Exploring Human-Crowd Interaction in Structural Monitoring: Insights from Two Decades of Events at the G. Meazza stadium

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Abstract. In recent times, a growing body of research has emerged to evaluate how structures respond to dynamic forces generated by human activities. Notably, stadia and sports arenas require significant attention due to the presence of spectators during events such as football matches and concerts.

The way the crowd behaves during such events causes meaningful vibration levels which can be critical for both human comfort and structural integrity. Generally, the interaction between humans and structures is a significant concern in structural health monitoring. While a structure behaviour may be considered more deterministic (albeit challenging to predict), the forces exerted by crowds are inherently variable and hardly controllable. A critical aspect is related to the fact that studying the crowd behaviour is a complex task, because a proper modelling not only implies engineering knowledge, but also taking into account other complex factors, e.g., the social and psychological aspects of the human behaviour.

In this context, this paper provides a unique contribution by presenting and analysing vibration data gathered by the monitoring system of the G. Meazza stadium in Milan during a series of concerts. This extensive dataset, built over the past 16 years, represents a one-of-a-kind contribution in the literature on stadia and sport arenas, offering valuable insights into possible factors that influenced the evolution of crowd behaviour during large-scale events.

Keywords: Structural Health Monitoring, Vibration Monitoring, Human-Structure interaction, Large-Scale Civil Structures, Arenas

1. Introduction

Understanding the dynamic interaction between human activities and structures has become increasingly important in recent years, especially in large-scale structures such as stadia and sports arenas. These venues host a variety of events, from football matches to concerts, drawing crowds in the order of tens of thousands; the presence of such crowds, moving,

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jumping or bouncing poses significant challenges for both structural integrity and human comfort.

The crowd exerts dynamic forces on the structure, resulting in vibrations which could be critical for a number of aspects [1]. Existing codes, which evaluate both human comfort and structural safety, primarily rely on raw accelerations [2,3]. Therefore, structural health monitoring (SHM) systems emerge as invaluable tools, providing crucial insights into these complex dynamics.

Among the limited number of such systems, the G. Meazza Stadium stands out as a notable example. Over the years, numerous papers have explored various facets of the stadium dynamics (e.g., [4,5]) and focused on the development of data-driven strategies for continuous health assessment (e.g., [6,7]). This paper aims to introduce another intriguing aspect: the study of the crowd behaviour during concerts, leveraging a comprehensive database spanning approximately 16 years. While this aspect will be briefly introduced here, the focus of this paper is primarily on presenting the database itself.

2. The G. Meazza Stadium

The Giuseppe Meazza Stadium in Milan, also known as the "San Siro" Stadium due to its location in the San Siro district, stands as an emblematic football arena on a global scale. Its distinctive architecture comprises three tiers and an intricate roofing system (Fig.1).

Originating in 1925, the stadium initially featured a singular tier resting directly on the ground. A significant expansion took place in 1955 with the addition of a second tier, elevating the capacity to host up to 90,000 spectators. This tier is characterized by 134 vertical support columns interconnected by cantilever beams, forming 14 distinct sections, each constituting an independent grandstand.

The third tier and the roofing structure were later introduced for the FIFA World Cup in 1990. The grandstands of the third tier are supported by 10 post-tensioned box girders, anchored to 11 towers. Notably, the four corner towers stand taller, serving as pivotal supports for the primary steel beams of the roofing system. This roofing system consists of an upper steel truss, which, through bolted joints, sustains a lower steel truss composed of 37 modular structures, outfitted with plastic shields, to shield spectators from rainfall.

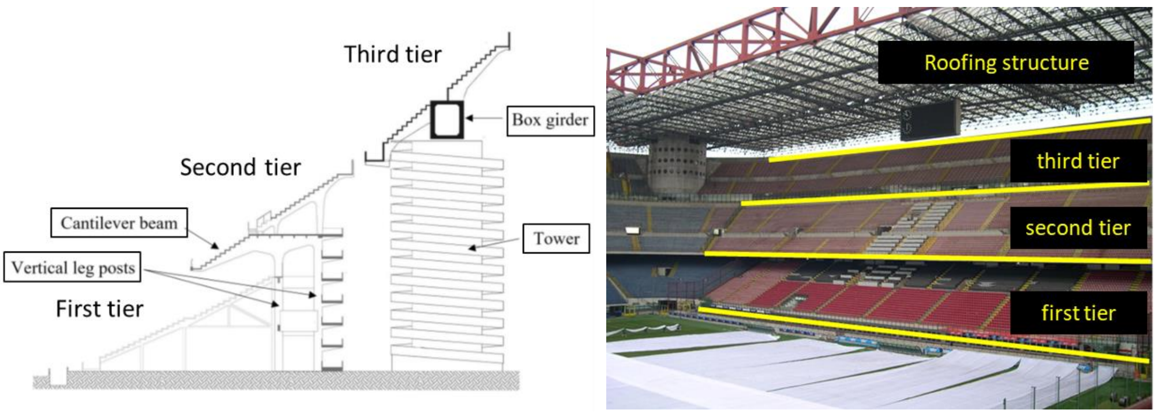

Fig. 1. The Giuseppe Meazza stadium: external view (left) and its substructures (right)

3. The Structural Health Monitoring System

The G. Meazza Stadium is a highly complex structure, comprising multiple substructures built at different times, using various materials and design approaches. Since 2006, a permanent SHM system has been developed and continuously improved to assess the condition of these structures [8].

This system consists of a network of modular and expandable acquisition units. It continuously collects, processes, and stores data from over a hundred sensors. Some sensors measure static quantities like rotations or displacements, while others focus on dynamic quantities like accelerations, which are the main focus of this study.

The current version of the monitoring system covers all the grandstands of the second and third rings of the stadium; each stand can be referred to, according to the numbering scheme reported in Fig. 2, left. The system uses high-sensitivity piezo-accelerometers to measure structural vibrations. The layout of the measurement network was designed to gather diagnostic information without making the system too complex or expensive.

The optimal number and position of the sensors were determined based on results from preliminary experimental modal analysis campaigns. As a result, a pair of accelerometers was installed for each grandstand, positioned at 1/3 of the stand width and near the lower side of the cantilever beam, at the edge (see Fig.2, right). One sensor measures the vertical acceleration, while the other measures the horizontal acceleration.

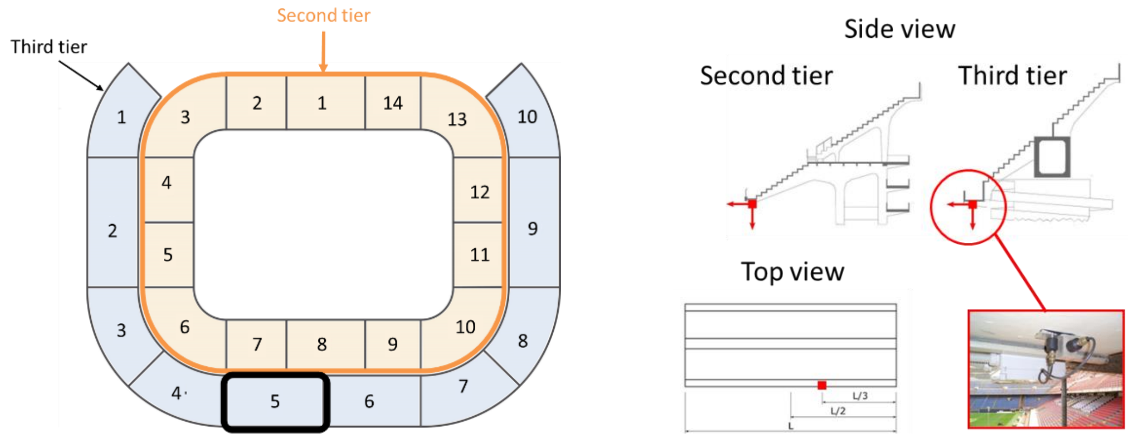

Fig. 2. Stand numbering scheme (left) and sensor position (right)

Data from 48 measurement channels (24 grandstands with two sensors each) are continuously collected at a sampling frequency of 128 Hz by five CompactRIO (cRIO) peripheral units by National Instruments. Every ten minutes, each cRIO creates a file with the time records of the collected sensors and sends it to a central unit, where it is stored locally and transmitted on the cloud (more details can be found in [9]).

4. The Database of Events

Since the installation of the SHM system at the Giuseppe Meazza Stadium, a comprehensive database has been collected to store data obtained from various events. Over the years, a substantial amount of data has been stored, encompassing both routine, environmental and operational excitations as well as the input given during specific events held at the stadium. The archival of data collected over an extended period provides invaluable insights into the long-term evolution of the stadium behaviour and driving maintenance strategies, as well as detecting the peak vibrations in view of a serviceability assessment.

Within this vast repository, data captured during events such as concerts offer unique opportunities for understanding the dynamic interaction between the stadium infrastructure and the energetic ambiance of live performances. Concerts are precious in determining the extreme excitation values, as the crowd behaviour is strongly influenced by the music, providing a good synchronization with a narrow band excitation, whose main frequency is driven by the song rhythm.

While real-time monitoring aspects of the system are detailed elsewhere [9], this paper focuses on presenting the concert database: which is unique as, along the years, several concerts have been recorded, under different environmental conditions, with different artists, of different musical genres. Also, some artists held several concerts in different years, providing an opportunity to assess reproducibility. For example, comparing the structural response to the same song performed in different years allows for an examination of consistency over time. Table 1 presents a chronological list of concerts for which data are available in the database. For each concert listed in table 1, three columns contain: an ID for reference, the name of the performing artist or band, and the date of the concert. This tabulated information serves as a reference point for the next analyses presented in the following chapter.

Table 1. List of concerts of the database

ID	Artist	Date	ID	Artist	Date	ID	Artist	Date	ID	Artist	Date
1	Negramaro	31/05/2008	23	Vasco Rossi 3	09/07/2014	45	Vasco Rossi 1	01/06/2019	67	Ultimo 2	24/07/2022
2	Springsteen	25/06/2008	24	Modà	19/07/2014	46	Vasco Rossi 2	02/06/2019	68	Tiziano Ferro 1	15/06/2023
3	Muse	08/06/2010	25	Vasco Rossi 1	17/06/2015	47	Vasco Rossi 3	06/06/2019	69	Tiziano Ferro 2	17/06/2023
4	Ligabue 1	16/07/2010	26	Vasco Rossi 2	18/06/2015	48	Vasco Rossi 4	07/06/2019	70	Tiziano Ferro 3	18/06/2023
5	Ligabue 2	17/07/2010	27	Jovanotti 1	25/06/2015	49	Vasco Rossi 5	11/06/2019	71	Coldplay 1	25/06/2023
6	Vasco Rossi 1	16/06/2011	28	Jovanotti 2	26/06/2015	50	Vasco Rossi 6	12/06/2019	72	Coldplay 2	26/06/2023
7	Vasco Rossi 2	17/06/2011	29	Jovanotti 3	27/06/2015	51	Ed Sheeran	19/06/2019	73	Coldplay 3	28/06/2023
8	Vasco Rossi 3	21/06/2011	30	Tiziano Ferro 1	04/07/2015	52	Ligabue	28/06/2019	74	Coldplay 4	29/06/2023
9	Springsteen	07/06/2012	31	Tiziano Ferro 2	05/07/2015	53	Laura e Biagio 1	04/07/2019	75	Ligabue	05/07/2023
10	Madonna	14/06/2012	32	Pooh	10/06/2016	54	Laura e Biagio 2	05/07/2019	76	Pooh	06/07/2023
11	Springsteen	03/06/2013	33	Modà 1	18/06/2016	55	Muse 1	12/07/2019	77	Mengoni	08/07/2023
12	Jovanotti 1	19/06/2013	34	Modà 2	19/06/2016	56	Muse 2	13/07/2019	78	Pinguini Tattici Nucleari 1	11/07/2023
13	Jovanotti 2	20/06/2013	35	Springsteen 1	03/07/2016	57	Elton John	04/06/2022	79	Pinguini Tattici Nucleari 2	12/07/2023
14	Bon Jovi	29/06/2013	36	Springsteen 2	04/07/2016	58	Cremonini	13/06/2022	80	Depeche Mode	14/07/2023
15	Negramaro	13/07/2013	37	Rihanna	13/07/2016	59	Mengoni	19/06/2022	81	Ultimo 1	17/07/2023
16	Depeche Mode	18/07/2013	38	Beyoncè	18/07/2016	60	Rolling Stones	21/06/2022	82	Ultimo 2	18/07/2023
17	Robbie Williams	31/07/2013	39	Ferro	16/06/2017	61	Salmo	06/07/2022	83	Blanco	20/07/2023
18	Ligabue	06/06/2014	40	Coldplay	04/07/2017	62	Guns N Roses	10/07/2022	84	Muse	22/07/2023
19	Ligabue	07/06/2014	41	JAX & Fedez	01/06/2018	63	Amoroso	13/07/2022	85	Maneskin 1	24/07/2023
20	Pearl Jam	20/06/2014	42	Cremonini	20/06/2018	64	Pezzali 1	15/07/2022	86	Maneskin 2	25/07/2023
21	Vasco Rossi 1	04/07/2014	43	Negramaro	27/06/2018	65	Pezzali 2	16/07/2022			
22	Vasco Rossi 2	05/07/2014	44	Beyoncè	06/07/2018	66	Ultimo 1	23/07/2022			

For each of these events, data acquired by the SHM system are available. In addition to raw sensor data, the database also includes environmental information such as temperature on the day of the concert. Furthermore, details regarding the performing artists are included to facilitate the interpretation of the crowd behaviour. Factors such as music genre and tempo play a crucial role in determining the excitation frequency of the jumping crowd, while artist popularity is closely linked to the crowd participation and the exerted forces.

It's noteworthy that the use of the stadium for concerts has seen a gradual increase over the years, evolving from just two concerts per year in 2008 to nearly 20 concerts in the past year (2023). This escalating trend underscores the importance of comprehensively understanding the impact of such events on the stadium structural health.

As it is possible to see from Table 1, world-famous artists have performed at the G. Meazza stadium over the years. Some instances involve the same artist performing in multiple years (for example, Bruce Springsteen in 2008, 2009, 2013, and twice in 2016) and/or staging the same concert on consecutive nights (such as Vasco Rossi, who performed six times in 2019, or Coldplay, who performed four times in 2023), enabling the comparative analyses about reproducibility already mentioned above.

5. Long-Term Data

To provide an example of vibration data acquired during a concert, we present some of the most recent data. In Fig. 3, as an example, we present the raw acceleration data for the concert hosted by the artist Blanco on July 20th, 2023. The figure displays acceleration time histories for stand 5 of the third tier in both vertical (top) and horizontal (bottom) directions. The stand, highlighted within a rectangle in Fig. 2 (left), is positioned in front of the stage during the vast majority of concerts. These data are particularly interesting, as this concert exhibited exceptionally lively activity and significant crowd participation. This is a rare example, as previous studies [4,8] have shown that historically, the third tier has rarely shown significant vibration levels (e.g., during Ligabue concerts in 2014, as we will discuss later).

The data of both channels presented in Fig. 3 are normalized with respect to the maximum peak, which is in the vertical direction. The data are shown for a window of 3 hours, encompassing the duration of the concert. As depicted in Fig. 3, the vertical direction exhibits higher values than the horizontal one. In both channels, high-energy events can be readily identified in the raw time histories, particularly towards the end of the concert between 7000 s and 8000 s. These events correspond to the final songs of the setlist, which are characterized by their popularity and upbeat tempo.

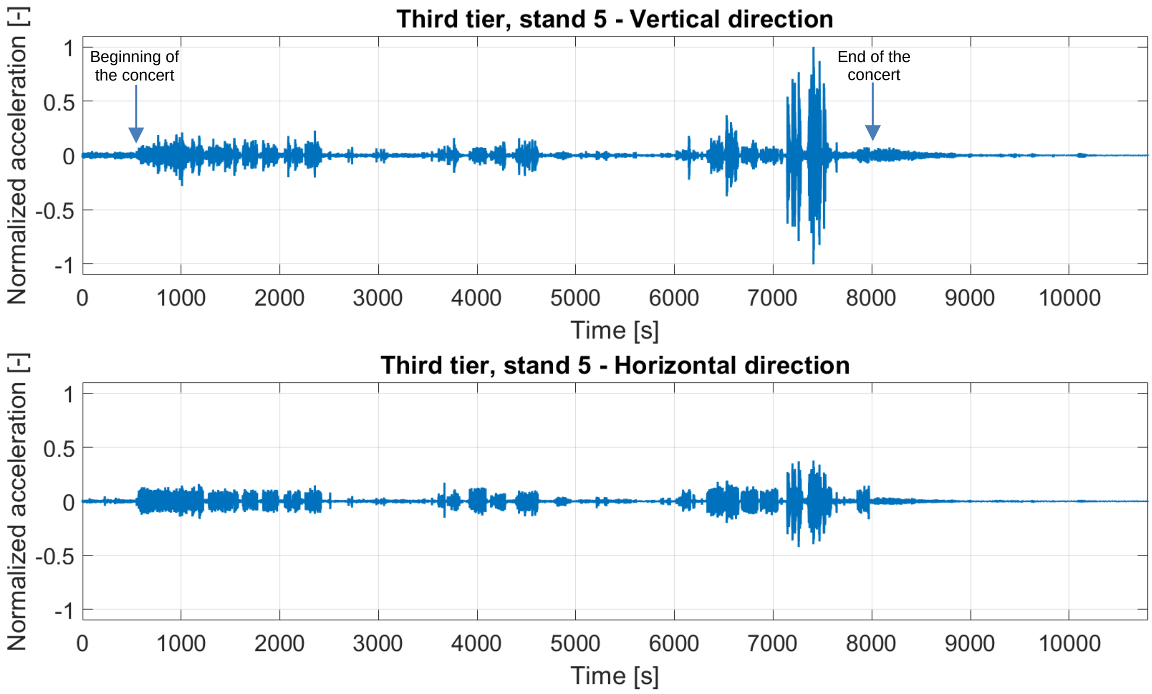

Fig. 3. Acceleration time histories for stand 5 of the third tier: vertical (top) and horizontal (bottom) direction

Among the various indexes that can be used to synthetically represent acceleration levels, the peak acceleration (a_{pk}) is often adopted, defined as half the difference between the maximum and minimum acceleration evaluated over windows lasting 1 s. As explained into details in [9], this index is directly calculated during events and compared against thresholds which could be data established by experts, or obtained from the database built on the preceding events. In Fig. 4, a_{pk} is plotted for stand 5 in the vertical (top) and horizontal (bottom) directions using the normalized data from Fig. 3. Although the trend of a_{pk} can be used to quickly detect the moment characterized by the highest vibration levels (indicated with a red arrow in Fig. 4), this alone does not provide exhaustive information about the nature of the vibration. It's worth noting that the maximum peak could potentially be associated with a low average energy level, for example, due to an electrical spike. To extract additional information, the ratio between a_{pk} and the root mean square (RMS) value of the signal, evaluated over windows lasting 1 s, is presented in Fig. 5. It is interesting to observe that, for the majority of the concert, the ratio between a_{pk} and the RMS is greater than 2. Sometimes, however, it drops at lower values, close to 1.5, as seen at the moment corresponding to when the maximum a_{pk} is reached (highlighted by a red circle in Fig. 5). Knowing that for a perfect sinusoidal wave the ratio between a_{pk} and the RMS should be equal to 1.41, this simple index can provide additional information about the type of phenomenon that caused the maximum vibration level.

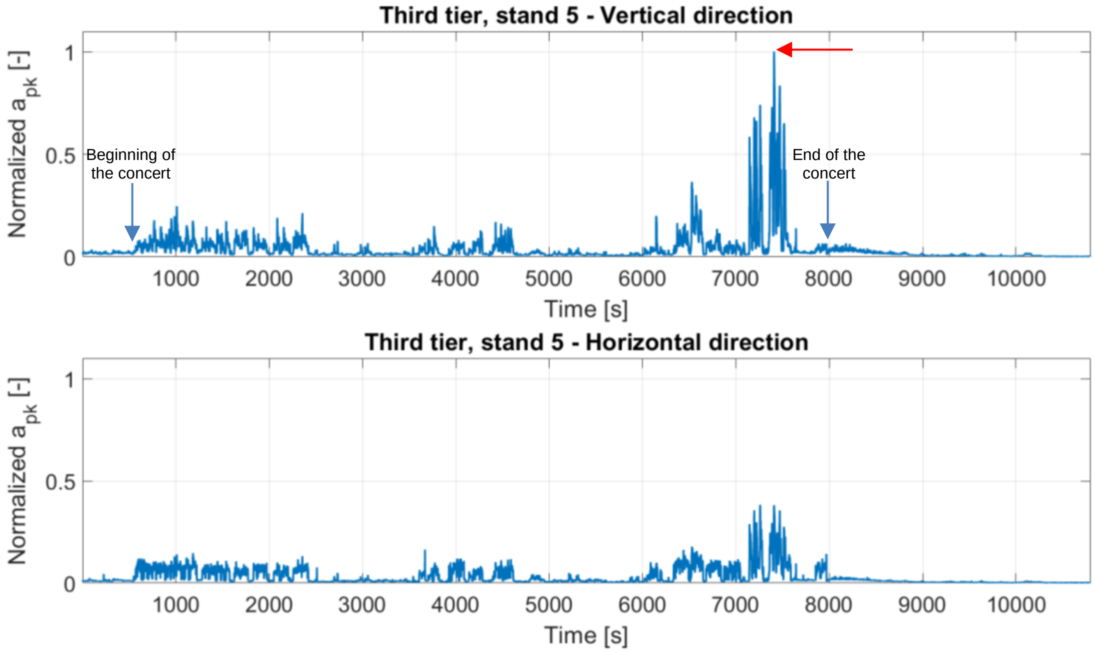

Fig. 4. Peak acceleration (a_{pk}) time histories for stand 5 of the third tier: vertical (top) and horizontal (bottom) direction

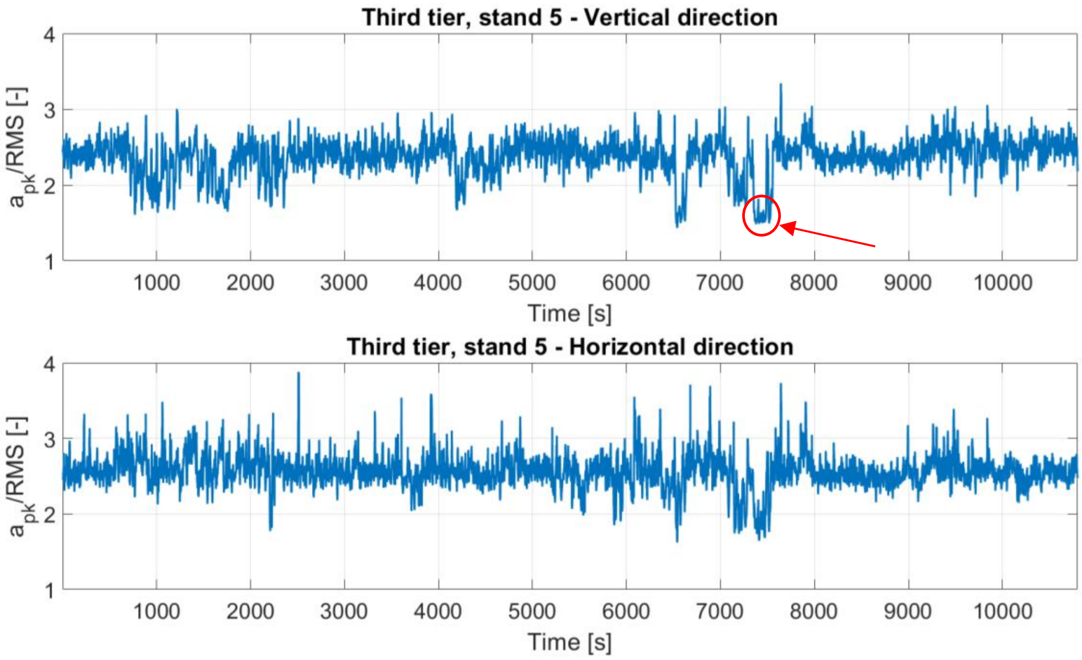

Fig. 5. Peak acceleration (a_{pk}) divided by the RMS, evaluated over windows lasting 1 s, for stand 5 of the third tier: vertical (top) and horizontal (bottom) direction

A closer examination of the event where a_{pk} reaches its maximum value, and the ratio between a_{pk} and the RMS shows a drop, is depicted in Fig. 6, where a clear harmonic motion is observed. It must be pointed out that this occurrence is rare for the third tier, given that the first vibration mode is around 3 Hz. This frequency is difficult to excite consistently by a jumping crowd, as it is too fast for humans to jump at such a frequency. In this rare case, the popularity of the song encouraged intense crowd participation. According to live recordings of the song during the concert, it was performed with a tempo approximately equal to 170 bpm (2.83 Hz). The rhythmic beat of the music synchronized the movements of the crowd, likely more related to bobbing than jumping, and a high-quality sound system further enhanced this synchronization, resulting in a frequency that is close to one of the natural frequencies of the stand. This phenomenon leads to dynamic amplification of vibrations, significantly magnifying the structural response. Unlike the case of football matches, where music synchronization is absent, this phenomenon could persist for minutes, as the rhythm of the music synchronizes people throughout the entire duration of the song. However, in the case of the third-tier stand, the phenomenon typically lasts only a few tens of seconds because individuals struggle to maintain the high-frequency jumping movement.

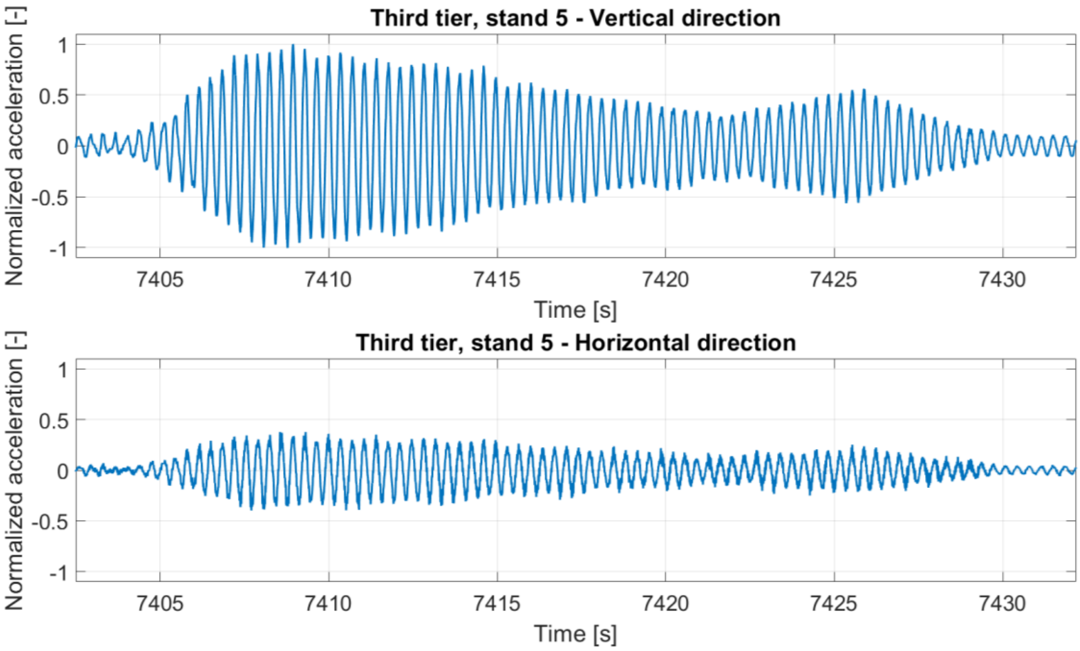

Fig. 6. Normalized acceleration time histories for stand 5 of the third tier, zoom on the event with highest values: vertical (top) and horizontal (bottom) direction

In the end, Fig. 7 provides a plot of a_{pk} for stand 5 of the third tier, for all concerts in the database. The maximum a_{pk} observed on a one-second basis is reported for each concert captured by the SHM system. The x-axis denotes the event ID, referenced to the list provided in Section 4, while the y-axis represents the maximum a_{pk} reported for every concert. Vertical-dashed lines are used to separate the events by year. Similar to previous figures, data normalization is adopted; in this case, all data are normalized with respect to the maximum a_{pk} for the considered stand, which was observed on the vertical direction for ID 18 (artist Ligabue, June 6th, 2014).

For this specific stand, the analysis of a_{pk} over the years reveals no clear increasing or decreasing trends and, for the majority of the concerts, the highest a_{pk} is observed on the vertical direction. A good repeatability can be assessed by comparing values reached during consecutive concerts held by the same artist in the same year: by adopting the most recent data as an example, IDs 71-74 (highlighted by a dashed ellipse in Fig. 7) which refers to 4 concerts of the band Coldplay show similar values among each other. It must be noted that, in those 4 concerts, the setlist was mostly the same.

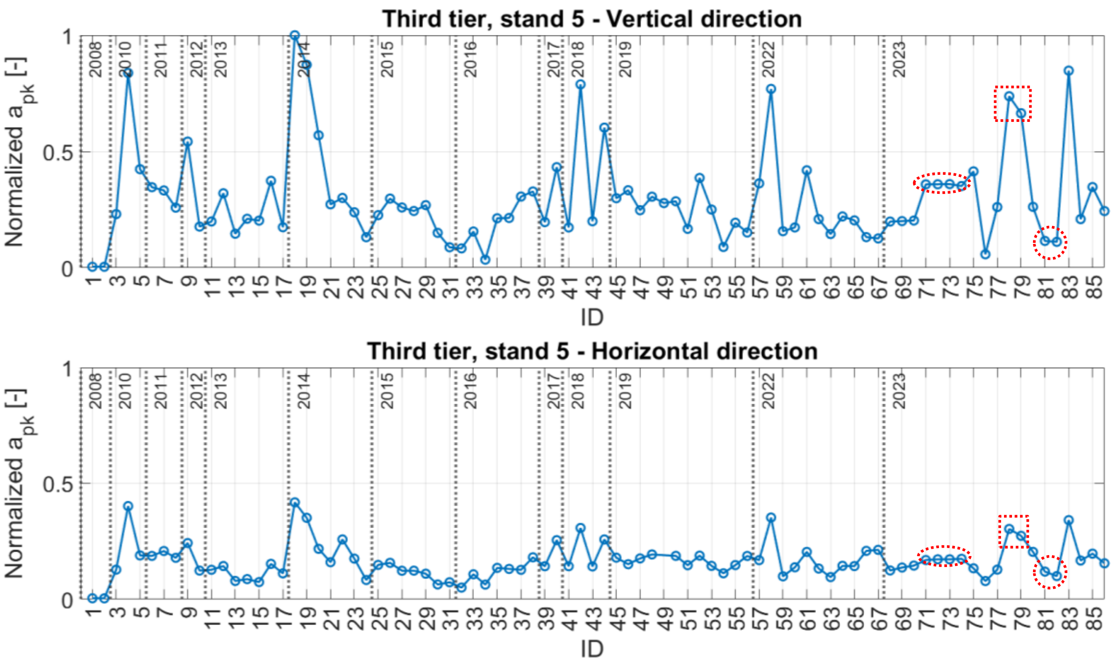

Fig. 7. Peak acceleration (a_{pk}) for stand 5 of the third tier: normalized maximum values recorded for each concert in the database, shown separately for vertical (top) and horizontal (bottom) directions.

In the same concert season, other artists who performed multiple shows exhibited similar attendance patterns. For instance, Bands Pinguini Tattici Nucleari (IDs 78-79, highlighted by a dashed square in Fig. 7) and artist Ultimo (IDs 81-82, highlighted by a dashed circle in Fig. 7) both demonstrated consistency in attendance across their respective performances. However, the variation in energy levels among these sets of concerts can be attributed to differences in musical style. Pinguini Tattici Nucleari's performances featured more upbeat songs, triggering dynamic participation from the crowd. In contrast, Ultimo's performances comprised downtempo songs and ballads, resulting in a more subdued audience response.

6. Final Remarks

This paper has introduced the concert data database gathered by the structural health monitoring system at the G. Meazza Stadium in Milan spanning the past 16 years. This unique resource offers valuable insights into crowd behaviour during large events, such as concerts attended by tens of thousands of people. Moving forward, armed with this extensive historical dataset, the authors are actively exploring novel approaches to data modelling and condensation, aiming to enhance comprehension of stadium dynamics and crowd behaviour during events of this scale.

Funding

The research presented in this paper has been funded by the Italian National Research Program, in a project named “Life-long optimized structural assessment and proactive maintenance with pervasive sensing techniques” PRIN 2017.

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