Cloud Computing Strategies for Health Monitoring of Bridge Structural Systems

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ABSTRACT
In last years procedures for structural health monitoring have been more and more improved, thanks to growing innovation in sensor technology and in knowledge of damage detection strategies. Nonetheless, in the recent past some collapse events of important bridge structures have occurred, and significant social and economical losses have been experienced. Such catastrophic events have been caused by the superposition of several factors, at both local and global levels, such as corrosion of ordinary and post-tension reinforcements, carbonation of concrete, damage on concrete cover, and so on. Thus, many experimental and research activities have been focused on the definition of health monitoring systems, in order to provide the correct maintenance of all structural elements.
In this endeavor a standardized system for health monitoring of bridge structures is described. Formerly, the main aspects which lead to significant cumulative damage of structural elements have been analyzed and then the most appropriate sensor have been selected. In addition, a cloud-based web interfaced is presented, able to make data available for post-processing computations, which could lead to the proper monitoring and maintenance of the whole structural system.

1 INTRODUCTION

Monitoring and maintenance have become key aspects, especially for bridge infrastructures. Recent catastrophic events, among the others the collapse of the Polcevera bridge in Italy (Calvi et al. 2019) have additionally highlighted such a need, and consequently the interest in research and applications about the topic has grown (Cancelli et al. 2019, Chang et al. 2003, Ranieri et al. 2011b). Bridge structures are continuously subjected to aggressions due to serviceability and extreme conditions. During ordinary scenarios, environmental factors lead to progressive damage to a number of structural elements, such as carbonation, corrosion, fatigue loading, etc. (Bossio et al. 2013, Del Vecchio et al. 2016, Koompong and Herabat 2010, Ruofan Gao et al. 2019); on the other hand extreme conditions, like earthquake excitations, could cause residual displacements, which have to be checked (Mackie and Stojadinovic 2004). Given the strategic importance of such structural systems, the structural health monitoring is essential, in order to assess the effective health status of the overall bridge, by providing easy-friendly interfaces between data and users.

In this work guidelines for the definition of an optimized Structural Health Monitoring (SHM) system are provided, and a cloud-based framework is presented, which allows to manage in the easiest way possible the monitoring status of a number of sites. Thanks to the proposed strategy, users can access to the available recorded data through a web interface, with personal credentials, and both raw and automatically post-processed data can be downloaded. Consequently, the proper maintenance can be planned, and the probability of unexpected collapses can be significantly reduced.

2 GUIDELINES FOR SHM DEFINITION

In order to define an optimized Structural Health monitoring system, a number of key issues have to be studied (Gastineau et al. 2009). At a first stage, the monitoring time window has to be defined, in agreement with the scope of the study and depending on the health status of the infrastructure at the time of the analysis. Precisely, short and long term monitoring time frames can be adopted. A short term can be assumed, whenever the monitoring system has to analyze the evolution of the response of a bridge structure in a short time period; on the other hand, a long term monitoring is generally designed for new, rather than retrofitted structures; furthermore, long term monitoring is also considered for bridges with uncertain structural behaviour, with a time windows which could be greater than one year. Within the defined time frame, inspections can be planned and carried out, according to an ad hoc maintenance procedure, which represents a significantly useful activity, to periodically assess the proper working condition of the overall structure, aiming at detecting some important change in the response. The designed SHM system should also be able to provide early warning and collapse warning: the early warning alarm automatically sends notifications, whenever proper threshold values for some specific response parameters are overcome (Ranieri et al. 2011a); whereas, the collapse warning immediately leads to the bridge closure, and consequently people is informed about the high possibility of the structural collapse.

Once time frame and inspections are defined, the scale of the considered monitored elements needs to be assumed, and finally response parameters and an optimized layout of the system have to be respectively listed and designed. In order to define the layout of sensor for the SHM system, weak points of the infrastructure have to be studied and localized. In addition, all possible damage/collapse scenarios have to be studied, in order to establish the scale of the monitored portion of the bridge infrastructure. For local monitoring, the attention is mainly focused on a specific location in the bridge, and local phenomena are then considered, such as increasing width of known cracks, rather than local buckling of single elements, corrosion at specific locations, and strain measurements at overstressed points. Finally, the widest point of view of a SHM system considers the whole structure, in a global way: the global monitoring focuses on the overall health of the entire bridge, by providing results, which are referred to global characteristics of the system: the most common global analysis is the assessment of natural frequencies and mode. To this aim, recorded acceleration time series represent a very useful tool. Precisely, it is possible to define modal frequencies and mode shapes of the structural system thanks to cross-correlation analyses of signals recorded at different locations. Thus, the damage progression can be highlighted, by monitoring the variation during time of dynamic properties, such as elongation of period values which corresponds to a decrease of the overall stiffness characteristics, and then the proper maintenance can be accordingly planned. The recorded signals are measured by accelerometers, located at different sections of the infrastructure. The definition of the location of such acceleration sensors strongly depends on the results which have to be achieved: in order to modal frequencies only, a smaller number of sensors have to be installed, at several plan locations, so that both flexural and torsional vibration modes can be obtained; on the other hand, if also modal shapes have to be computed, much more accelerometers are needed. In Figure 1 horizontal modal shapes are shown for two individual bridge structures, modelled through F.E.M. models.

As can be noted, the topography of the construction site strongly significantly influence modal displacements, which can result non negligible not only at pier and midspan locations, but, in some cases, also at 25% and 75% of the spans. Thus, a large number of accelerometers may be needed, to be able to catch the correct modal deformed shapes (Chang and Pakzad 2014, Meo and Zumpano 2005). In Figure 2 an example of sensors layout is shown.

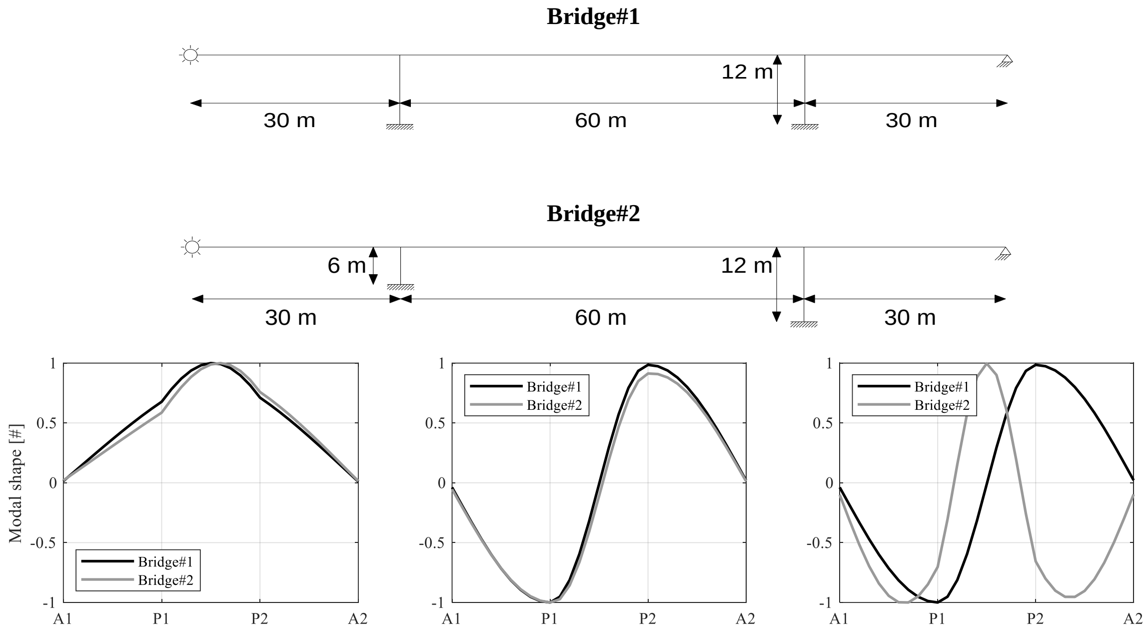

Figure 1. Examples of mode shapes in structural layouts

Other important parameters which can highlight the health status of a bridge structure are curvature, especially for piers bases, displacements, strains and cracks developing. The curvature, which is directly related to the flexural strength of a given section, can be monitored through series of inclinometers, which provide the rotation at different locations. Such sensors can be used also for an indirect evaluation of vertical deflections in the deck spans: precisely, thanks to the slope evaluation at the sections where the sensors are installed, the vertical displacement profile can be found through numerical integration.

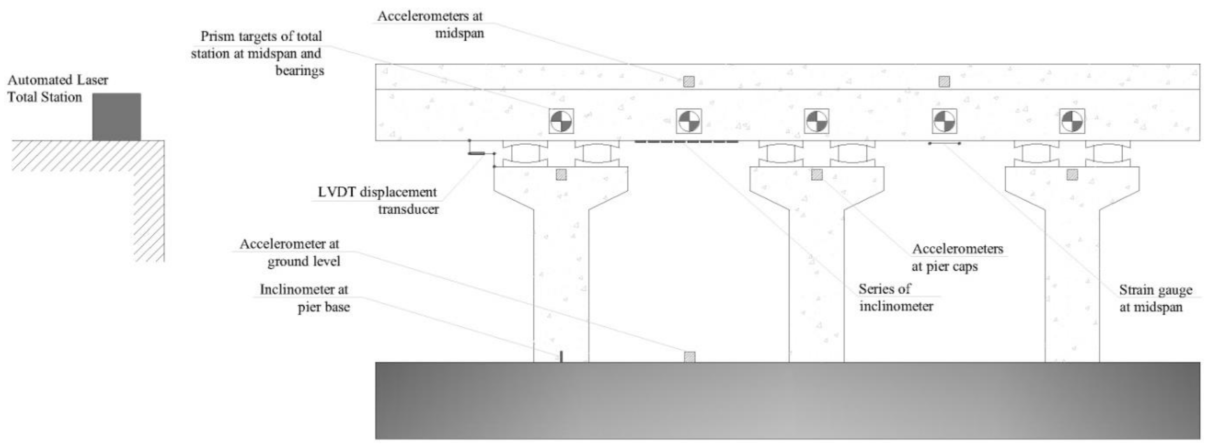

Figure 2. Example of instruments layout

For a more direct evaluation of static displacements, a laser total station can be adopted, which returns distance and relative angles values of prism target points, consequently converted into 3-dimensional coordinates. If dynamic displacement monitoring is needed, Linear Variable Differential Transformer (LVDT) sensors are commonly used, which provide continuous signals of the relative uniaxial displacement between two points of interest. One of the most important applications could be the monitoring of the net displacement demand of seismic isolators, installed at the top of pier caps: recorded signals can lead to evidences of possible serious damage after an earthquake, if the displacement capacity of the devices is achieved or even overcome (Furinghetti and Pavese 2019), or highlight residual displacements if frictionbased isolators are implemented (Quaglini et al. 2016); in addition triggering actions can be set, according to specific thresholds.

For strains and crack developing monitoring (Yan et al. 2019), strain gauges and fiber optic sensors can be adopted in practical applications, can be either embedded in concrete components or placed on exposed components.

3 CLOUD COMPUTING FRAMEWORK

A cloud-based framework is proposed, developed at EUCENTRE Foundation in Pavia (Italy), in order to acquire, store and post-process data, recorded by the installed sensors for Italian school buildings (OReilly et al. 2019).

In Figure 5 the home page of the web administration interface is shown, which allows to analyze recorded and post-processed signals of different monitored structural systems.

Figure 3. Home page of the web administration interface

The presented solution for the management of a given structural health monitoring system allows to acquire, store and post-process data coming from all the installed sensors at some important key points of an infrastructure. Engineers can access to the home page of the administration interface through personal credentials, and the first page provide an overview of the overall monitoring system. Precisely, the cloud-based framework is capable to manage monitoring systems of a number of sites, so that engineers and practitioners have all situations under control, and can assess the health status of all the considered infrastructures. The home page contains a list of all the monitored structural systems, together with a map, which shows where the considered sites are located. In addition, news about recent earthquakes are continuously provided, thanks to the connection to important reference sources (INGV, USGS, etc.). In order to analyse a specific site, the user has just to click on one of the names in the list and immediately the site administration interface is opened (Figure 4).

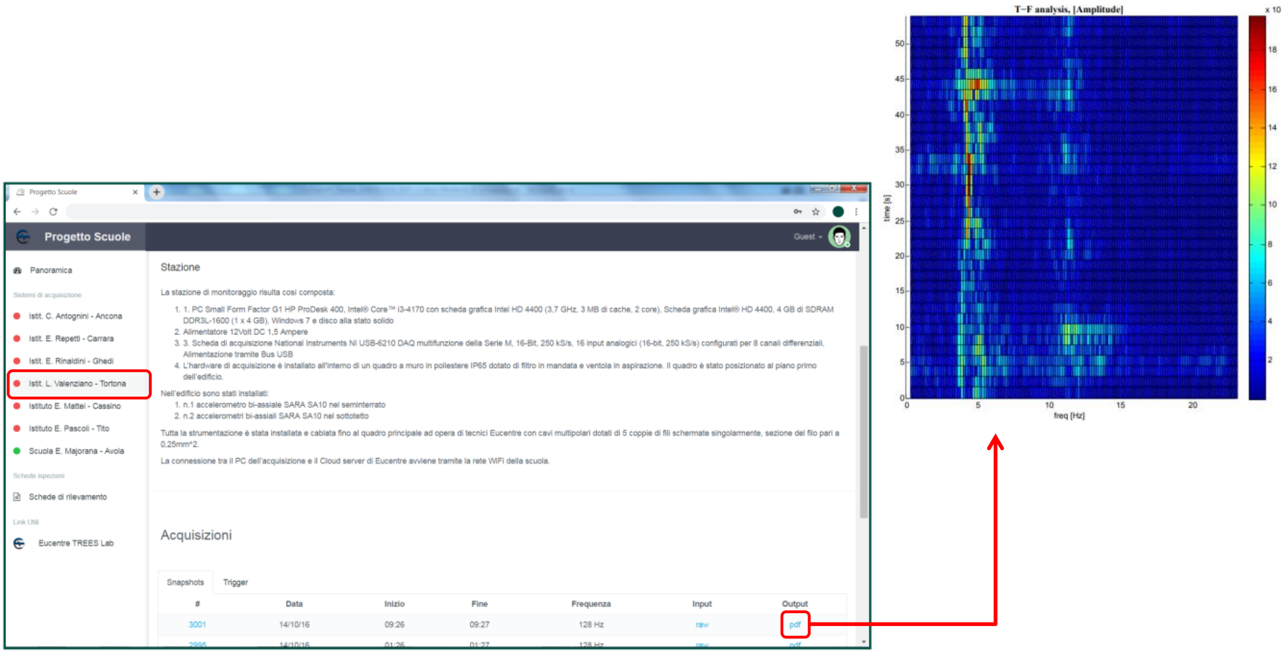

Figure 4. Site administration interface

Such a web page provide a number of useful information about both the structural health monitoring system and the considered site. Media contents can be visualized, which contain photos of the structural system and of the monitored points of interest; in addition, datasheets are also available, related to all the installed sensors, in order to check limitations and the effective working conditions of the instruments, in comparison to nominal characteristics. The main page is the information page, which reports a detailed description of the considered site, together with a summary of all the installed sensors in the monitoring station. The station is able to acquire and synchronize signals of all the installed instruments, according to a common clock, and then to store files into the cloud; it has to be noted that a proper utility (called EuSender) recognizes old and new files, so that updates are just stored, and consequently no lack of storage space occurs. The cloud-based framework, thanks to connected applications, provides to the user both raw and post-processed data, listed in the *Snapshots* frame of the *Information* page. Pdf format automatic technical reports can be also downloaded, which contain all the post-processed analyses, such as the time-frequency analyses of some recorded acceleration time series, which provide evidences of damage progression in the monitored structure, as discussed above (Figure 4). Furthermore, a *Trigger* frame can be found, which lists all the times that specific sensors recorded signals have overcome the previously set threshold values, which activate the monitoring system acquisition. The proposed cloud-based framework provide a very useful tool which allows to plan the proper maintenance of a give infrastructure, by making data (raw and automatically post-processed) available to engineers and practitioners.

4 CONCLUSIONS

In the present endeavour some guidelines for the definition of the key aspects to monitor in order to check the health status of a bridge structural system are provided. A number of response quantities are analysed, together with the related measuring sensors. In addition, the time frame definition is also considered, in agreement with the scope of the monitoring study, and details on the selection of the scale of interest are reported. Finally, a cloud-based framework for the management of a structural health monitoring system is proposed. Such a framework provide a very user-friendly interface between users and recorded raw and automatically post-processed data, and consequently engineers and practitioners are able to plan the proper maintenance, if notifications of excessive damage progressions occur.

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