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STRUCTURAL PERFORMANCE AND HUMAN COMFORT ASSESSMENT OF RC CANTILEVER GRANDSTANDS: THE CASE OF THE SECOND RING OF SAN SIRO MEAZZA STADIUM IN MILAN

Martina Cogliano[1], Nicola Scattarreggia[2], Matteo Moratti[3], and Gian Michele Calvi

[1] University School for Advanced Studies IUSS Pavia, Pavia, Italy
Piazza della Vittoria, 15, Pavia 27100, Italy
e-mail: martina.cogliano@iusspavia.it

[2] University School for Advanced Studies IUSS Pavia
Piazza della Vittoria, 15, Pavia 27100, Italy
{nicola.scattarreggia, gm.calvi}@iusspavia.it

[3] Studio Calvi Ltd
Via S. Severino Boezio, 10, Pavia 27100, Italy
matteo.moratti@studiocalvi.eu

Abstract

Reports from all over the world highlight that several stadiums with cantilever grandstand have shown problems due to excessive vibrations during soccer matches, requiring a more detailed and careful evaluation of the actual structural performances with the aim of assessing both human comfort and structural safety. As a matter of fact, many of the stadiums currently used have been designed and built neglecting some phenomena (e.g., dynamic load of spectators), because of the limited knowledge and computational resources. This work intends to examine the San Siro Meazza reinforced concrete Stadium, located in Milan; in particular, the analysis focuses on the study of a portion of the second sector, for which observed acceleration values could disturb the spectators according to literature's reference. The dynamic behavior of the structure has been evaluated under different conditions of dynamic loads in terms of frequency and synchronous/asynchronous motion of people through a linear finite element model (FEM). The model has been calibrated on experimental dynamic data. The studies have highlighted the importance of the dynamic characterization of the structure for both human comfort and structural safety; under certain load conditions, numerical results are consistent with those obtained experimentally.

Keywords: reinforced concrete, stadium, dynamic analysis, human comfort, Finite Element Method.

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1 INTRODUCTION

Nowadays stadiums are multifunctional facilities, being used not only for sport events but also, for instance, for concerts. During these events, people may jump following music's beat, with the consequence of generating a strong dynamic periodic load on the structure. Typically, old stadiums have not been designed for this type of dynamic excitation, therefore different matters may arise, among which excessive level of vibrations, which can disturb audience or even generate panic, with the extreme possibility of endangering human life; and excessive level of demand on the structure, in terms of both stress and strain, that can compromise the structural safety. With the purpose of studying these issues, different load models have been considered to represent a dynamic crowd acting on the grandstand of the Giuseppe Meazza Stadium in Milan. It is a reinforced concrete stadium, characterized by a peculiar construction history, as illustrated in section 3. The study takes advantage of the several experimental data available for this structure acquired by the monitoring system handled by Politecnico di Milano. The availability of the acceleration (and displacement) time-histories recorded during several events, mainly soccer games, has allowed the authors to better calibrate numerical assumptions, obtaining a robust structural model. Indeed, structural modelling plays a significant role in evaluating the realistic response of the structure; as a matter of fact, both two-dimensional and three-dimensional models have been developed in order to find a balance between computational demand and model accuracy. Consequently, sensitivity analyses have been performed to calibrate each model, by varying those parameters which may affect the static and dynamic properties of the structure, as shown in section 5.1. Once proved the model feasibility with respect to experimental results, the dynamic response of the structure has been studied, first through steady-state analysis, followed by time-history analysis. Two different jumping load models in combination with the synchronism and asynchronism of the crowd have been used to characterize the structure response at significant frequencies.

2 HUMAN ACTIVITIES AND COMFORT

Grandstands are susceptible to human-induced movements; particularly when they are sustained by slender cantilever structures. Depending on the stadium employment and occupancy, human activities can significantly vary, as described in [1]: from a predominantly seated crowd for classical concerts and regular sport events, to excited crowd during more extreme events, such as important football matches and rock concerts, where fans may bob and jump following the music beat. Dynamic loads characterizing intense events might be much higher than the static ones, thus inducing concerns for both structure safety and serviceability.

An important issue is the mutual effect of people movement and structure response; it has been shown [2] that the human body does not simply represent a mass, but can adsorb and release energy due to its flexibility. Consequently, it will interact with the structure depending on its response. A distinction between two extreme cases is useful, i.e., considering a stationary and a moving crowd. A stationary crowd will affect the structural behavior, altering its frequencies and possibly increasing its damping properties; a moving crowd can be considered solely as a load hence the "empty" structure properties remain intact [3].

A very severe condition is represented by the entire crowd jumping at a frequency resonant with one of the structure main response frequencies, a possible consequence of a music recurring rhythm [4].

2.1 Load models

Possible models of the vertical loads considered to represent the human crowd dynamic loading are those proposed in [5], [6] and [7].

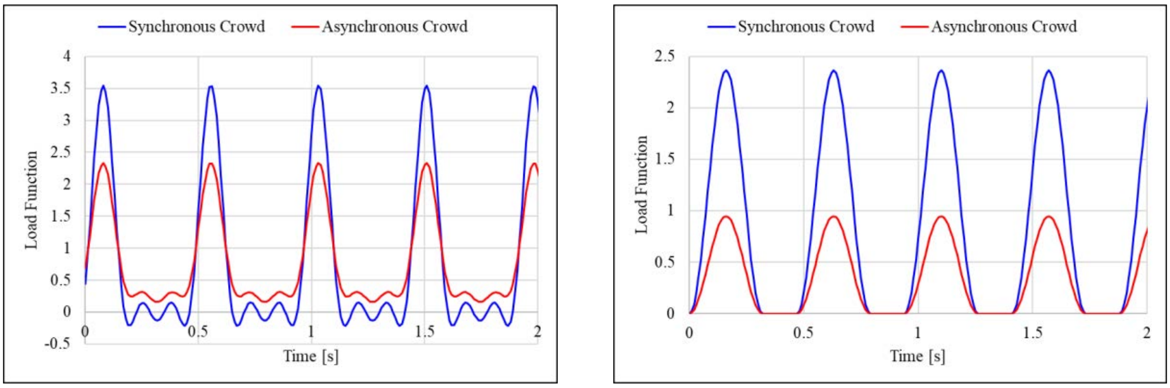
Two independent numerical loads, experimentally calibrated, are described by periodic functions defined as a function of different parameters, e.g.:

- The average weight of each person;
- The jumping period (or frequency);
- Duration of the contact between the jumping person and the structure, i.e. how long a jumping person is in contact with the structure between two consecutive jumps.

In addition, a parameter that accounts for different levels of synchronism between persons needs to be considered, for instance as proposed by [7] as function of the number of people involved in the activity. Indeed, most likely the asynchronism increases while the number of people increases. However, this study refers to two different jumping crowds:

- *Synchronous crowd*, assuming all people jumping in perfect synchronicity;
- A*synchronous crowd*, assuming 3 persons per square meter, according to [5, 6] the multiplier factor reduces the load of the synchronous crowd of about 34% for the load model proposed in [5] and 60% for the one proposed in [6].

Figure 1 illustrates the difference in shape between the two load models, for each of which a representation for both synchronous and asynchronous crowd is given for frequency equal to 2.14 Hz.



(a) **(b)**

Figure 1: Load model 1 a) and 2 b) representation with frequency equal to 2.14 Hz for both synchronous and asynchronous crowd.

2.2 Comfort

An excessive level of vibrations may annoy the audience, especially those not participating in generating the excitations, or even generate panic. There are different methods to assess whether an acceleration level is disturbing or not, based on different definition of intensity measures, as illustrated in [8], among which peak acceleration, root mean square of acceleration (arms), which represents the square root of the mean square of the acceleration history, and the vibration dose values (VDVs), which combines amplitude and duration of vibrations. For simplicity, the peak acceleration approach has been followed. The maximum vertical acceleration recorded during the analyses has been compared with the vibration limits proposed in [9] and shown in Table 1.

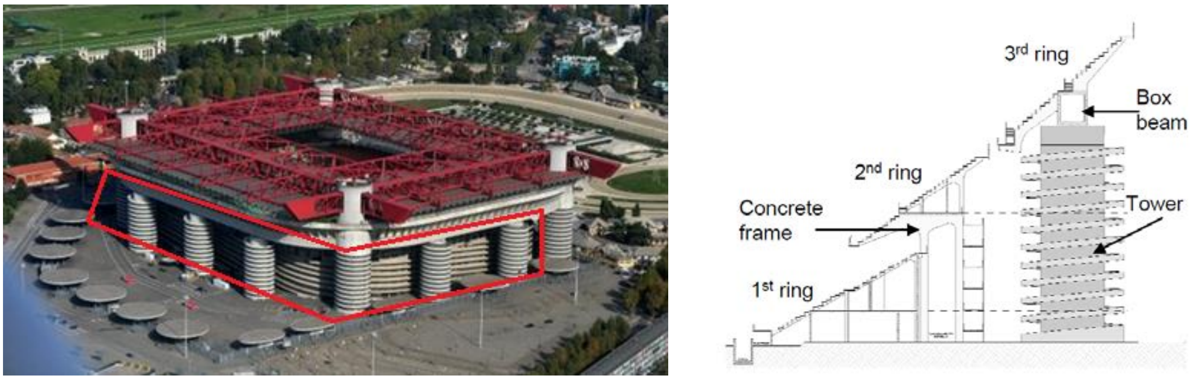
Vibration level	Reaction
$< 5\%\ g$	Reasonable limit for passive person
$< 18\%\ g$	Disturbing
$< 35\%\ g$	Unacceptable
$> 35\%\ g$	Probably causing panic

Table 1: Peak vertical acceleration limits

3 THE SAN SIRO MEAZZA STADIUM CASE STUDY

The Giuseppe Meazza stadium, also known as *San Siro* from the name of the neighborhood that hosts it, was built in Milan in 1925, and is the largest sport arena in Italy. Initially it consisted of four straight concrete stands, with a capacity of 35,000 spectators; the extension work, begun in 1935, led to the realization of the connecting curved corners, shaping what nowadays is the first ring and increasing the maximum number of spectators up to 55,000 [10].

Later, a new concrete structure, which embraces the existing one, was built in 1955, with the aim of supporting a second tier, the so called second ring, which surrounds and partially covers the first ring. The total capacity raised to 80,000 people, of which 60,000 seated.



(a) **(b)**

Figure 2: San Siro Stadium a) and section view of the three rings b) ([11]).

On the occasion of the 1990 World Cup, the need of a larger capacity and a more reasonable distribution of spectators for safety purposes induced the municipality of Milan to decide to further expand the stadium. A new structure was again added: eleven towers, with helicoidal-shaped ramps, were erected as supports for the third ring, which develops only on three sides. This third grandstand is characterized by post-tensioned concrete box girders, each of them carrying two cantilever tiers. Four red truss beams, supported by the corner towers, form the roof structure covering all the 80,000 seats.

The Meazza Stadium has undergone several reinforcement and restoration interventions; in particular, seismic retrofitting was necessary to adapt the structure to modern standards in 2014.

As described in detail in [11, 12], the stadium is subjected to permanent continuous monitoring, in consideration of its complexity and relevance.

3.1 The second ring

The subject of this study is the second ring, built in the 1950s, whose structure is made of 132 reinforced concrete frames, perpendicular to the soccer field, about 20 m tall; they are grouped in 14 sections that can be considered as independent structures. Each frame comprises the main following elements:

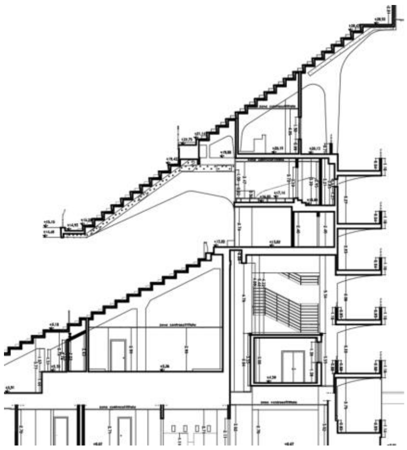


Figure 3: Section view of the second ring.

- Two columns with different heights (about 16 m and 18 m high) and same rectangular cross-section 1.20 x 0.70 m;
- A beam with variable depth (from 0.25 m to 2.90 m), 0.70 m wide, characterized by supported and cantilevered portions;
- Two beams with rectangular cross-section of 1.90 x 0.70 m, located at intermediate heights of the frame to link the columns.

In the direction parallel to the field, the frames are connected at a height of about 20 m by concrete slabs, transverse beams and outer ramps.

Each frame of the second ring has been strengthened applying two continuous plates, laterally bolted to the cantilever beam.

The interest in the second ring of San Siro stadium arises from vibration levels higher than usual recorded during some recent football events, particularly in areas where organized supporters are located. The maximum accelerations attained were about 2.5 m/s^2 in the vertical direction and 1.2 m/s^2 in the horizontal one. These values were recorded at the knee of the cantilever beam. These occurrences induced to investigate how a dynamic crowd load may affect and interact with the structure.

4 STRUCTURAL DYNAMIC AND HUMAN COMFORT ANALYSIS

4.1 Dynamic identification from experimental tests

Dynamic identification tests performed by Politecnico di Milano in 2006 show that the dynamic behavior is governed by few harmonics:

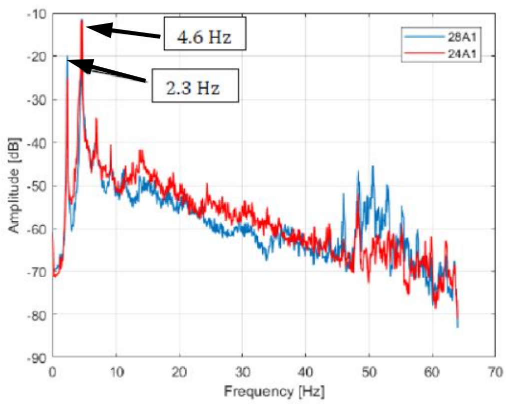


Figure 4: Dynamic identification for the Second Ring of San Siro Stadium

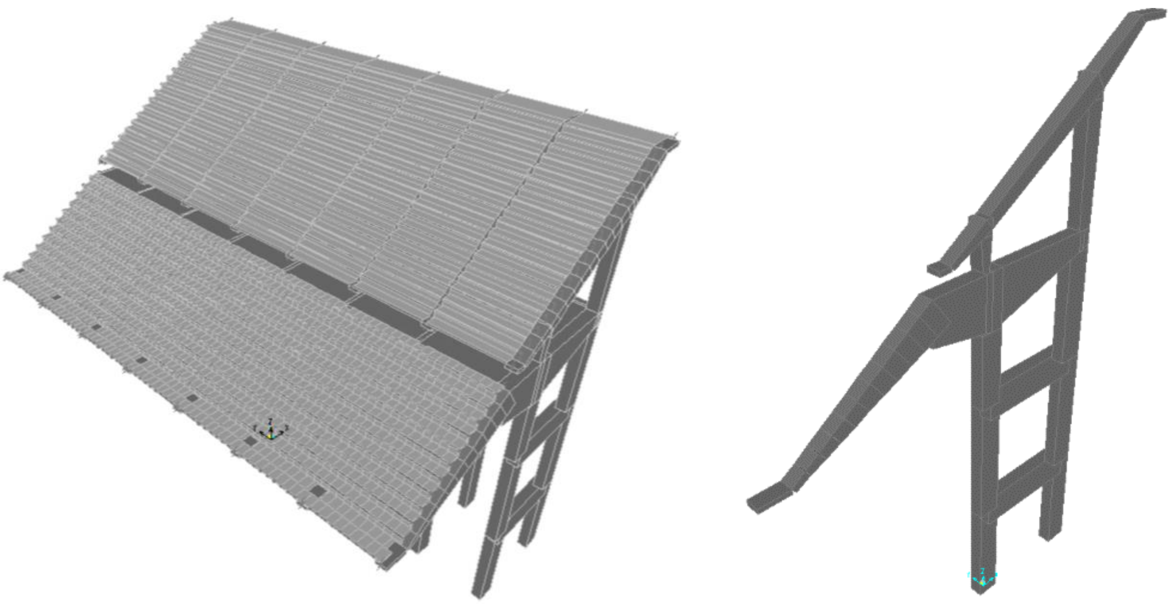
- A first mode with frequency of 2.2-2.3 Hz, related to the horizontal movement of the second ring's main frames;
- A second mode with frequency of 4.4-4.6 Hz, related to the vertical movement of the cantilever portion of the beam.

Tests have also indicated that the structural damping coefficient is between 1.9% and 2.2%; consequently, the numerical models adopt a damping coefficient equal to 2%.

4.2 Structural modelling

Two different models have been developed using SAP2000 software [13]:

- A 3D-model of eight frames, which corresponds to sector of the second ring mainly interested by the vibration phenomena event mentioned in 3.1, shell elements have been added to consider the grandstands effects. This model is meant to be used for the numerical calibration of 2D-model.
- A 2D-model of a single internal frame, with loads derived considering an area of influence equal to 5 m (distance between two consecutive frames in the direction parallel to the field).



(a) **(b)**

Figure 5: Numerical models of the Second Ring of San Siro Stadium built within SAP2000: 3D-model a) and 2D-model b).

5 DYNAMIC STRUCTURAL PERFORMANCE ASSESSMENT

Four different types of analysis have been performed to reconstruct the system response:

- An Eigenvalue analyses of the empty structure on both 3D- and 2D-models;
- A steady state analyses on the 2D-model;
- A linear Time-History analyses on the 2D-model.

5.1 Analysis assumptions

The variability of parameters not fully known has been taken into account by performing parametric analyses that included:

- A Young modulus calibration with respect to the first two periods of vibration;

- Various assumptions on the grandstands – frames connection;
- Various levels of the live loads acting on tiers;

The aim of these sensitivity analyses was to better approximate the dynamic behavior experimentally captured.

The dynamic live load represented by the crowd is located on the cantilever grandstand with a load distribution of 3 persons per square meter.

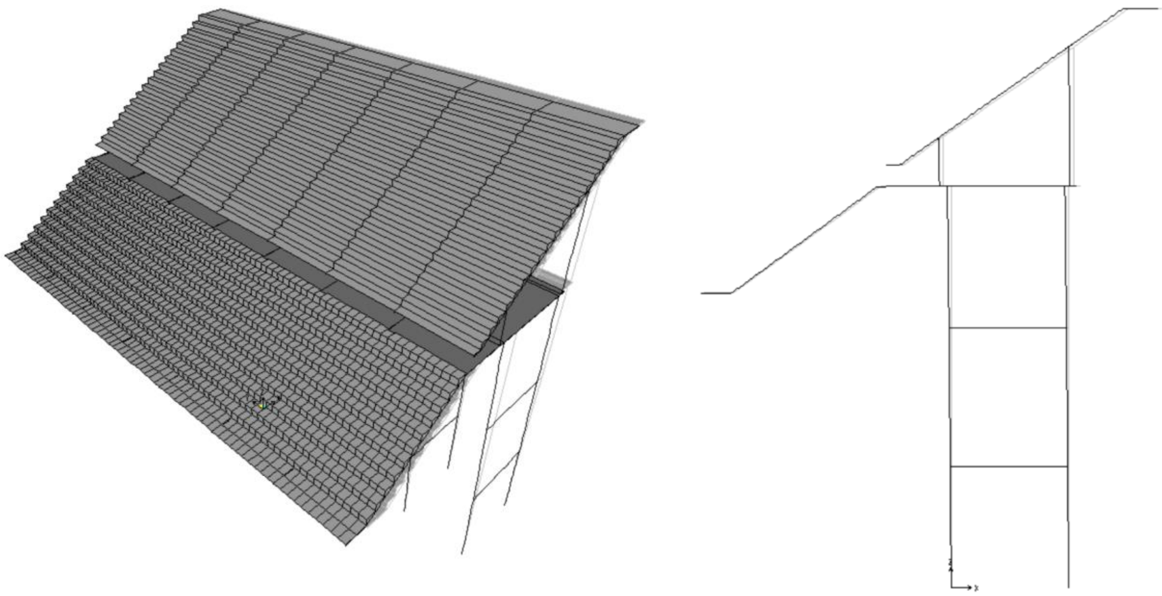
5.2 Eigenvalue analyses results

The first modelling validation has been obtained by comparing the eigen properties of the numerical 3D-model with the ones obtained experimentally.

The differences in terms of eigen frequencies, shown in Table 2, between tests results and numerical modelling are always lower than 10%.

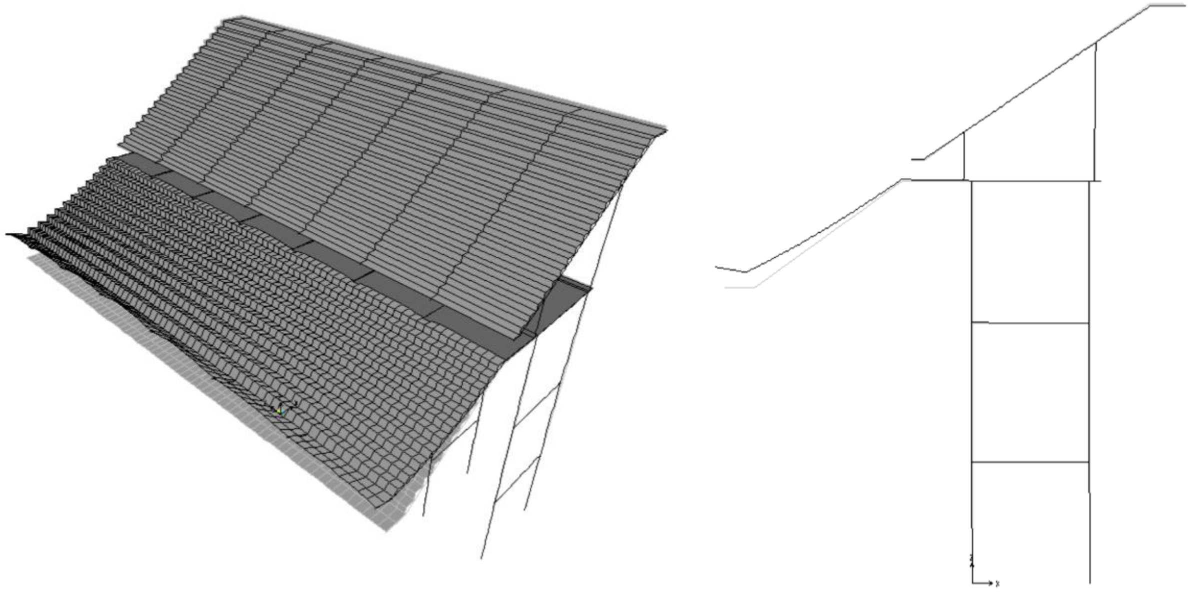
Mode Case	Test result	3D model	Difference
Horizontal movement	2.2 - 2.3 Hz	2.14 Hz	2.7% - 7%
Vertical movement	4.4 - 4.6 Hz	4.38 Hz	0.45% - 4.8%

Table 2: Comparison of first two natural frequencies of the structure obtained by experimental tests and numerical modelling.



(a) (b)

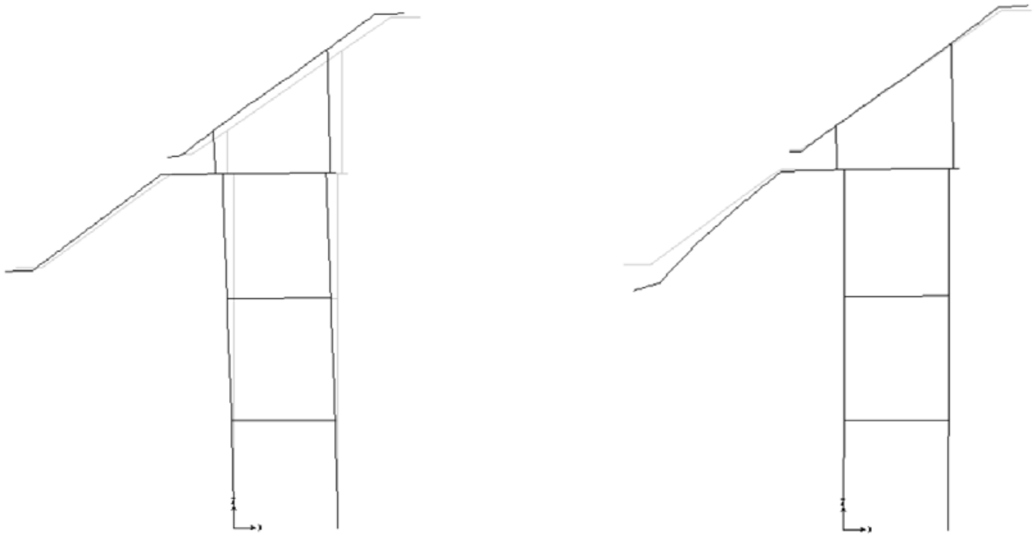
Figure 6: First modal shape related to the horizontal movement of the entire frame of the 3D-model: 3D view a) and 2D view b).



(a) **(b)**

Figure 7: Second modal shape related to the vertical movement of the cantilever grandstand of the 3D-model: 3D view a) and 2D view b).

Relying on these results, the 2D-model has been calibrated to obtain the same dynamic properties of the 3D-model, as Table 3 shows. Successively, a steady state analysis has been performed to identify the frequencies that amplify the structural response to a larger extent.



(a) **(b)**

Figure 8: Modal shapes of the first two vibrational modes for the 2D-model: horizontal mode of the entire frame a) and vertical mode of the cantilever grandstand b).

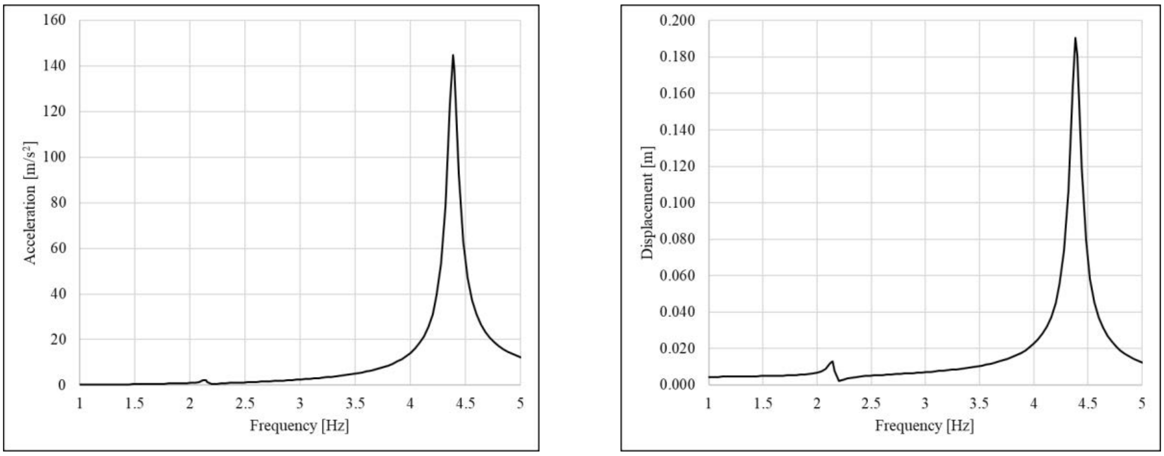
Mode Case	Model	T [s]	f [Hz]
Horizontal movement	3D	0.466	2.14
	2D	0.466	2.14
Vertical movement	3D	0.228	4.39
	2D	0.228	4.39

Table 3: Eigen properties of both 3D- and 2D-models

5.3 Steady-state analyses results

The steady state analysis allows determining the probabilistic response of a structure subjected to a cyclic load (harmonic, sinusoidal) included within a specific range of frequencies and is useful for studying the vibrational behavior of the structures.

Results of the steady state analysis, reported in Figure 9, highlights that in correspondence with the natural frequencies of the system, 2.14 Hz and 4.39 Hz, there a considerable amplification of the structural response may occur. The largest acceleration is attained for a dynamic excitation close to the frequency of 4.39 Hz, i.e., the first vertical mode of the tier.



(a) **(b)**

Figure 9: Vertical acceleration a) and vertical displacement b) response spectra derived from the steady state analysis

The experimental measurements during an intense event are about 1/45 of the theoretical maximum in terms of acceleration and 1/4 as in terms of vertical displacement. As previously specified, this type of analysis is conducted using a harmonic, sinusoidal forcing, which however is not perfectly representative of the type of load acting on the structure. However, this analysis has been carried out to support that maximum amplifications of the response are obtained when the forcing load is applied with a frequency close to or equal to those of the structure itself. For the evaluation of the effects on the structure of a dynamic load, reference is made to time history analyses conducted with the load models described in section 2.1.

5.4 Time-histories analyses results

The linear time history analysis allows studying the structural response to a vertical dynamic load, simulating the jumping crowd, varying its frequency, in order to determine a frequency response spectrum, with a procedure similar to that of the steady state analyses.

Figure 10 and Figure 11 show response time histories in terms of both vertical acceleration and vertical displacement recorded at the knee of the cantilever grandstand for the two load models, when the load frequency is equal to that of the horizontal movements of the structure.

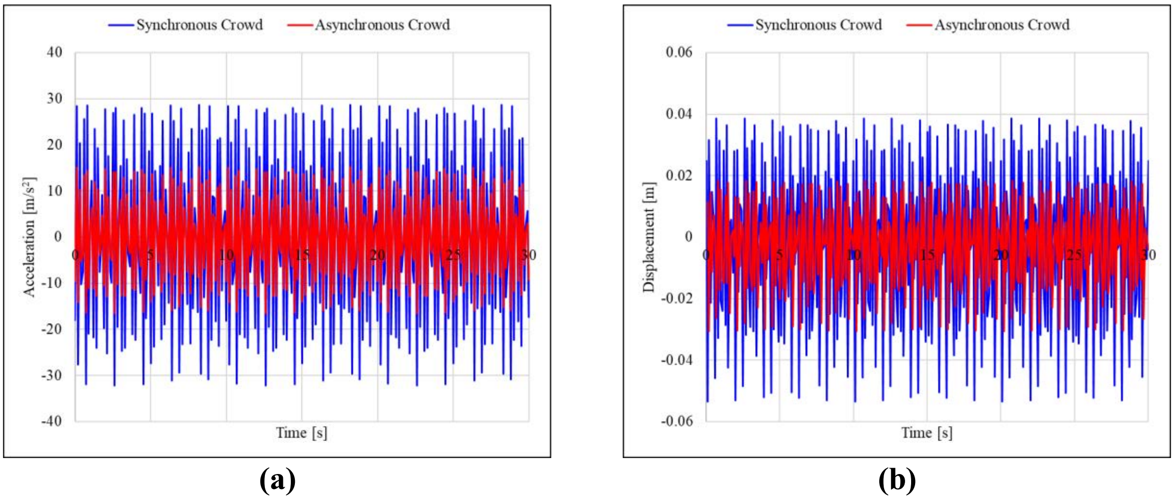


Figure 10: Vertical acceleration a) and vertical displacement b) time histories for load model 1 with load frequency = 2.14 Hz (i.e. first mode of vibration)

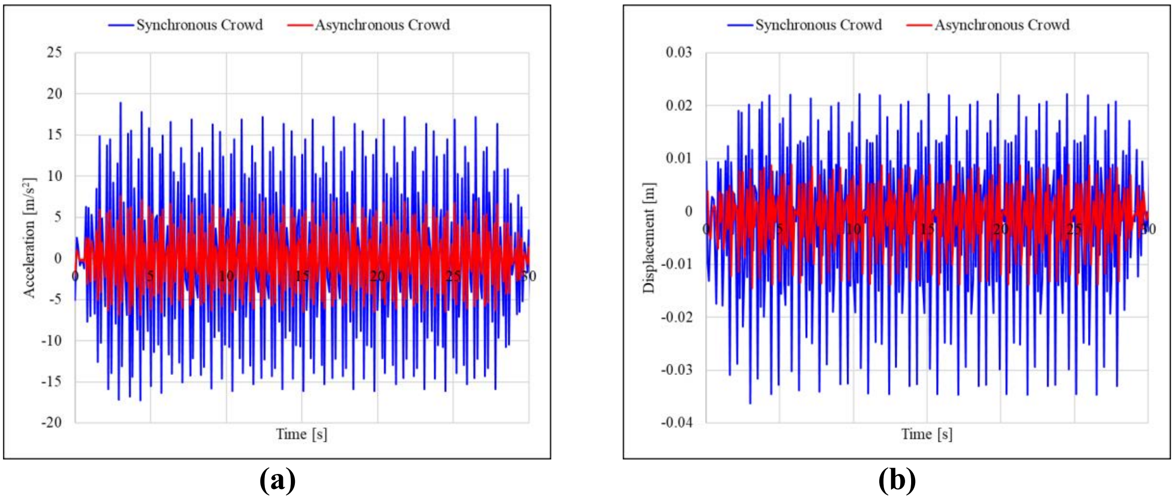
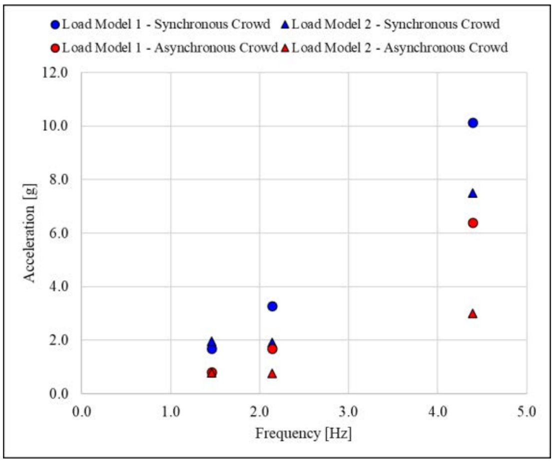
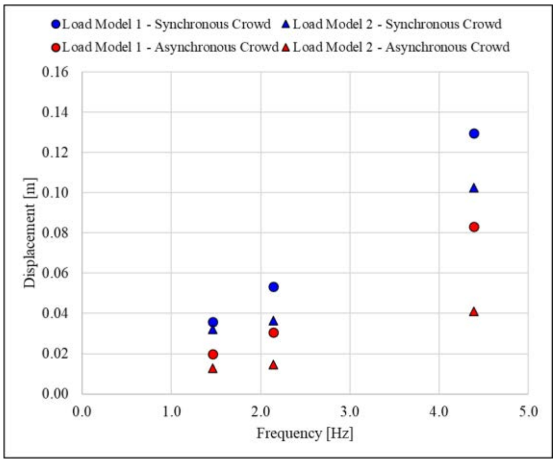


Figure 11: Vertical acceleration a) and vertical displacement b) time histories for load model 2 with load frequency = 2.14 Hz (i.e. first mode of vibration)

Recording the peak responses by varying the load frequency in order to match the fundamental ones of the structure, few points of frequency response spectra have been identified in Figure 12. Results underline how important is the synchronism of the crowd: if the spectators move in a perfectly synchronous way, peak response might be 35% - 60% higher.



(a)



(b)

Figure 12: Peak vertical accelerations a) and peak vertical displacements b) obtained from linear time history analyses

Crowd Type	Load Model	Peak Vertical Acceleration [m/s²]		
		f_1=1.46 Hz	f_2=2.14 Hz	f_3=4.39 Hz
Synchronous	1	1.7	3.3	10.1
	2	2.0	1.9	7.5
Asynchronous	1	0.8	1.7	6.4
	2	0.8	0.8	3.0

Table 4: Peak vertical accelerations obtained from linear time history analyses

Crowd Type	Load Model	Peak Vertical Displacement [m]		
		f_1=1.46 Hz	f_2=2.14 Hz	f_3=4.39 Hz
Synchronous	1	0.036	0.053	0.130
	2	0.032	0.036	0.103
Asynchronous	1	0.020	0.031	0.083
	2	0.013	0.015	0.041

Table 5: Peak vertical displacements obtained from linear time history analyses

Results of the steady state analysis, reported in Figure 9, highlight a peak in vertical response at both the first frequency of vibration (horizontal movement of the frame) and the second frequency of vibration (vertical movement of the cantilever).

Furthermore, as [2] report, the achievable frequency for a jumping crowd is between 1.5 Hz – 3.5 Hz; jumping at frequency equal to 4.39 Hz is unrealistic for a group of people. This implies that the vertical mode can be actually excited when the activity matches a submultiple of the vertical mode (e.g., 1.46 Hz).

For what concerns human comfort assessment, according to the acceleration limits reported in Table 1, the acceleration recorded during time history analyses is always above 35% g, which means that it might cause panic. This consideration should be associated to the investigated load frequencies, which are the closest to the natural frequencies of the structure; consequently, they represent the worst-case scenario for the cantilever assessment.

6 CONCLUSIONS

- Cantilever grandstands are sensitive to dynamic load, which should be taken into account during both design and assessment process. In this study, only the vertical response has been investigated; consequently, further evaluations are needed to assess the structural behavior along the horizontal direction, also considering the potential coupling.
- When experimental data are available, a Finite Element approach is efficient in terms of computational demand and the results reasonably accurate for studying the structural dynamic behavior. The dynamic identification allowed to adequately calibrate the numerical model.
- The nonlinear behavior of the grandstand has not been taken into account. The structure will enter in the nonlinear field when subjected to significant load conditions, implying changes in its dynamic properties; consequently, further evaluations are needed to consider how it affects the response, especially for what concerns assessment up to collapse.
- Different load conditions and configurations might be of interest in order to assess human comfort during more frequent events, not only for the worst-case scenario.
- Studying the response of the grandstand by varying the frequency of the excitation allows to build acceleration and displacement response spectra, that might be advantageous to assess the structural behavior.

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