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Identification of a steel stairs by operational vibration measurement

Identificación de una escalera de acero por mediciones de vibración operacional

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Abstract

This work presents the results of structural evaluations carried out from numerical models based on the finite element method (FEM) for a steel stair with 22.70 meters long, 8.37 high and 1.68 wide, belonging to Olympic Tennis Center, Rio de Janeiro/Brazil. A numerical model was elaborated and fitted to natural frequencies of real structure, which in turn were obtained from an operational modal test. The test was conduced by recording vibrations due to wind and traffic of people at six points over the structure, and from stochastic signals processing of these data considering frequency domain decomposition (FDD) procedure, the experimental natural frequencies were extracted. The calibrated numerical model was then used in the structural evaluation for static and dynamic loads, and it was observed that while the structural behavior obtained through the initial numerical model (used in the development of the project) indicated compliance with design codes criteria, calibrated model pointed out the need for structural reinforcement to meet vibrations service limit.

Keywords: Operational modal analysis, finite element method, numeric model calibration, signal processing, natural frequencies

Resumen

Este trabajo presenta los resultados de las evaluaciones estructurales realizadas a partir de modelos numéricos basados en el método de elementos finitos (FEM) para una escalera de acero con 22,70 metros de largo, 8,37 de alto y 1,68 de ancho, perteneciente al Centro Olímpico de Tenis, Río de Janeiro / Brasil. Se elaboró un modelo numérico y se ajustó a frecuencias naturales de estructura real, que a su vez se obtuvieron de una prueba modal operativa. La prueba se realizó registrando las vibraciones debidas al viento y al tráfico de personas en seis puntos sobre la estructura, y del procesamiento de señales estocásticas de estos datos considerando el procedimiento de descomposición del dominio de frecuencia (FDD), se extrajeron las frecuencias naturales experimentales. El modelo numérico calibrado se utilizó luego en la evaluación estructural para cargas estáticas y dinámicas, y se observó que si bien el comportamiento estructural obtenido a través del modelo numérico inicial (utilizado en el desarrollo del proyecto) indicaba el cumplimiento de los criterios de los códigos de diseño, modelo calibrado señaló la necesidad de refuerzo estructural para cumplir con el límite de servicio de vibraciones.

Palabras clave: Análisis modal operativo, Método de elementos finitos, calibración de modelos numéricos, procesamiento de señales, frecuencias naturales

1. Introduction

The finite element method consists of a numerical technique used to obtain approximate solutions to a large number of real physical problems. Due to its ability to model a wide variety of complex problems, extensive scientific developments and technological enhancements, it is nowadays the most useful computational tool for solving engineering problems.

In this technique is generated a set of differential equations that represent the real physical problem in an approximate way. Simplifications from the method itself and those due introductions of data by analyst will have significant influence at quality of the numerical response. The numerical model can be improved by fitting some parameters extracted from real structure. Among the various structural properties that can be fitted in a numerical model, adjusting from its modal parameters constitutes a robust and adequate way of constructing reliable numerical models (Benedettini et al., 2015), (Londoño et al., 2013), (Matta and Stefano, 2015), (Osmancikli et al., 2015), (Türker and Bayraktar, 2014). The modal parameters of a structure are closely related to the stiffness of its structural elements. It is possible to estimate, from its modal parameters, the changes in the mechanical properties, geometry, releases and restrains. This information is important for structural health monitoring and damage detection, as well as for the calibration of numerical models.

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The procedure for identifying the dynamic characteristics of a structure is called Experimental Modal Analysis. This process consists of the application of a known vibration and the measurements of the structure responses. This method is widely used in Mechanical Engineering. Its use in Civil Engineering is restricted by the difficulty of applying test loads in large and heavy structures, besides the risk of collapse for high damaged constructions (He and Fu, 2001).

In this context, Operational Modal Analysis (OMA) was developed (Rodrigues, 2004), which is a measurement of the dynamic characteristics of the structures submitted to ambient loads, without the need to use equipments to provide artificial vibrations (Brincker, 2014), proving to be an excellent tool for determination dynamic parameters (Benedetti and Gentile, 2011) of civil structures.

This work presents the results of the structural evaluations carried out on a steel stair belonging to the Olympic Tennis Center, located at Rio de Janeiro, Brazil. From an operational modal test performed on May 27, 2016 it was obtained experimental modal parameters and a numerical model calibrated by fitting natural frequencies of structure was obtained. This numerical model was then used for structural investigations, and it was observed from these evaluations the need for structural reinforcement to meet service limit of excessive vibrations.

2. Development

2.1 Description of structure

The stair tested has its steps composed by steel plates with 6.30 mm thickness. These ones are supported by lateral beams with double 2C300x140x4.75 section. The stair is anchored in the existing concrete structure by means of anchors bolts of varying diameters and lengths. (Figure 1) shows a draft of the geometry. (Figure 2) shows front and bottom view while (Figure 3) shows existing connections. (Table 1) describes the main mechanical characteristics of the materials composing the structure.
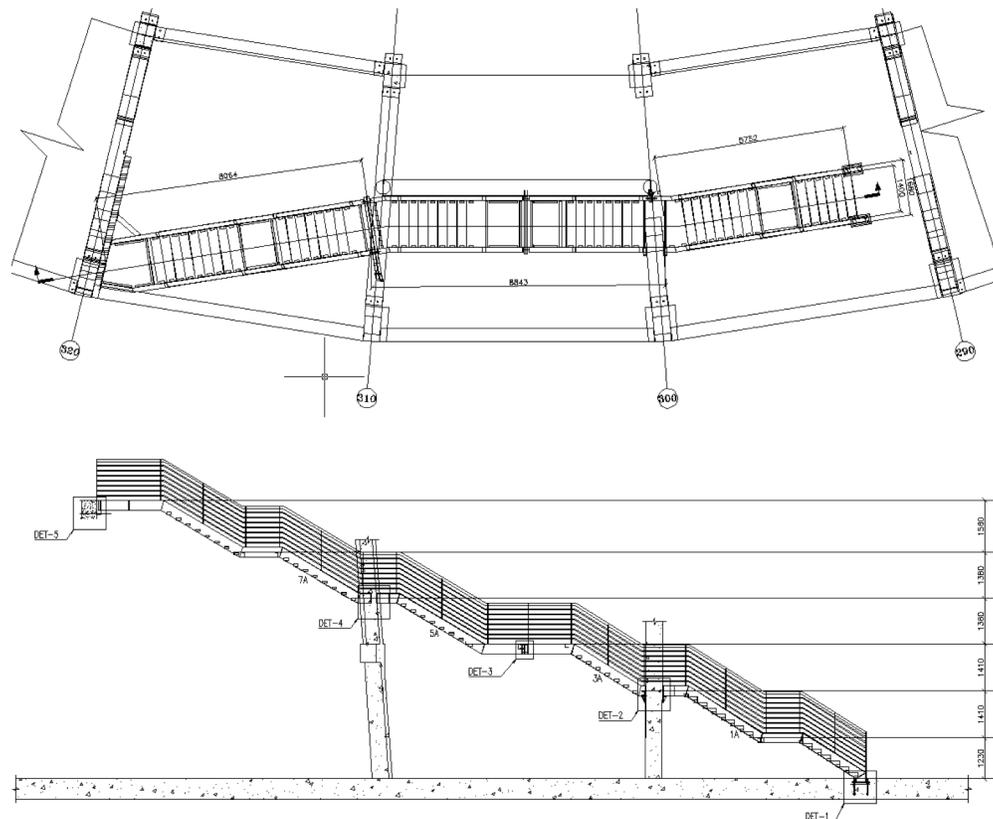

Figure 1. Draft of structure (mm)

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a)   Frontal view
b)   Bottom view

Figure 2. View of structure

a)   Det. 1
b)   Det. 2

c)   Det. 3
d)   Det. 4
e)   Det. 5

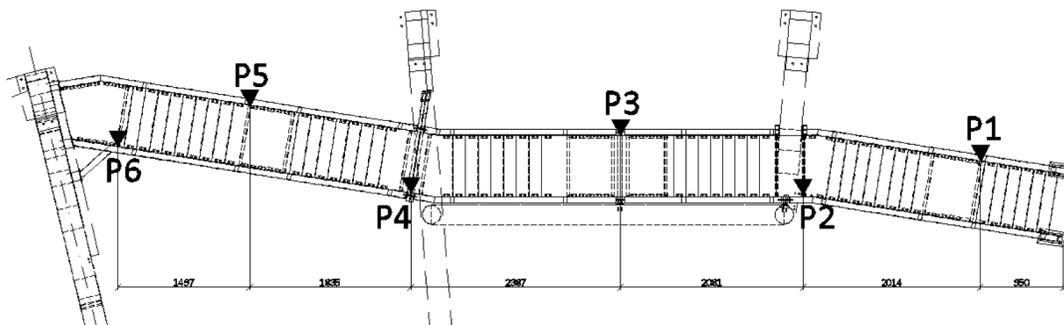*Figure 3.* Restrains of structure

Table 1. *Mechanical properties*

Element	Material	Elasticity modulus (GPa)	Poisson	Specific weight (kN/m³)	Yield stress (MPa)	Limit stress (MPa)
Plates	ASTM A36	200.00	0.30	75.00	250.00	400.00
Beams	ASTM A572	200.00	0.30	75.00	350.00	440.00
Bolts	Grade 5.8	200.00	0.30	75.00	400.00	500.00

2.2 Description of modal test

The equipment used to perform the field measurements was the SYSCOM MR3000C which has a wide acquisition frequency range, capable of fully covering the test requirements. It is composed of a 24-bit acquisition system and integrated highly sensitive triaxial accelerometers (1.5 V/g). It was positioned in 6 points (P1 to P6) over structure (Figure 4), selected for capturing as many possible modes. The data acquisition rate was 200 Hz. Each measurement had duration of 1 hour, totalling 6 hours of vibrations recording.

The measures of accelerations captured along structure were processed using stochastic signal process procedure based on frequency domain decomposition (FDD). The processing considered several options for FDD parameters related to resolution, standard deviation, among others, which were omitted due to the large number of analyzes performed. For this activity, the ARTeMISv3.0 software was adopted. (Figure 5) shows the main singular values of the spectral density matrix. Modal parameters of the structure, obtained from data processing, are presented in (Table 2).
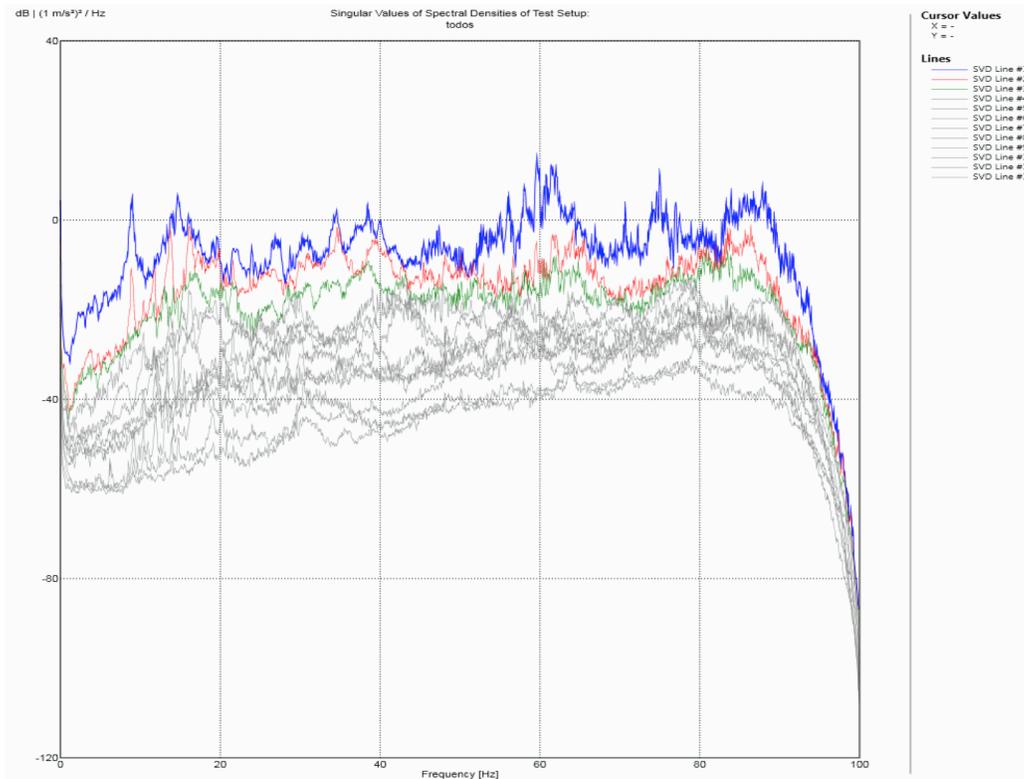

Figure 4. *Modal test setup*

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Figure 5. Single value decomposition of recorded signals

Table 2. *Experimental natural frequencies and damping rates*

Frequencies [Hz]	Std. deviation [Hz]	Damping rate [%]	Std. deviation [%]
8.605	0.111	2.598	2.754
11.985	0.124	4.264	0.843
15.659	0.068	8.228	0.779
19.526	0.131	6.992	0.83
20.995	0.357	7.962	1.215
28.959	0.194	3.662	0.46
30.702	0.369	9.496	0.121
34.949	1.525	2.94	2.198
38.243	0.343	3.574	2.279
42.808	0.144	1.123	0.281
42.834	0.074	1.487	0.24
47.029	0.474	3.327	1.878
52.56	0.851	3.683	1.958
53.97	1.373	3.003	2.145
56.04	0.276	1.648	0.378
58.594	0.643	6.78	1.192
60.549	1.462	4.152	1.146
64.029	0.644	4.153	1.458
70.403	0.036	0.99	0.068
75.31	0.382	1.59	0.441
78.331	0.726	3.774	1.145
86.99	1.897	5.234	1.326
88.858	0.796	2.856	1.969

2.3 Calibrated numerical model

An initial numerical model (used at design stage) was developed in SAP2000v16 software, based on the finite element method. 2857 linear thin shell elements were used for the floor and base plates and 1157 linear elements for support beams (Figure 6). The handrails were included in the model as mass linearly distributed over the lateral beams, considering the value of 19.97 kg/m. The restrains were inserted in the positions of the connection of the anchors bolts, considered initially pinned supports.

Next, the numerical model previously described was calibrated. This calibration process is an iterative process where changes in the structure stiffness (material properties, restrain stiffness, element releases) to approximate the natural frequencies of the numerical models to the respective experimental frequencies. At (Figure 7) it is showed the natural frequencies obtained by means of signal processing, obtained from the numerical model and those resulting from the calibrated one are plotted. (Figure 8) shows the error of the natural frequencies of the calibrated model in relation to the experimental data. The trend line of these errors is also showed for the 23 vibration modes captured in the test.
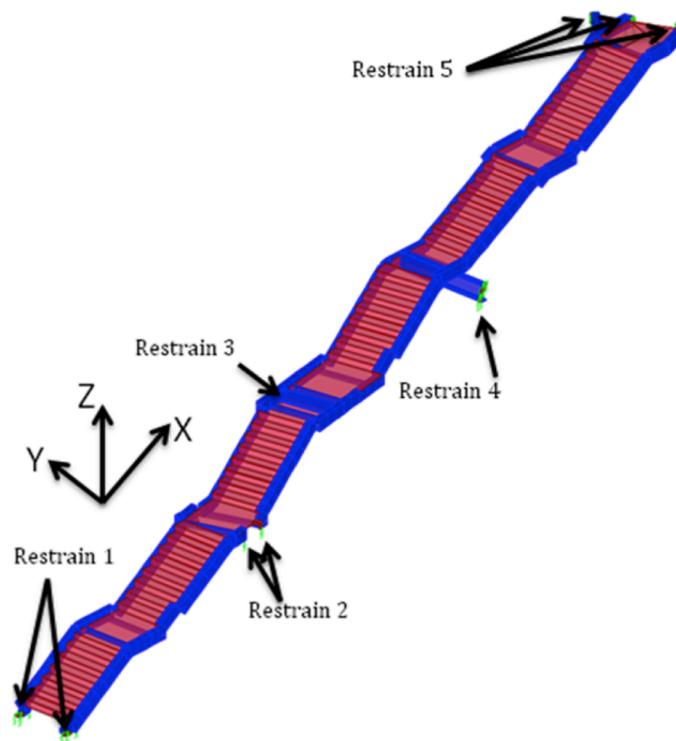

Figure 6. FEM numerical model

It is observed that the errors resulting from the calibration procedure are always less than 15.00%, and the error trend curve is approximately constant with an average value of 1.40%. In addition, by the mass participation curve of each mode (Figure 9), it can be observed that the most important modes, that is, modes 1, 7 and 11, present errors of 1%, 0%, and 1% respectively. These numbers indicate that the calibrated numerical model will accurately represent the dynamic behavior of the actual structure.

The changes in the numerical model occurred mainly in the stiffness of restrains. In the initial model the restrains were considered simple supports, that is, the translational stiffness in the three directions are infinite while the three rotational stiffness are zero. After the calibration procedure, these restrains underwent changes, and they reach translational stiffness varying from 2.26 to 3.93 GN/m and rotational from zero to 613.59 kNm/rad. (Table 3) summarizes the main changes.
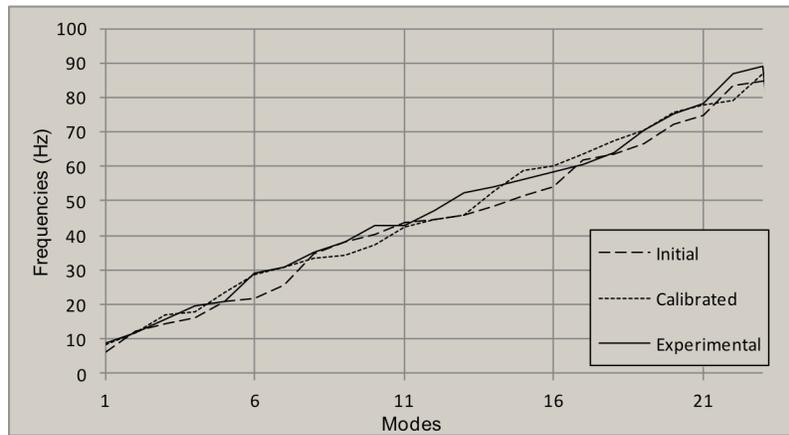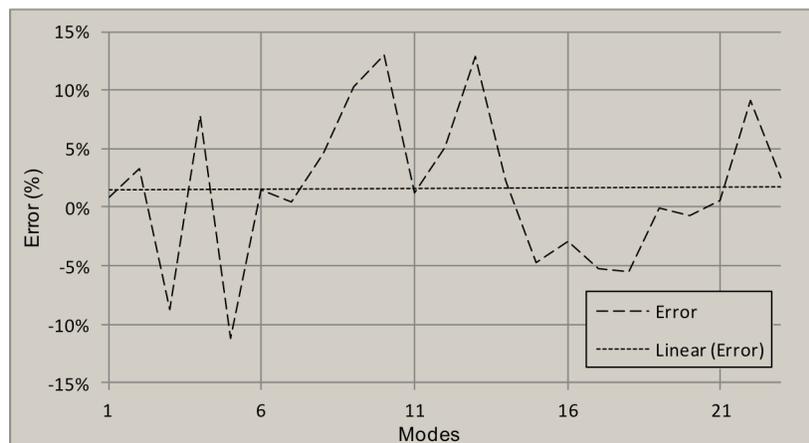
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Figure 7. *Vibration modes x natural frequencies*

Figure 8. *Calibration error*
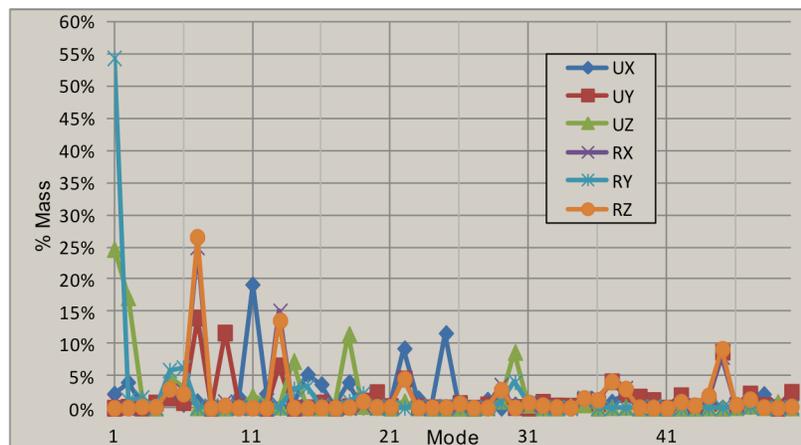
Figure 9. *Mass participation factor of vibration modes*

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Table 3. *Changes in numerical model*

Parameter	Initial model	Calibrated model
Modulus of elasticity - Plates (GPa)	200.00	198.20
Poisson coefficient- Plates	0.30	0.305
Modulus of elasticity - Beams (GPa)	200.00	198.70
Restrain 1 - K_x (GN/m)	infinity	3.93
Restrain 1 - K_y (GN/m)	infinity	3.93
Restrain 1 - K_θ (GNm/rad)	0	0.62
Restrain 2 e 3- K_x (GN/m)	infinity	0
Restrain 2 e 3 - K_y (GN/m)	infinity	2.26
Restrain 4- K_x (GN/m)	infinity	0
Restrain 4 - K_y (GN/m)	infinity	3.15
Restrain 4 - K_θ (GNm/rad)	0	0.16
Restrain 5- K_x (GN/m)	infinity	3.93
Restrain 5 - K_y (GN/m)	infinity	3.93
Restrain 5 - K_θ (GNm/rad)	0	0.44

3. Discussion

3.1 Structural checking

The calibrated numerical model was used for the structural evaluations. The following actions were adopted for these analyze: self weight of the structure considering specific weight of steel of 75.00 kN/m^3 and live load 3.00 kN/m^2. The criteria of the (ABNT NBR-8800, 2008) code were used to check service limits (displacements) and failure (structural beams). For the verification of Von Misses stress, the criterion of limit state was adopted. The vibration analyzes were evaluated according (DIN4150-3, 1999).

(Figure 10) presents the results of displacements for the initial and calibrated numerical models. The maximum displacements found were 5.20 and 10.98 mm, which correspond to distortions of 1/690 and 1/327 for initial and calibrated models, respectively. These values are less than the standard code limit, that is, 1/300. (Figure 11) presents the results of structural verification for beams. The relationship between the applied and structural capacity is presented. Value smaller than unit indicate that code criteria were met. It is observed that all values shown in (Figure 11) are less than one. A good approximation between the initial and calibrated models is observed. Von Misses tensions for shell elements showed at (Figure 12) indicates that the values found are lower than 75% of the yield limit, indicating that the stress level meets the limit state criterion. In addition, there is a good approximation between the two models.

Regarding the vibrations checking, it is observed that the natural frequencies of the structure are bigger than maximum value established by code, that is, 4.50 Hz. The vibration response was evaluated in the two numerical models by applying harmonic load with frequency of oscillation 4.50 Hz. It was observed that the maximum velocity responses were 3.45 and 6.17 mm/s for initial and calibrated models, respectively. While the initial model met the code limit (5.00 mm/s) the calibrated indicates the need for structural reinforcement..
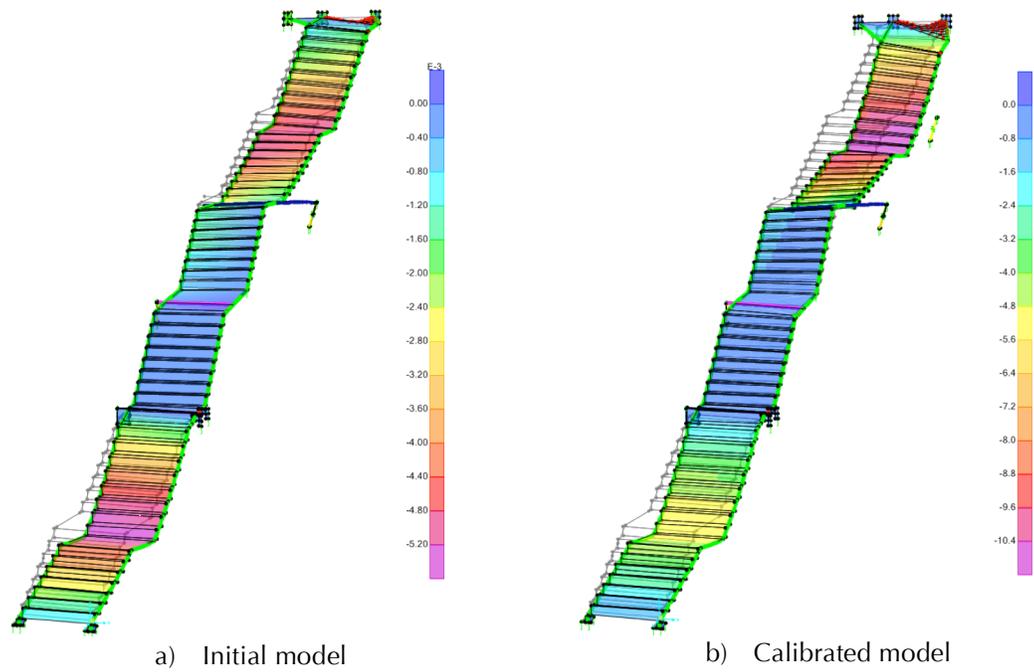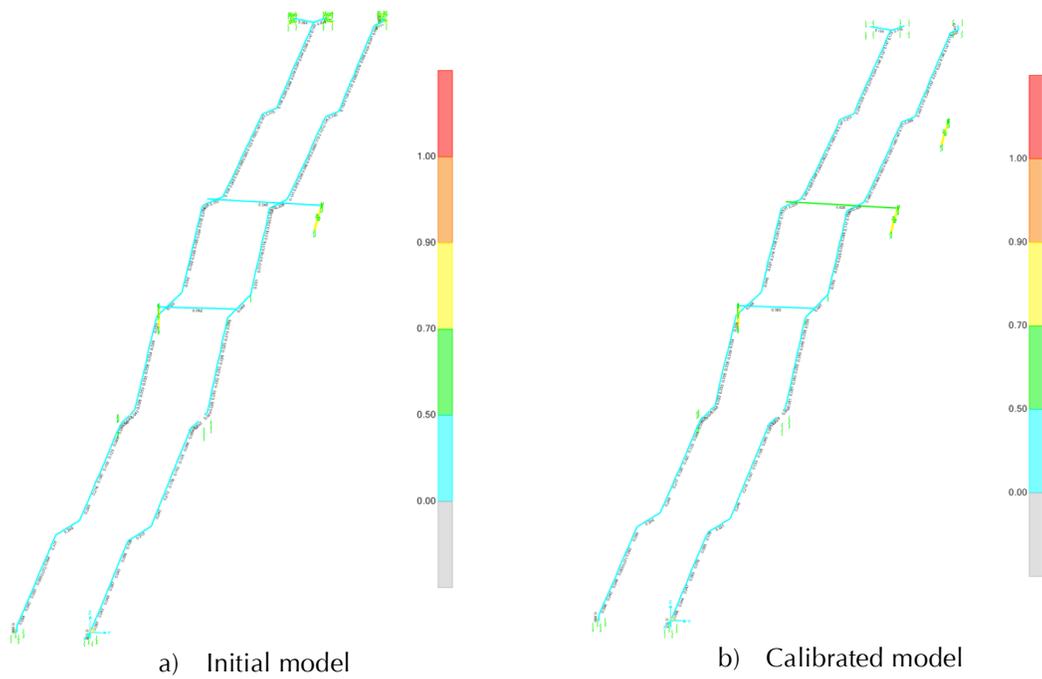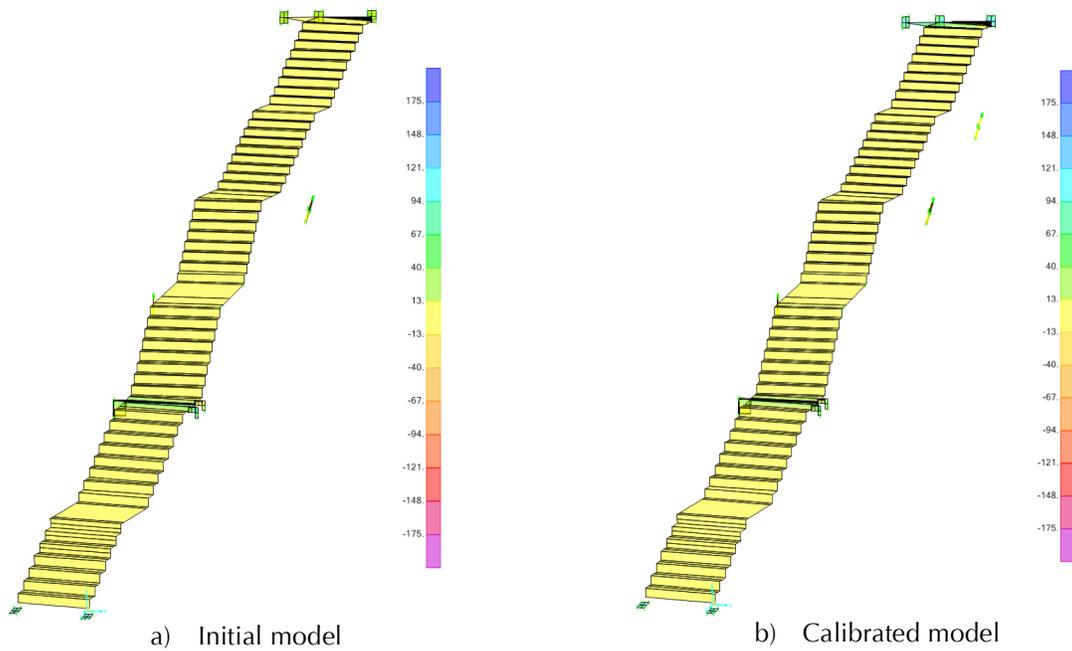
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a)   Initial model   b)   Calibrated model

Figure 10. *Displacements (mm)*

a)   Initial model   b)   Calibrated model

Figure 11. *Stress applied/allowed factor*

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a)   Initial model   b)   Calibrated model

Figure 12. *Von Misses Stress (MPa)*

(Figure 13) presents the proposed reinforcement with the aim of attenuating the vibrations predicted in the numerical analysis via calibrated model. (Figure 14) and (Figure 15) present the vertical displacements, structural verification of beam and Von Misses stress for the calibrated numerical model, including the proposed reinforcement. The effectiveness of the reinforcement is clear, and leads to the maximum vibration velocity of 2.59 mm/s, lower than code limit.
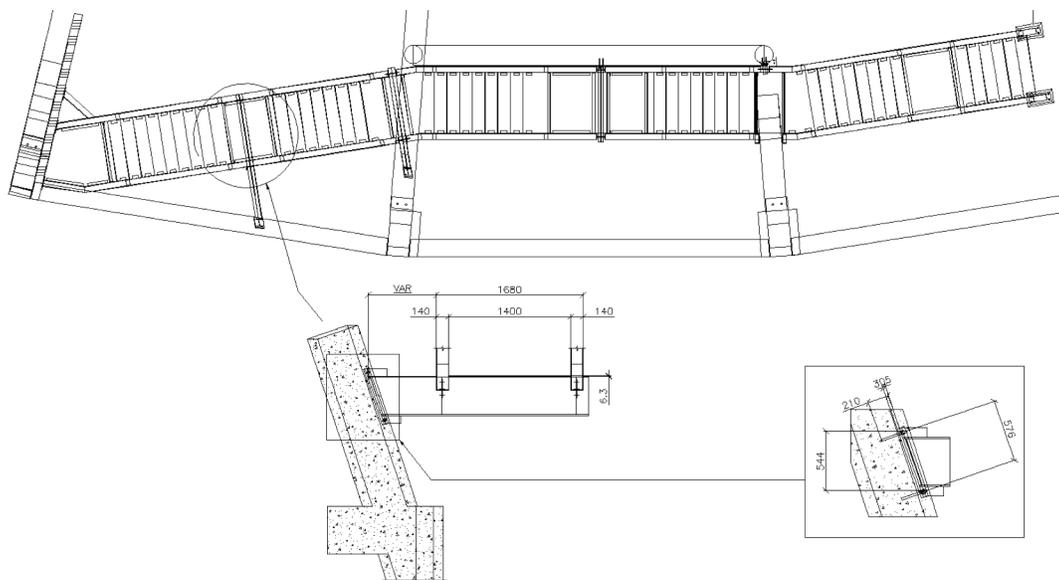
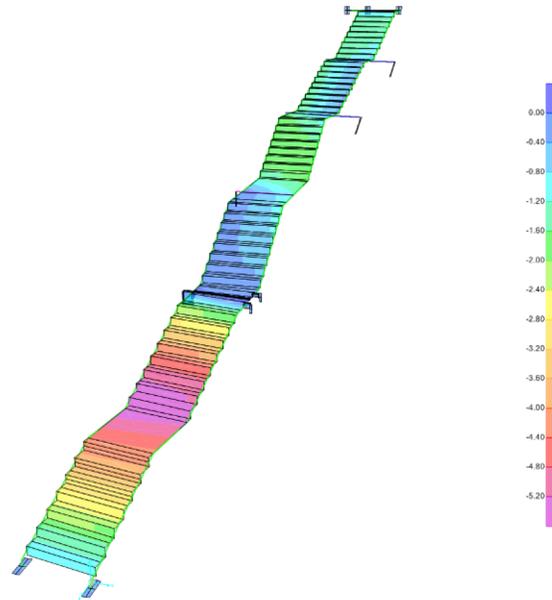**Figure 13.** *Proposed structural reinforcement (mm)*

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Figure 14. *Displacement – reinforced model - (mm)*

a)   Stress applied/allowed factor

b)   Von Misses stress (MPa)
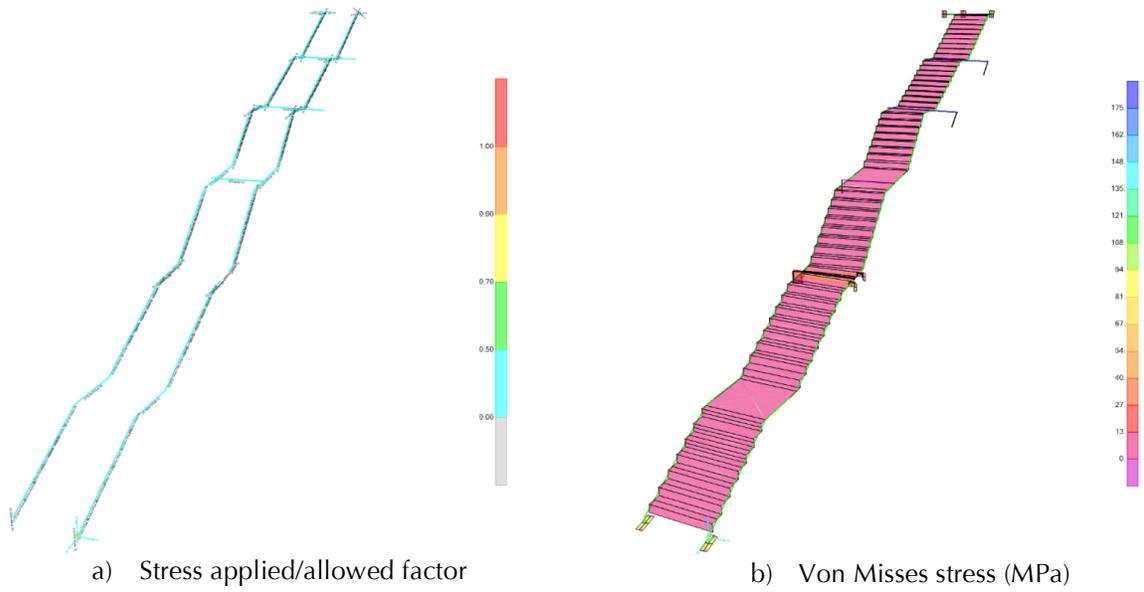
Figure 15. *Structural checking – reinforced model*

4. Conclusion

This work reported the results of the structural evaluations performed for a metal stair belonging to the Olympic Tennis Center, located in the city of Rio de Janeiro/Brazil. The results for the numerical model elaborated and adjusted to the natural frequencies of the real structure point to the need for structural reinforcement to meet the service limit of vibrations, while the structural behavior obtained using the initial numerical model (used in the design of the project) indicated compliance with all code criteria.

The modal test was able to extract the main modal parameters of the structure, considering operational sources of vibration (wind and pedestrian walking). This result was possible with the use of accelerometers of high sensitivity and system of acquisition with 24 bits resolution.

A precise numerical model was constructed, with mean errors lower than 1.40%, adjusting the numerical modal parameters to those obtained from the modal test. In this way it was possible to evaluate with greater reliability the behavior of the steel stair according code loads.

This work evidences the need of elaboration of precise numerical models for the evaluation of the static and dynamic behavior of structural systems, especially in relation to the service limits states. While failure limit states obtained via the initial and calibrated numerical model presented close results, the service limit presented significantly different values. The modal analysis used in the elaboration of calibrated numerical model pointed to the need for structural reinforcement. After checking structure considering proposed reinforcement, it was observed good attendance to codes criteria.

5. Acknowledgements

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