Structural Health Monitoring of the Roman Arena of Verona, Italy

Filippo CASARIN*, Claudio MODENA*, Filippo LORENZONI*, Francesca DA PORTO*, Enrico BELLO**
* DICEA, Padova University, via Marzolo 9, Padova, Italy, filippo.casarin@dicea.unipd.it
** IRS srl, via Vigonovese 81, Padova, Italy, bello@irsweb.it

Abstract. Ancient structures - especially very old ones - prove their soundness and the correctness of their structural layout by reaching our days in relatively good conditions. This is the case of the Roman Arena in Verona, Italy, likely built in the I century A.D., and still standing in the historical centre of Verona, being the symbol of the city and open to public use for visits but also for operas, concerts and relevant shows.

With a closer look however, it is possible to appraise the damages that the passing of time and the natural or man induced events such as historical earthquakes, floods or wars and sieges left on the structure. The seismic events (the worst recorded in 1116, 1117 and in 1183) induced serious damage on the Arena, being the cause of the almost complete collapse of the third (external) ring of the monument, today only remaining in the so called "wing" of the Arena, an isolated portion of stone blocks curved wall characterized by a repetition of arches and massive pillars.

With the purpose of evaluating the structural response of the Arena to static, dynamic (e.g. shows, concerts) and seismic loads, a Structural Health Monitoring system was installed in the Arena in 2011, with state of the art technology for the data recording in relevant positions of the Arena. A detailed crack pattern survey was carried out in order to locate the main cracks of the structure, or to identify the most suitable positions where to apply the displacement sensors to determine the reversibility of the natural displacements or deformations trends of the monument.

Finite Elements models were employed to define the relevant modal parameters of the Arena: global modes were identified and thus - with a special focus on the wing - acceleration sensors were installed in the areas where significant dynamic amplifications are expected according to the FE modelling approach.

Results of the SHM system will be employed for tuning the available behavioural models (FE, but also Limit Analysis), in order to trace the structural response of the monument for assessing the operational conditions and predicting the safety conditions of the Arena in the eventuality of a major earthquake.

Introduction

The Roman Amphiteatre or “Arena” (latin for “Sand” which at the time was used for covering the central elliptical courtyard) undoubtedly represents the most important roman monument in Verona, a city in Northern Italy between Venice and Milan, to the point of being the city symbol and main landmark. The building, one of the best preserved ancient structures of its kind, is internationally famous for the large-scale opera performances given there. It is still today able to accommodate an audience of 20’000 (Fig. 1).

Fig. 1 aerial view of the Roman Amphiteatre of Verona, the “Arena”

The monument was erected between the 2nd and 3rd decades of the 1st century AD, on a site which was then beyond the late-republican city walls. The first modern times opera (Giuseppe Verdi’s Aida) was played in the Arena in 1913, to mark the birth of Verdi 100 years before in 1813. Since then, summer seasons of opera have been mounted continually at the Arena, except in 1915–18 and 1940–45, when Europe was convulsed in war. Still today, every summertime over 500,000 people see productions of the popular operas in the Arena. In recent times, the monument has also hosted several concerts of international rock and pop bands, among which Pink Floyd, Simple Minds, Duran Duran, Deep Purple, The Who, Dire Straits, and several others.

1. Structural features

The Arena round façade was originally composed of white and pink limestone from Valpolicella, but after a major earthquake in 1117, which almost completely destroyed the structure's outer ring, except for the so-called "ala" (the remaining section of the outer ring), the stone was quarried for re-use in other buildings.

Its dimensions are about 138 x 109 meters on the outside while the inner elliptic pit is about 44 x 73 meters. There are 45 tiers of steps wherein the opera audience can sit. The building, as other structures of its kind, is composed by a symmetrical arrangement of radial masonry walls separating the the 72 “Arcovoli” (accesses to the courtyard) and three concentric distributive elliptical galleries. Main employed materials are the “opus caementicium” that is to say the roman concrete, and a massive squared stone masonry block masonry.

The monument was subjected to several natural and man induced actions, like the flooding of 589 AD, the earthquakes of 1116 and 1117 – inducing major damages to the structure, corresponding to the almost complete collapse of the outer ring of the Arena, the collapse of 5 arcades on Bra square in 1579, and the continuative stealing of stones and material for re use in other constructions, until being treated like an “historical” monument, with archeological excavations, starting from the XVIII century.

XX century structural interventions and induced damages are documented more in detail: in 1939, both the need of intervening on the external “Ala” for manifest tilting and the necessity of protecting the same structural portion from the possible damages induced by the II w.w. consequences, rendered necessary the construction of massive buttresses, removed after the end of the war by an intervention of post tensioned tendons vertically positioned within the pillars (Morandi, 1956).

2. SHM system in the Arena of Verona

2.1 The need for monitoring the Arena

In recent years the Verona municipality manifested a visible interest for controlling the structural response of the Arena to different external actions, also considered its relevant use. Vibrations caused by concerts were and still are in fact object of discussion, especially for what concerns structural safety of the monument connected to the use of it and the conservation issues. Several investigation campaigns were applied in the last decades, both for defining the state of stress of the composing materials and for measuring the vibration level in the masonry structures. Maintenance is another key aspect of the monument, since hundreds of thousands of people visit the arena yearly, and thus their safety has to be guaranteed.

Also, being Verona located on a seismic prone area, even if moderate, the seismic associated risk has to be evaluated and minimized, if possible, and monitoring may be a viable and effective option for assessing the response of the structure in case of an earthquake and for calibrating behavioral reference models.

In 2011 the Verona Municipality gave the task to the ICEA Department of the Faculty of Engineering of the University of Padova to install and to manage a broad Structural Health Monitoring system for assessing the main structural parameters of the Arena in order to assess more in detail its structural safety.

2.2 Structural Health Monitoring (SHM) system

The SHM system has been designed and installed by the authors in order to monitor the mechanical behavior of the Arena, through the experience gained by several SHM systems applied to CHBs (Ref. [1],[2],[3],[4]). The final aim is the acquisition of the dynamic characteristics of the monument by means of acceleration transducers, and the control of the surveyed crack pattern through the implementation of displacement transducers installed on the main cracks. The acquired data are constantly related to the environmental parameters (temperature and relative humidity).

The evaluation of the measured quantities, and in particular their changes over time, allows having useful indications in the definition of the structural behavior and in the determination of the presence or occurrence of damage’s phenomena.

Important information are currently recorded by the monitoring system, in relation both to the static displacements (deformation of the controlled cracks) and the dynamic response of the monument, evaluating the accuracy of the adopted numerical models on the basis of the actual behavior, also in case of possible seismic events.

The installation of the monitoring system was carried out between October and December 2011. The preliminary phase before the installation consisted in: (i) design of the system (hardware - types of sensors and acquisition units); (ii) development of appropriate software in relation to the selected monitoring strategy; (iii) choice of the system’s layout and the points of structural control according to the outcomes of reference numerical models, the survey of the damage pattern and the results of dynamic identification tests of the structure.

The system is composed by sixteen single-axial accelerometers (acceleration transducers), twenty linear potentiometers (displacement transducer) and four integrated sensors of temperature and relative humidity. Given the huge dimensions of the structure it was decided to develop and implement a hybrid system: static sensors are connected through six wireless slaves placed around the perimeter of the Arena to the principal acquisition unit and data are transmitted via a radio antenna, whereas the accelerometers are connected with three wired slaves that transmit the signals to the master via ethernet cables.

Displacement transducers were installed in correspondence of the main surveyed cracks and are connected to a wireless node, each with four channels, that send the signals to the master unit by means of a radio link. The acquisition unit continuously communicates with the Wireless Sensor Network (WSN). Eight sensors were installed on the ground floor in the first internal gallery at a height of about 9 meters in correspondence to a big crack that runs almost along the entire perimeter of the Arena's ellipse (Fig. 2). Twelve transducers were positioned from outside in the vaulted niches (called "arcovoli") at the second order of arches of the monument: some of them on isolated cracks, some others on the surveyed detachment between the perimeter stone wall and the radial walls.

The position of the sixteen single-axis accelerometers (Fig. 3) was decided according to the dynamic characteristics and vibration modes of the structure, evaluated through both numerical models and Operational Modal Analysis (OMA). Six accelerometers were installed on the wing of the Arena on two different levels along the out-of-plane direction. The wing is composed by a freestanding wall connected to the rest of the structure only at the first level and it is considered the most vulnerable structural element. Seven accelerometers were positioned on the top of the second order of arches along the elliptical perimeter of the structure, according to the radial configuration of the monument. Finally three sensors were placed at the base of the building along two orthogonal horizontal directions and a vertical one in order to record the ground acceleration in case of seismic events and evaluate the dynamic amplification of the structure.

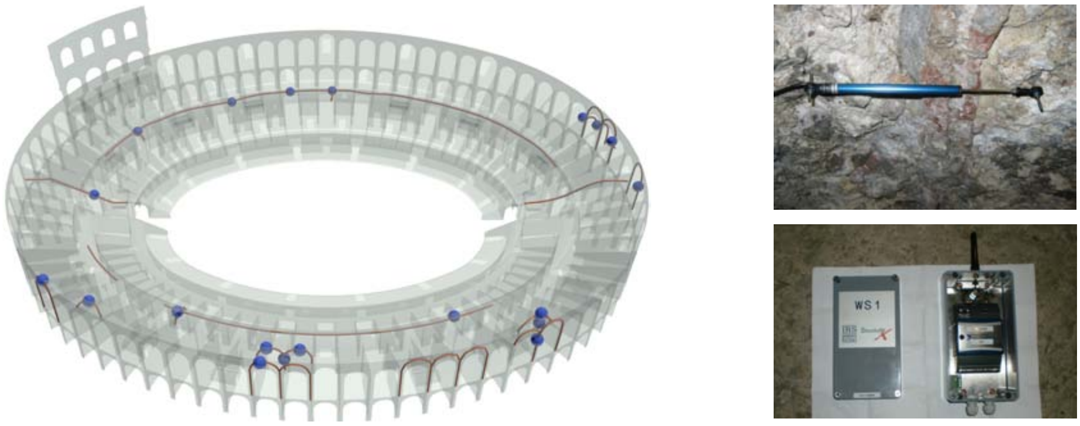


Fig. 2 Layout of the static system (left); displacement transducer and wireless slave (right)

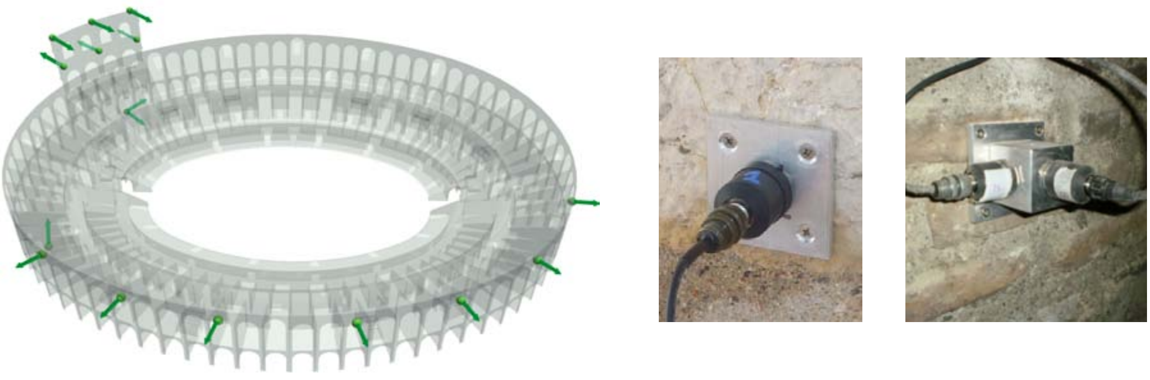


Fig. 3 Layout of the dynamic system (left); accelerometers installed on the wing and at the base of the structure

With regard to the dynamic measurements, two strategies have been selected: "long" acquisition, on regular intervals to allow subsequent identification by means of structural vibration in different environmental conditions (seasonal cycle), and "short" acquisition which is done automatically when the vibrations exceed the trigger (significant event). In the latter case, the system during an event that exceeds the established level, records the data from several seconds before and after the violation. This methodology ensures that the registration does not lose important data for the event. Moreover the system is equipped with a router for remote data transmission to the central server of the University of Padova.

3. First results & the recorded seismic events

3.1 First results - modal analysis of the wing

The installed monitoring system allows the analysis of a huge amount of data taking into account three main aspects: (i) control of variations of the static measurements, (ii) daily extraction of the fundamental modal parameters; (iii) registration and analysis of possible seismic events.

Significant effort is devoted to the analysis of recorded data. In particular the research activities are currently focused on the implementation in MATLAB environment of automatic and semi-automatic procedures for both static and dynamic data processing. The automatic procedure applied to static data elaborates a standard .txt file acquired by the static system and create automatically a series of graphs, representing the variation over time of the monitored parameters and correlating them with temperature and humidity variations. The algorithm allows also applying corrections on acquired data in order to remove errors caused by human interaction or system’s malfunctioning. The automatic procedure applied to dynamic data elaborates the acquisition files and automatically estimate and extract modal parameters from measured vibrations.

Usually this process involves a large amount of user interaction, especially when lots of data need to be processed in a short amount of time. The developed algorithm, based on MACEC 3.2, 2011 (Ref. [1]), implements the poly-reference Least Square Complex Frequency Domain method (pLSCF) in order to extract automatically modal parameters (frequency and damping ratio development over time, MAC indexes variation between the starting reference identification and the daily identification).

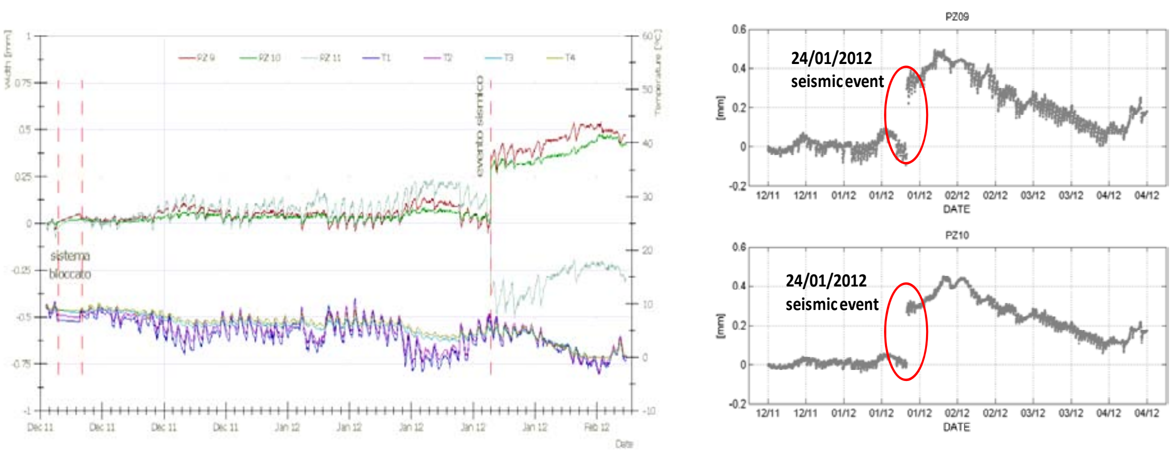
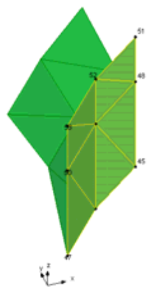
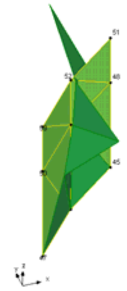
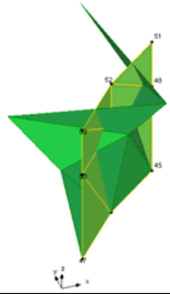
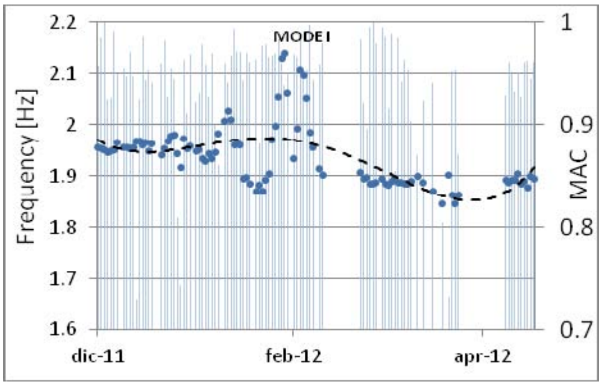


Fig. 4 Displacements of about 0.3 mm recorded during the seismic event in correspondence to the cracks PZ9 and PZ10 located in a ‘arcovolo’ of the second level.

Table 1. Identification of the modal parameters performed by FDD technique

Mode	Freq. [Hz]	comment	Mode 1	Mode 2	Mode 3
1	1,929	1st out-of-plane bending			
2	2,637	1st torsional			
3	5,078	2nd out-of-plane bending			
4	5,884	3rd out-of-plane bending			
5	/	1st in-plane bending			
6	7,300	2nd torsional			
7	9,302	/			
8	10,940	/			



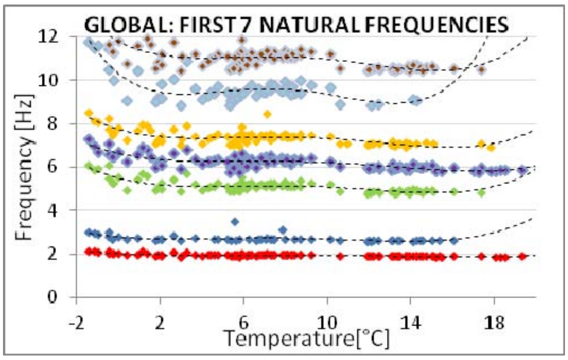


Fig. 5 First frequency development over time in the period Dec 2011 - April 2012 (left). Frequency variation in function of the temperature (right)

During the first months of monitoring no worrying displacements were recorded and the crack's deformations follow the temperature variation. Some movements were recorded after the seismic events occurred at the end of January 2012 with the epicenter located at about 11 km from the Arena, whose effects were carefully evaluated and the main results connected to the dynamic aspects presented in the following paragraph. As it can be noted in Fig. 4 the earthquake induced a slight relative displacement of the transducers PZ9 and PZ10 located in a vaulted niche ("arcovolo") at the second level. The recorded displacement resulted to be quite reduced (about 0.3 millimeters), in the range of the drifts induced by the temperature variation. Based on the initial dynamic identification (Tab. 1), the variations of the fundamental natural frequencies of the wing are constantly extracted from the measured vibrations, acquired every 24 hours. The frequency development over time gives a sound indication on the dynamic characteristics of the structure and it is strongly related to the environmental parameters (Fig. 5).

3.2 January 2012 seismic events

At the end of January 2012 a series of low/moderate seismic events hit the northern part of Italy and in particular the surrounding areas of Verona. Thanks to the monitoring system of the Arena it was possible to capture every single event and control the response of the structure during the earthquakes, evaluating the possible induced damages. The records of the seismic events give also crucial indications on the site effects and allows characterizing the amplification factors of both soil and structure itself.

Three main earthquakes were recorded, each of one followed by smaller aftershocks. The first earthquake, occurred in the province of Verona (11km north from the Arena, 10 km deep, magnitude 4.2 on the Richter scale), induced the strongest vibrations on the structure of the Arena. The other two seismic events (Reggio Emilia: 75 km from the

Verona, 30 km deep, magnitude 4.9 and Parma: 130 km from Verona, 60 km deep and magnitude 5.4), even if characterized by a bigger magnitude, induced lower accelerations on the monument due to probably the greater distance from the epicenter, the deeper position of the fault and the different frequency content of the main shock.

The identification procedure consisted in applying the base acceleration in the two orthogonal directions recorded by the system to the nodes at the model's base. Subsequently the accelerations extracted from the numerical calculations were compared with the experimental accelerograms of the monitoring system recorded in the same positions. This analysis allows calibrating the FE model to a real earthquake and updating the elastic mechanical properties of the structure in order to obtain comparable values of acceleration. The maximum values of acceleration recorded at the top of the wing by the system and simulated by the FE models are very similar and equal to about 2 m/s^2 (Fig. 6). Thus it is possible to state that the reference behavioral model of the wing is correctly calibrated and, more important, that the structure during the earthquake remained in the elastic range. Finally a dynamic identification was performed using the Frequency Domain Decomposition (FDD) technique on the recorded earthquake in order to evaluate the variation of modal parameters during the seismic excitation. It was possible to note that the first modes are subjected to a clear decrement of the frequency values during the earthquake. The frequency decrement was recorded only during the main shock and in the following days the extraction of the modal parameters give similar results to those recorded before the seismic event, indicating that the earthquake did not induce permanent and significant structural damages to the building.

Table 2. Comparison between Peak Ground Accelerations (PGA) recorded by the INGV station (part of the Italian Accelerometric Network) and the Arena monitoring system

TREGNAGO INGV STATION (15 km from epic.)			MONITORING SYSTEM		
PGA [cm/s^2]	Component	Distance [km]	PGA [cm/s2]	Component	Distance [km]
24.1567	HNE	15.4	61.9	HNE	about 11
24.7744	HNN	15.4	35.7	HNN	about 11
12.0584	HNZ	15.4	26.5	HNZ	about 11

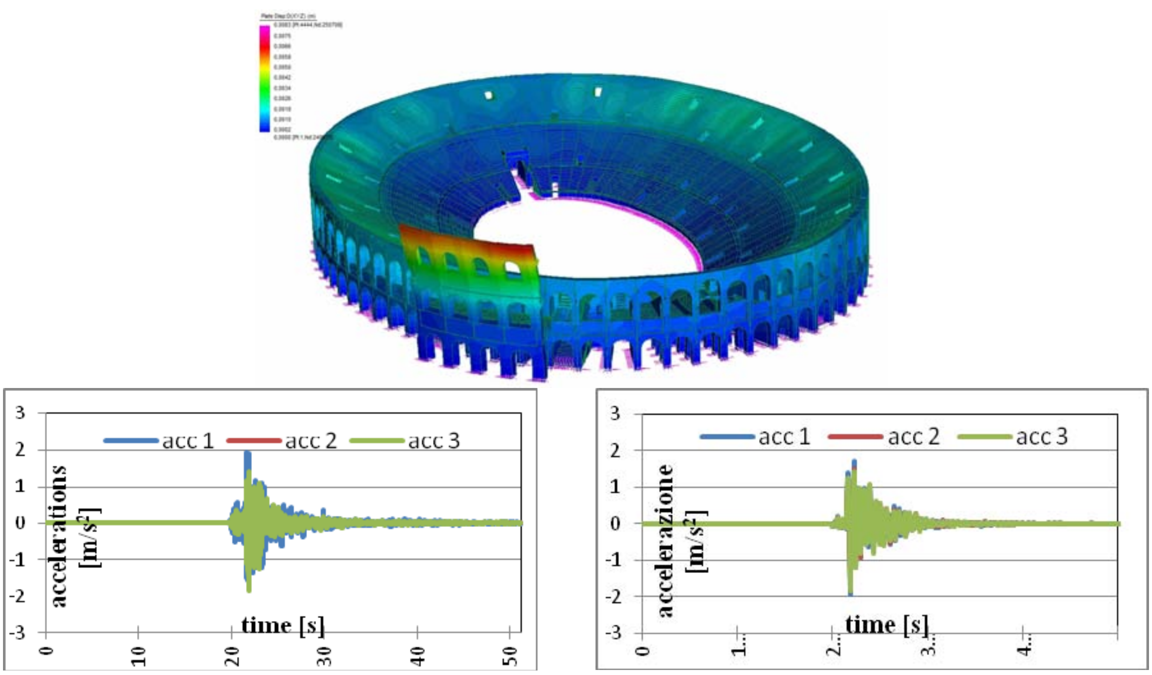


Fig. 6 top: FE model of the Arena; below: comparison between time histories recorded by the Arena monitoring system at the top of the wing (left) and those obtained numerically on the FE model

4. Conclusions & perspectives

Monitoring is being more and more considered, in the field of cultural heritage buildings, as a key activity in order to increase the knowledge on the structural functioning of monuments and therefore to have a deeper insight on their conditions (Ref [6], [7]). In case of a seismic event, monitoring can furthermore prove its usefulness in quantitatively assess the real entity of structural damage.

Between the available techniques that may be profitably used to control the response of a historic masonry building, dynamic identification proves to be a very effective tool, since it allows to experimentally measure parameters related to the global structural behavior. The combined use of dynamic identification procedures and "local" controls (besides the monitoring of the environmental parameters), providing quantitative information on local conditions of structural elements (e.g. cracks opening), can be an important asset in the effort of attaining a deeper degree of awareness on the "real" structural functioning of the monuments.

The SHM system installed in the Arena of Verona allowed in fact to quantitatively define the actual PGA at the foundation of the structure during moderate seismic events happened after the system completion in 2012, gave the possibility to appraise the maximum accelerations attained at the top of the monument, which in the 24th of January event resulted to be quite significant (approx 2 m/s^2), and rendered possible the evaluation of the permanents effects on the structure, both from a static (residual crack openings) and dynamic point of view (absence of evident frequency shifts).

Behavioral models were finally tuned on the experimental records of the SHM system, and will be used in successive steps for simulating the design earthquake expected in Verona, for defining the seismic performance of the Arena in case of major events, studying then possible remedial measures if a satisfactory performance is not achieved. Future research will be also devoted to structural models relying on a data driven approach.

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