optimal balance between frequency and time resolution is achieved by the WA. Indeed, the elementary wavelet function, used to represent and to decompose the signal, can be modified specifically to analyze high or low frequencies.

2.3 Data Interpretation

The general purpose of the structural health monitoring, not only in the case of CH, is to determinate the various stages of damage due to an exceptional event or to the aging. The damage can be identified following different hierarchical levels:
level 1: detection, i.e., determinate the presence of damage;
level 2: localization, i.e., evaluate the position of damage;
level 3: quantification, i.e., estimate the extension of damage;
level 4: assessment, i.e., evaluate the residual of the structural;



(a) (b) (c) (d)

Fig. 2 HM sensors: (a) wireless sensor node with a MEMS accelerometer and temperature and humidity sensors, (b) electrical displacement transducer, (c) inclinometer and (d) FBG embedded in a layer of Fiber Reinforced Polymer used to retrofit a masonry vault

Today, the vibration based techniques used to identify the damage constitute effective tools applicable to the first two levels, Ditommaso *et al*. (2015). The research in this specific field aims to realize a complete integration between monitoring sensors network and monitored structure, with the final goal of developing intelligent systems, which can be capable of responding properly and fulfil specific requests – according to each level – thanks to the implementation of autonomous functions, e.g., self-analysis, self-diagnosis, and also energy self-sufficiency.

In the literature the damage detection has been pursued by two main groups of methods: global and local health monitoring. The first set includes those procedures able to determine if a damage occurred (i.e., presence of damage) but they do not give sufficient information about the location and the severity of damage. For this particular purpose, they must be complemented by local methods, such as visual inspections – the easiest to perform – or strain gauges – to monitor crack opening or closure. Other non-destructive techniques include ultrasonic guided waves – to measure stress states – or the tap-test – useful for void measuring or wrap debonding detection. In this section global vibration-based methods will be presented (i.e., based on the change of the modal properties: frequencies, modal shape, modal damping).

The first and intuitive method is based on the shifts of the resonant frequencies. Indeed, the modal frequencies are related to the mass and stiffness values and so their variation will be reflected on the frequencies values. The drawbacks of this criteria are the following: the evaluation is global and it doesn’t give information on the damage location; for very large structures and for a low level of vibrational amplitude the sensitivity of frequency to damage is relatively low; sometimes hidden damage, like the corrosion on the steel bars in the concrete structures, haven’t a significant effect on the resonant frequencies because the stiffness depends mainly on the behaviour of concrete, and not so much on the steel reinforcement. Another difficulty is the separation of the contributions due to damage and those due to environmental (temperature or moisture) and operational factors (e.g. machine noise).

An alternative method is associated to the variation of both modal shape vector and modal shape curvature. In some cases, minor local damages could not significantly influence the modes with lower frequency, typical of the large structures. Indeed, these damages are mainly influencing the higher frequency modes that, however, are more difficult to excite and thus less easy to identify on the base of measurements from vibrational tests or monitoring systems. The modal curvature value is also more sensitive to small stiffness variations, but in this case, for the low frequency modes. Moreover, the modal shapes are difficult to be identified with accuracy because a large number of measurements are required. However, a comparison between numerical and experimental modal shapes or between the modal shapes identified in two different time intervals (e.g. referred to a pair of successive periodic tests or before and after a retrofitting intervention) can be performed also using modal expansion techniques, see Foti *et al*. (2014).

Among the more important indicators employed to compare the modal shapes, the Modal Assurance Criterion (MAC) and the COordinate Modal Assurance Criterion (COMAC) must be cited. They are defined in the following way

$$MAC_{ij} = \frac{\left|\boldsymbol{\varphi}_i^{\mathrm{T}} \mathbf{W} \boldsymbol{\psi}_j\right|^2}{(\boldsymbol{\varphi}_i^{\mathrm{T}} \mathbf{W} \boldsymbol{\varphi}_j)(\boldsymbol{\psi}_i^{\mathrm{T}} \mathbf{W} \boldsymbol{\psi}_j)} \qquad COMAC_d = \frac{\sum_{i=1}^{m} \left|\boldsymbol{\varphi}_{ir}^{(d)} \boldsymbol{\psi}_{ir}^{(d)}\right|^2}{\sum_{i=1}^{m} \boldsymbol{\varphi}_{ir}^{(d)} \boldsymbol{\varphi}_{ir}^{(d)} \cdot \sum_{i=1}^{m} \boldsymbol{\psi}_{ir}^{(d)} \boldsymbol{\psi}_{ir}^{(d)}} \tag{1}$$

in which $\boldsymbol{\varphi}$ and $\boldsymbol{\psi}$ are two different modal vectors in both cases, in the definition of MAC $\mathbf{W}$ is a weighting matrix (in general can be taken the mass diagonal matrix) while in the COMAC m is the number of the measurements, i.e., the number of modal component (size of the modal shape vectors), r is the number of mode and d is the specific degree of freedom to be checked. The MAC is defined as a scalar and aims to define the degree of consistency (collinearity) between a generic modal vector and the corresponding reference one. Usually, the closeness of the MAC_{ij} to unity measures how the i-th and j-th vectors are consistent to each other. In the structural identification, the comparison between numerical and experimental modes, both listed according to ascending frequencies, should give MAC_{ij} values close to one for the diagonal entries (i=j) and close to zero for the out-of-diagonal entries ($i \neq j$) of the MAC matrix. The COMAC is also a scalar, it is an extension of the MAC, and it is an attempt to identify what measure (degree-of-freedom) gives a negative contribution to the MAC value.

3. Health monitoring and dynamic testing: two case studies

3.1 Basilica of S. Maria di Collemaggio

The Basilica of S. Maria di Collemaggio (BSMC) is the most important church of L'Aquila (Fig. 3). It was heavily damaged in the 2009 L'Aquila earthquake. The church plan has a central nave, which measures 61 m in length and 11.3 m in width, and two side aisles measuring 7.8 m and 8.0 m in width, respectively. The nave and the side aisles are separated by the inner longitudinal walls, sitting on seven columns with a height of 5.3 m and an average central section of about 1 m in diameter. The inner and outer longitudinal walls, with a masonry thickness varying from 0.95 m to 1.05 m are transversally connected by the church facade and the transept structure. The church has a wooden gable roof supported by trusses orthogonal to the longitudinal walls. The dynamic behavior of the undamaged Basilica was characterized in numerical and experimental studies conducted in the early 90's, when a light retrofitting intervention was completed. The 2009 L'Aquila earthquake caused a partial collapse of the structure in the transept area, see Gattulli *et al*. (2013).

After the earthquake, a permanent wireless structural monitoring system was developed and installed inside the damaged church. The main goals of this project were, (i) to investigate the possible causes of the collapse; (ii) to monitor the performance of the scaffolding structures and other installed reinforcements (tendons between the walls and temporary composite tape wrapped around the columns for confinement), (iii) to avoid the progression of damage, and (iv) to make a long-term analysis of the structure dynamic response and its modification after final retrofitting and reconstruction.

During the June 2011, 16 wireless sensor nodes were installed in the church (Fig. 3). The majority of sensor nodes were placed inside the structure: 10 along the main nave, 1 at the base of a column, and 1 in the transept area. The main monitoring platform is based on a wireless communication platform, MEMSIC Imote2 mote, which includes a sensor board, MEMSIC SHM-A. The latter features an advanced 16-bit data acquisition system (QuickFilter QF4A512 model) and a MEMS tri-axial accelerometer (ST miroelectronic LIS344ALH). More details on the characteristics of the wireless sensor node system are reported in Potenza *et al*. (2015). A node gateway collects the measurements recorded that are uploaded to a remote server using a 3G modem/router.

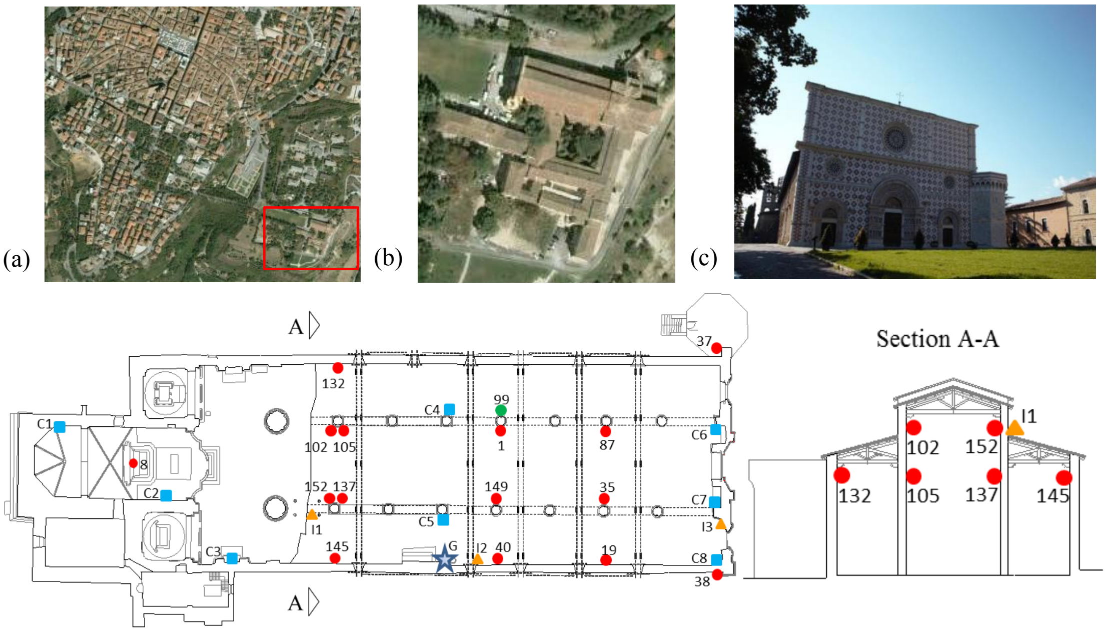


Fig. 3 On the top: Basilica of S. Maria di Collemaggio: (a) map of L'Aquila with evidence of the Basilica's location, (b) view from above, (c) main facade. On the bottom: Complete layout of the SHM system for the BSMC: 16 accelerometers (red circles, nodes 99 on the ground), 8 crackmeters (blue square), 3 inclinometers (orange triangles), 1 node gateway (star)

The latter provides also an internet access useful when local tests are performed. A scheduling algorithm able to alternate two groups of nodes, every 15 minutes, in the mentioned operation was developed within the project. In particular the nodes 8, 102, 105, 1, 87, 132 and 37 constitute the Group I while the nodes 152, 137, 149, 35, 145, 40, 19 and 38 the Group II. In this way, continuous coverage of the dynamic response of the building was obtained. A second monitoring network including crackmeter and inclinometer sensors was also installed in the Basilica.

During the months following the installation, the monitoring system was continuously enhanced to the point of complete and automated operation in sensing seismically-induced vibrations. To date, several events with relevant dynamic effects have been observed and measured, among them structural accelerations induced by far- and near-field earthquakes. A more detailed description of the recorded seismic events is illustrated in Potenza *et al*. (2015).

The signal processing has been pursued by both frequency and time domain techniques. Indeed in the Figs. 4(a) and 4(b) are illustrated two typical results such as the Power Spectral Densities and the stabilization diagram of SSI procedure. Sometimes the interpretation from these results may be very difficult. Indeed in the Fig. 4(a) the peaks associated to the structural modes are not clear. Obviously, the PSD of the response depend on the characteristics of the seismic input.

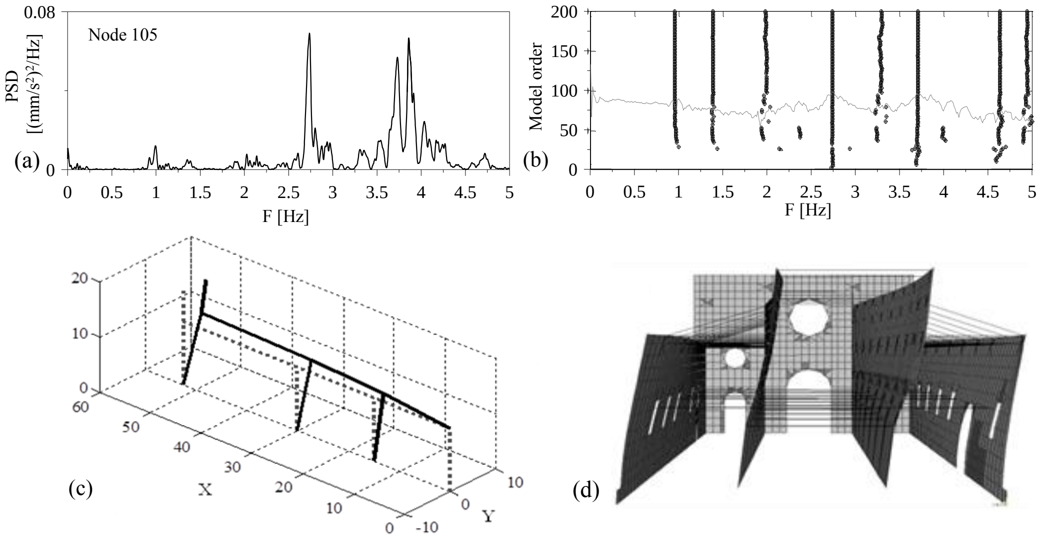


Fig. 4 Signal processing of the data acquired during the seismic events: (a) power spectral densities (PSD), (b) SSI stability diagrams, identified (c) and numerical (d) mode

For example a far- or near- field event, due to different energy and/or frequency content could induce interaction between the structure and the safety system or increase the contribution of the higher modes. The use of the time domain techniques can improve and strengthen the interpretations of the structural behaviour.

The stability diagrams present in Fig. 4(b), which were calculated from the same data used to calculate the PSD, confirm the presence of the same frequencies in the identified state-space model but it helps to associate these frequencies to the structural modes.

The last part of the activity regards the finite element model updating which minimizes the differences between the experimentally identified frequencies and modes (Fig. 4(c)) and their numerical counterparts (Fig. 4(d)). Varying the values of several mechanical properties and introducing specific modeling assumptions concerning in particular the connections of tie rods under the roof a satisfactory matching has been obtained between experimental and numerical modal quantities, see Potenza *et al*. (2015).

3.2 Engineering faculty building of the University of L'Aquila

The group of buildings belonging to the Engineering Faculty of the University of L'Aquila arise in Monteluco of Roio (Fig. 5(a)). The so-called Edifice A, B, C are buildings recently constructed (90's) while the so-called historic building date back to the 30's. In particular the Edifice A was heavily damaged during L'Aquila Earthquake (Fig. 5(b)), details are reported in Ceci *et al*. (2013).

The Edifice A is composed by 7 seismically-jointed reinforced concrete substructure (A1 – A7 in Fig. 5(c)). The structure is formed by frames in which the vertical elements are shear-walls and columns while the horizontal ones are RC beams, many of which have a thickness contained in the slab. An important element that characterizes both the architectural and structural feature of the building A is the main facade (Fig. 5(c)). This one was linked, in the last three levels, by 31 metallic tubes, 120 mm in diameter and horizontally displaced. The tube's steel plates, poorly connected to the reinforced concrete structure, haven't shown an adequate behaviour during the seismic sequence of the L'Aquila Earthquake leaving completely free the main facade. The high out-of-plane deformability of this planar frame has produced an heavy damage scenario in terms of non-structural component in particular for the infill walls collapsed for the overturning (Fig. 5(b)).

To better understand the structural behaviour of the Edifice A a testing campaign has been performed. The dynamic tests were carried out in only two days (February 4th and 5th 2010), and the external conditions (i.e., aftershocks and heavy snow) made difficult the accelerometer installation.

The testing equipment included 16 servo-accelerometers with a full scale range of 0.5 g (model SA-107LN Columbia) and their location was designed on the basis of specific considerations suggested by the preliminary results provided by FE models. Some difficulties in the arrangement of the experimental setup have been encountered due to damaged conditions of the building. Indeed, the sensors used for the main facade have been located only in those floors reachable through external stairs (no cranes were available). The dynamic tests regarded the substructures A3 and A1 in which the structural response have been recorded under environmental excitation with a sample of 400 Hz for more or less 30 minutes. In Fig.3 6a is illustrated one of the accelerations acquired during the tests. It is the transversal acceleration of the sensors placed in the main facade, as shown in Fig. 6(b).

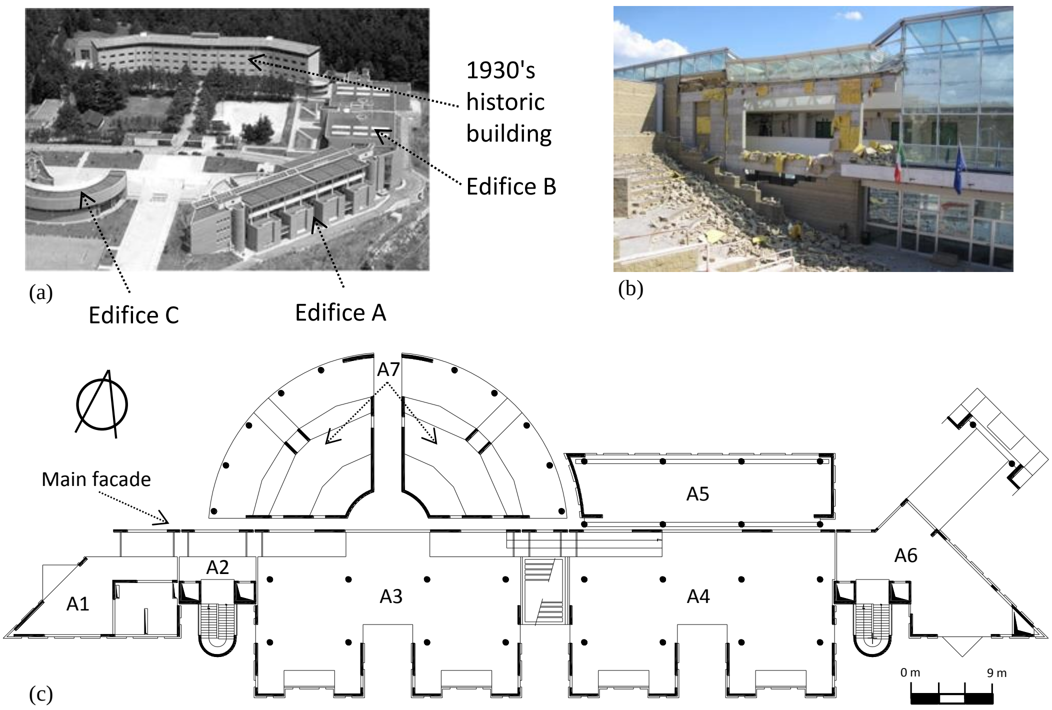


Fig. 5 Engineering Faculty of the University of L'Aquila: (a) overview of the buildings' set, (b) photo of the main facade of the Edifice A damaged during the L'Aquila Earthquake and (c) plan map of Edifice A

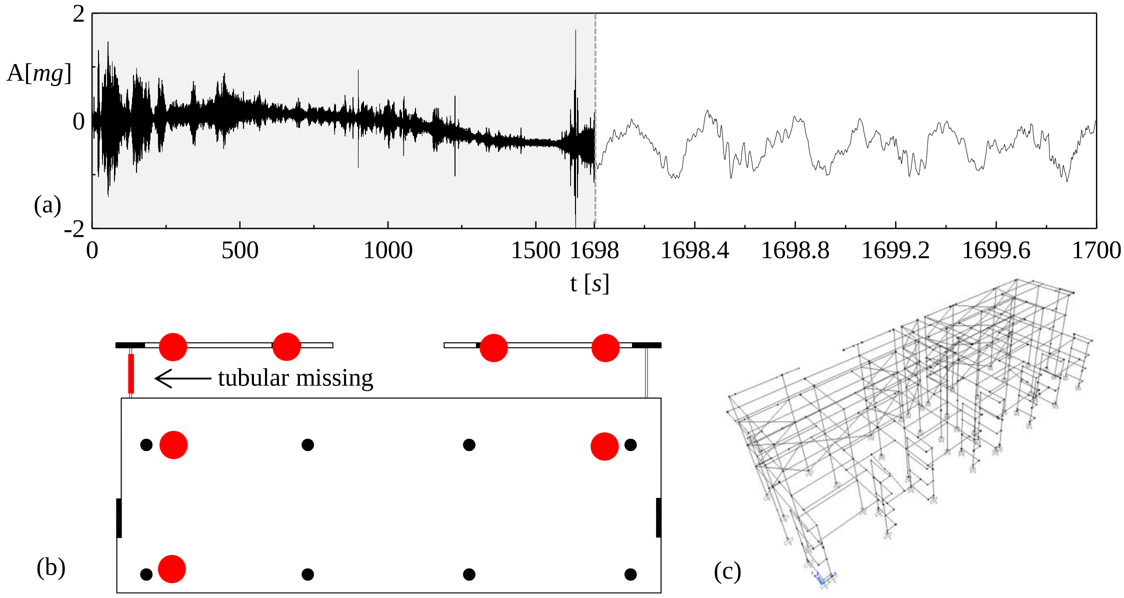


Fig. 6 (a) One of the accelerations recorded during the experimental tests, (b) Typical floor experimental layout for the substructure A3 and (c) FE model representative of the structural interaction between A3 and A4

Indeed, the experimental tests aim to identify the presence of damage produced by the breakage of one of the tubular linking the main planar facade and the corresponding 3D structure. SSI-data and the SSI-data/ref procedures have been used to identify the main modes. The FE model, representative of the substructures in which the dynamic tests have been performed (A3 and A1), have been realized by three-dimensional frame structures and the manual modal updating have been made through iterating on the modal solutions changing the selected parameters as the elastic modulus. Moreover, in the model updating specific issues have been taken into account as, e.g., the effect of the presence three Gerber-type RC slabs connecting the substructures A3 and A4. For this reason the final FE updated model, reported Fig. 6(c), had to take into account both structural systems. More details about the main obtained results can be found in Foti *et al*. (2014).

4. Conclusions

The paper summarizes the most recent activities conducted in the field of SHM in the Italian territory. These efforts have been performed for different reasons such as: to make a rapid evaluation of the structural damages produced by natural events in the whole Italian territory (macro scale); to realize a network of systems in an urban area with the aim of programming an effective management of the assets (medium scale); to follow the effects of aging and the damage status on CH (small scale). A number of actions have regarded the characterization of the vibration levels induced by different excitation sources for complex monumental masonry buildings possessing an historical and economic value. The critical analysis of a relevant number of case studies has highlighted the existence of crucial decisions in SHM or DTs such as: the importance to choose the scope of the investigation, the needs to design the main phases of the system realization, the selection of effective tools for data treatment (signal acquisition, signal processing and data interpretation) that permits to effectively conclude the entire process.

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