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# NUMERICAL DYNAMIC ANALYSIS OF THE NEW BRASILIA NATIONAL STADIUM

**Gustavo V. F. Lima*[1], Suzana M. Avila[2], Graciela N. Doz[1]**

[1]Universidade de Brasília (UnB)
fiuzagustavo@hotmail.com
graciela@unb.br

[2]Universidade de Brasília (UnB) – Faculdade do Gama (FGA)
avilas@unb.br

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**Abstract:** *This work deals with a numerical dynamic analysis of the new Brasilia National Stadium, based on the Finite Element Method. The first part of the study is a modal analysis, focusing on the 12 first vibration modes, which are the ones of most interest, because their associated natural frequencies are all approximately in the same frequency range of the dynamic loads developed by human activities in grandstands, such as jumping and bobbing. Secondly, simulations of jumping crowds on the grandstands are made with different pacing rates, trying to simulate the most probable load situations. An international standard that deals with vibration problems in structures is presented, in order to analyze dynamic responses. Finally, the dynamic responses of the stadium (vertical accelerations) are compared to limit ranges suggested by this international standard.*

# 1 INTRODUCTION

There are numbers of reasons that make excessive vibration in structures more noticeable each day. Not only are the structures becoming more slender and flexible (due to the new architectural daring standards, with more spacious rooms and longer spans, and to the development of more resistant materials and more powerful computers, both of which enable the design of smaller cross sections of structures), but also because structures can sometimes be subjected to unpredicted dynamic loads. As an example of that fact, [1] makes a dynamic analysis of a commercial building in Brasília, Brazil, which was turned into a gym.

After Brazil was chosen to base the FIFA world cup 2014, some of the stadia were demolished for the construction of brand new arenas, such as the new Brasilia National Stadium. This fact suggests that these structures need to be dynamically analyzed, taking into account the comfort of the future crowds that will use them, because jumping crowds in grandstands can induce excessive vibration in these structures. So in this work, a numerical dynamic analysis of the Brasilia National Stadium was proposed, based on the Finite Element Method, with commercial software SAP2000, to analyze the vibration induced by these crowds.

# 2 STADIUM STRUCTURE AND NUMERICAL MODEL

The stadium was designed with a big frame structure of four columns connected by sloping beams, which support the steps of the grandstands. The grandstands are separated in three levels: lower, intermediate and upper. Radially they are divided in 12 independent sectors, 3 at each side, one behind each goal and one at each corner. Underneath the grandstands there are six internal levels. Around the grandstands there is an independent structure formed with three circular rows of columns which support the stadium roof. The stadium roof has one external concrete crown and an internal steel truss structure covered by a special membrane that protects the grandstands and partially the field. Figure 1 shows a 3D model of the stadium sectioned at midpoint, which makes it possible to see the three grandstand levels, the internal levels, as well as the steel truss of the roof.


Figure 1: Section of the Stadium.

From the four different kinds of sectors, one of intermediate width was selected (in a way it would properly represent a mean behavior of the different sectors) to build the numerical model. Shell elements were used to simulate slabs, steps, walls and the big columns and beams and frame elements were used to simulate the internal beams. The shell elements used have each 4 nodes and six degrees of freedom at each node. The frame elements are two-node elements, also with six degrees of freedom at each node, which allows perfect transferring of displacements and rotations from one element to the other. There are overall 91505 shell elements, 3100 frame elements and 92819 nodes. The structure was modeled according to the geometry description of the structure project, and the material considered was reinforced concrete, with a modulus of elasticity of 30GPa. At each column support restraints were applied at all three directions displacements and rotations. The sector modeled has 5 rows of columns, so there are 4 spans of grandstands steps and internal slabs. The numerical model is shown in Figure 2.

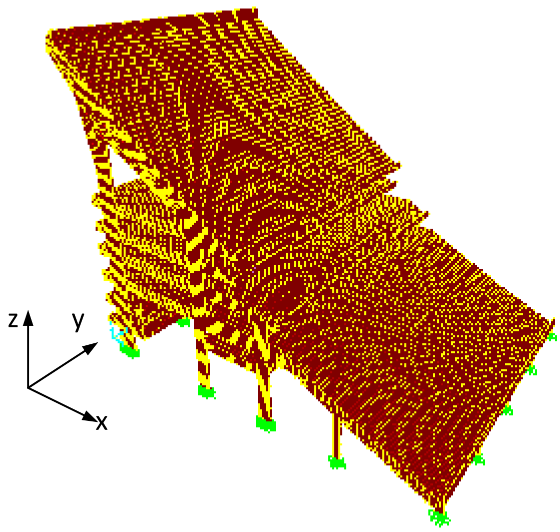
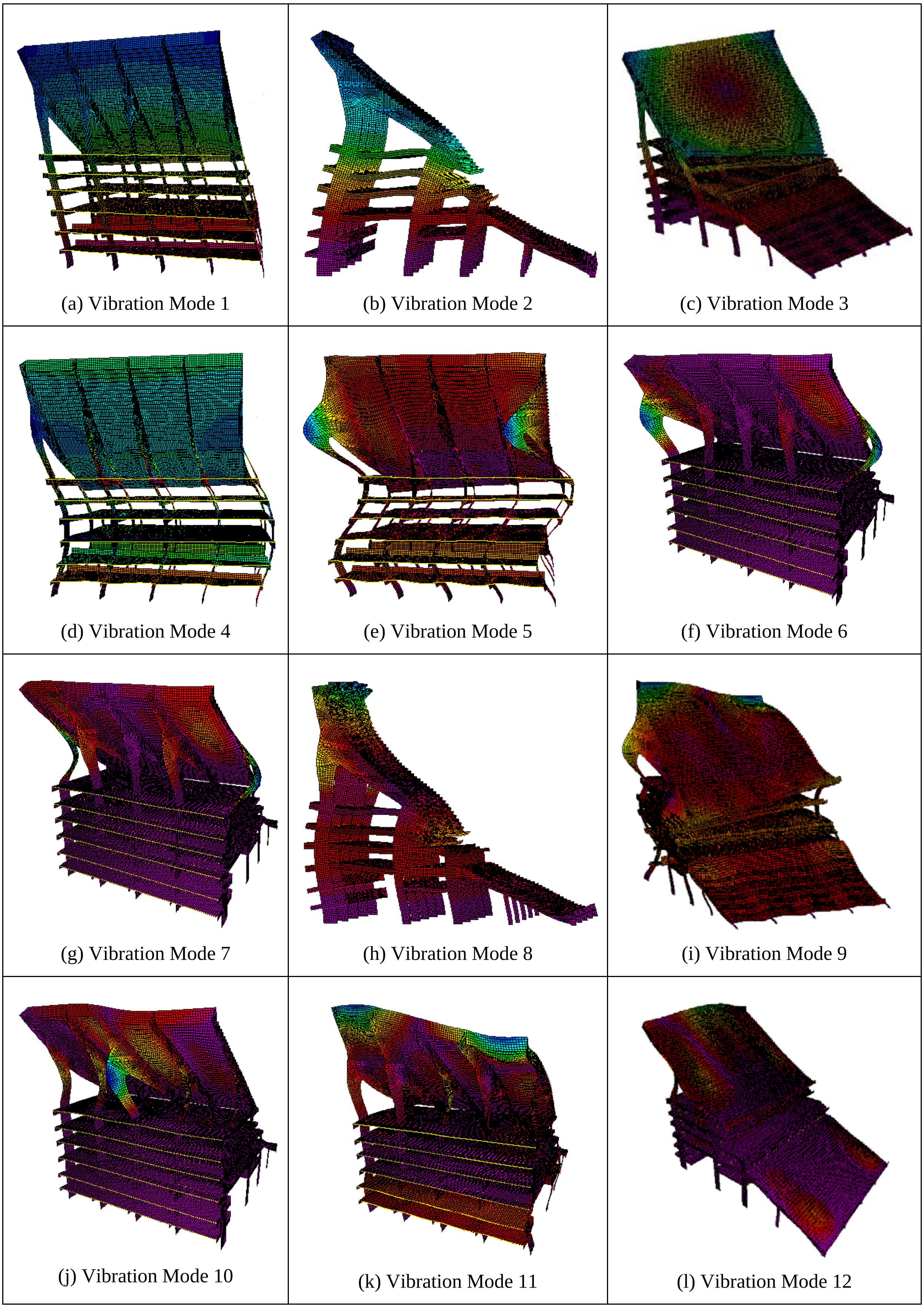



Figure 2: Numerical Model of Intermediate Sector of the National Stadium.

## 3 MODAL ANALYSIS

The great amount of degrees of freedom on the adopted model, due to the existence of almost 100000 nodes, indicates that too many vibration modes could be obtained. For this study, only the 12 first vibration modes were calculated, to make it more practical and simple, which are the ones related to the lowest natural frequencies and, therefore, the ones of most interest, because their associated natural frequencies are close to the frequency range of human activities.Figure3 shows the 12 vibration modes shapes and Table 1 shows their associated natural frequencies and the mode descriptions.

Convergence analyses made with models of more simple structures show that modal responses converge with meshes that used elements with dimensions as big as 10% the structures greatest dimension. In this model, the mesh used had elements with dimensions as big as 1% the structure greatest dimension.



(a) Vibration Mode 1 (b) Vibration Mode 2 (c) Vibration Mode 3
(d) Vibration Mode 4 (e) Vibration Mode 5 (f) Vibration Mode 6
(g) Vibration Mode 7 (h) Vibration Mode 8 (i) Vibration Mode 9
(j) Vibration Mode 10 (k) Vibration Mode 11 (l) Vibration Mode 12

Figure 3: Vibration modes shapes.

| Mode | Frequency (Hz) | Description |
|---|---|---|
| 1 | 1.02 | Bending on tangent direction |
| 2 | 2.27 | Bending on radial direction |
| 3 | 2.48 | Torsion on “xy” plane |
| 4 | 2.78 | Bending on tangent direction |
| 5 | 4.95 | Bending on tangent direction |
| 6 | 5.07 | Bending on the upper grandstand |
| 7 | 5.12 | Bending on the upper grandstand |
| 8 | 5.48 | Bending on radial direction and upper grandstand |
| 9 | 5.71 | Bending on tangent direction |
| 10 | 6.31 | Bending on the upper grandstand |
| 11 | 6.66 | Bending on tangent direction and upper grandstand |
| 12 | 6.67 | Bending on radial direction and upper grandstand |

Table 1: Vibration modes descriptions.

These results show that the first vibration modes (especially the first four) have low natural frequencies (between 1Hz and 3Hz). Human activities usually happen in the frequency range between 1.5Hz and 3Hz [2].This first response points out a disturbing fact, which is the possibility vibrations being amplified due to the nearness of natural frequencies of the stadium and pacing rates of human activities.

Although it was not yet possible to run experimental analyses on the stadium to validate the numerical model (the stadium was under construction while this study was being developed), other researchers who studied stadia with similar structures show that they also have vibration modes with natural frequencies below 3Hz, as shown on Table 2.

| | Brasilia National Stadium (numerical evaluation) | Morumbi - [3] | Ibirapuera - [3] | Estádio Algarve - [4] |
|---|---|---|---|---|
| 1 | 1.02 | 2.17 | 2.19 | 1.06 |
| 2 | 2.27 | 2.23 | 3.51 | 1.73 |
| 3 | 2.48 | 2.24 | 5.19 | 2.67 |
| 4 | 2.78 | 2.71 | - | 3.52 |

Table 2: Natural frequencies (Hz) of Morumbi, Ibirapuera and Algarve Stadia compared to Brasilia National Stadium.

## 4 LOAD MODELING

The mathematical model considered to simulate the action of jumping crowds is described on Eq.(1) bellow [5].

$$F_p(t) = k_p \cdot G \cdot sin\left(\frac{\pi \cdot t}{t_c}\right) \rightarrow \text{for } t \leq t_p \tag{1}$$

$$F_p(t) = 0 \rightarrow \text{for} t_p < t \leq T_p$$

with:

$k_p = F_{P,max}/G$ = dynamic impact factor;

$F_{P,max}$ = peak dynamic load;

$G$ = weight of individual;
$t_p$ = contact duration;
$T_p = 1/f_s$ = pace period.

Impact factor depends on the contact ratio ($t_p/T_p$), as shown on Figure4.

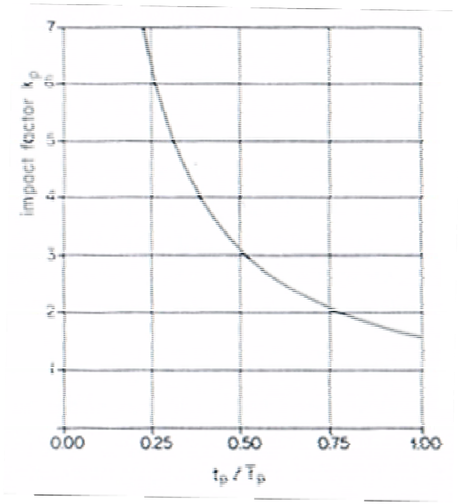



Figure4:Impact factor depending on contact ratio [5].

[3] considers an impact factor of 3 in his study. An inverse analysis of the curve shown on Figure 4 gives the value of 0.5 for the contact ratio. So the contact ratio considered in this study was also 0.5, which leads to the same impact factor of 3. The weight of each individual was arbitrated at 800N and it was considered that the Stadium was at its full capacity and the crowds were jumping all at the same time.

Five load models were created, each one with different pacing rates, as proposed by [6]. The selected pacing rates were 1.8Hz, 2.2Hz, 2.4Hz, 2.5Hz and 2.7Hz.

## 5 TRANSIENT ANALYSIS

The points that showed highest acceleration levels were all located at the upper grandstand, which is the most flexible one. Figure 4 displays the location of the 3 most critical points. Table 3 presents the peak acceleration values for these 3 points for each load model.

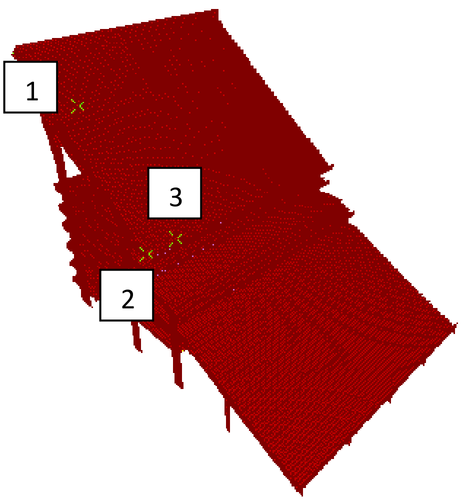



Figure 4: Critical acceleration points.

| | | $a_{máx.}$ (m/s²) | | |
|---|---|---|---|---|
| Model | f (Hz) | Point 1 | Point 2 | Point 3 |
| 1 | 1.8 | 0.31 | 0.19 | 0.22 |
| 2 | 2.2 | 0.63 | 0.25 | 0.25 |
| 3 | 2.4 | 1.38 | 0.3 | 0.36 |
| 4 | 2.5 | 2.52 | 0.47 | 0.55 |
| 5 | 2.7 | 1.67 | 1.21 | 1.44 |

Table 3: Peak accelerations at vertical direction.

As presented on table 3, the highest acceleration response happens at point 1 when the pacing rate is 2.5Hz.

The RMS (root mean square) values of the accelerations were then compared to the limit ranges suggested by [2], as shown on Table 4.

| Model | f (Hz) | Point | $a_{Zrms}$ (m/s²) | Human Perceptibility |
|---|---|---|---|---|
| 1 | 1.8 | 1 | 0.22 | Clearly Perceptible |
| | | 2 | 0.13 | Clearly Perceptible |
| | | 3 | 0.16 | Clearly Perceptible |
| 2 | 2.2 | 1 | 0.45 | Clearly Perceptible |
| | | 2 | 0.18 | Clearly Perceptible |
| | | 3 | 0.18 | Clearly Perceptible |
| 3 | 2.4 | 1 | 0.98 | Disturbing |
| | | 2 | 0.21 | Clearly Perceptible |
| | | 3 | 0.25 | Clearly Perceptible |
| 4 | 2.5 | 1 | 1.78 | Disturbing |
| | | 2 | 0.33 | Clearly Perceptible |
| | | 3 | 0.39 | Clearly Perceptible |
| 5 | 2.7 | 1 | 1.18 | Disturbing |
| | | 2 | 0.86 | Disturbing |
| | | 3 | 1.02 | Disturbing |

Table 4: Human Perceptibility to RMS accelerations according to[2].

According to the limit ranges suggested by [2], in all cases presented, the vertical vibrations are at least clearly perceptible, and in 5 of all cases it is disturbing. None of the responses exceeded the tolerable limit.

## 6 CONCLUSIONS

The modal responses display that the natural frequencies of the first vibration modes are very low (bellow 3Hz). [3, 4] show that Morumbi, Ibirapuera and Algarve Stadia also have vibration modes with natural frequencies below 3Hz. These frequencies are all near pacing rate ranges of human activities. This fact suggests the possibility of amplified vibrations and can put the comfort of the future crowds at risk.

Transient analysis were then carried out in five different situations, varying pacing rates, and the responses showed that, in five cases, the vibrations induced are considered disturbing, but none is considered intolerable.

Though these responses may give the assumption that the stadium might not be considered comfortable for the fans, some relevant facts must be raised. First of all, in the load models applied to the study it was considered that the grandstands were completely full and all fans were jumping at the same time with perfect synchronization, which is a very conservative hypothesis. [3, 7, 8] prove experimentally that jumping crowds induce lower vibration responses than numerically expected, due to lack of synchronization. Secondly, no human-structure interaction was considered. [7, 9, 10] show that passive crowds (people seated at the grandstands) increase the structure mass and damping ratio. Both these facts reduce significantly the induced vibrations. Third and last of all, these responses shown were read at critical points, located at very specific spots on the upper grandstand. This means that the response vibration could be disturbing for a small share of the crowd. The majority of the crowd, who would be everywhere else wouldn’t feel such intense vibration. It is interesting to highlight that none responses read at the intermediate or the lower grandstand were considered disturbing.

So considering the three last points that were brought up, it is possible to conclude that the Brasilia National Stadium has overall an acceptable dynamic performance, taking into account the comfort of the crowds.

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