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Improvement of Staircases Vibration Serviceability to Human Ergonomics: A Case Study

Pedro Andrade[a], José Santos[b,c,*], Lino Maia[b,c]

[a]University of Madeira, 9020-105 Funchal, Portugal
[b]University of Madeira, Faculty of Exact Sciences and Engineering, Department of Civil Engineering and Geology, 9020-105 Funchal, Portugal
[c]CONSTRUCT-LABEST, Faculty of Engineering (FEUP), University of Porto, Portugal

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Abstract

Contemporary, slender and lightweight monumental staircases are often highly susceptible to resonance phenomena, due to typically low fundamental frequencies, which can considerably amplify their responses, raising major serviceability problems and causing discomfort and unsafety concerns to its users. This paper presents a case study of a low fundamental frequency steel staircase with known high levels of vibration since the beginning of its construction, in which various improvement solutions were proposed in order to increase its vibration serviceability. In total, six improvement measures were proposed, being tested using the Finite Element (FE) software SAP2000. The initial FE staircase model was first calibrated with the vibrations experimentally measured on the real staircase. Then, the original FE model was modified with the six improvement measures and the resulting vibrations were compared with those initially obtained and the acceptable limits suggested by the design guide SCI P354, to verify their viability. The most efficient numerical improvements were those that increased the staircase fundamental frequency, off the range of frequencies excitable by pedestrians walking.

Keywords: Improvement Measures; Vibration Serveciability; Pedestrian's Comfort; Resonance Phenomenon; Low Frequency Staircases.

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1. Introduction

Nowadays, for aesthetic reasons, slender and lightweight monumental staircases are becoming major architectural features of many buildings, hotels and other public areas. Design requirements for these are usually very aggressive,

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* Corresponding author. Tel.: +351 291 705 197.
E-mail address: jmmns@fe.up.pt

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with long and unsupported spans being the standard, often resulting in flexible staircases that are highly susceptible to human induced vibrations. In extreme cases, when the step frequency of pedestrians matches the staircase fundamental frequency or is one of its submultiples, a resonance phenomenon can occur, which amplifies the vibrations to a great extent and could cause discomfort and the feeling that the structure is not safe. In the traditional design of steel staircases, loads caused by pedestrians were usually treated as static loads. However, when assessing vibrations, taking into account only static loads, it will probably give rise to the conception of steel staircases subject to an unsatisfactory dynamic behaviour. Although, there is a growing need to design staircases with human-structure interaction in mind, in order to avoid excessive vibrations, scientific knowledge on this subject is still scarce. This paper aims to study a low frequency steel staircase (i.e. susceptible to resonance effects), which had a well-known level of liveness, since the beginning of its construction. In order to increase the vibration serviceability and, consequently, reduce the discomfort felt by the occupants who walk it, several improvement measures are proposed.

All proposed solutions were numerically tested using the FE software SAP2000, but with the purpose of being feasible employed in a real context. First, the vibrations on the steel staircase analysed in this study are experimentally measured. A very realistic FE model of the steel staircase is created and then calibrated, so the vibrations numerically calculated were close to those experimentally measured. After the FE model being calibrated, it is modified with the various improvement measures and the vibrations are recalculated. In total, six different solutions are proposed that could be applied to the actual staircase without changing the original structure, because it was intended to improve the dynamic behaviour and not, by any means, demolish to rebuild again. In the end, the vibrations calculated numerically through each improvement measure are compared with those initially obtained and with the serviceability criteria proposed by the design guide SCI P354, in order to verify their effectiveness.

2. Experimental program

2.1. Staircase description

The steel staircase studied in this paper is located inside a building in Funchal, Madeira, Portugal and is known for its vibration problems, causing discomfort and being the object of several adverse comments by its users. Hence, with a clear need of an intervention to increase its serviceability.

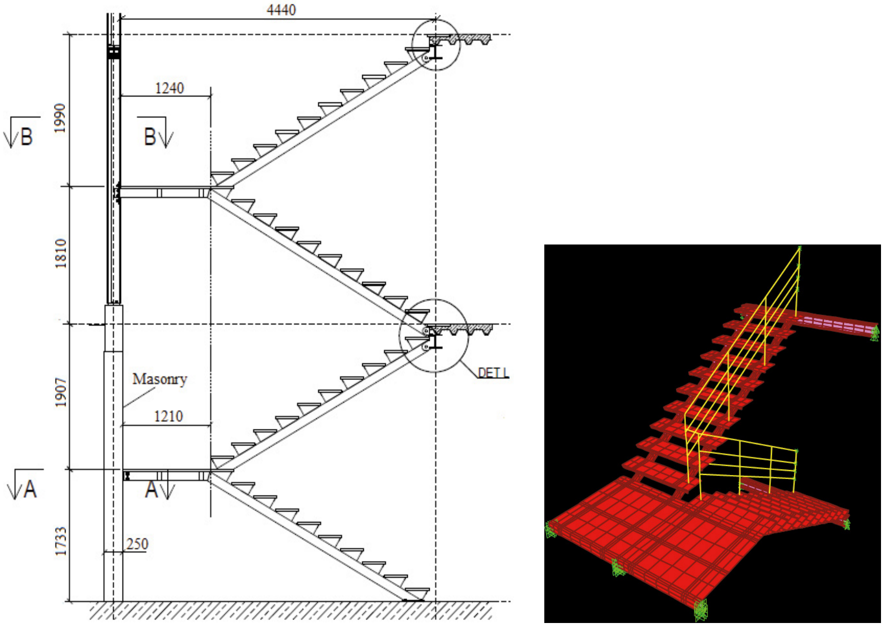
The sample staircase is composed of four flight of steps, with identical geometry, which serve as a connection between the three floors of the building, as represented in Fig. 1. Sample staircase: (a) complete drawing of project (mm); (b) FE numerical model.a). The staircase is supported on each floor by a European wide flange beam HEB180, which is connected to two hollow structural section (HSS) 120x60x4 mm stringers \that support the flight of steps, by means of an 8 mm metal plate and an M 20x100 mm screw (area indicated with circles in Fig. 1a)). Due this solution, rotational movement is possible, so the support could be assumed as pinned with the behaviour of the two upper flights being independent of the two lower flights. The span between supports makes a total of 4.44 m. The stair steps have a length of 1.15 m and a width of 0.32 m and are composed, as the intermediate landings, of a 3 mm thick metal plate coated by a granite sheet stone of 30 mm thick.

2.2. Modal properties

A battery of experimental modal tests was conducted on the analysed staircase to determine its dynamic properties. The natural frequencies and corresponding vibrations modes were obtained by applying multiple instant strikes along the staircase and recording accelerations in free vibration near to the driving and other locations of interest, for subsequent calculation using a subroutine developed in MATLAB. Table 1 shows the natural frequencies and shapes of the vibrations modes experimentally measured. The half-power bandwidth method was applied to the free vibrations of the staircase to estimate the damping coefficient. The damping was consistently estimated to be about 1.18 % of critical, being in accordance with the authors Bishop et al. (1995), Davis et al. (2015; 2009) and González (2013), who obtained in their measurements on steel staircases a value of approximately 1 %.

2.3. Walking tests results

After measuring the modal properties, the vibrations to which the sample staircase was subjected were experimentally measured, so later being able to verify the viability of the various improvement measures proposed. Assuming that from the frequency of the 4th harmonic amplitude a resonant build-up cannot occur and that is possible to walk staircases with step frequencies up to 4Hz (Kerr, 1998; Kerr and Bishop, 2001), according to Andrade et al. (2017a) and Santos et al. (2019), the cut-off frequency for staircases should be considered equal to 16 Hz. Considering that the fundamental frequency of the studied staircase is 13.9 Hz (see Table 1), this mean that descending and ascending at 3.5 Hz (4th sub-multiple of the fundamental frequency) is a plausible scenario to originate resonant effects and amplify its response. Therefore, various walking tests with this step frequency were performed to estimate the staircase's vibrations due ascents and descents, for a single pedestrian and a group of pedestrians. It was observed that the maximum vibrations occurred for descents, reaching peak accelerations of approximately 2.0 m/s^2 and 5.4 m/s^2, for a single pedestrian and a group of pedestrians, respectively.



a) b)

Fig. 1. Sample staircase: (a) complete drawing of project (mm); (b) FE numerical model.

Table 1 – Experimental and numerical vibration modes.

Modes		Experimental	Numerical
Nº	Shape	Frequency (Hz)	Frequency (Hz)
1	Vertical	13.9	13.9
2	Vertical	14.5	14.9
3	Torsion	20.9	23.4
4	Torsion	21.9	26.5
5	Torsion	22.4	27.1
6	Torsion	23.2	29.3

3. Numerical Analysis

3.1. Dynamic properties

In order to numerically calculate the accelerations, a FE model of the studied staircase was created using the structural analysis software SAP2000. For the purposes of the analysis, only the two upper flights of steps were modelled, since their behaviour is independent of the two lower flights, as explain in Subsection 2.1. A comprehensively detailed FE model of the staircase was created using shell elements for all the structural elements described in Subsection 2.1, i.e. HSS stringers, HEB180 beams, metal plates and granite sheet coating of the stair steps and intermediate landings, and, using beam elements for the non-structural elements, i.e. the guardrails. Fig. 1. Sample staircase: (a) complete drawing of project (mm); (b) FE numerical model.b) represents the FE staircase model built.

The natural frequencies and corresponding modes shapes of the FE model created were predicted using the standard eigenvalue analysis option. Table 1 shows the comparison between the first six vibrations modes numerically computed and experimentally measured. From the 2nd vibration mode, the numerical natural frequencies begin to differ from the experimental natural frequencies. However, the frequencies and shapes of the first two modes were accurately predicted, and the difference for the higher modes is not expected to significantly change the numerical results. Moreover, it was possible to estimate with close approximation the vibrations modes within the frequency-band where a resonant build-up is plausible to occur, i.e. lower or equal to 16 Hz (Santos et al.(2017a; 2019)).

3.2. Numerical results

For the improvement measures could be reliably applied in practice, it was necessary that the initial FE staircase model was calibrated, so the numerical accelerations obtained were close to those experimentally measured. Currently, there are four main existing numerical methods to predict human induced vibrations on low frequency staircases: i) footfall force time histories (GRFs), ii) Fourier series walking models, iii) steady-state analysis and iv) simplified vibration evaluation. An extensive number of analysis were performed employing the four different numerical methods, and it was verified that applying footfall forces force time histories to the FE model, realistically simulated the pedestrian's walking on the actual staircase, being the most accurate procedure. Hence, this was the method used throughout this work to calculate the accelerations numerically. To date, the most comprehensive work conducted to measure footfall time histories directly on stairs was developed by Kerr (1998; 2001). This researcher obtained more than 500 footfall traces from 25 individuals ascending and descending the stair at different step frequencies on an instrumented stair with a force plate. Footfall traces obtained by Kerr (1998; 2001) for a descent with a step frequency of 3.5 Hz were used to calculate the accelerations numerically. Simulations for a single pedestrian and a group of pedestrians descending the FE staircase model were performed applying footfall traces at increments of 1/3.5 Hz, to obtain the maximum accelerations in resonance and to be comparable with the experimental results (see Subsection 2.3).

The accelerations were calculated performing time histories analysis in SAP2000, being obtained for a single pedestrian and a group of pedestrians, peak accelerations of approximately 2.1 m/s^2 and 6.6 m/s^2, respectively. This is in agreement with the walking tests results observed in Subsection 2.3 and, therefore, validating the initial FE model and numerical method used.

4. Application of the improvement measures

The maximum peak accelerations measured for a single pedestrian and a group of pedestrians, as seen in Subsection 2.3, were approximately 2.0 m/s^2 and 5.4 m/s^2, respectively, which are significantly higher than the acceptable limits proposed by design guides and researchers (SCI P354 (2009)/Bishop et al. (1995), AISC 11 (1997) Davis et al. (2015; 2009), and Zhou et al. (2011)). Considering the high level of vibration that the studied steel staircase is subjected, various improvement measures have been proposed in order to reduce it. The different proposed measures were tested by modifying connections and/or adding structural elements to the original FE model and then recalculating the accelerations, to compare with the initially obtained and the acceptable limits, i.e. verifying their effectiveness. It should be emphasized that the improvement measures aim to be employed in practice for increasing the serviceability of the actual staircase, not being intended to alter or demolish the existing structure.

To be consistent with Subsection 3.2, after employing the proposed measures, accelerations were recalculated using the same footfall traces obtained by Kerr (1998; 2001) for a descent at 3.5Hz.

In total, six improvement measures were tested and are presented below:

- Improvement measure 1 – Weld or Screw an additional stringer, in the longitudinal direction, between the two existing stringers.

In the first improvement measure, a stringer with a commercial steel hollow structural section (HSS) 250x100 mm was connected, in the longitudinal direction, between the two existing stringers, modelled by a beam element. The cross-section of the added stringer is approximately twice the height of the two existing stringers (120x60 mm), however it was the necessary cross-section for the accelerations to be under the acceptable limits.

- Improvement measure 2 – Connect a steel cable between the HEB180 beam and the intermediate landing.

In second improvement measure, a steel cable was added to connect the HEB180 beam (located in the floor area) and the intermediate landing area, with the aim of reducing the flight of steps deflection and, therefore, decreasing the vibrations. The cable was modelled by a beam element with a circular cross-section. However, this measure proved to be ineffective, not significantly decreasing the accelerations.

- Improvement measure 3 – Weld beams at the flight of steps midspans, in the transverse direction, supported by an added column.

In the third proposed measure, the placement of two additional beams at the flight of steps midspans, perpendicularly to the existing stringers, was tested. These beams are supported by an added column located between the flights of steps. The beams employed in this measure consisted of a steel hollow structural section (HSS) 150x100 mm. This cross-section giving rise to the lowest accelerations. From this cross-section, accelerations cease to decrease significantly. The employed column must consist of a European wide flange beam HEB180 or HEB160, not being possible higher cross-sections, due to the reduced spacing between the flights of steps.

- Improvement measure 4 – Add an intermediate column in the landing area, simulated by a fixed support.

In this measure, it was decided to add a column on the intermediate landing in order to reduce the length of the staircase span, thus decreasing the vibrations. The column was simulated by a fixed support and not by a beam element, as opposed to improvement measure 3. The fourth proposed measure did not nearly affected the first vibration mode frequency, which also caused the accelerations to not substantially reduce. Both this and the second improvement measure did not generate the expected results.

- Improvement measure 5 – Duplicate the height of the sample staircase stringers.

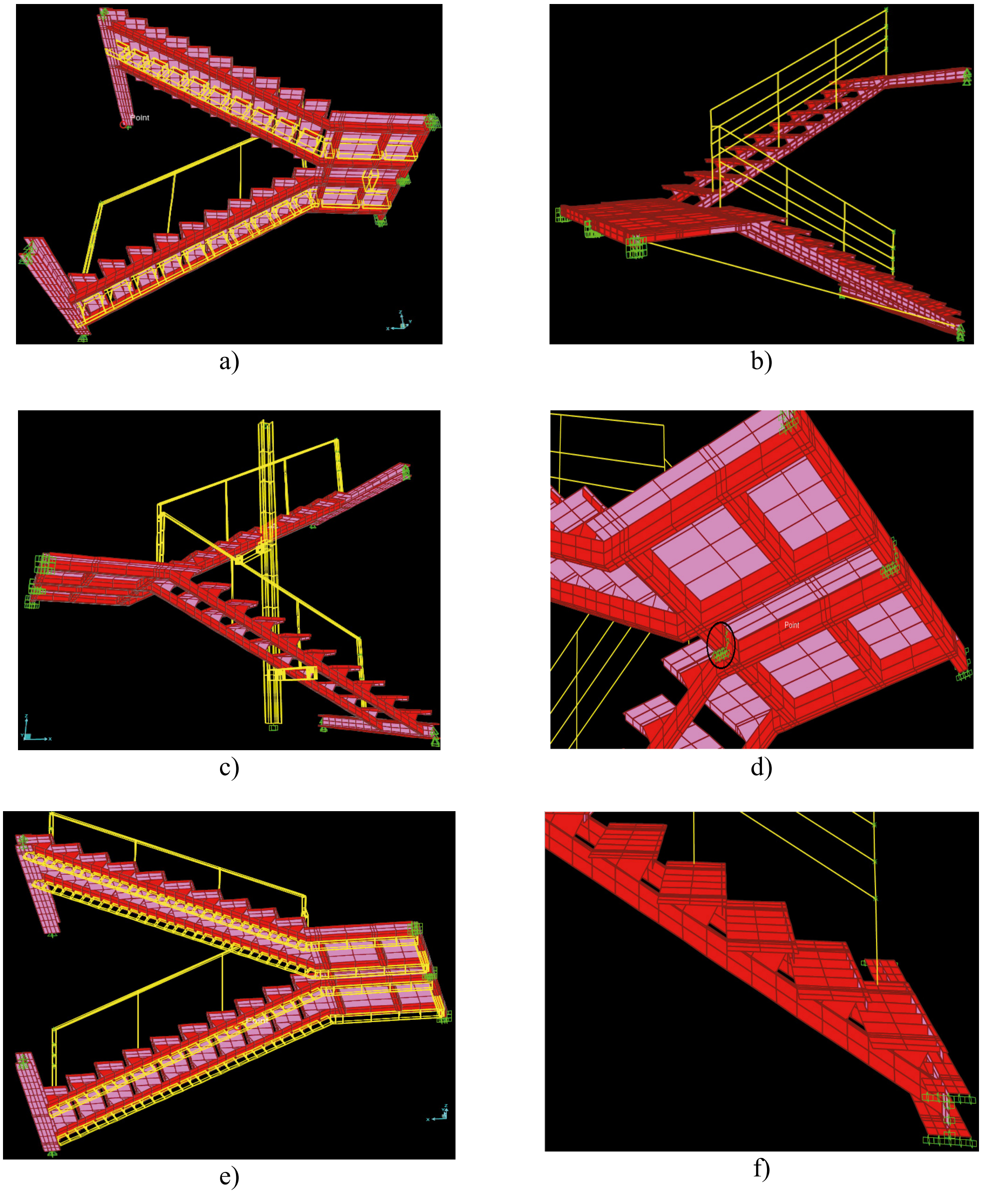
In the fifth proposed measure, HSS steel stringers with a cross-section of 120x60 mm were added to the initial FE model, placed under the existing stringers supporting the flight of steps. HSS stringers with a cross-section of 120x60 mm were used for two reasons: first, the aesthetically visual impact is less with the placement of stringers coinciding with the dimensions of the existing HSS stringers (120x60 mm) and, second, the accelerations values obtained considering this cross-section are considerably lower. In order to further reduce the accelerations, it is necessary to use HSS stringers with much higher cross-section dimensions, which would be hardly feasible in practice.

This reinforcement measure implies that the sample staircase should have been initially designed with HSS stringers about twice the height, to avoid excessive vibrations.

- Improvement measure 6 – Eliminate the connecting rod between the flight of steps and the HEB180 beam, making the connection rigid.

As described in Subsection 3.1, the flight of steps is supported on a HEB180 beam, with the connection between both elements allowing rotation to occur, its behaviour being assimilated to a pinned support. Consequently, it is suggested as an improvement measure to transform the current pinned support, referring to the connection, into a fixed support, i.e. welding or screwing the stringers directly into the HEB180 beam. Hence, increasing the rotational stiffness between the flight of steps and the HEB180 beam, and, decreasing the vibrations. Through this measure, the accelerations decreased to approximately half of the initially obtained, however continuing to be relatively higher than the acceptable limits, mainly for a group of pedestrians.

In Figs. 2a) to 2f) are represented the FE models after applying the six improvement measures proposed.



a)
b)
c)
d)
e)
f)

Fig. 2. FE numerical model with the: (a) first improvement measure; (b) second improvement measure; (c) third improvement measure; (d) fourth improvement measure; (e) fifth improvement measure; (f) sixth improvement measure.

5. Comparison of the accelerations after the improvement measures with an acceptance criteria

The accelerations obtained after employing the six improvement measures were compared with the acceptable limits proposed by the SCI P354 (2009), since this is the only design guide that directly refers to an acceptance criteria for staircases. The limits proposed in SCI P354 (2009) are given by a frequency-weighted base curve multiplied with factors of 32 and 64, respectively, for a single pedestrian and a group of pedestrians. As the fundamental frequencies of the FE models change when applying the various improvement measures, the acceptable limits are different for each proposed solution. Table 2 presents the peak accelerations initially obtained and after each proposed measure compared with the peak limits given by SCI P354 (2009).

Table 2 – Comparison of the accelerations obtained after employing the several improvement measures with the SCI P354 (2009).

Office Building Staircase		Peak acc. [m/s^2]	Peak Lim. [m/s^2]	Acc. Verif.
Single Pedestrian	Initial	2.07	0.39	KO!
	Imp. Meas. 1	0.37	0.63	OK!
	Imp. Meas. 2	1.82	0.39	KO!
	Imp. Meas. 3	0.48	0.61	OK!
	Imp. Meas. 4	2.32	0.42	KO!
	Imp. Meas. 5	0.35	0.60	OK!
	Imp. Meas. 6	1.19	0.44	KO!
Group of Pedestrians	Initial	6.62	0.79	KO!
	Imp. Meas. 1	1.27	1.27	OK!
	Imp. Meas. 2	5.82	0.79	KO!
	Imp. Meas. 3	1.60	1.21	KO!
	Imp. Meas. 4	7.03	0.83	KO!
	Imp. Meas. 5	1.28	1.20	KO!
	Imp. Meas. 6	3.85	0.88	KO!

As can be observed, measures 1, 3 and 5 gave rise to peak accelerations lower than the peak limits for a single pedestrian. Of these, only measure 1 meets the proposed limit for a group of pedestrians. However, given the significantly high accelerations initially obtained for a group of pedestrians, measures 3 and 5 resulted in peak accelerations substantially lower, being only slightly higher than the acceptable limits. Improvement measures 2 and 4, as can be seen from Table 2, do not present peak accelerations relatively different from those initially calculated, being the most ineffective solutions. From Table 2, it is also possible to verify that the peak accelerations obtained with measure 6 are approximately half of the originally generated, but continuing to be higher than the peak limits, mainly for group simulations.

6. Summary and conclusions

The low frequency steel staircase studied in this paper presents a well-known level of liveness, as demonstrated in Subsection 2.3, thus various improvement measures being proposed to reduce its vibrations and pedestrians comfort. With the aim of realistically apply the different measures on the actual staircase, the initial FE model was calibrated, so the numerical accelerations obtained through footfall time histories were close to the experimental accelerations.

In total, six improvements measures were tested. Measures 2 and 4 were the less effective solutions to be employed in practice, while measure 6 decreased to half the accelerations initially obtained, although still being relatively higher than the peak limits from SCI P354 (2009). Measures 1, 3 and 5 were the most accurate, since reduced the accelerations and increased the fundamental frequencies, placing it off the range of submultiples excitable by pedestrian's step frequencies, where a resonant-build is possible. These measures also being the more technically feasible on site. The improvement measure 5 is of particular relevance, since it demonstrates that the staircase stringers should have been initially designed with a HSS cross-section twice the height, in order to verify the serviceability limit state.

All proposed measures were developed with the possibility to be implemented in practice, without changing the existing staircase, however, inevitably with additional costs which are not predict in the original design. Hence, future designs of low frequency staircases should be perform considering the dynamic behaviour and employing different numerical methods to estimate human induced vibrations, consequently, avoiding pedestrian's unsafety and later modifications to the structure after construction. This being already observed and a reported concern in previous works developed by the authors (Andrade et al. (2017b) and Santos et al. (2019)).

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