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Serviceability of the Stadium Seating Decks Under Dynamic Loading: Experimental and Numerical Evaluation

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Abstract

Seating decks (used for stadium grandstands) are usually made of precast concrete elements and are characterized by a significant level of slenderness which makes them vulnerable to vibrations. Because their dynamic response is difficult to predict in the design stages, the seating decks are often experimentally tested, during the construction phase. The current paper presents the methodology of the dynamic testing of stadium seating decks. The results obtained experimentally are compared to corresponding results, obtained numerically. A modal testing is carried out using two different methods: impact analysis and operational modal analysis. The measured vibration levels are interpreted according to European dedicated standards in order to assess the seating decks serviceability for crowd-induced vibrations. The analyses show that, while the structural safety is satisfied, the vibrations level is likely to cause significant discomfort to the human body.

Rezumat

Gradenele sunt realizate de obicei din elemente prefabricate din beton armat fiind caracterizate de un coeficient de zveltețe ridicat și, deci, de o sensibilitate ridicată la vibrații. Deoarece răspunsul dinamic al unor astfel de elemente structurale este dificil de evaluat în fazele de proiectare, gradenele sunt adesea testate în fazele de execuție. Studiul curent, prezintă o metodologie de evaluare a comportării gradenelor din beton armat solicitate dinamic. Rezultatele obținute experimental sunt comparate cu rezultatele analoage, obținute numeric. Evaluarea comportării dinamice a gradenelor din beton armat se face prin intermediul a două metode diferite: analiza de impact respectiv analiza modală operațională. Nivelurile de vibrații măsurate astfel sunt interpretate în conformitate cu standardele europene existente, în vederea stabilirii unei concluzii privind comportarea gradenelor din beton armat sub acțiunea vibrațiilor induse de mulțimi. Rezultatele analizelor indică faptul că, în timp ce exigențele privind siguranța structurală sunt îndeplinite, nivelurile de vibrații înregistrate pot provoca o stare de disconfort accentuat organismului uman.

Keywords: vibrations, dynamic behavior, seating decks, modal testing, FE modelling, natural frequencies

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1. Introduction

The use of simple or post/pre-tensioned precast concrete resisting elements (bridge beams, double-T beams, hollow-core slab elements etc.) in structural design of buildings is continuously increasing because of several significant advantages over the site-cast concrete elements: reduced tolerances, thinner sections, material savings, etc. Under dynamic loading, these very-slender elements are sensitive to vibrations. A category of structures where engineers should carefully consider the vibrations effect refers to stadiums; these structures are frequently used to organize major events, such as football games, concerts, parades, etc., with tens of thousands of participants. High levels of vibration can become unpleasant to spectators or, in extreme cases could lead to panic, which is only one step away from serious disasters. For these reasons, there is a wide number of relevant works that approach the dynamic behavior of stadiums' structural elements [1-6]. Following numerical and experimental analyses of currently in-use stadiums, the mentioned studies draw qualitative and quantitative conclusions regarding the vibration modes of seating decks, the agreement between the design values and testing values concerning key dynamic properties, the vibration levels and serviceability requirements, and the human perception of vibrations. The conclusions are based on the provisions of European dedicated standards [7-13]. The Romanian design codes do not provide dedicated guidelines or explicit provisions regarding the performance criteria that these structures should meet in terms of vibrations.

Romania has a large sport infrastructure built under the communist regime, which nowadays is almost entirely out-of-date. Therefore, five new stadiums were built between 2011 and 2017. The current paper presents the experimental and numerical study of the vibrations behavior of seating decks designed for the built stadiums. Briefly, the presented study consists of the experimental and numerical assessment of the dynamic behavior for L-shaped precast concrete seating decks. The dynamic behavior is assessed, experimentally and numerically, in terms of natural frequencies, modes of vibrations, displacements and accelerations, measured in key-points of the analyzed elements. Following the analysis of the experimental and numerical results, conclusions regarding the dynamic behavior of the seating decks elements are drawn and possible design options to improve this behavior are suggested.

2. Characteristics of the Analyzed Specimen

The seating decks have the length L = 9.28m, while the cross-section dimensions are: the horizontal flange H = 0.99m, the vertical flange V = 0.44m and the thickness t = 0.15m. During the experimental study, the seating decks were simply supported on timber elements (Fig. 1). This type of support assured by the producer for testing is not identical with the one designed for the stadium structure, therefore, the conclusions based on the experimental results do not reflect 100% the structural behavior of the tested elements during the exploitation phase. Since in-situ the seating decks will be partially restrained at both ends, it is expected a stiffer response under dynamic loading. Nevertheless, the presented analyses offer a valuable insight on the vibration behavior of these elements, they were used for calibrating the numerical models, and also, they represent a general method of testing which can be applied after the final installation of the seating decks.

The materials used for the precast concrete L-shaped elements have, according to the producer, the following mechanical characteristics: the concrete class C40/50, while the steel used as reinforcement is of S500C class. Other properties are as follows: volume V = 1.78m3, mass M = 4.63t. Prior the experimental assessment of the dynamic behavior of the seating decks, the cracking state of the tested elements was analyzed. In the central zone of the span, small vertical cracks, of length varying in the range of 2cm - 10cm, with openings of 0.1mm – 0.2mm were observed. No supplementary development of the cracks was detected following the completion of the two phases of the dynamic testing.

Figure 1. The tested seating decks

3. Experimental study

3.1 General presentation

The experimental study aims to assess the vibration response of the tested specimens, in order to predict the safety level assured by the current design of the elements, in the exploitation phase of the structure. The safety level of the seating decks can be associated with the following aspects:

- the strength and general stability of the structure under dynamic actions
- the human perception regarding the vibration level (ranges between *imperceptible vibrations* level and *panic-triggering vibration* level)

Another objective is the calibration and validation of a FE numerical model capable to reproduce the dynamic structural response of the investigated elements. In order to achieve the described objectives, the experimental study is divided into two distinct phases with different methodologies:

1) Experimental Modal Analysis (EMA) using impact excitation [13,14]
2) Operational Modal Analysis (OMA) [15] and Operating Deflection Shape (ODS) analysis [16] under human-induced dynamic loading

Following the results interpretation, conclusions are drawn regarding two main aspects: the first one refers to how the crowd-generated vibrations affect the safe exploitation of the structure while the second one refers to the effect of the crowd-generated vibrations on the crowd itself.

3.2 Experimental modal analysis

The experimental study involves the use of several instruments designed for the nondestructive study of structural vibrations (the mentioned instruments are parts of the instrumentation available in "Actions on buildings and structures" laboratory, at Faculty of Civil Engineering – Technical University of Cluj-Napoca, Romania). The main equipment elements are produced by Bruel&Kjaer [0] and are briefly presented as follows:

- data acquisition system: vibrations analyzer type PULSE 3560C, with a data recording frequency up to 25.6kHz
- piezoelectric accelerometers type 4507B002, with a frequency recording domain ranging between 0.4kHz - 6kHz
- calibration system type 4294 used to check and calibrate the accelerometer before its use
- impact hammer type 8210, with an applied force of up to 45kN
- software: Pulse Labshop v12

EMA using the impact hammer was performed using two of the three available seating decks: due to accessibility reasons imposed by their support conditions (Fig. 1), the accelerometer was impossible to mount on the first (the lowest) seating deck located close to the floor. On each of the two-studied seating decks, a network consisting of nine points (evenly, longitudinally distributed along the center of the horizontal flange) was defined. The structure was subjected to an impact force (three times in each point) using the impact hammer. Following each impact excitation, the response in terms of accelerations was measured using the fixed accelerometer. The results are interpreted using the Bruel&Kjaer Pulse Labshop software. The average of the input signals (the impact force transmitted through the hammer) and output signals (the accelerations values) is automatically determined. Following the input-output data processing, based on the Fast Fourier Transform, the Frequency Response Functions (FRF) of the structure are determined. The detected amplitude peaks indicate the vibration modes of the analyzed structural element. The natural frequencies, as well as the corresponding deformed shapes for the first two vibration modes identified experimentally, are presented in Fig. 2, respectively in Fig. 3. Other higher vibration modes were not clearly activated and identified.

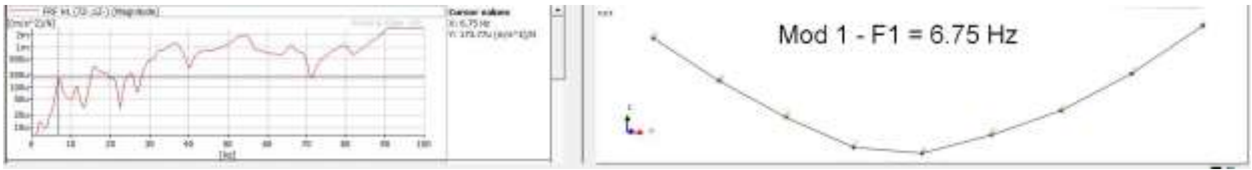

Figure 2. The 1st natural (fundamental) vibration mode: frequency and deformed shape

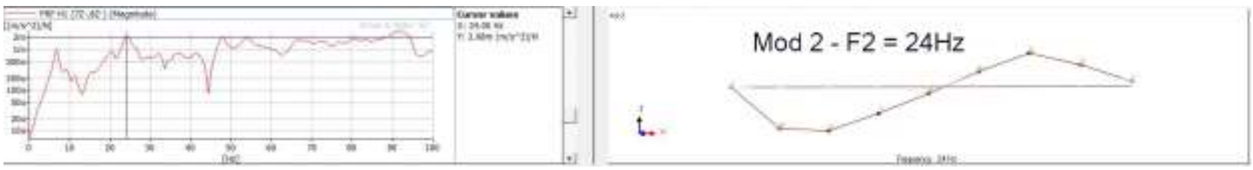

Figure 3. The 2nd natural vibration mode: frequency and deformed shape

The dynamic characteristics, evaluated following the presented experimental phase of the study, define the dynamic structural behavior and allow the calibration and validation of a FE numerical model capable to offer more detailed information regarding the dynamic structural response of the analyzed structure and, generally, of reinforced concrete elements. Following EMA several preliminary conclusions can be drawn:

- The frequency value of the fundamental vibration mode corresponding to the unloaded state of the structure has been experimentally evaluated, for both tested seating decks, at 6.75Hz. The British design code BS 6399-1 [0] sets the lower limit of the fundamental frequency for vertical vibrations of unloaded seating decks to 8.4Hz, and the so-called Green Guide [0] sets the same limit to 6Hz but taking into account the weight of people on the structure. These limits were intended to ensure that the resonance phenomenon will not appear under crowd-induced vibrations, particularly during concerts, when people jump at a regular beat.

- Vibrations ranged in the frequency domain 3Hz – 9Hz could induce discomfort sensation to human organism.

3.3 Operational modal analysis. Operating deflection shape analysis

This time, the accelerometer is placed at the mid-span of the seating decks, respectively at the middle of the horizontal flange. For this position, the fundamental vibration mode (longitudinal bending vibration mode) determines vertical displacements of maximum amplitude. Once again, due to accessibility restrictions, the accelerometer was impossible to mount on the third (the closest to the ground) seating deck. Consequently, the vibrations behavior is analyzed only for the first seating deck (denoted D1), respectively for the second seating deck (denoted D2). The vibrations behavior is studied under human induced vibrations. In order to achieve this effect, the working personnel of the hosting assembly hall was coordinated to simulate the crowd induced vibrations through vertical movements (Fig. 4) for a period T = 100s.

The results obtained by recording the accelerations for the period T = 100s are processed using the Operational Modal Analysis Pro software developed by Structural Vibration Solutions A/S [19]. The natural frequency was found once again at 6.75Hz for both tested seating decks. Based on the measured accelerations and using the Operating Deflecting Shapes module, the speeds and vertical displacements (for the accelerometer position) are next determined and the maximum values are identified.

Figure 4. Generation of human induced vibrations for the seating decks

The structural safety is analyzed from the vertical displacements' perspective and also from the resonance phenomenon's perspective. The recorded maximum vertical displacement values for the two analyzed seating decks are as follows:

- D1: $\Delta_{min/max}$ = +1.19/-1.11 mm
- D2: $\Delta_{min/max}$ = +1.27/-1.26 mm

For the measured clear span of the seating decks (9.17m), the maximum recorded vertical displacement is equivalent with a fraction of 1/7220, much less compared with the allowed value which corresponds, according to STAS 10107/0-90 [0], to a ratio of 1/350 of the clear span. During the experimental tests, the resonance phenomenon did not occur; in addition, the cracks measurements recorded after the tests indicate no increase of the existing cracks. The described behavior indicates that de tested seating decks successfully fulfill the strength and safety requirements.

The dynamic comfort conclusions are drawn as a consequence of the evaluation of human perception regarding the vibrations level (ranging from *imperceptible vibrations* to *panic-triggering vibrations*). The British design code BS6841 [0] indicates, as a method for the vibrations level evaluation, the weighted acceleration method RMS (root-mean-square). The human reaction to vibrations depends on the vibrations frequency and also on the human body position. This method can be used only if the peak RMS factor (known also as *crest factor*) does not exceed a value of 6. The peak RMS factor represents, in this case, the maximum measured value of the acceleration divided by the RMS value of the weighted acceleration ($C = |a|_{max}/a_{RMS}$). The previously mentioned design code does not clearly specify the time interval associated with the weighted RMS acceleration value. As a consequence, establishing the time interval for the weighted RMS acceleration value was a trial-and-error process based on the crest factor. The European design code ISO2631-1 [0] sets the value of 9 as upper limit of the peak RMS factor and a time interval of 1 second for the frequency weighted RMS acceleration value. The maximum measured acceleration values are around 50m/s^2, but only accelerations corresponding to frequencies ranged between 0.5Hz - 80Hz are relevant for the human perception (when characterizing the exposure to whole-body vibration), respectively accelerations corresponding to frequencies ranged between 0.1Hz - 0.5Hz (when characterizing the motion sickness state [3]).

Fig. 5 illustrates three main ISO weighting curves which can be used when assessing the harmfulness of a vibration [7, 21, 22].It can be noticed that for a human body positioned vertically, the maximum perception is characterized by frequencies ranging between 3Hz - 9Hz. The human reaction to vibrations is described in Tab. 1, based on the RMS values of the frequency weighted acceleration.

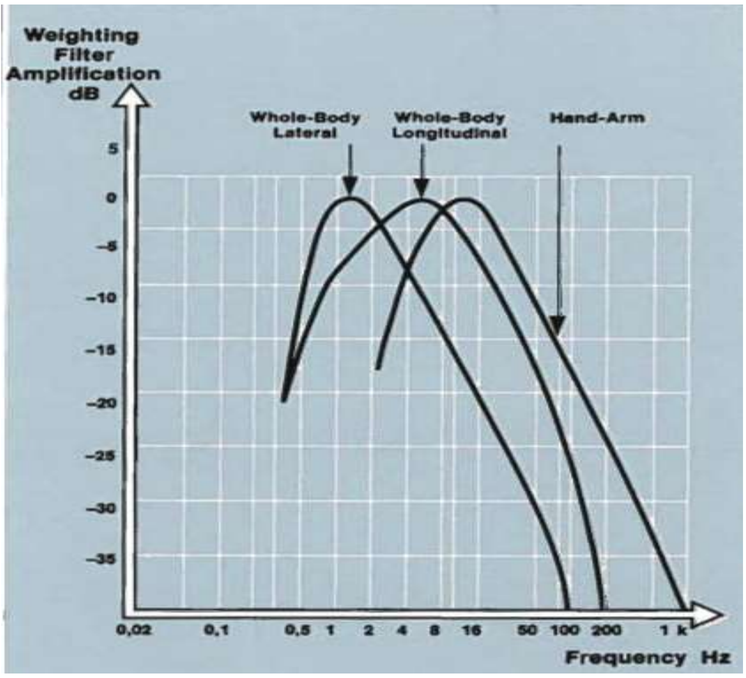

Figure 5. ISO frequency weighting curves

Table 1. Human reaction vs. frequency weighted RMS [7, 8, 10]

Frequency weighted RMS (m/s^2)	Human reaction
<0.135	Not uncomfortable
0.135 - 0.63	A little uncomfortable
0.5 - 1.0	Fairly uncomfortable
0.8 – 1.6	Uncomfortable
1.25 – 2.5	Very uncomfortable
>2.5	Extremely uncomfortable

Fig. 6a displays the measured accelerations, filtered on a frequency band of 0Hz -100Hz. Fig. 6b displays the frequency weighted RMS acceleration values for a time window of 1 second. In order to determine these data, a Matlab application [0] was written.

The crest factor values obtained are 3.233 for seating deck D1, respectively 3.388 for seating deck D2. Both values meet the European design codes requirements. In terms of frequency weighted RMS, the maximum obtained values are 0.647 for seating deck D1, respectively 0.848 for seating deck D2. Comparing these values with the ones displayed in Tab. 1, it can be stated that the human perception is in the range between *fairly uncomfortable* and *uncomfortable* reaction. The fact was indeed confirmed by the personnel of the hosting assembly hall that participated to the experimental study.

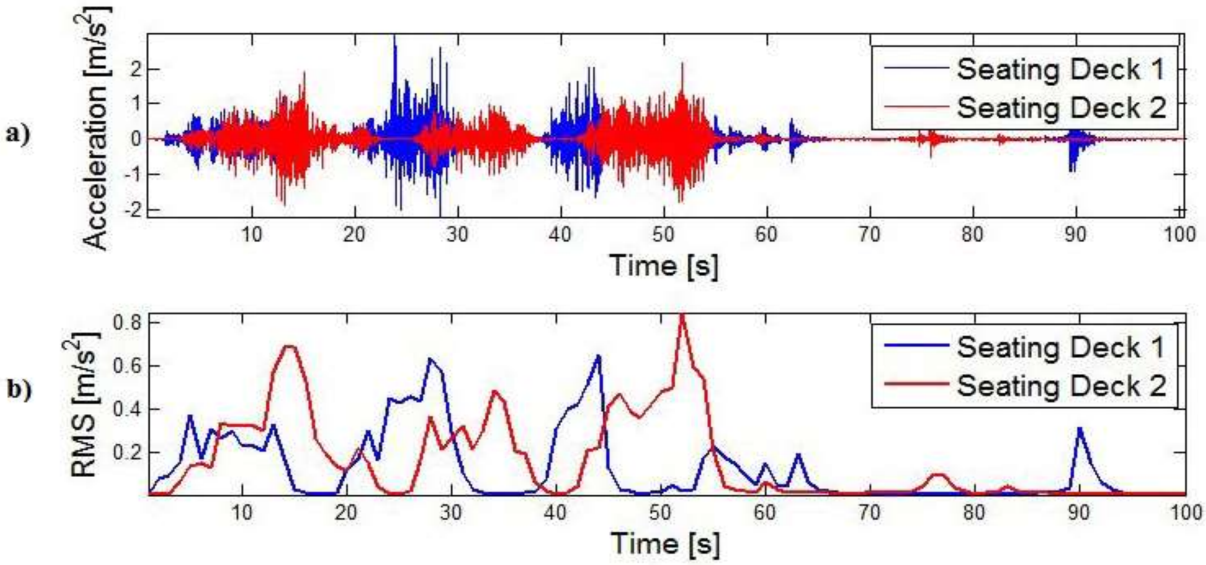

Figure 6. a) Acceleration vs. time b) RMS vs. time

4. Numerical study

One seating deck was modeled in the FEM based software Abaqus [0] using shell elements S4R. From the boundary conditions perspective, the seating decks are considered as simply supported at the end edges of the horizontal flanges. The mechanical characteristics of the materials (concrete class C40/50) are specified by the designer: Young modulus E = 35011MPa, Poisson coefficient μ = 0.2. The modeling of the reinforcement proved to have no significant effect on the dynamic response. The numerical assessment of the dynamic response of the studied seating deck consists of four frequency analyses: (i) considering the entire flexural stiffness of the unloaded element, (ii) considering the entire flexural stiffness (EI) of the element subjected to an uniformly distributed load of 5.75kN/m^2 (the loads that correspond to the fundamental load combination considered in the design process) (iii) two more similar numerical analyses are performed considering only 90% of the flexural stiffness, in order to take into account the cracking state detected at the beginning of the experimental phase of the study.

The numerical results extracted from the model, considered relevant from the dynamic structural response point of view, are the deformed shapes corresponding to the first six vibration modes with the associated natural frequencies. The previously mentioned deformed shapes are the same for all four numerical analyses performed and are illustrated by Figs. 7 - 9.

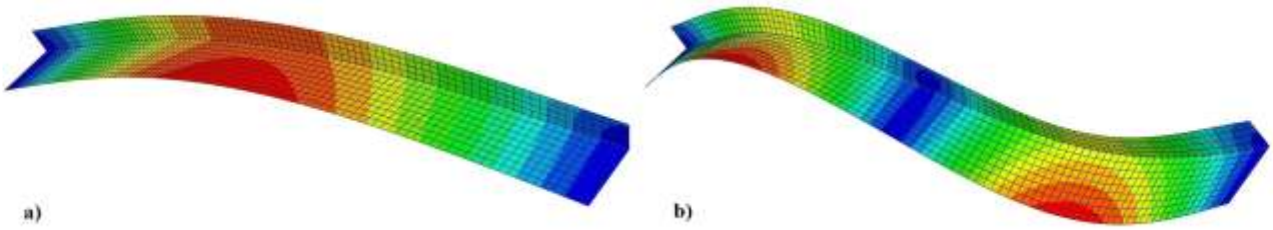

Figure 7. a) Fundamental (1st) vibration mode: Half-wave vertical bending vibration mode
b) 2nd vibration mode: Two-wave vertical bending vibration mode

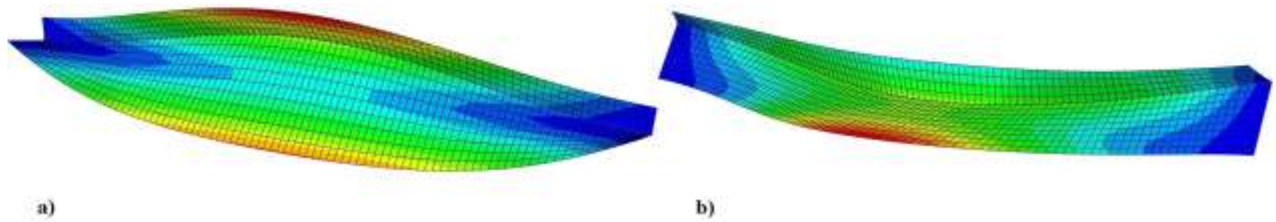

Figure 8. a) 3rd vibration mode: Half-wave torsion vibration mode
b) 4th vibration mode: One-wave torsion vibration mode

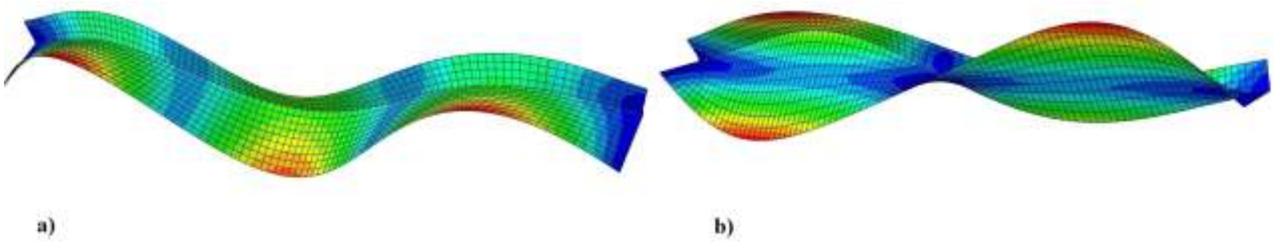

Fig. 9. a) 5th vibration mode: Three-wave vertical bending vibration mode
b) 6th vibration mode: Two-wave torsion vibration mode

The natural frequency values associated with the six identified vibration modes, for all four numerical analyses performed, are displayed in Tab. 2.

Table 2. Numerical results: Natural vibration frequencies

Vibration mode	**Natural vibration frequencies (Hz)**			
	Unloaded structure		**Loaded structure (5.75kN/m^2)**	
	E	**0.9E**	**E**	**0.9E**
1	7.13	6.76	5.01	4.75
2	24.08	22.84	16.63	15.78
3	30.01	28.47	22.97	21.79
4	38.35	36.18	26.99	25.61
5	50.76	48.16	34.42	32.66
6	63.88	60.60	49.02	46.51

The FE numerical model is successfully calibrated against the experimental results which are consistent with the numerical ones. EMA indicates (for the unloaded seating deck) a frequency of 6.75Hz associated with the fundamental vibration mode, respectively a frequency of 24Hz for the second vibration mode. The numerical results reveal that both modeling options (the one that considers the entire flexural stiffness and the one that considers 90% of the flexural stiffness) supply satisfactory representations of the dynamic structural behavior of the seating decks. However, the fundamental vibration mode is more accurately represented in the numerical model that takes into account the initial cracking state. It has to be mentioned that all numerical analyses reveal frequency values associated with the fundamental vibration mode that are ranged between 3Hz - 9Hz (Tab. 2), the vibration domain where the human body, vertically positioned, is characterized by maximum receptiveness to vibrations.

5. Conclusions

Seating decks (used for stadium grandstands) are usually made of precast concrete elements and are characterized by a significant level of slenderness which makes them vulnerable to vibrations. Because their dynamic response is difficult to predict in the design stages, the seating decks are often experimentally tested, during the construction phase. The current paper presents the methodology of the dynamic testing of stadium seating decks. Both, impact modal testing and operational modal testing, were carried out successfully. The FE model was calibrated based on the experimentally found dynamic characteristics (modes of vibrations, natural frequencies). Regarding the dynamic response of the tested elements, the following main conclusions can be drawn:

- Taking into consideration the natural frequency of the fundamental vibration mode, the analyzed seating decks are susceptible to the resonance phenomenon that could eventually lead to partial or total collapse of the structure. However, the experimental study performed on the seating decks specimens subjected to dynamic loads indicates that the resonance phenomenon did not occur (there is sufficient damping) and that the structural elements performed well from the structural strength and safety perspectives. Consequently, the risk of resonance to occur is considered to be reduced while the structural response in terms of vibrations reveals an adequate dynamic behavior. It should however be emphasized that the experimental support conditions of the seating decks were not identical with the ones specified in the design, fact that could significantly influence the seating decks behavior in the exploitation phase of the structure.
- Regarding the human perception of the crowd induced vibrations, the behavior of the analyzed seating decks corresponds to a sensation ranged between *fairly uncomfortable* and *uncomfortable* reaction. It should be mentioned once again that the accurate representation of the designed support conditions could influence this conclusion.

In order to improve the analyzed seating decks behavior, the following recommendations are made:

- The increase of the natural frequency associated with the fundamental vibration mode by augmenting the element’s stiffness through pre-tensioning or through the increase of the cross-sectional properties.
- The re-iteration of the experimental study following the assembly of the seating decks into the stadium structure that will allow the consideration of the real support conditions.
- The set-up of a monitoring schedule of the seating decks during the activities hosted on the stadium, activity that will allow a complete and accurate study of the seating decks dynamic behavior.

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