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Reinforcement Measures to Reduce the Human Induced Vibrations on Stair Steps – A Case Study

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Abstract: The human induced vibrations seen on stairs are usually a global phenomenon, however in some cases, if the connection between the treads and the rest of the structure has a very low rotational stiffness, a so-called local vibration phenomenon can happen, i.e. the vibrations in the treads may be independent from those verified on the staircase that it supports them. This paper presents a case study of a particular metal staircase in which the local vibrations were high. The objective of this study was to measure the vibrations experimentally and then to propose several reinforcement measures in order to reduce them. A total of eight reinforcement measures were proposed, being tested through the construction of several numerical models using the software SAP2000. The numerical accelerations obtained with each reinforcement measure were compared with those obtained initially and with the design guide SCI P354 to verify their effectiveness. The most effective reinforcement measures were those that significantly increased the stiffness of the treads.

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Keywords: Vibration Serveciability; Local Vibrations; Human induced vibrations; Reinforcement measures.

1. Introduction

In recent years, mainly for aesthetic reasons, it has become increasingly popular to design educational buildings, hotels, hospitals and other public areas with slender and lightweight monumental staircases. This often results in

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flexible staircases which are highly susceptible to vibrations induced by man and fails to satisfy the serviceability limit states (Belver et al. (2012)). Most of the information found in the literature (Bishop et al. (1995), Davis et al. (2009), González (2013)) on flexible staircases that are dynamically responsive is mainly associated only with global vibrations, i.e. vibrations in which staircases moves as a whole. However, if the connections between the steps of the staircase and the staircase itself have low stiffness, this may cause the dynamic behavior of these two structural elements to be independent of each other. When the steps response is independent of the staircase response it's referred as local vibrations. In many cases, especially when the length of the steps is long, it is observed that local vibrations can reach excessive levels of response.

This paper presents a case study of a steel staircase whose local vibrations were quite significant. With the aim to reduce them several reinforcement measures are proposed. In order to achieve this, initially the vibrations on the steps of the steel stair analyzed were measured experimentally, then a realistic numerical model of one of the stair steps was elaborated using the software SAP2000 (2013). The model was calibrated so that the numerically obtained vibrations were very close to those measured experimentally. After the numerical model was calibrated, it was modified with several reinforcement measures and the vibrations were recalculated for each of the proposed solutions. In total, eight reinforcement measures are proposed, all of them are made with the objective to be possible to apply in practice. Finally, the vibrations obtained numerically through each reinforcement measure were compared with the level verified experimentally and then with the limits proposed by the design guide SCI P354 (2009).

2. Experimental measurements

2.1. Staircase geometry

The staircase analyzed in this paper is located in a public building in Funchal, Madeira and it connects the first and second levels of the building as it can been seen in Figure 1. The sample staircase has serious vibration problems and is the subject of several adverse comments from the walkers who cross it. The vibrations observed in the staircase studied, besides being elevated, are also at the local level and not at the global level, that is, the movement of the treads when subjected to walking forces is different from the movement of the rest of the staircase.

From what has been previously referred, it becomes only relevant to describe the geometrical properties of the stair steps. Its geometric characteristics were obtained with measurements on the site since it was not possible to have access to the design drawings of the staircase. The treads are made of 6 mm thick steel plates and a thin coating of synthetic rubber sheet. Its dimensions, height, length and width are shown in Figure 1. An auxiliary plate that is welded to the treads and to the stringers makes the connection between the treads and the rest of stair structure.

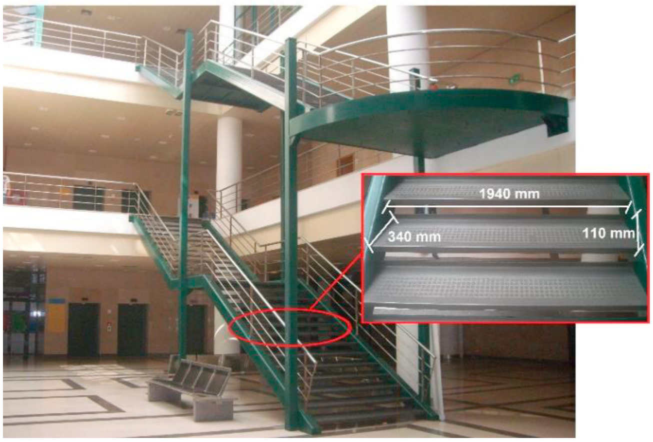

Figure 1 – Sample staircase and geometrical properties of the treads

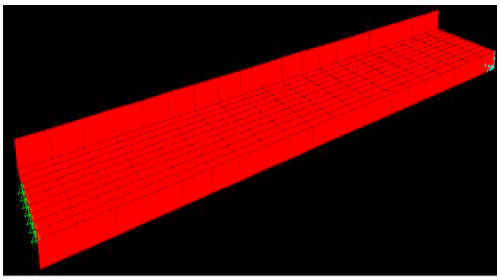

Figure 2 – FE model of the stair tread

2.2. Dynamic properties

An ambient modal analysis has been performed to determine the natural frequencies, the corresponding mode shapes and damping of the staircase steps. The first two local vibration modes have a frequency of respectively 24.0Hz and 45.6Hz. The first mode is vertical with some torsion and the second mode is exclusively of torsion. The measured frequencies of the local vibration modes are different from the measured frequencies of the global vibration modes, showing that the dynamic behavior of the steps is independent from the rest of the staircase. Due to pedestrian's use of the staircase over the years, the weld connecting the steps to the stringers has a practically negligible rotational stiffness which helps to explain why the vibrations are at the local level. The damping was consistently estimated to be 0.82% of critical, applying the half-power bandwidth method in every test. The authors Bishop et al. (1995), Davis et al. (2009) and González (2013) obtained in their measurements a damping of approximately 1%, thus validating the damping measured in this study.

2.3. Experimental results

Several walking tests were performed to verify the maximum acceleration on the stair steps. To perform the tests various individuals ascended and descended the sample staircase at different step frequencies, ranging from normal walks to fast runs. According to various authors (Bishop et al. (1995), Kasperski et al. (2012), Davis et al. (2009)) it is possible to walk on stairs with step frequencies situated in the interval of 2.0 to 4.5 Hz approximately, therefore in the tests performed, were used step frequencies within this range. Tests were carried out for an isolated pawn and for a group of pedestrians.

In the walking tests for both an isolated pawn and a group of individuals, it was verified that the maximum accelerations occurred for descents at step frequencies close to 3.30Hz, reaching a value of approximately 18 m/s^2.

3. Numerical analysis

3.1. Modal properties

In order to determine the accelerations numerically, a finite element (FE) model of one of the stair steps was created using the analysis structural software SAP2000 (2013). It has become unnecessary to create a finite element (FE) model of the entire staircase since the vibrations are at local level. The metal plate that constitutes the step was modelled by shell elements with a thickness of 6 mm. The thickness of the synthetic rubber sheet coating is minimal and its contribution to the stiffness of the tread is practically null, so in the modelling only its mass (6 kg/m^2) was considered. The FE model of the tread was constructed taking into account the dimensions indicated in the Figure 1. The lack of rotational stiffness in the join between the treads and the stingers, verified in the actual stair, was simulated using pinned supports. In the Figure 2 is represented the created numerical model of the stair tread.

The natural frequencies and corresponding modes shapes of the FE model constructed were predicted using the standard eigenvalue analysis. In Table 1 are compared the local vibration modes obtained numerically with those measured experimentally (see Subsection 2.2). The vibration modes obtained numerically and measured experimentally are approximate, demonstrating that the assumptions made in the construction of the numerical model were adequate.

Table 1 – Local vibration modes measured experimentally and obtained numerically

Nº	Shape	Experimental Frequency [Hz]	Numerical Frequency [Hz]
1	Vertical w/ torsion	24,0	24,1
2	Torsion	45,6	42,6

3.2. Numerical results

For the proposed reinforcement measures to be valid and could be implemented with confidence it was important that the numerical accelerations obtained initially were close to the experimentally measured. The most realistic and reliable method of obtaining accelerations numerically is through the application of footfall force time histories, obtained from force plate measurements, directly on the numerical model, thus simulating the pedestrians locomotion on the actual staircase. This was the method used in this paper to determine the accelerations numerically. To date the most extensive study undertaken to obtain footfall force time histories on stairs was developed by Kerr (1998; 2001). Kerr (1998; 2001) measured on an instrumented stair with a force plate more than 500 footfall traces from 25 individuals ascending and descending the stair with different step frequencies.

To determine the accelerations numerically was chosen a footfall trace obtained by Kerr (1998; 2001) for a descent with a step frequency close to 3.30Hz and then a time history analysis was performed using Sap2000 (2013). The maximum acceleration obtained numerically was approximately 18 m/s^2, being in agreement with the measurements during the walking tests (see Subsection 2.3), demonstrating that the numerical model and method used are calibrated with the verified experimentally.

4. Proposed reinforcement measures

The maximum acceleration measured experimentally in the steel staircase analyzed is 18 m/s^2, being evidently much higher than the acceptable criteria proposed by various design guides (SCI P354 (2009), AISC 11 (1997)) and authors (Bishop et al. (1995), Davis et al. (2009)). Taking into account that the sample staircase is subject to excessive vibrations, some reinforcement measures have been proposed in order to reduce them. The reinforcement measures were tested by making several changes to the initial numerical model and later verifying if with them, the obtained accelerations were lower than the proposed criteria. It should be mentioned that in the changes made to the initial numerical model, the original structure was always maintained since it was intended to propose solutions that aimed to improve the dynamic behavior of the existing stair and not to demolish to build again. The numerical accelerations after the application of the reinforcement measures were also determined using the footfall trace obtained by Kerr (1998; 2001) for a descent at 3.30Hz and performing a time history analysis.

In total, eight reinforcement measures were tested and are presented below:

- Reinforcement Measure 1 – Make rigid the connection of the tread to the stringers, placing solder where it doesn't exist and improving the existing one

Due to the wear caused over the years by the occupants in the welding of the auxiliary metal plate connecting the treads to the stringers, the first more obvious measure is to reinforce this same weld. In the numerical model of the stair step this solution was tested modifying the pinned supports for fixed supports, in order to increase the rotational stiffness and reduce the vibrations.

- Reinforcement Measure 2 – Weld or screw a European I or wide flange beam under each tread

The second proposed reinforcement measure is to weld or screw a metallic beam under the stair steps. In this reinforcement measure, European I beams (IPE) and European wide flange beams (HEB) were tested using frame elements with different dimensions and verified which one produce better results. First, the IPE beams were tested, starting with the first metallic beam given by a commercial table, which is the IPE80 and ending with the IPE300. The IPE300 beam clearly has dimensions too high, however the objective was to verify how the accelerations varied with the increase of the beam dimensions. The HEB beams were then tested, starting with the first metallic beam given by a commercial table, which is the HEB100 and ending with the HEB300. The two types of metallic beams, IPE and HEB, were also tested in a numerical model of the tread with simple supports and in a numerical model with fixed supports. The graph of Figure 3 demonstrates the variation of the peak accelerations with the increase of the IPE and HEB beams dimensions, in the numerical model of the tread with pinned supports and with fixed supports.

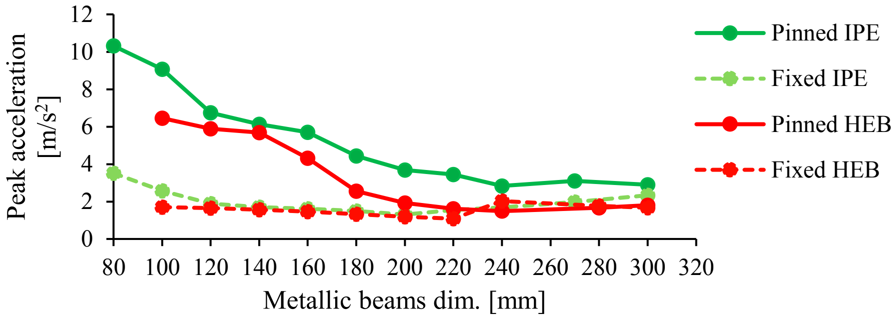

Figure 3 – Variation of the peak accelerations with the increase of the IPE and HEB beams dimensions, in the numerical model with simple and fixed supports

It can be observed that from a height of 240 mm the values stabilize and stop decreasing and the accelerations obtained in the numerical model with pinned supports start to be close to those obtained in the numerical model with fixed supports. This may be related to the fact that the numerical model created no longer makes sense when simulating the IPE and HEB beams with a high height through frame elements. Probably to test the IPE and HEB beams with heights higher than 240 mm the numerical model would have to be created entirely with shell elements.

Observing the graph of the Figure 3 and taking into account the practical application, it was concluded that the metallic beam IPE100 was the most suitable, being decided to use it in the calculation of the numerical accelerations (see Table 2).

In Figures 4 and 5 are represented the numerical models of the treads with the application of the first and second reinforcement measures respectively.

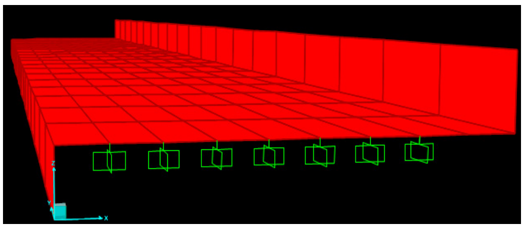

Figure 4 – Numerical model of the step with the first reinforcement measure

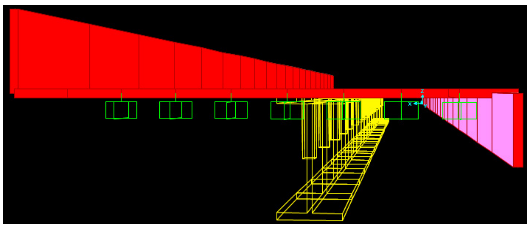

Figure 5 – Numerical model of the step with the second reinforcement measure

- Reinforcement Measure 3 – Weld a metal plate between the treads

In the third reinforcement measure the idea is to weld a metal plate between the treads, with the same thickness of them (to facilitate the welding), in order to treads to move in unison causing the stiffness to be increased significantly and reducing the vibrations. The same is conventionally identical to that used in many sports stadium benches, such as the Barreiros Stadium, Alvalade XXI Stadium, etc ..., where each row of chairs is attached to the front and back row. In the numerical model this reinforcement measure was simulated placing shell elements joining the stair steps.

- Reinforcement Measure 4 – Weld a metal plate between the treads only in some areas

The fourth reinforcement measure is identical to the third reinforcement measure, however instead of being welded a metal plate between the treads along its length, completely "filling" the spacing thereof (see Figure 7), it is suggested that metal plates be welded between the stair steps only in some areas.

In Figures 6 and 7 are represented the numerical models of the treads with the application of the third and fourth reinforcement measures respectively.

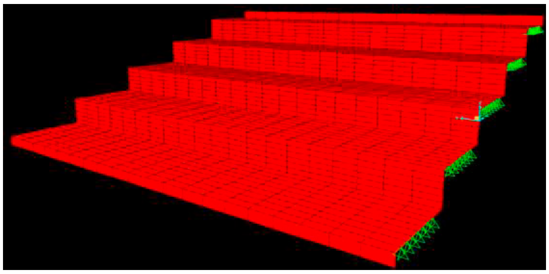

Figure 6 – Numerical model of the step with the third reinforcement measure

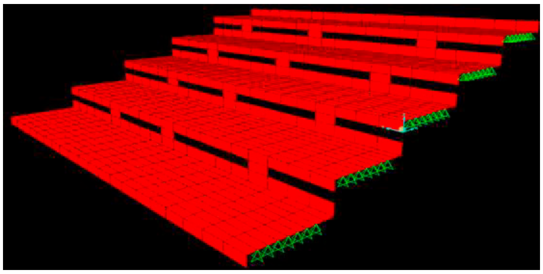

Figure 7 – Numerical model of the step with the fourth reinforcement measure

- Reinforcement Measure 5 – Weld metal bars between the treads

The fifth reinforcement measure is also similar to the third reinforcement measure but rather than welding a metal plate between the treads, it consists of welding metal bars between the treads. This reinforcement measure was simulated in the numerical model connecting the steps with several metal bars modeled as frame elements. To significantly reduce the accelerations it was necessary to use 19 metal bars between each tread with an area of 20 cm^2. This area as well as the number of bars is clearly excessive and can hardly be feasible.

- Reinforcement Measure 6 – Place dampers between the treads

The sixth proposed reinforcement measure consists of placing dampers between the stairs steps in order to increase damping and reduce vibrations. Numerically this solution was tested by defining dampers with a given damping value C (Ns/m) and modelling them between the treads. The accelerations were calculated for a different numbers of dampers, with different damping values C (Ns/m). It has been found that regardless of the damping value C (Ns/m) and the number of dampers used, the accelerations during the time the footfall force is applied never significantly reduce, decreasing sharply to almost null values only when the load ceases to act.

In Figures 8 and 9 are represented the numerical models of the treads with the application of the fifth and sixth reinforcement measures respectively.

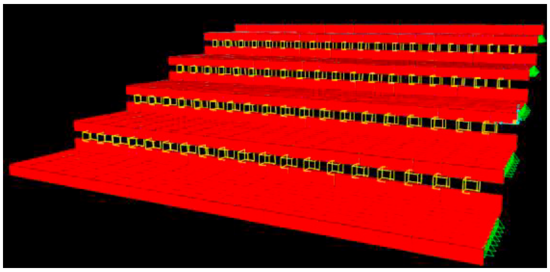

Figure 8 – Numerical model of the step with the fifth reinforcement measure

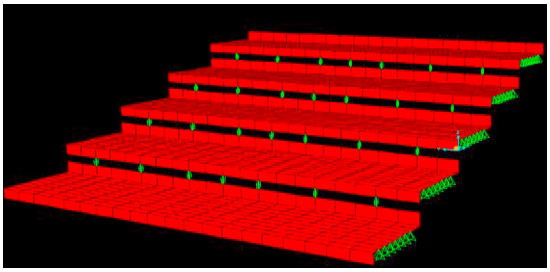

Figure 9 – Numerical model of the step with the sixth reinforcement measure

- Reinforcement Measure 7 – Weld a metal plate under the treads, forming a coffin

In the seventh reinforcing measure it is proposed to weld a metal plate under each tread, along its length. It is also suggested that a triangular metal plate, perpendicular to the latter, be welded in the middle of the treads. This reinforcement measure aims to significantly increase the stiffness of each stair step. Numerically the metal plate placed under the treads and the triangular metal plate perpendicular to it were modeled by shell elements with a thickness of 6 mm (equal to the thickness of the existing tread).

- Reinforcement Measure 8 – Add a stringer in the middle of the treads

The eighth reinforcement measure resides in placing a metallic beam to pass longitudinally in the middle of the treads parallel to the stringers of the sample staircase, i.e. to add an extra stringer between the two existing ones. In the numerical model referring to this reinforcement measure, first all stair steps were modeled up to the intermediate landing and then the extra stringer was modeled under the treads and in the middle of them, by means of a frame element. The stringer shall be supported above on the intermediate landing and below on the pavement. This was simulated using pinned supports. Finally, the connection between the steps and the stringer was made through metal plates, which were modeled with shell elements 6 mm thick (thickness equal to the existing treads).

The beam, modeled under the treads, consists of a metal tube with a rectangular hollow section of 120x80 mm. It was verified that with this section the accelerations were already minimal, so it was not necessary to increase the dimensions of the metal tube. It should be noted that the rectangular hollow section 120x80 mm is about half the section dimensions of the two stringers on the studied staircase (250x150 mm).

In Figures 10 and 11 are represented the numerical models of the treads with the application of the seventh and eighth reinforcement measures respectively.

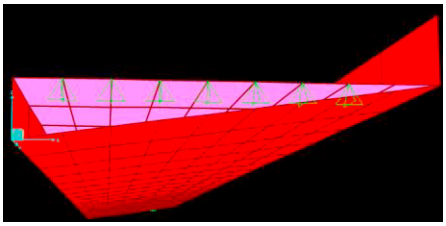

Figure 10 – Numerical model of the step with the seventh reinforcement measure

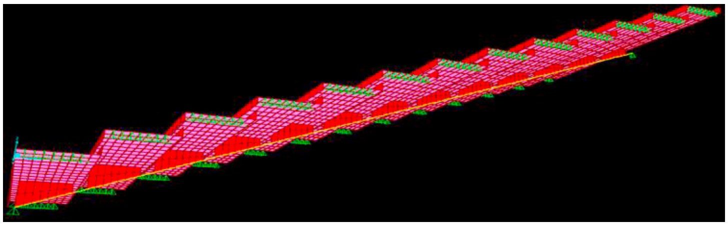

Figure 11 – Numerical model of the step with the eighth reinforcement measure

5. Comparison of the accelerations obtained after the reinforcement measures with the acceptability criteria

For the sake of simplification the accelerations obtained after the application of the eight reinforcement measures were only compared with the limits proposed by the SCI P354 (2009), since this design guide presents a tolerance criteria specifically aimed for stairs. In the Table 2 are presented the initial accelerations and after the application of each reinforcement measure and the limits proposed by SCI P354 (2009) for each reinforcement measure. Only the accelerations obtained for an isolated pawn were considered since they were approximate to those determined for a group of walkers (see Subsection 2.3). Therefore the limits present in Table 2 also refer to an isolated pawn.

Table 2 – Comparison of the accelerations obtained after application of reinforcement measures with SCI P354 (2009)

Public building staircase	*Isolated Pawn*					
	Peak [m/s²]	*Peak Lim. [m/s²]*	*Peak Verif.*	*r.m.s [m/s²]*	*r.m.s Lim. [m/s²]*	*r.m.s Verif.*
Initial	18,09	0,68	KO!	10,68	0,48	KO!
Ref. Mes. 1	13,34	0,76	KO!	6,51	0,54	KO!
Ref. Mes. 2	2,58	1,39	KO!	1,04	0,98	KO!
Ref. Mes. 3	0,86	1,21	**OK!**	0,38	0,86	**OK!**
Ref. Mes. 4	3,73	0,95	KO!	1,26	0,67	KO!
Ref. Mes. 5	1,31	1,10	KO!	0,54	0,78	**OK!**
Ref. Mes. 6	7,83	0,68	KO!	3,17	0,48	KO!
Ref. Mes. 7	0,56	0,82	**OK!**	0,23	0,58	**OK!**
Ref. Mes. 8	0,34	1,64	**OK!**	0,14	1,16	**OK!**

Observing Table 2, it can be seen that the accelerations obtained with reinforcement measures 3, 7 and 8 are lower than the proposed limits. These measures proved to be the most effective. Although the accelerations obtained with reinforcement measures 2 and 5 are slightly higher than the limits proposed by SCI P354 (2009), they are much lower than the accelerations obtained initially, which makes these reinforcement measures also to be satisfactory. Reinforcement measures 1 and 6, as can be seen from Table 2, are the least efficient and those with higher accelerations, however, they are still relatively lower than the initially obtained. The accelerations obtained by reinforcement measure 4 are higher than the limits proposed by SCI P354 (2009), but it is a measure in which the amount of material required is smaller than the reinforcement measure 3 and more easily executable in practice, so it should be taken into account.

6. Summary and Conclusions

The accelerations measured in the studied staircase were extremely high reaching values close to 18 m/s^2. In order to reduce the accelerations, eight reinforcement measures were proposed. Reinforcement measures 3, 7 and 8 were found to be the most efficient. These three measures were those that significantly increased the stiffness of the treads.

The reinforcement measure 1 is of particular relevance because it shows that initially when the public building staircase was designed and the welding between the treads and the stringers hadn't yet experienced any type of wear, the accelerations, most likely, were already significant.

In terms of conclusion, it should be noted that it was not possible with all eight reinforcement measures applied to achieve accelerations lower than the limits proposed by the design guide SCI P354 (2009). However, considering the fact that the experimental accelerations are approximately double the gravity acceleration (≈9,81 m/s^2), it can be affirmed that with almost all proposed solutions it was possible significantly reduce these accelerations.

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