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Dynamic characterization and vibration serviceability assessment of two bare high-frequency CLT floors

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Abstract. The building construction industry currently represents around 11% of the global carbon emissions. Thus, nowadays the widespread use of low-carbon footprint materials such as timber is considered a priority within the sector. Timber buildings have shown adequate structural performance in terms of capacity and stiffness; however, their extremely lightweight nature makes them more prone to develop excessive vibration responses. This fact is especially remarkable in modern buildings mainly built with engineering wooden products (EWPs) such as Cross Laminated Timber (CLT). Focusing on timber floors, their vibration serviceability limit state (VSLS) usually consists of limiting their dynamic response to human-induced loads as those produced when walking or performing aerobic activities. During the last three decades, the study of floors' VSLS has been developed in parallel by two methodological schools, that of concrete/composite floors and that of timber ones. New Eurocode 5 has faced this inconsistency by updating its vibration-checking method, moving closer to the approaches used for concrete ones. However, there is still some controversy regarding these new vibration limits and the way of analyzing the response of lightweight floors with natural frequencies over 15 Hz. This paper provides an additional case study on the literature, in which two high-frequency CLT floors have been dynamically characterized using operational modal analysis. Additionally, a subsequent experimental assessment of their VSLS has been performed. The results shed light on the dynamic behavior of these types of floors increasingly used in the building construction sector.

Keywords: Timber buildings · CLT floors · Floor Vibrations · Vibration Serviceability

1 Introduction

The building construction industry represents nowadays around 11% of the global carbon footprint. This fact combined with a higher sensitivity to climate change has prompted a trend in the industry towards using low-embodied carbon materials [1]. In this context, the use of structural timber in building construction has been popularized during the past decades as a de-carbonization solution. This boom has also been driven by the development of the so-called engineering wooden products (EWPs) mainly consisting of structural elements made by gluing together timber boards to make beams or slabs. The two products with the greatest projection, in this respect, are Glue-laminated beams (Glulam) and cross-laminated timber panels (CLT) [2].

Particularly, CLT results in a rather convenient material as its prefabricated nature enables reducing construction times, enhancing quality control, and easing transportation. Because of all of this, and due to its high stiffness-to-weight ratio, CLT has become popular for building low and medium-rise buildings and even for designing some high-rise buildings. [2]. Although CLT has many advantages, lightening the building floors by replacing concrete with timber has the undesired effect of making them more responsive in terms of vibration. Thus, the vibration serviceability limit state (VSLS) can be a limiting criterion for their design.

Usually, VSLS in floors is related to human-induced vibration problems in which humans are both the vibration sources and receivers. This complex issue has been deeply investigated during the past fifty years, and the research has been mainly divided into two methodological schools: i) VSLS in concrete/composite floors, and ii) VSLS in timber floors. Concrete floor researchers preferred using vibration limit criteria in terms of response parameters as root-mean-square (RMS) accelerations, a_{rms}, or the response factor, R (those nowadays present in the reference guidelines for VSLS analysis [3]). Instead, timber floor researchers opted for empirical design rules (as, for example, frequency limits > 15 Hz) and stiffness criteria based on the maximum deflection of the floor under a 1 kN pointed load, w_{1kN} (still used nowadays in some CLT design guidelines [4]).

With respect to codes, Eurocode 5 currently has an obsolete methodology for assessing floor vibrations based on a sequential checking of three floor's parameters: i) its fundamental natural frequency $f_1 > 8$ Hz, ii) its stiffness, and iii) its peak velocity response under a unitary impulse. In its new version, this approach is replaced by a classification of the floor's comfort level (see Figure 1) based on two parameters, R and w_{1kN}, [5]. There, the computation of R considers the classical division between low-frequency floors (LFFs) and high-frequency floors (HFFs) at 8 Hz. While this is an improvement, there is still some controversy regarding the extremely high response factor limits, R_{lim}, proposed for low-performance levels, and the difficulties of reaching a high-performance level with fully timber structures. Furthermore, the continuity of the deflection limits, w_{lim}, within the methodology is a matter of discussion. Finally, this method has some inconsistencies with approaches used nowadays to experimentally check the comfort of the floors through vibration measurements.

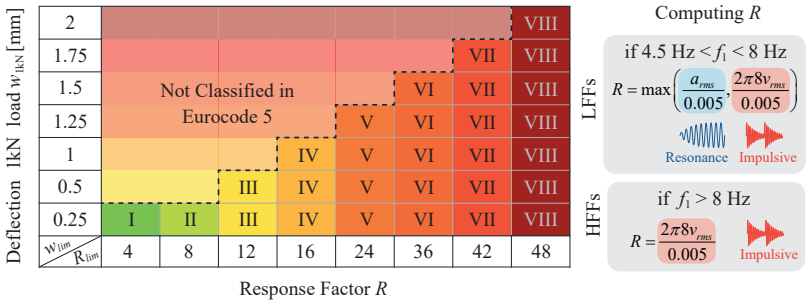


Fig. 1: Floor Performance levels according to the new version of Eurocode 5.

Vibration on CLT floors has been intensively investigated during the past decade, primarily by authors using clean laboratory structures. Some matters of interest for them have been the influence of the inter-panel joints modeling on the dynamic response of the floor, the role of human-structure interaction in these floors, and the influence of non-structural partitions on their behavior. However, there is still a lack of experimental case studies developed in real structures. In this sense, the present paper aims to fill this gap. For that, two bare HFFs made of CLT have been dynamically characterized, and their VSLS have been experimentally assessed [6].

The paper is organized as follows. Section 2 describes the structure being tested. Section 3 describes the experimental campaign carried out. Section 4 provides the experimental results explaining how they have been post-processed, and Section 5 discusses these results, additionally providing some conclusions.

2 Description of the tested CLT building floors

The floors studied belong to the third story of the Tomás Breton Building built in Madrid in 2024 using almost entirely structural CLT panels (except for the foundations and the first floor made of concrete). Two floors were tested as indicated in Figure 2. Floor 1 is composed of single-spanning panels saving a distance of 6m between walls (depicted in red in Figure 2.(a)), and of a balcony with diagonal panels (coloured in orange). Red panels are a 7-layer CLT-240 L7-2s made of C24 timber boards with the following thickness in mm 40+40-20-40-20-40+40. These panels have double eccentric layers with fibers oriented in their longitudinal direction. Orange ones are 5-layer panels type CLT-140 L5s with the following thicknesses 40-20-20-20-40 made of timber C24. Floor 1 has a symmetric floor on its left side. Both are divided by a structural partition not made of CLT. Floor 2 consists of CLT-140 L5s panels with double spanning distances of 4.5 m and 3.8 m. The walls of the building are made of different types of CLT panels ranging from CLT-80 to CLT-140 depending on their position. The inter-story height is 3 m. On floor 2, the wall defining the intermediate

support is interrupted by two beams. This fact makes the floor more flexible around this region.

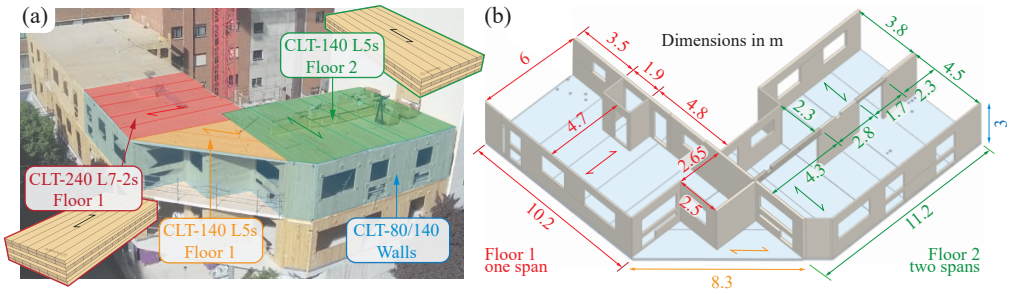


Fig. 2: (a) Different CLT panels used in the building structure. (b) Geometry of the floor.

3 Description of the experimental campaign

The experimental vibration-based monitoring campaign was conducted in July 2024 by using four triaxial wireless accelerometer sensors MR3000C from BARTEC SYSCOM (see Figures 3.(a) and (b)). The floors were tested at an intermediate stage of their construction, when the concrete screed and the non-structural partitions had not yet been installed so that they may be considered as bare timber floors. All the vibration data was acquired with a sampling frequency of 1000 Hz, a digital quantization of 24 bits, a dynamic range of ± 4 g, and a noise level of 7 $\mu g_{\,\mathrm{rms}}/\sqrt{\mathrm{Hz}}$. Two types of tests were performed on each floor.

3.1 Operational modal analysis (OMA)

First, ambient vibration measurements were taken for conducting OMA. This was done using a multi-setup strategy. 26 locations were measured in floor 1 in 12 setups, and using 2 reference accelerometers that did not move along the setups. On floor 2, 32 locations were measured with 2 reference accelerometers in 15 setups. The exact locations of these points are detailed in the following section. Reference accelerometers were disposed of so they could be excited by almost all the fundamental modes of the floors. The duration of each setup was 8 minutes, which corresponds to 7400 vibration cycles of the lowest fundamental mode of vibration of the floors. Additionally, it is important to consider that floor 1 was measured during working time, so construction activities significantly excited the floor and not always in a random manner. However, floor 2 was measured after construction works finished with almost absolute calm. Due to this, the floor was not properly excited over the noise level of the sensors. Moreover, during these setups, the reference accelerometer located at point 31 lost the GPS synchronization. These facts made the floor 2 dataset a challenge for the OMA analysis.

3.2 Vibration serviceability tests

Secondly, vibration serviceability tests were carried out on each floor. These tests were measured with the 4 accelerometers located in the most responsive points of the floor, i.e.: points 5, 6, 9, and 26 in floor 1, and points 5, 10, 19, and 32 in floor 2. Two types of serviceability tests, illustrated in Figure 3.(c), were performed on each floor:

- Heel-drops. Two types of them, with and without the presence of three additional standing still people over the floor (to consider their influence on floors' damping). In floor 1, two heel drops of each type were performed on each one of the points 2, 5, 6, and 26 by three different people. In floor 2, this was done on points 2, 5, 8, 19, 24 and 32.
- Walking tests. Two types of tests were performed, free walking and synchronized walking. On floor 1, the walking path was set from point 2 to point 15. Two back-and-forth walks of each type were performed by three different people. On floor 2, two walking paths were defined, one from points 3 to 11, and another from points 16 to 19.

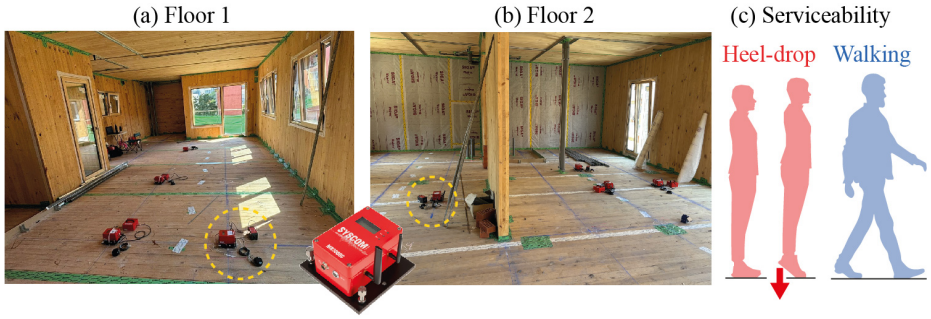


Fig. 3: (a) Floor 1. (b) Floor 2. (c) Vibration serviceability tests performed

4 Postprocessing and results

The results of both the OMA and the vibration serviceability of both floors have been presented in Figures 4 and 5, respectively. The following subsections describe the post-processing applied in each case.

4.1 Postprocessing 1: multi-setup OMA

OMA has been performed adopting the Dohler et al. [7] multi-setup techniques, which have been implemented in the open-source Python package PyOMA2 [8,9]. According to Dohler et al. [7], using the stochastic subspace identification (SSI) algorithm, it is possible to estimate modal parameters from multiple setups and then normalize the different results. This should provide a global estimate of

the modal parameters of interest by leveraging the information captured from the reference sensors among all the setups. This technique is also acknowledged in the literature as Post Separate Estimation Re-scaling (PoSER) approach [7]. Conversely, the Pre Global Estimation Re-scaling (PreGER) method differs from PoSER since the normalization is performed beforehand conducting the various SSI analyses in each setup, and therefore the analysis is conducted only one time. This latter method is stricter because it requires that the reference sensors are enough dynamically excited in every setup. However, when insufficient common information is available among the setups, the PreGER is not ideal for performing a global estimate of modal parameters. Recorded vibration data have been pre-processed with a de-trending procedure, followed by an under-sampling with a decimation factor of 5 and eventually employing an anti-aliasing FIR filtering. After that, both PoSER and PreGER multi-setup strategies were implemented on both floors to extract their fundamental natural frequencies, damping ratios, and mode shapes.

Concerning PoSER modal analysis, a novel strategy has been implemented. This development has been motivated by two facts, first, the great number of setups that were carried out, and second, the noisy signals measured, especially on floor 2 (where in most of the setups the sensors were not able to capture the low-amplitude vibration of the floor occurring under their base noise level). To remove those noisy setups and to provide an accurate identification of the stable poles, the stabilization diagrams for each setup have been overlapped, as can be seen in Figures 4.(d) and 5.(d). Thus, a normalized overlapped stabilization diagram composed of pixels has been created. The width of each pixel is a fixed value of frequency resolution and its height is a model order unit. Each stable pole within a certain frequency interval and with a certain model order contributes to its corresponding pixel with one scoring point. After adding up the contributions of all stable poles of every setup, the overlapped stabilization diagram is normalized by dividing the accumulated scores by the number of setups. The pixel with the highest normalized score is considered the final stable pole that provides the value of the natural frequency of that mode of vibration. To obtain its associated modal damping ratio, another normalized overlapped chart is created representing the damping ratio of each stable pole against its frequency, as can be seen in Figures 4.(e) and 5.(e).

4.2 Postprocessing 2: serviceability tests

For the serviceability tests, two types of post-processing have been performed:

- Heel drops. First, the points in which heel drops caused the highest vibration response of the fundamental vibration mode were identified. Second, at those points, the vibration responses to heel drops performed at the same location were analyzed. From each free decay response (see Figures 4.(i) and 5.(i)), the damping ratio ξ has been calculated using the logarithmic decrement formula between two peaks distant N oscillations. This has been repeated peak by peak; thus ξ has been computed in terms of the mean amplitude of

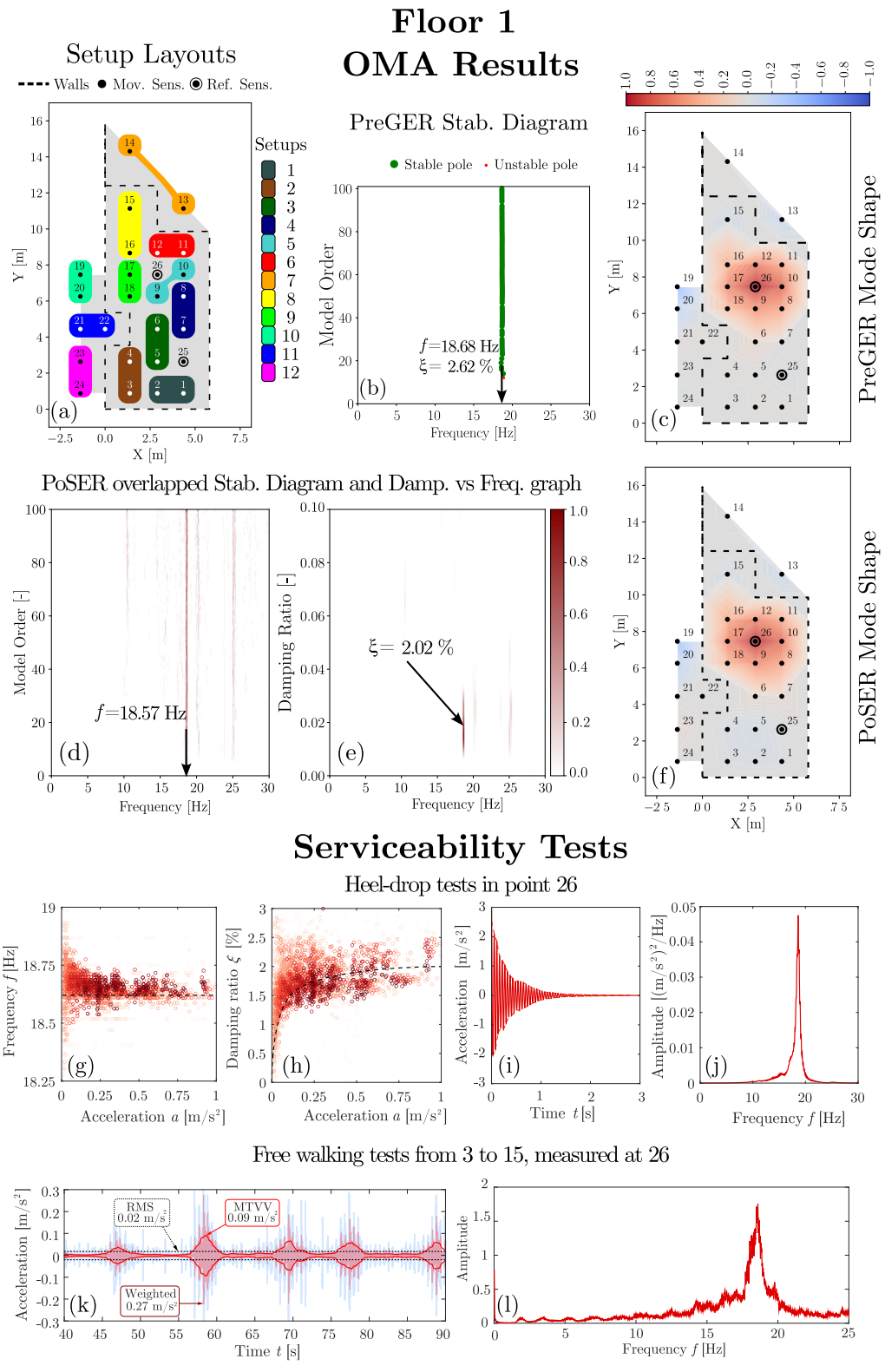
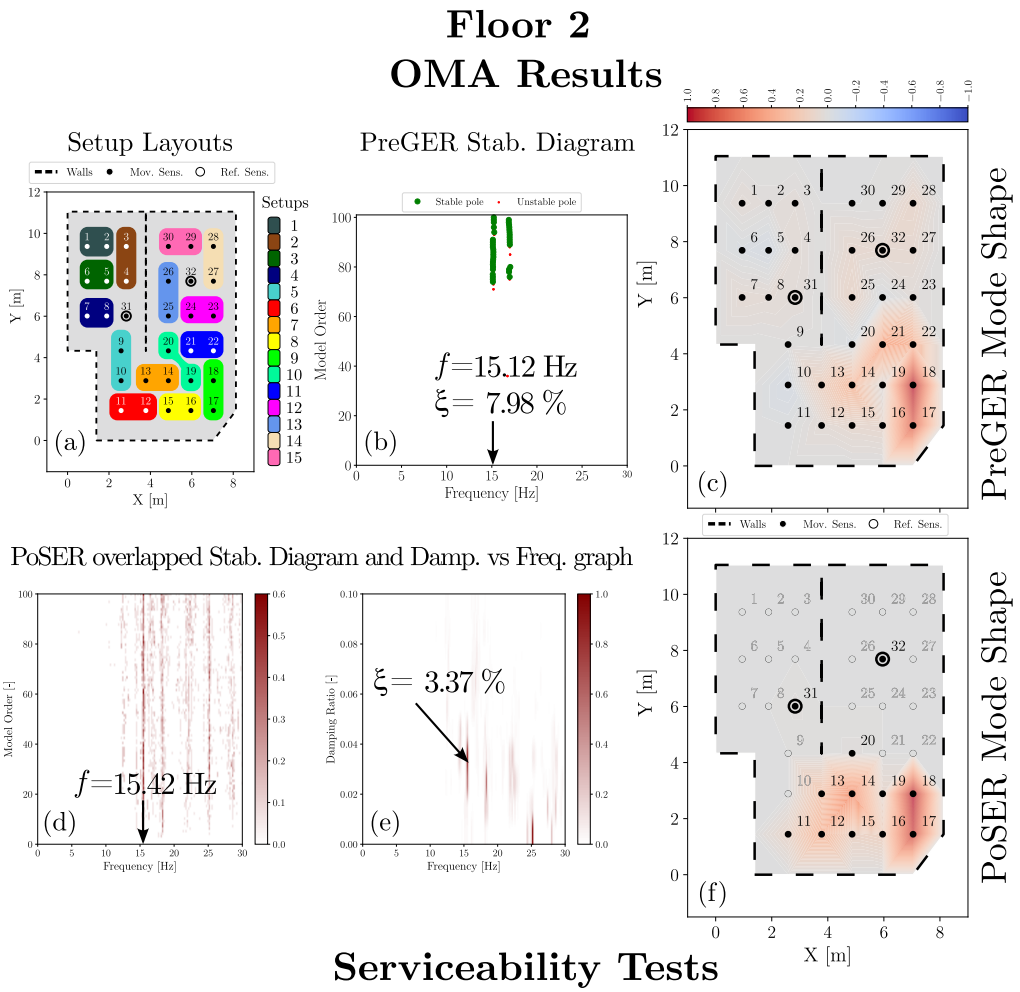
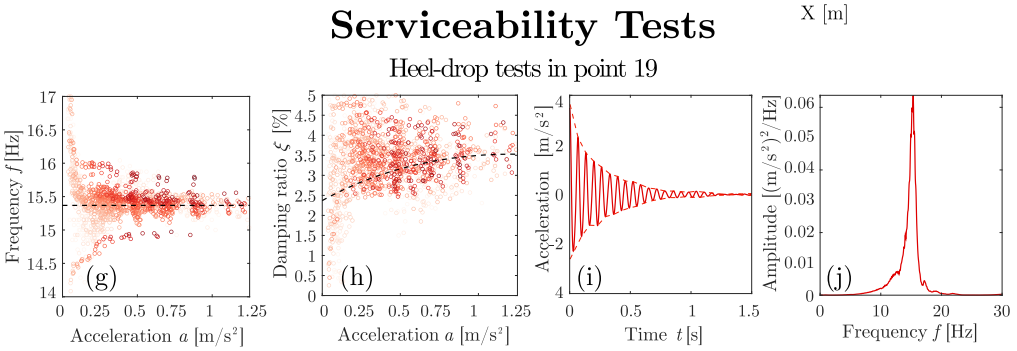


Fig. 4: OMA and serviceability results for floor 1.





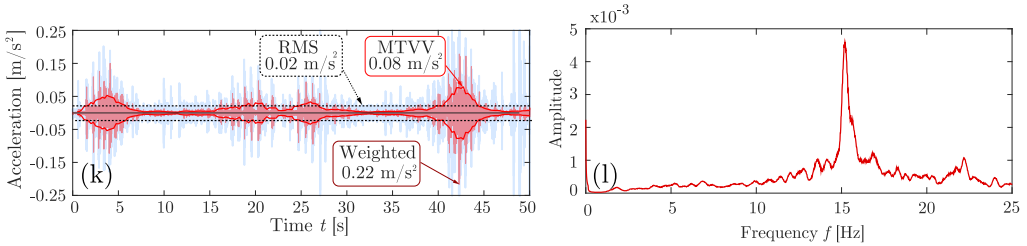


Fig. 5: OMA and serviceability results for floor 2.

the selected peaks. This procedure has been carried out considering different values of N varying from 3 to 40 on floor 1, and from 3 to 20 on floor 2. The higher the intensity of the color of the dots in these figures, the higher N. The fundamental natural frequency f of each floor was also computed using this procedure. These results have been presented in the subfigures (g) and (h) of Figures 4 and 5.

– Walking response. At the same location analyzed in the heel drops, the response to free walking was investigated. First, the signal has been weighted by the w_k window of ISO-2631 to include the effect of human perceptibility on vibration. The weighted peak acceleration has been identified. Then, the root mean square (RMS) acceleration of the whole register has been computed. In addition, a moving RMS with a one-second window length has been derived. The maximum of this moving RMS, named the maximum transient vibration value (MTVV), has been detected. Finally, the spectrum of the original signal is also computed to check which vibration mode is most responsive to walking excitation. These results have been included in the subfigures (k) and (l) of Figures 4 and 5.

5 Discussion and conclusions

Regarding OMA, the results obtained on floor 1 with both the PoSER and PreGER strategies appear to be satisfactorily correlated, showing a greater variation in the values predicted for ξ. This does not occur in floor 2, where the modes of vibration resulting from both analyzes show clear differences. In this sense, the applied normalized overlapping PoSER appears to provide a confident result for the mode shape (as the floor is more mobilized in the zone where the splitting CLT wall is replaced by a more flexible beam). This novel strategy also provides a more reliable damping value of 3.37% compared to the almost 8% provided by PreGER. In both floors, PreGER has provided a higher ξ. Concerning OMA, this study has evidenced that the use of noisy accelerometers combined with extremely calm measurement environments can be a problem when performing multi-setup OMA in empty floors under construction.

In terms of vibration serviceability, heel drop analysis has been shown to be especially useful for identifying the fundamental natural frequency of the floor and its associated modal damping ratio. These values have proved to be quite similar to those predicted with the normalized overlapping PoSER methodology, which contributes to increasing confidence in it. In terms of walking tests, the new Eurocode 5 will impose a vibration limitation on floors in terms of RMS acceleration. This RMS value is computed by assuming that a pedestrian always walks in the most adverse location of the floor, without moving. Hence, this RMS value from codes appears to be more similar to the computed MTVV rather than to the whole RMS of the tests. Today, the question of which parameter to use when assessing the comfort level of floors from experimental data remains open. This is something to be defined in the near future, due to its critical impact on the final comfort level assigned to the analyzed floor. Regarding the tested floors,

they may have a response factor R of 4 or 16 depending on the type of criteria to be used. Based on this, they could be classified as premium or base-quality floors depending on this.

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