A Real-Time Monitoring Strategy for the Assessment of Vibration Levels on Stadium Grandstands During Events

Simone Turrisi[1](✉), Emanuele Zappa[1], Alfredo Cigada[1], and Francesco Romanò[2]

[1] Department of Mechanical Engineering, Politecnico di Milano, Milan 20156, Italy
simone.turrisi@polimi.it
[2] Mildred S.a.s., Cesano Boscone, Milan 20090, Italy

Abstract. Stadiums represent a class of civil structures that deserve major concern, mainly because they are frequently subject to the dynamic loads of thousands of people that participate in live events. Their slender and long-span grandstands may reach critical limits, which are dangerous for both the comfort of the participants and the structural safety. This work describes the strategy adopted for the case of the Giuseppe Meazza Stadium in Milan to guarantee the vibration serviceability of grandstands during real events. The existing vibration monitoring system was originally designed for a different purpose, that is to evaluate the dynamic behaviour of the grandstands over the long-term period. For this reason, the collected data were postprocessed offline, so as to extract some relevant indicators (e.g. modal parameters) to assess the structural health. More recently, the system has been updated to include an online component that checks in real-time the vibration levels achieved during concerts or football matches. This allows to evaluate the grandstand behaviour also in case of short-term and extreme events. This paper focuses on the latter aspect, with particular emphasis on the challenges related to the data acquisition strategies, distributed processing, data synchronization and transfer. The monitoring system in use today can be considered a unique example either for the complexity of the implementation and for the innovation of the adopted solutions.

Keywords: structural health monitoring · vibration serviceability · dynamics · stadium · grandstands

1 Introduction

Vibration serviceability of stadium grandstands is receiving increasing attention for many reasons. On one side, old structures were not designed to withstand the dynamic loads induced by the occupants. On the other, modern grandstands are more slender and lighter, and therefore prone to significant motion amplitudes. In response to the concern over the crowd action on these structures, the available codes propose several criteria to assess both human comfort and structural

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safety relying on the measurement of raw accelerations [1,2]. Therefore, it is of utmost importance to develop structural health monitoring (SHM) systems able to evaluate the dynamic behaviour of grandstands during the events. Unfortunately, such kind of implementations are extremely rare. In 2005, Caprioli et al. [3] carried out a measurement campaign on two spot grandstands of the G. Meazza stadium during live events in response to some complaints about the high vibration levels reached in the neighbouring buildings. In 2007, Salyards and Hanagan [4] performed the vibration monitoring of different locations of a stadium during football matches to make an assessment on the severity of the vibrations. Catbas et. al. [5] showed the results of an on-going monitoring study of a stadium during different games. The same research group [6] investigates the vibration acceptability of a grandstand portion under different types of human loads that occur during the game. However, the evaluations made in all these studies were carried out through the post-hoc analysis of the data collected by the monitoring system deployed in the stadium.

The main goal of this work is to present a real-time vibration monitoring system that has been recently deployed at the G. Meazza Stadium in Milan to assess the grandstands serviceability during concerts and football matches. Such a solution has been realized starting from the architecture of the continuous monitoring system already in place at the stadium, which is briefly described throughout the paper. With the addition of a new control unit, the system is now able to perform the online visualization and the further assessment of the acceleration levels measured on the grandstands during the events. Thanks to its high reliability, robustness and ease-of-use, this system represents an efficient and cost-effective tools for the real-time monitoring of stadium structures.

2 The Giuseppe Meazza Stadium in Milan

The Giuseppe Meazza Stadium in Milan, also known as "San Siro" Stadium for the name of the district in which it is located, is one of the most iconic football temples worldwide. Its peculiar structure is made of three rings and a roofing structure (Fig. 1). The stadium was originally built in 1925 and consisted of a single tier lying directly on the ground. A second and independent tier was built in 1955, to increase the number of participants up to 90'000. This tier, structured as ring, is made of 134 vertical leg posts linked to cantilever beams, to support the stands. The vertical leg posts are grouped into 14 main sections, which constitute 14 independent grandstands. The third ring and the roofing structure were built in occasion of the FIFA World Cup in 1990. The grandstands of the third ring are fixed to 10 post-tensioned box girders sustained by 11 towers. The four corner towers are higher than the others and act as the support for the main iron beams of the roofing structure. This latter is made of an upper steel truss that sustains, by means of bolted joints, a lower steel truss made of 37 modular structures called "rafts". These are covered with plastic shields to shelter the spectators from rainfalls.

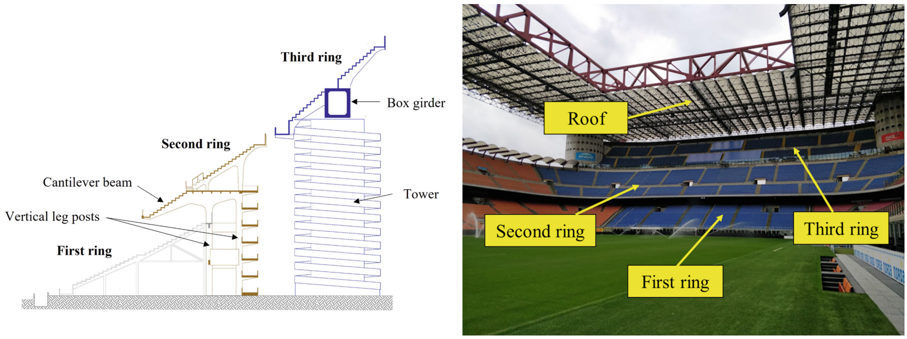


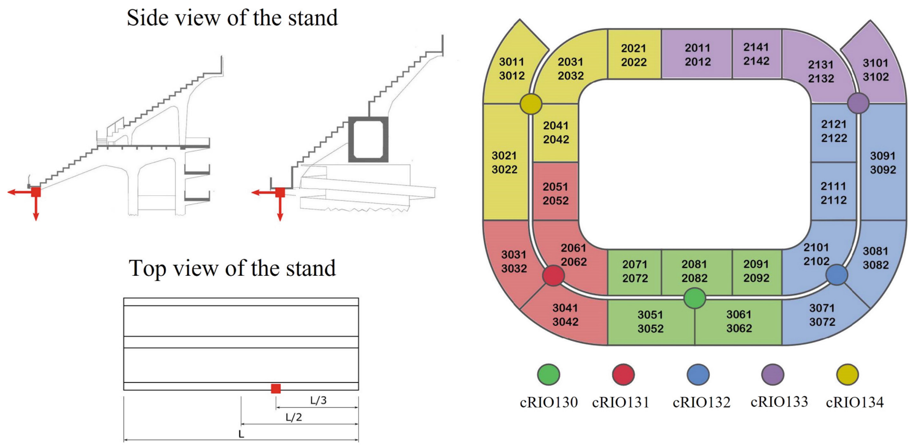
Fig. 1. The Giuseppe Meazza Stadium and its substructures.

3 The Vibration Monitoring System of the G. Meazza Stadium

Since 2006 a permanent SHM system has been developed and gradually enlarged and improved to evaluate the health status of the G. Meazza Stadium [7]. This system consists of a network of acquisition units which are modular and expandable. Data from more than a hundred of sensors are continuously acquired, processed and stored. Some of them measure static quantities, like rotations or displacements, while others measure dynamics quantities, like accelerations.

The remaining of this paper refers to the part of the SHM system related to the vibration monitoring of the grandstands. The current version of the monitoring system covers all the grandstands of the second and the third stadium tiers and uses monoaxial high sensitivity piezo-accelerometers (PCB 393B12) to measure the structural vibrations. The layout of the measurement network was originally designed to obtain diagnostic information of the structures without increasing the complexity and the costs of the system. To satisfy these requirements, the optimal number and the position of the sensors was determined based on the results emerged from preliminary experimental modal analysis campaigns. According to these, a couple of accelerometers was installed for each grandstand at 1/3 of the stand width and close to the lower side of the cantilever beam (Fig. 2a)) to get a reasonable value for all the lower frequency vibration modes. One sensor measures the vertical accelerations, while the other the horizontal accelerations towards the playing ground. Since this measurement point participates to most of the relevant modes of the grandstand, it was possible to extract features related to structure dynamics and use them for long term monitoring purposes and damage detection under operational conditions [8,9]. Because of the cantilever structure of the stands, this point is also the one where the highest vibration levels (and thus the most severe conditions) are reached.

The acceleration time series from 48 measurement channels (24 grandstands with two sensors each) are continuously acquired with a sampling frequency of 128 Hz by five CompactRIO (cRIO) peripheral units by National Instruments, which are real-time controllers equipped with FPGA cores and data acquisition modules (NI 9234 and NI 9230). In order to prevent from any data loss in case of network failures, they are programmed to work independently from the rest of the system. In addition, each cRIO has independent power supply, analog-to-digital conversion, filtering and temporary data storage. Figure 2b shows the layout of the data acquisition system. Stands have the same color of the cRIO unit used to acquire the acceleration data. For each structure, the two measurement channels are represented by a numeric ID: the first digit indicates the number of the ring, the second and the third digit refers to the assigned number of that stand and the last digit indicates the measurement direction (1 vertical, 2 horizontal towards the paying ground).



a) b)

Fig. 2. a) Accelerometers position on the grandstands of the second and third ring. b) Measurement channels and data acquisition units (cRIO) of the permanent vibration monitoring system of the grandstands of the G. Meazza Stadium.

Every ten minutes, the cRIO creates a file with the time histories of the collected sensors and sends it to the central unit. Here, the system management software accounts for communication tasks between the peripheral units and the PC, permanent data storage and post-processing operations. Synchronous data sampling and communication between the different part of the system are guaranteed with high accuracy and low latency thanks to a TCP/IP protocol sent through a wired LAN connection. As the collected data are used for long-term monitoring purposes, any uncertainty linked to short delays between synchronization level of the peripheral units of the system is negligible.

To check the structural condition from any location, the central unit can be safely accessed through a Virtual Private Network (VPN), while both the raw and the elaborated data are transmitted on the cloud, thus becoming available to any authorized terminal. To enhance security and data protection, two networks are managed by the supervising unit: one is internal, just reserved to data streaming, while a second deals with the outside data exchange: in this way data are managed in a hidden and secure environment which cannot be reached from the outside. The scheme of Fig. 3 illustrates the hierarchical structure of the monitoring system, highlighting the four main levels described above.

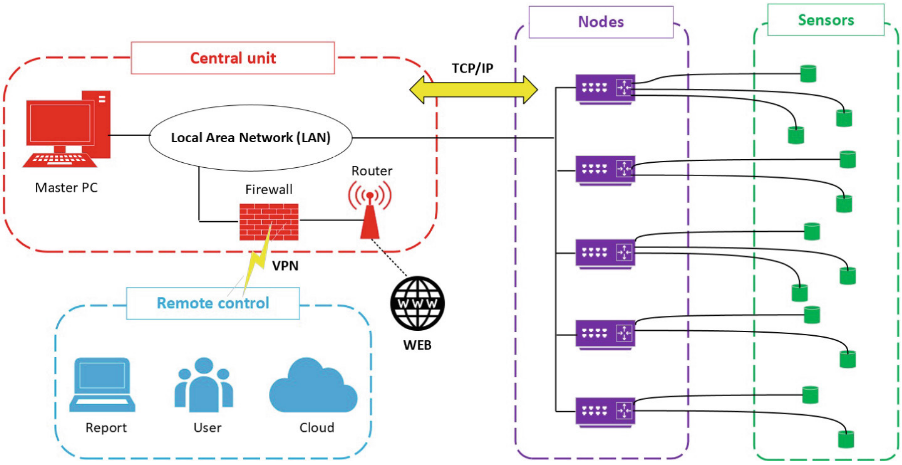


Fig. 3. Architecture of the permanent vibration monitoring system of the grandstands of the G. Meazza Stadium.

4 Real-Time Vibration Monitoring of Grandstands During Stadium Events

The ageing process of the stadium as well as the high vibration levels reached during some football matches in 2019 led the structural engineers to ask for a real-time strategy to assess the serviceability of the grandstands during the events. Both the measurement system and the damage detection methods already in place, however, were unable to meet such a requirement, as they were designed for long-term and offline purposes. Because of that, the system has been recently updated to include also an online component, able to perform a real-time check of the vibration levels reached on the grandstands and assess the structural response under extreme and unusual conditions. The main elements and characteristics of this new part of the system, developed by *Politecnico di Milano* in collaboration with *Mildred S.a.s.*, are provided below.

4.1 Data Acquisition Strategy

A real-time vibration-based SHM system for security purposes must respond to the following needs: (1) collect data from different sensors simultaneously;

(2) high robustness and low latency; (3) redundant hardware to work also in case of failure of some components; (4) sensing of relevant information that indicate structural performance; (5) short feedback time about possible performance deterioration.

To satisfy the above requirements, the existing system has been equipped with a new control unit, located in the room where the Security Operations Group (GOS) resides. With reference to Fig. 4, the host PC at the GOS, with its management software directly communicates with the acquisition nodes (cRIO) through a wired connection. In this way, the online component of the system is able to work independently, guaranteeing data acquisition and visualization without any delay or loss of information. The host PC of the control unit is also connected to the master supervision unit through a second communication channel for remote access and supervision tasks.

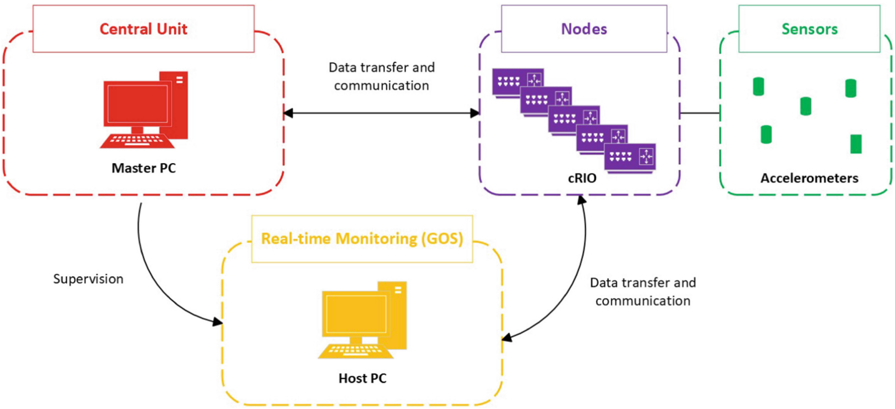


Fig. 4. Real-time vibration monitoring of the grandstands of the G. Meazza Stadium: system architecture

The real-time controller of the cRIO contains an industrial processor that reliably and deterministically executes either simple computing operations or data communication from the FPGA to the host PC, decentralizing some tasks. As the complete streaming cannot be intercepted and anyway a maximum delay of 10 min is possible (data are packed up into files sent every 10 min), the information made available in real-time are reduced: this to increase the security level, as the not overloaded network can easily manage the essential information with no delay or risk of loss. Therefore, some synthetic information related to the last second of acquisition are extracted from all the acceleration signals and sent to the control unit. According to the indications provided by the structural engineers, the variable to be monitored during the stadium events is the peak acceleration a_{pk}, expressed as half the peak-to-peak value between the maximum and the minimum acceleration. The assessment of the structural safety occurs by comparing the measured values with two threshold levels, one for the warning

(T_1) and the other for the alarm (T_2). The two limits were established by the experts based on detailed FEM simulations. T_2 corresponds to the acceleration amplitude which may cause the yielding of the main structural components, under the hypothesis of full stand occupancy and perfect synchronization of the dynamic loads. T_1, instead, is defined as the 80% of T_2.

The use of the one-second based peak acceleration allows for a quick assessment of the structural performance in presence of multiple grandstands and a poor sensor layout. Despite the simple and effective approach, it is recognized that this value, though being useful in a direct comparison against the limits provided by numerical simulations, can be misleading, as a cabled network, with long cables, can also work at the extent of an antenna. In turn, this means that electric noise can produce spikes creating false alarms: the careful experimenter's eye can easily recognize such kind of problem; however, to provide a good check, also the RMS is being sent in the internal network: a single high amplitude spike is not capable of raising the RMS too. When the structure is excited into resonance (almost a single harmonic motion), the ratio between the peak and the RMS has a well- defined value: this tool can be used to recognize high level vibrations out of single peaks and it is being implemented at the moment. Due to the complex architecture of the existing measurement system (48 sensors and 5 acquisition units), it has not been possible to add a redundancy for each component. Therefore, a trade-off solution has been implemented, which involves the installation of a backup position with redundant data acquisition devices and sensors only in those regions which are considered to be the most critical during a specific event.

4.2 System Management Software

The real-time monitoring system is controlled through a dedicated software, called *HMI GOS*, which is in execution on the host PC. Thanks to its user-friendly interface, it is very intuitive and easy to use. Therefore, it does not require any specific knowledge by the operator. This has been tested with the security personnel working at the stadium. The only real problem has been designing a simple user interface, keeping the operator's attention alive in a continuous check of a meaningful number of sensors. When the software starts, the one-second based signals of the peak accelerations are sent by the acquisition nodes and displayed in real-time on the PC. Simultaneously, the time histories of the previous eight hours are downloaded and used for comparison purposes. These information are also stored on a separate text file on the local computer, which can be used for advanced reporting and analysis. The main screen of the software is illustrated in Fig. 5 and consists of 4 sections:

- 'S1: Visualization' → Real-time plot of six time histories of the peak acceleration selected by the user. The position of the grandstand associated to the selected channel is reported on the left. There are also four buttons on the right that allow the user to change the length of the time record, selecting among 1 min, 10 min, 1 h and 8 h.

– 'S2: cRIO status' → Each led is linked to an acquisition unit (cRIO) and lights up in case of malfunctioning or lack of communication between the latter and the PC.
– 'S3: Automatic monitoring' → Channel names are in the first column of the table, while the second column shows the actual value of the peak acceleration for each channel. A color change of the cells is used to indicate the condition of the structure. If this value is below the predefined thresholds (safe condition), then the cell appears as green. The yellow colour indicates that the channel has exceeded the first limit (warning condition), while the red colour stands for the exceeding of the alarm limit (danger condition). In this way, the manager of the structure can tell if the structure is at risk just by looking at the colour of the cells and then choose how to intervene. Finally, the third and fourth column report the two threshold values for each channel. As the threshold exceedance can be very short, once a limit has been overcome, the led remains in the yellow or green status until the operator arms it again by pressing a button.
– 'S4: Sensor Layout' → Two maps have been added to help the operator to associate the name of channel to the correct location. Each map refers to a measurement direction (vertical or horizontal). By clicking on a specific region of the map, the name of the related channel will be highlighted in the table of section S2.

It is also noted that for the most important events a second dashboard has been added, mirroring the home page of the supervising software 5: one page is particularly important, as it translates the vibration levels of each grandstand into a colormap. A colored map of the stadium provides a quick and very effective survey about the most active parts of the stadium, allowing to select the most critical sensor traces in the surveillance GOS software.

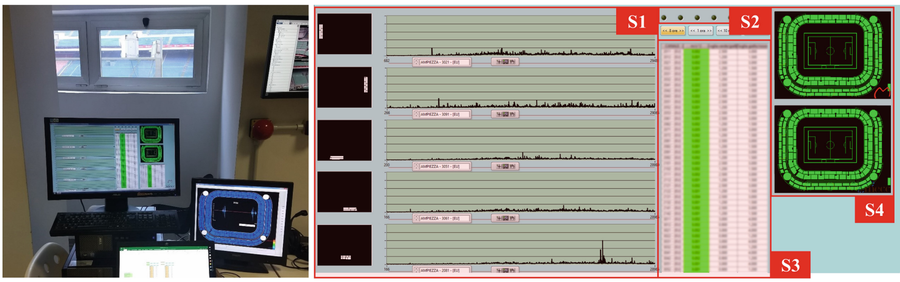


Fig. 5. Real-time vibration monitoring of the grandstands of the G. Meazza stadium: system management software.

4.3 Monitoring Results

The real-time monitoring system has been activated starting from the summer of 2019. After each event, a technical report is drawn up to summarize the trends of the peak accelerations, relying on the data stored on the host PC. Figure 6 shows as illustrative example the main results contained in the report of a concert, randomly selected from the entire dataset. For privacy reasons, the real values of both peak accelerations and threshold limits are not provided, but they are displayed within the limits on the y axis for comparison purposes. The acquired channels are grouped in four distinct plots, based on the type of structure (second/third ring) and the measurement direction (vertical/horizontal). First, it is possible to identify the excitation induced by the activities of the participants according to the rhythm of the song played. Considering the grandstands of the second ring, vertical vibrations are typically higher than the horizontal ones; this is due to the higher motion of the cantilever in the vertical direction when excited by the people motion. Vertical and horizontal accelerations are instead comparable on the grandstands of the third ring. Although the provided control limits are different for each scenario, the peak accelerations always remain well-below them. The maximum value of a_{pk} for the different subgroups varies between 10% and 60% of the warning threshold T_1.

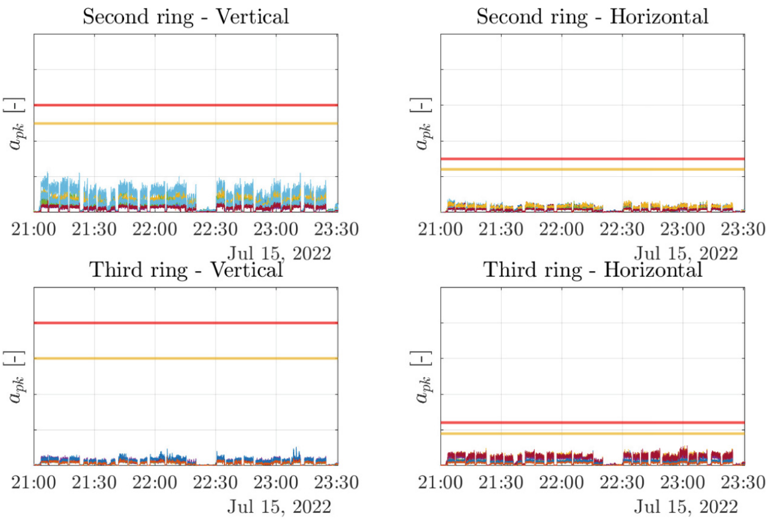


Fig. 6. Example of technical report for a concert. Each subplot shows the time histories of the peak accelerations based on the type of structure (second/third ring) and the measurement direction (vertical/horizontal acceleration). The warning and alarm thresholds T_1 and T_2 are represented as well in yellow and red colours, respectively.

5 Conclusions

This paper describes the development of a SHM system for the real-time assessment of the accelerations reached on the grandstand of the G. Meazza Stadium in Milan during real events. Such a solution has been realized starting from the permanent vibration monitoring system already in place at the stadium, therefore optimizing the costs and the complexity of the architecture. An independent wired network has been added, where an host PC, used for the supervision of the real-time component, directly communicates with the acquisition nodes (cRIO). Thanks to the embedded hardware of the cRIO units, synthetic structural performance indicators can be extracted onboard starting from the raw vibration data and sent to the PC with very high determinism. A system management software has been realized too, that allows an online visualization of the signals and perform an automatic assessment of the structural safety. In light of the few existing examples, this work represents an interesting cue for the design of real-time vibration monitoring systems of stadiums or, more in general, of civil structures hosting a large number of people.

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