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RELIABILITY OF SMARTPHONE SENSORS FOR THE VIBRATION COMFORT ASSESSMENT OF EXISTING TIMBER FLOORS

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ABSTRACT: The vibration serviceability assessment for existing timber floors represents a well-known issue, and many simplified strategies have been developed in the years. Among others, the availability of efficient and practical experimental non-destructive approaches is a very important step for the assessment of existing structural systems. This work faces the issue of the reliability of smartphone sensors for the comfort assessment of existing timber floors. To this aim, the study takes advantage of pilot experimental investigations (carried out with the support of two selected volunteers, commercial smartphone devices and conventional sensors for vibration analyses), and numerical simulations in SAP2000. A real-scale 1-way timber floor prototype (4 m in length) was in fact built for the non-destructive experiments, and subjected to human-induced actions. As shown, the analysis of some key performance indicators (such as the peak and root-mean-square accelerations and the Vibration Dose Value) provides some important comparisons and quantitative outcomes to assess the potential and limits of such a cost-efficient monitoring strategy.

KEYWORDS: timber floors, human-induced vibration, vibration assessment, smartphone sensors

1 – INTRODUCTION

Timber floors are extremely common in historical buildings. Floors made up of wooden joists and planks are widely used in existing masonry and timber structures, but they are generally under-designed with respect to current regulations and standards for structural design.

As known, timber floors have typically high flexibility and low mass, which makes it susceptible to human-induced vibrations. Current standards (such as the Eurocode [1], Canadian [2] and Australian/New Zealand codes [3]) provide simplified verifications for vibrations, generally based on deflection and frequency checks and on simply supported beam models. Given the consistent simplification, however, these methods may not be able to accurately evaluate the actual behavior of the floor, which depends on multiple factors, e.g. the boundary conditions and the connections between beams and panels [4], and many other influencing parameters that can mutually interact under dynamic loads.

To date, in fact, there are several studies in the literature that experimentally and numerically analyze the problem of vibrations in timber and composite floors [5]. Experimental analyses, in practice, are typically carried out with the support of commercial devices and professional instruments. Although the cost, size/weight and accuracy of these instruments have been significantly improved over time, smartphones can represent a valid alternative, thanks to their built-in high-performance sensors (e.g. accelerometers, GPS, …). Some applications and examples of smartphone-based investigations are already present in the literature for the Structural Health Monitoring of bridges [6] or for seismic actions analysis [7]. In this work, the reliability of smartphones for the comfort assessment of timber floors through experimental investigations is studied, and their possible use for simple but robust and fast in-situ tests is addressed.

2 – BACKGROUND

In the verification of timber floors, standards generally propose simplified methods based on deflection and

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frequency, often providing acceleration and velocity checks with analytical methods like in [1]. However, to obtain accurate evaluations, it is necessary to use more refined methods, calculating or recording accelerations and velocities over time.

To this aim, different indicators can be chosen for the analysis of floor vibrations and associated comfort levels. For example, widely used performance indicators and strategies are represented by:

- *Maximum methods*: the peak acceleration or velocity is taken as reference indicator for comfort check. ISO 10137 [8] or SETRA guidelines [9] provides limit values for the peak acceleration.

- *Averaging methods*: they take into account the excitation duration and consist in the calculation of the root-mean-square or root-mean-quad acceleration or velocity. Furthermore, rolling-root-mean-square can be evaluated over time. Comfort criteria can be found in ISO 10137 [8]. The evaluation of rms and rolling rms acceleration follows (1) and (2):

$$a_{RMS} = \sqrt{\frac{1}{T}\int_0^T a(t)^2 dt} \quad (1)$$

$$a_{RMS}(t) = \sqrt{\frac{\sum_0^n a(t)^2}{n}} \quad (2)$$

  with T (in seconds) the total duration of each signal, and n the number of recorded data in a time interval of 0.5 seconds.

- *Dose methods*: They start from root-mean-quad approach. The most used indicator is the Vibration Dose Value VDV (in $m/s^{1.75}$) proposed by [10, 11], which is given by the fourth root of the integral with respect to time of the fourth power of the weighted acceleration a_w. See (3):

$$VDV = \left(\int_0^T a_w(t)^4 dt\right)^{0.25} \quad (3)$$

The use of the weighting filter follows the assumption that the occupants are more sensitive to vibration within 4-10 Hz range [11]. Thus, reduction coefficients are applied to frequencies outside this range (Fig. 1).

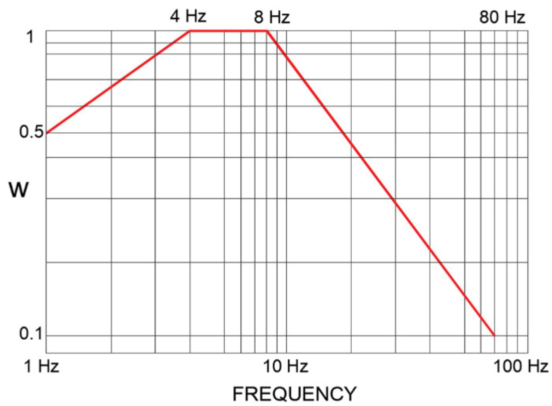

Figure 1. Frequency weighting curve for the evaluation of the VDV according to [11].

In this paper, accelerometers and smartphone are comparatively used in laboratory experiments, to record the vertical acceleration of a full-scale timber floor prototype. The comparison, in particular, is performed considering a_{peak}, a_{rms} (1) and VDV (3) performance indicators.

3 – PROJECT DESCRIPTION

3.1 SPECIMEN GEOMETRY

A real-scale timber floor was assembled at the University of L'Aquila laboratory (Fig. 2). The specimen consists in three glulam beams with cross section 130x240 mm and length L= 4000 mm ($f_{m,k}$=40.00 MPa, $E_{0,mean}$=14360 MPa, ρ_m=695 kg/m^3), secondary solid timber joists spaced 783 mm, with cross section 80x80 mm and length 400 mm, and solid wood planks with thickness 40 mm (D24 solid timber, $f_{m,k}$=24.00 MPa, $E_{0,mean}$=10000 MPa, ρ_m=580 kg/m^3). Mechanical characteristics of glulam were obtained from four-point bending test, while strength class of solid wood was assigned through visual classification.

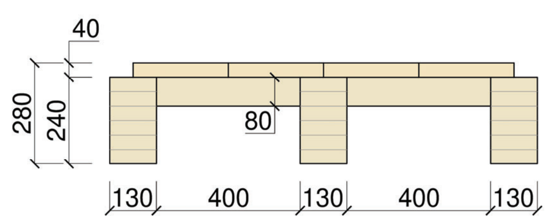

Figure 2. Section of the full-scale timber floor.

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The connection between planks and glulam beams was obtained by means of 9x160 mm 45° inclined screws, spaced 200 mm. The stiffness of the joint, referred to a single screw, was derived from push-out tests (K_{ser}=5.97 kN/mm).

3.2 EXPERIMENTAL SETUP

The complete test setup is reported in Fig. 3. To perform the dynamic tests, the floor was instrumented with three Force Balance accelerometers, positioned at ¼L and ¾L (A0, A2) and at midspan (A1). The sample rate was set to 200 Hz. Furthermore, a Smartphone (Xiaomi Redmi Note 7, MEMS accelerometer ICM-20607) was fixed to the floor near the central accelerometer (S0), in order to collect vertical acceleration data (sample frequency 250 Hz). Finally, another smartphone (iPhone 14) was placed in correspondence of the Center of Mass of the pedestrian volunteer (S1), by means of a belt secured at height H_G. Smartphone S1 collected triaxial accelerations and rotations at 100 Hz. For further details, see [12].

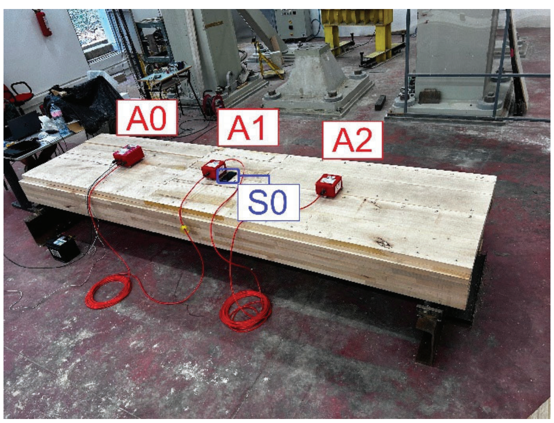

Figure 3. Test setup and overview.

3.3 LOADING PROTOCOL

A complete test-schedule was developed, to achieve 28 different load combination and 238 walking sequences.

Two volunteers were chosen, with different mass M, height H, and height of the center of mass H_G (Table 1, Fig. 4).

Table 1. Mass M, Height H and height of the center of mass HG of the two pedestrian volunteers.

ID	M [kg]	H [m]	H_G [m]
1	70	1.82	1.07
2	78	1.70	0.96

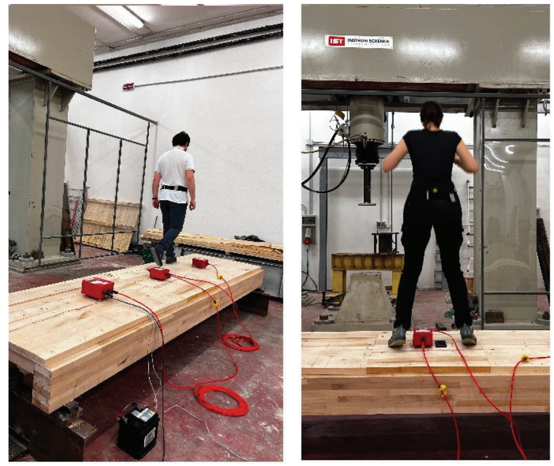

Figure 4. Test execution.

Furthermore, three walking frequencies were selected for the experimental configurations (1.0-1.5-2.0 Hz). The number of pedestrians walking simultaneously was also varied, considering three possible scenarios:

- a single volunteer walking alone,
- one volunteer walking, with the other standing at midspan,
- two pedestrians.

Finally, different walking path were considered (linear and random patterns respectively). The complete set of tests is reported in Table 2.

Table 2. Loading protocol.

Test ID	Description
A	Linear path – 1 pedestrian
B	Random path – 1 pedestrian
C	Linear path – 1 ped. + 1 ped. standing
D	Random path – 1 ped. + 1 ped. standing
E	Linear path – 2 pedestrians
F	Random path – 2 pedestrians

4 – RESULTS

Data collected from central accelerometer A1 and smartphone S0 are reported in Fig. 5. Each test acquisition was split in single walking sequences, in order to evaluate the vertical peak acceleration a_{peak} and the root mean square arms. An example of record of a single walking sequence is shown in Fig. 6. In parallel, the Vibration Dose Value was calculated for the whole test sequence.

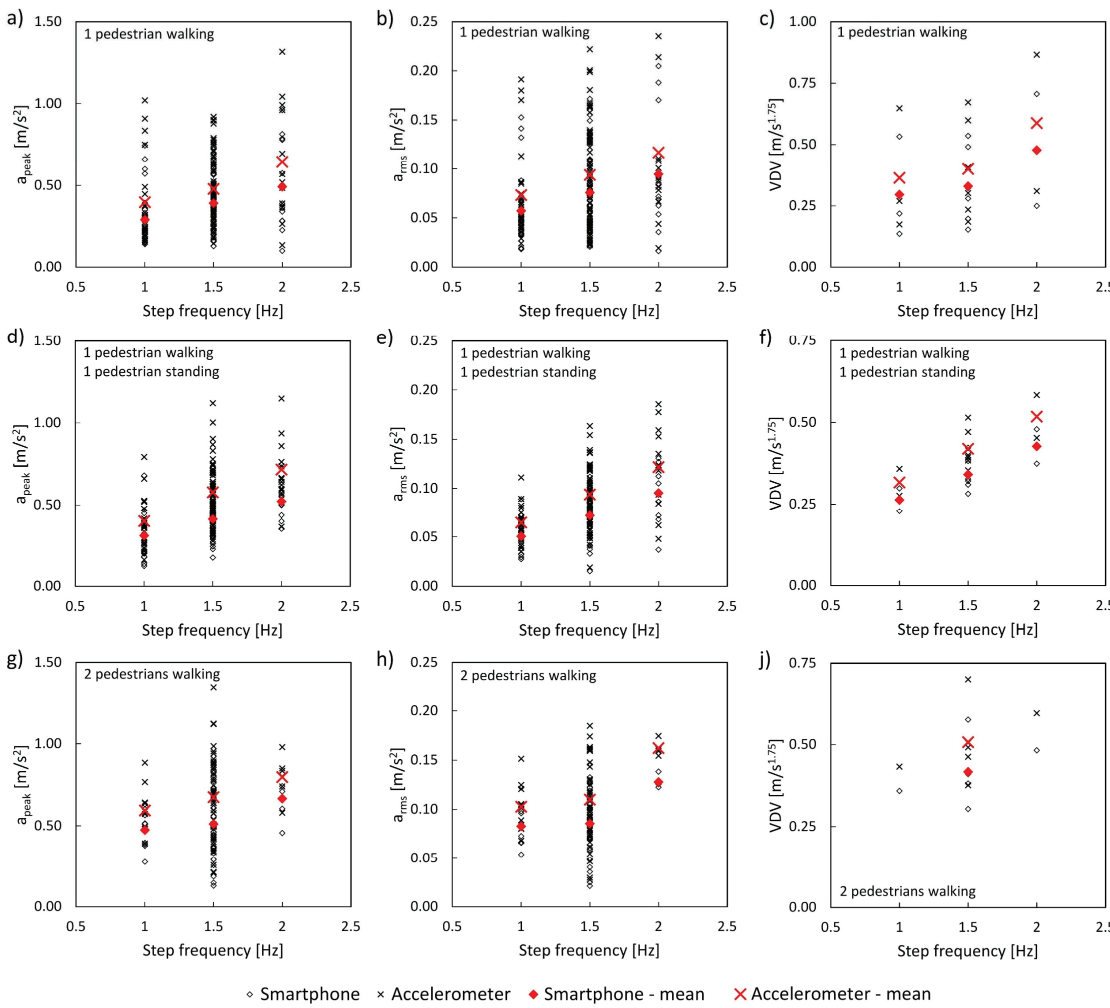

Figure 5. Result of the laboratory tests considering a_{peak}, arms and VDV. The results were divided based on the number of pedestrians involved: 1 volunteer walking (a,b,c), 1 volunteer walking and 1 standing (d,e,f), 2 volunteers walking (g,h,j).

The corresponding comfort indicators are shown considering the average step frequency of each walk (namely 1.0-1.5-2.0 Hz) and the number of pedestrian walking/standing simultaneously on the floor (i.e., 1 pedestrian walking as in Fig. 5a,b,c; one pedestrian walking and one standing as in Fig. 5d,e,f; both pedestrians walking as in Fig. 5g,h,j). Furthermore, the mean value is also reported in red, as obtained for smartphone (red diamond) and accelerometer (red cross) acquisitions respectively.

The experimental results show that the smartphone generally underestimates the vertical acceleration of the floor prototype, compared to more sophisticated instruments.

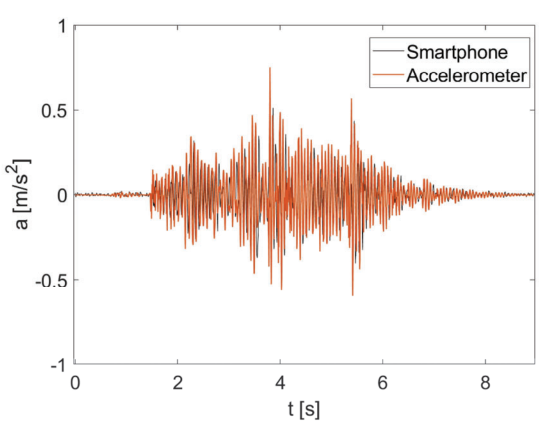

Figure 6. Vertical acceleration (Sequence of Test 2 – Walking 1.5 Hz – 1 pedestrian).

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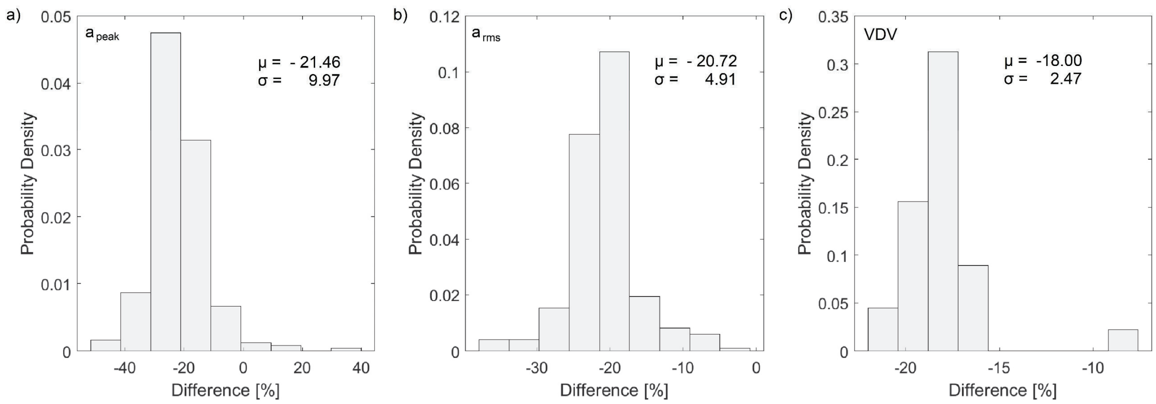

Figure 7. Differences between smartphone and force balance accelerometer: a_{peak} (a), a_{rms} (b) and VDV (c).

This is an expected outcome and addressable to the higher sensitivity of used force-balance accelerometers, which are utilised also in vibration assessment through ambient noise. For the present study, the a_{peak} difference varies in the range:

- from -10% ÷ -27% for 1 pedestrian,
- -22% ÷ -29% for 1 pedestrian walking and 1 standing,
- and -16% ÷ -24% for two walking volunteers.

The results are less scattered for a_{rms} (-19% ÷ -22%, -22% ÷ -23%, -19% ÷ -22%) and VDV (-18% ÷ -19%, -17% ÷ -19%, -17% ÷ -19%).

Furthermore, the data were collected in order to evaluate the overall differences and the standard deviation for each performance indicator. Fig 7 shows the histograms for a_{peak} (Fig. 7a), a_{rms} (Fig. 7b) and VDV (Fig. 7c). As already noted in Fig. 5, the peak acceleration gives worse and more scattered results, showing an overall difference of -21.5% and a standard deviation of 10.0%. The spread is due to the high sensitivity to peak excitation of the force-balance. In fact, averaging and dosing methods show a slightly lower mean (-20.7% and -18.0% for a_{rms} and VDV respectively) and, most significant, a consistent reduction of the standard deviation, which is 4.9% and 2.47% respectively. These results highlight that smartphones could be implemented in a fast assessment strategy through a_{rms} and VDV for flexible timber-to-timber composite floors, after appropriate calibration on a reference floor.

In this context, it is also important to remind that the presently reported laboratory tests were performed on a 1-way, three joist floors prototype only, which may not be representative of the response of a full-scale timber floor.

For this reason, a finite element model of the same full-scale specimen was developed SAP2000 [13], according to the geometrical and mechanical properties of its timber components. Frame elements were used for primary and secondary joist, and a thin-shell was implemented for the boards covering. Furthermore, elastic link elements were used at the interface, to describe the effect of screwed connections. A simply supported boundary condition was finally taken into account.

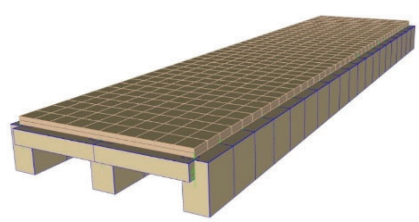

Figure 8. Timber floor FEM model in SAP2000.

Through the parametric analysis, the aspect ratio of the floor was changed modifying the number of timber joist, keeping fixed the span L=4.00 m. Overall, 7 configurations were analysed for a B/L ratio from 0.125 (single joist configuration) to 3 (corresponding to 25 joists). The parametric numerical results were again compared in terms of peak/rms acceleration and VDV.

To this aim, the reference numerical model was preliminary validated. The parametric numerical analysis was performed by simulating possible waling scenarios and by varying the step frequency of a single pedestrian from 1.5 to 2.5 Hz. This loading configuration was reproduced by using the consolidated deterministic

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analytical model proposed in [14, 15], that was taken into account to represent the typical footfall effects F(t) due to a single pedestrian:

$$F(t)/W = \sum_{i=1}^{8} K_i t^i \qquad (4)$$

In (4), W is the weight of the pedestrian (N), K_i are specific coefficients [15] and t is the time (in seconds) within a single footfall.

As an example, Fig. 9 shows the vertical acceleration at midspan for B/L=1 and an imposed step frequency 1.50 Hz. The rms acceleration over time was evaluated through (2).

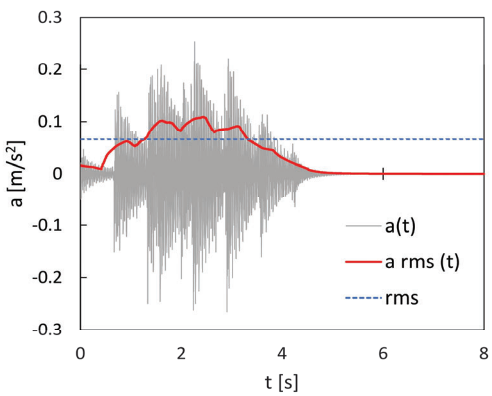

Figure 9. Vertical acceleration at midspan for B/L=1 and step frequency 1.50 Hz.

Fig. 10 shows the results of the parametric analysis for a_{peak} (a), a_{rms} (b) and VDV (c), normalized to B/L=0.25, which represents the 3-joist specimen.

The numerical outcomes highlight that aspect ratio has an important impact for B/L < 1.0, where the performance indicators are 1.3÷2.3 times higher than the tested configuration, indicating that an assessment procedure on a simplified model made of only one joist is in general not able to reproduce a realistic behaviour. However, it is worth noticing that the 3-joist configuration (B/L=0.25) still overestimates the selected comfort indicators. The peak acceleration ratio reduces to nearly 0.5 for B/L>1, whereas rms and VDV are close to 0.25. For B/L>1, the variation of these indicators tends in fact to stabilize.

To perform a comfort check, the aforementioned reduction should be consequently taken into account, in order to avoid overestimating the vibration response of the floor.

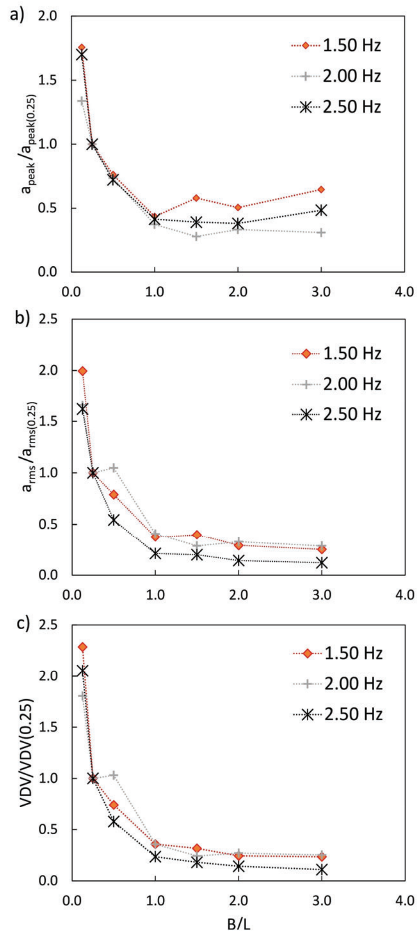

Figure 10. Influence of the ratio B/L on a_{peak} (a), a_{rms} (b) and VDV (c) for step frequency equal to 1.50, 2.00 and 2.50 Hz. Results are normalised to the B/L=0.25 (3 joists) configuration.

5 – CONCLUSIONS

In this paper, a full-scale timber floor prototype was subjected to human induced vibrations. Two volunteers walked together or separately, at different pacing frequencies, and the vertical accelerations were recorded simultaneously by force-balance accelerometers and built-in sensors of commercial smartphones.

The collected results were compared in terms of peak vertical acceleration a_{peak}, root mean square acceleration a_{rms} and vibration dose value VDV. The comparison showed that the smartphone-based acquisitions tend to underestimate the actual accelerations of the system, being less sensitive than a professional accelerometer. The largest difference (-21.5%) and dispersion (10.0%) was identified in a_{peak}. However, the rms and VDV results highlighted slightly lower differences than the maximum

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acceleration (-20.7% and -18.0%), with a limited dispersion (4.9% and 2.5%).

Furthermore, a parametric numerical analysis was performed in SAP2000, to study the influence of the width/span ratio B/L on the selected comfort indicators. The collected numerical results showed that the analysis of a simple 3-joist floor (B/L=0.25) tends to overestimate the expected accelerations of a full-size floor, due to lack of lateral restraints. For a B/L>1 ratio floor, the peak acceleration looked reduced by 50%, and rms and VDV by 75%, with respect to the B/L=0.25 case.

In conclusion, the calculated scatter in terms of a_{rms} and VDV with low dispersion suggests that the use of smartphones can be a cost-effective alternative for fast assessment of composite timber floors. Besides, a preliminary calibration is needed to minimize the error. In the next steps of this running research program, a larger set of smartphones will be used, and floor prototypes will be tested under different configurations, to evaluate the influence of boundary conditions, as well as the presence of additional masses (e.g. screed, furniture), and even including a larger group of pedestrians.

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