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Effect of Live Load on the Dynamic Performance of Joisted Timber Floors

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Abstract

Timber constructions has increasingly grown popular over the last decades due to the environmental benefits compared to concrete and steel. Although there are many other benefits such as the high strength to low mass ratio, lowering gravity load and the foundation cost, there are still challenges. A lot of research has been done on timber construction and a new Eurocode 5 for timber construction is being discussed.
Vibration serviceability of timber floors is one of the challenging topics. As timber has a relative high strength-to-mass ratio, the floors are often highly susceptible to vibration from excitation of different kinds. Human-induced vibration due to occupants activities including walking is a main concern.

There are different types of timber floors used in constructions, including cross laminated timber (CLT) floors, joisted timber floors, timber-concrete-composite floors, and more. This study focuses on joisted timber floors. The influence of different structural characteristics and non-structural parts such as partition walls and floor finishing, has been investigated by several researchers indicating their potential to affect the vibration performance. This study investigates via experimental testing, the influence of furniture on the vibration performance of joisted timber floors.

In this study, tests have been performed to capture the modal characteristics in terms of the natural frequencies, mode shapes and damping of different configurations of floors with and without furniture. Time-history acceleration response from walking excitation has been measured and analysed to evaluate the vibration response and human perception using peak acceleration, root mean square acceleration, weighted root mean square acceleration and vibration dose values.
The results indicate that placing furniture on joisted timber floors can significantly affect the vibration response of joisted timber floors exposed to walking excitation and alter the modal characteristics of the floors. The vibration response is generally lowered, and vibration comfort enhanced. The natural frequencies are generally lowered, and damping is generally increased when adding furniture (considering the first two modes). However, these effects vary greatly between different floors and different arrangements of the furniture. Thus, quantifying any effect in relation to imposed mass to floor mass ratio require further studies.

Lastly, imposed load with lower centre of gravity was used to investigate the impact of elevating the centre of gravity on the modal characteristics of the floors. The results indicate that elevating the imposed mass amplify the effect of lowering the fundamental frequency of the floors.

Sammendrag

Trekonstruksjoner har økt i popularitet i løpet av de siste tiårene grunnet miljømessige fordeler sammenlignet med betong og stål. Selv om det er mange andre fordeler, som høy styrke i forhold til masse som senker belastning av grunnen og fører til lavere kostnader forbundet med fundamentering, er det fortsatt utfordringer. Mye forskning er gjort rundt trekonstruksjoner og en ny Eurokode 5 for trekonstruksjoner blir diskutert.
En utfordring er vibrasjon i gulv av tre i bruksgrensetilstand. Siden tre har høy styrke i forhold til masse, er gulvene ofte ganske mottakelige for vibrasjon når de blir utsatt for forskjellige typer eksitasjon. Vibrasjon forårsaket av brukeres aktiviteter, deriblant brukere som går på gulvet, er spesielt i fokus.

Det finnes forskjellige typer tregulv som blir benyttet i trekonstruksjoner. Blant disse er krysslimt tre (KLT eller «massivtre»), gulv med trebjelkelag og komposittgulv av tre og betong. I denne studien fokuseres det på gulv med trebjelkelag. Påvirkningen av forskjellige strukturelle karakteristikker og ikke-strukturelle detaljer som lettvegger og gulvavslutning, er undersøkt av flere forskere som indikerer potensialet disse har til å påvirke vibrasjonen. Denne studien undersøker hvordan møbler påvirker vibrasjon i gulv med trebjelkelag ved eksperimentell testing.

I denne studien er det utført tester med forskjellige konfigurasjoner av gulv med og uten møbler for å identifisere modale egenskaper i form av egenfrekvenser med tilhørende former og demping. Akselerasjon i gulv over tid ved eksitasjon fra en gående person er målt og analysert for å evaluere vibrasjonen i gulv og menneskers oppfatning av vibrasjonen ved å benytte maksimal akselerasjon, kvadratisk gjennomsnitt av akselerasjonen, vektet kvadratisk gjennomsnitt av akselerasjonen og såkalt «vibration dose values».

Resultatene indikerer at vibrasjonen i gulv med trebjelkelag utsatt for gående personer, og modale egenskaper, kan påvirkes betydelig ved å plassere møbler på gulvene. Det fører hovedsakelig til mindre vibrasjon, og øker opplevd komfort i forhold til vibrasjon. Egenfrekvensene synker og dempingen øker, for det meste (kun de to første egenfrekvensene er analysert). Disse effektene varierer ganske mye mellom de forskjellige gulvene og konfigurasjoner av møbel. Videre studier behøves for å kunne tallfeste noen effekt ved bruk av forholdet mellom pålagt masse og massen av gulvet.

Til slutt er det undersøkt om pålagt masse med lavere tyngdepunkt påvirker de modale egenskapene forskjellig fra pålagt masse med høyere tyngdepunkt. Resultatene indikerer at pålagt masse med hevet tyngdepunkt senker egenfrekvensen til gulv mer enn pålagt masse med lavt tyngdepunkt.

Acknowledgements

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Ås, May 2024

Richard Håndlykken

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1 Introduction

The use of timber in construction has grown substantially over the last decades. As the knowledge around timber engineering grows, and the environmental benefits of using timber as a construction material are recognized, this development will most likely continue.

A lot of research has been carried out on the topic of timber and vibration, and a new Eurocode 5 is under development. However, there are still uncertainties regarding timber construction, where different topics show themselves to be quite challenging. One of these topics is floor vibration. Due to the high-strength to low-mass ratio, timber floors are highly susceptible to vibration caused by different sources of excitation. With a desire for longer floor spans, more accurate knowledge for design and verification to mitigate vibration problems is needed.

Vibration is considered a service limit state (SLS) verification and mostly affects the occupants' comfort. Excessive vibrations can in the outermost consequence cause health problems and affect the performance of gadgets/equipment such as smartphones and personal computers (PC's). Thus, mitigating uncomfortable vibrations is considered important. As mentioned, vibration can be caused by different sources. Often, vibrations on floor surfaces annoying humans are from their own activities such as walking, running and jumping. However, wind, machinery, trains, or heavy traffic passing by are some other examples of sources of excitation. The common source of vibration, upon which this thesis is focused, is walking excitation.

Floor vibration is a complex phenomenon influenced by many factors. Mass, stiffness, and damping are key factors. As well, mode shapes and the nature of the excitation are contributary factors. This thesis seeks to explore the effect furniture has on the dynamic performance of joisted timber floors (modal characteristics and motion responses under walking excitation). In meeting this goal experimental tests have been carried out on three joisted timber floors with different configurations, with furniture placed in different arrangements. For every floor, modal analysis is performed and measurements of vibration responses due to walking excitation are captured and analysed.

1.1 Research questions and objectives

Most of past and current studies on the vibration serviceability of timber floors have been carried out on the bare floors. Thus, the uncertainties surrounding the vibration performance of the floors are limited to the inherent properties of the systems. Extra materials such concrete toppings are sometimes added to as it were, improve floors adjudged to be underperforming (Skinner et al., 2014). In other instances, floor material quantities are altered by increasing sizes of sheathing and joists (joisted floors) or increasing thickness of cross laminated timber floors (CLT) with the aim of improving timber floor serviceability (Woeste & Dolan, 2007). Whilst such measures may be beneficial, they add extra weights and cost defeating the purpose of reducing total superstructural gravitational weights, foundation cost and overall construction economics as envisaged for timber buildings.

A hypothesis of this study is that the presence of furniture on floor surfaces as components of live loads are likely sources of absorbers that can improve vibration performance. Depending on their configuration, masses, and locations on floors, they can improve damping and stiffnesses to enhance the dynamic characteristics of various floors. Therefore, the following research questions form the basis of this study:

- Do furniture alter the modal characteristics of floors – modal frequencies, shapes, and damping ratios?
- To what extent do furniture influence motion responses on floor surfaces due to human induced vibrations?
- What is the ratio of mass of furniture to floor mass that can significantly affect the vibration performance of floors?
- What is the effect of centre of gravity of the imposed load in relation to the surface of joisted timber floors on the modal characteristics?

The research objectives are assessing the effect of:

- Different arrangements of furniture on the modal characteristics of joisted timber floors
- Different arrangements of furniture on the motion responses of joisted timber floors under walking excitation.
- Imposed weight to floor weight ratio on the dynamic characteristics of the floors.
- Centre of gravity of the imposed load in relation to the surface of the floors on the modal characteristics.

1.2 Scope of study

This study focuses on the various items listed below.

Laboratory experimental work on:

- The modal properties and time-history responses due to human footfall excitation of joisted timber floors with perforated particleboard versus non-perforated particleboard.
- How transversal blocking at mid-span affects the dynamic performance of the joisted timber floors – Modal properties and time-history responses.
- What effect live load in the form of furniture, and its arrangement has on the natural frequencies, damping and the overall vibration performance of joisted timber floors during walking excitation.
- How elevating parts of the live load from the floor surface affects the natural frequencies and damping of joisted timber floors.

Analytical evaluations of:

- Root mean square acceleration response in joisted timber floors both with and without furniture placed on the floor surface, exposed to walking excitation.
- Peak acceleration response in joisted timber floors both with and without furniture placed on the floor surface, exposed to walking excitation.
- Weighted root mean square acceleration and vibration dose values (VDV) from walking excitation on joisted timber floors both with and without furniture placed on the floor surface.

With the given limitations:

- This study focuses only on vibration comfort on floors excited by walking excitation. Vibration issues regarding motion sickness or health risks is not considered.
- The floors tested in this study contains only the structural parts, meaning joists and particleboards only, simply supported by wooden blocks on each corner. Any effects of support conditions, additional flooring or roofing is not covered by the tests performed. Preliminary studies had been done to determine the support conditions appropriate for this study.
- All the experimental work were done with 4-corner point support based on various trials with 2 fully supported sides and 4 fully supported sides. However, due to the uneven nature of the concrete floor at the laboratory and the timber beams used as the supports, the results were not satisfactory with inconsistent and unclear mode shapes. This due to gaps between the floor edges and the beams resulting in bouncing mimicking the so called “second order” effect.

- Vibration is only considered in the vertical direction.
- The calculation of Weighted Root Mean Square Acceleration and Vibration Dose Value proved to be quite time consuming. Due to time constraints, the calculation of these values was limited to only the time histories giving the highest Root Mean Square Acceleration from walking tests with 1,5Hz walking frequency (M).
- The study had plans to incorporate some numerical studies in addition to the experimental work. However, time constraints did not allow this portion of the work to be carried out.

1.3 State of the art

A lot of research has been done on the subject of vibration in timber floors. Many of the past and present research to characterize modal parameters has been done on isolated laboratory-tested floors (Weckendorf, 2009). Numerical analysis using finite element models has been performed (Andersen et al., 2020). Some have also conducted experimental testing on in-situ floors and compared the modal parameters to corresponding laboratory-tested floors (Casagrande et al., 2018; Jarnerö et al., 2015). Natural frequencies, mode shapes and damping are the parameters mostly emphasized while analysing.

The number of published research papers on vibration in timber constructions has grown substantially over the last decades (Aloisio et al., 2023). As the number of publications continues to increase, papers are published to serve as encyclopaedias presenting the recent research published. One example which can be useful for further reading is Aloisio et al. (2023).

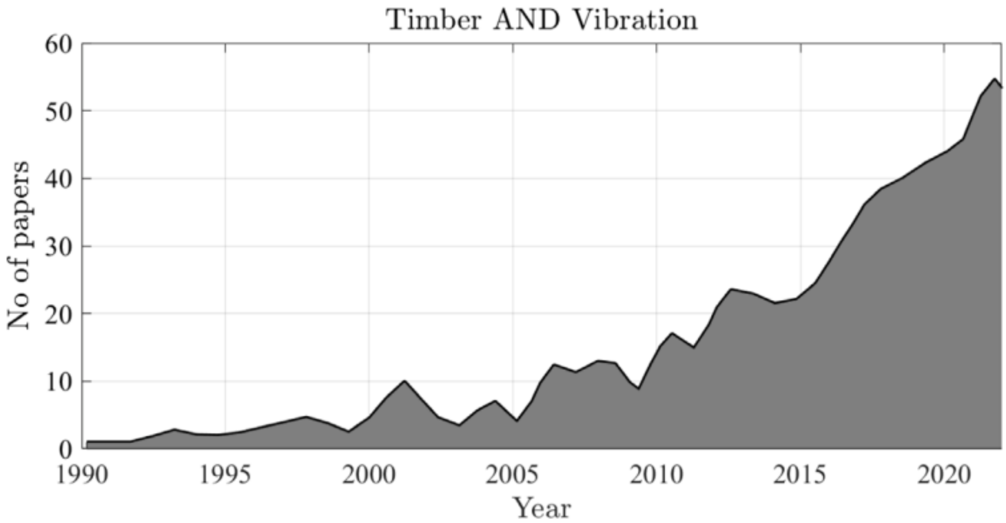


Figure 1-1. Total number of publications obtained by reviewing 572 papers. (Aloisio et al., 2023)

Weckendorf (2009) conducted vibration tests on sixty-seven light-weight I-joist floors with different structural and non-structural configurations. It was observed, that for all floor structures in the study, the addition of equally distributed dead load significantly lowered the natural frequencies. Damping ratios were also influenced by the added mass, with reduced damping for the fundamental mode and higher damping for the higher modes. Lastly, the added mass was found to narrow the spacing between adjacent modes, which can result in co-action of modes. However, Weckendorf limited his work to estimating the modal parameters of all the floors developed and static deflections of some selected floors. His study did not cover time-history responses – a major technique for assessing human response to vibration.

Opazo-Vega et al. (2019) performed an operational modal analysis of lightweight residential joist floors excited by human walking, both in the laboratory and in situ. Modal parameters were deduced using EFDD and SSI. The results showed higher damping ratios for the in-situ floors compared to laboratory-tested floors. The tests were performed on bare floors and did not involve imposed loads such as furniture. Additionally, only the fundamental mode was analysed. Ussher et al. (2022) concludes that modes higher than the fundamental mode may contribute significantly to the aggregated motion levels caused by impact or impulsive forces, and ignoring this could lead to gross underestimation of the motion levels.

Casagrande et al. (2018) assessed the dynamic properties and vibration performance of timber floors using analytical, numerical and experimental methods. Specifically a timber-concrete composite floor and a cross laminated timber floor was investigated. Evaluating multiple analytical methods, the vibration dose value was used as a reference method. Experimental tests was performed on site, as well as on mock up samples of the floors in laboratory. The study found that internal partitions and non-structural elements greatly influence the dynamic response of the floors. Damping values of around 3,5-4% were measured on site, approximately 1 % higher than the values measured from the laboratory tests, proving the influence of non-structural elements such as partition walls, finishing layers and boundary conditions. However, elevated centre of mass of the live load, i.e. furniture, was not involved in the testing.

ISO 10137:2007 (ISO, 2007) recommends methods to evaluate the vibration response with regards to human perception. Frequency weighting of time-history response to calculate weighted root mean square acceleration and vibration dose value is suggested. A base curve showing the relative sensitivity of vibration in vertical direction is presented, showing that humans are more sensitive to vibrations with frequencies between 4Hz-8Hz. The base curve is used to evaluate root mean square (rms) acceleration by multiplying the base curve by a factor so that the measured or predicted values are under the curve. The size of the factor defines the performance level.

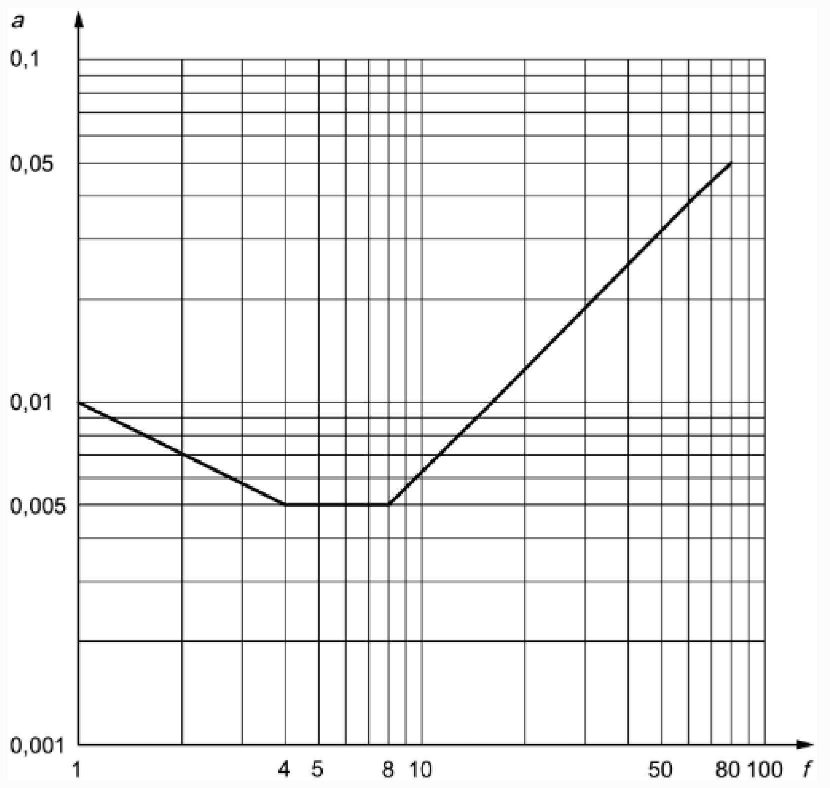


Figure 1-2. Base curve for evaluation of vibration on the vertical direction. On the horizontal axis is frequency (Hz) and on the vertical axis is rms acceleration (m/s²). (ISO, 2007)

Work towards a new Eurocode 5 (EC5) is ongoing. The proposal (CEN, 2023) has adopted a more comprehensive approach to vibration design. The approach introduces more variables than the current EC5 (CEN, 2014). The current EC5 separates high frequency and low frequency floors as floors with fundamental frequencies over and under 8 Hz, respectively. No guidelines for the design of low frequency floors are presented, except a recommendation of performing a special investigation. For high frequency floors, criteria involving deflection and velocity are presented to classify the floors as good or poor performing floors. The proposed new EC5 takes more factors into account. The number of spans, support conditions, effect of non-structural layers (e.g. screed) and openings are examples of such factors. Additionally, improved recommendations for damping ratios and definition of mass to include in the calculations.

A response factor “R” is presented and used to classify floors by performance levels 1 to 7, with 1 being the best performing. The frequency limit between high frequency floors and low frequency floors is between 7 Hz and 10 Hz depending on performance level and whether a walker can walk more than 10 m unobstructed. Floors with fundamental frequencies down to 4,5 Hz are allowed, but low frequency floors has to satisfy an additional criteria regarding acceleration. A stiffness criteria involving deflection calculation must be satisfied for all floors, as well as a velocity criteria.

	Floor performance levels					
Criteria	**I**	**II**	**III**	**IV**	**V**	**VI**
Response factor R	4	8	12	24	36	48
Upper deflection limit $w_{lim,max}$ in mm	0,25		0,5	1,0	1,5	2,0
Stiffness criteria for all floors	$w_{1kN} \leq w_{lim}$ mm					
Frequency criteria for all floors	$f_1 \geq 4,5$ Hz					
Acceleration criteria for resonant vibration design situations ($f_1 < f_{1,lim}$)	$a_{rms} \leq 0,005\ R$ m/s²					
Velocity criteria for all floors	$v_{rms} \leq 0,0001\ R$ m/s					

Figure 1-3. The main criteria for vibration verification. From the proposed new EC5 (CEN, 2023).

Andersen et al. (2020) conducted a brief analysis of furniture's influence on the modal properties of wooden floors. A finite-element model of a floor consisting of particleboard and timber joists was used. Non-structural mass was placed randomly in different arrangements over the floor, initially placed on the board surface, and then elevated at different heights. First, adding non-structural mass to the floor surface lowered the natural frequencies significantly. Furthermore, the natural frequencies were lowered even more when the non-structural mass was elevated from the floor. This effect was more pronounced when the non-structural mass was placed between the joists. Note that the non-structural mass in total was approximately 1,44 times the structural mass of the floor. Also, while the mass was elevated, it was still fixed to the floor surface.

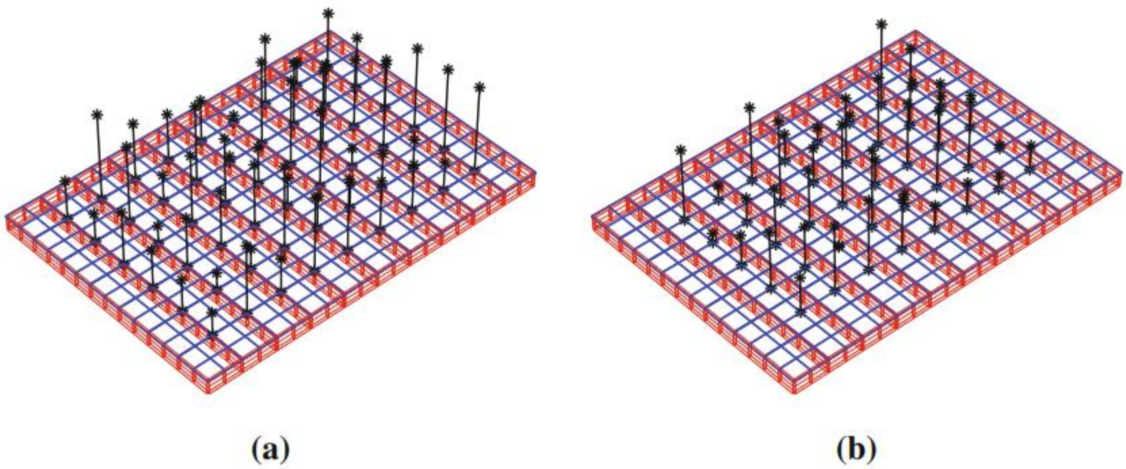


Figure 1-4. Models with furniture placed (a) on top of the joists, and (b) between the joists. (Andersen et al., 2020)

Figure 1-5 and Figure 1-6 show the results from the study by Andersen et al. (2020). The dashed lines show the original frequencies of the first five modes. The continuous lines show the cumulative frequencies after a great number of simulations.

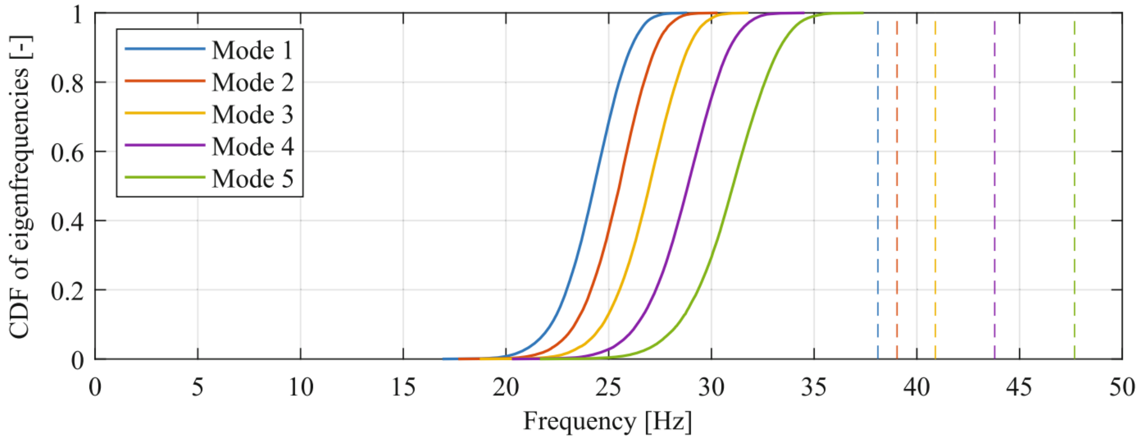


*Figure 1-5. Cumulative distribution functions for the first five natural frequencies – mass **over** joist **without** elevation. (Andersen et al., 2020)*

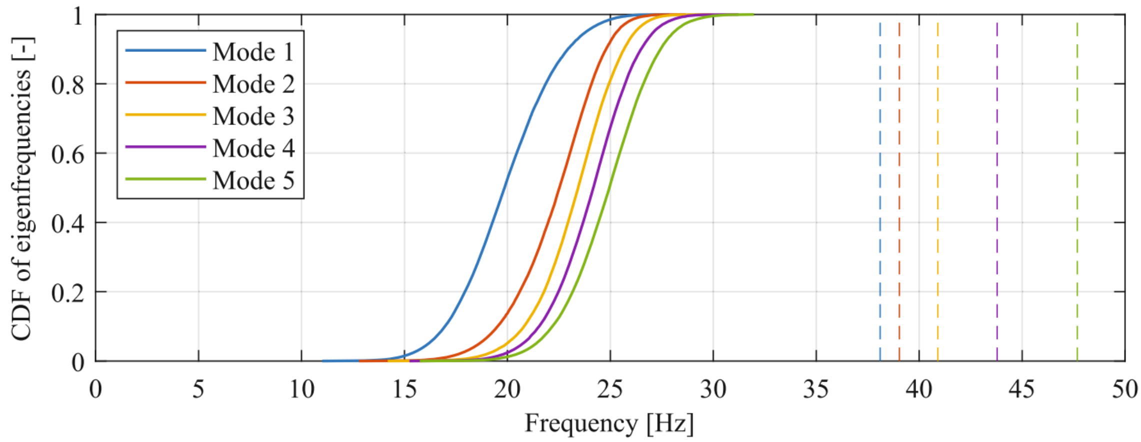


*Figure 1-6. Cumulative distribution functions for the first five natural frequencies - mass **over** joist **with** elevation. (Andersen et al., 2020)*

From the literature, limited studies on how parts of the live load, i.e. furniture, affect floor vibration performance and the consequence on occupants is observed. The influence of added mass has been anticipated (Andersen et al., 2020). However, experiments measuring how modal parameters and vibration response in joisted timber floors are impacted by furniture and its positioning has to the best of my knowledge not been conducted. Some only proposed a percentage of the imposed load as part of the mass to be accounted for in estimating vibration parameters in judging whether a floor is acceptable or not (CEN, 2023). This study assesses the effect of furniture on floor vibration whilst providing the basis for quantifying some of the uncertainties associated with live load on human perception of floor vibrations.

2 Theory

This chapter will present the necessary theory and principles needed to understand the following discussion and conclusions. The general vibration theory relies mainly on Chopra (2020) and Smith et al. (2007), while the theory of evaluation of vibration response relies mostly on CEN (2023) and ISO (1997). Concepts are briefly presented, and further knowledge can be obtained from relevant literature, standards and research.

2.1 Vibration theory

Vibration can be described as the oscillating movement of mass initiated by a force or motion (Chopra, 2020). Mass, stiffness and damping are three key factors for vibration calculation. The equation of motion for free vibration of an undamped single degree of freedom (SDOF) system is shown in equation (2.1) (Chopra, 2020).

$$m\ddot{u} + ku = 0 \tag{2.1}$$

- m is the mass
- $\ddot{u}$ is the second derivative of the displacement over time
- k is the stiffness
- u is the displacement relative to the equilibrium position

Frequency is a value for how many oscillations, or cycles, there are per second. It’s given in Hz (1/s) for the ordinary frequency or radians per second (rad/s) for the circular frequency. Every system has its fundamental frequency, which can be measured while the system vibrates freely. Through equation (2.1) one can also derive an expression for the fundamental frequency of the system, which is shown below.

$$\omega_1 = \sqrt{\frac{k}{m}} \tag{2.2}$$

- ω_1 is the fundamental frequency in rad/s
- k and m are as defined above

The equation above shows an important relation between the stiffness and mass of a system (Chopra, 2020). Higher stiffness while maintaining the same mass, will increase the fundamental frequency. Increased mass with stiffness held constant will lower the fundamental frequency. This concept generally applies to more advanced multi-degree-of-freedom (MDOF) systems as well.

The ideal situation for undamped systems is modelled to estimate the inherent natural frequencies and other properties of the systems. However, such systems do not exist. All structural systems will oscillate and eventually come to rest. The phenomenon that enables a system under vibration to come to rest is damping (Chopra, 2020).

A simple SDOF system is a system that can be simplified to one lumped mass connected to a spring and damper (Chopra, 2020). This system has only one mode with the mass oscillating with a frequency corresponding to the fundamental frequency. A simple MDOF system is a system that is simplified to two or more lumped masses connected to springs and dampers. MDOF
systems have more than one mode of vibration, with the number of modes corresponding to the number of degrees of freedom. Each mode has its frequency.

2.1.1 Resonance

Resonance is a phenomenon that happens when the frequency of the source of excitations aligns with one of the natural frequencies of the system being subjected to vibration (Smith et al., 2007). With insufficient damping, this will likely cause a buildup in vibration energy and magnitude, and ultimately have detrimental effects. The relation between the frequency ratio (β), damping ratio (ζ) and the dynamic magnification factor is shown in Figure 2-1. The frequency ratio is the excitation frequency divided by the natural frequency. When this ratio is 1, it means that the frequency of the excitation equals the natural frequency, and a buildup of vibration energy will likely happen, depending on the damping ratio. A damping ratio of 1 says that the system is critically damped, meaning that the system will come to rest after just one oscillation (Chopra, 2020). The damping ratio is explained in section 2.2.2.

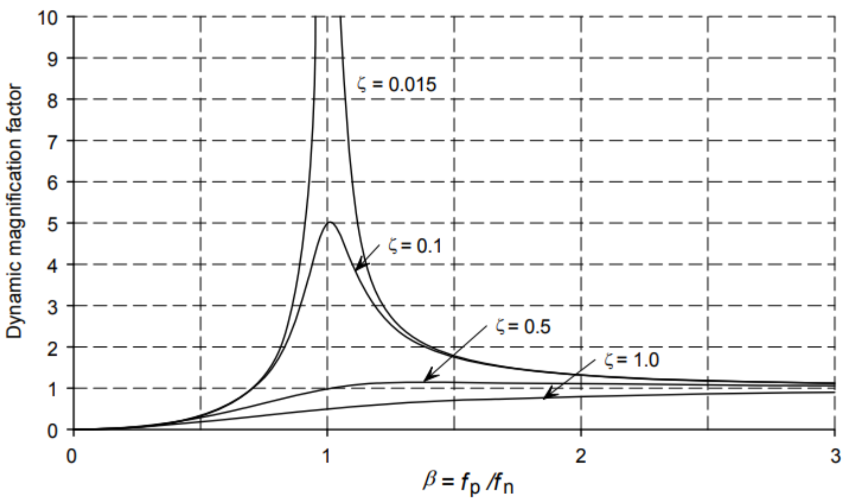


Figure 2-1. Dynamic magnification factor for accelerations. (Smith et al., 2007)

2.2 Modal properties

Modal properties are used to describe the vibrational behaviour of a system. Some are easier to measure than others, and some require analytical effort to be obtained. The most relevant modal properties are natural frequencies, mode shapes, damping and stiffness. Each of these variables play their part in evaluating and predicting the vibration response of system. Natural frequencies with regards to resonance, mode shape for classifying of the modes, damping with regards to dissipation of vibration energy and stiffness with regards to deflection. They are presented briefly in the following sections.

2.2.1 Natural frequencies and mode shapes

Every system has one or more natural frequencies. The first natural frequency is defined as the fundamental frequency, which corresponds to the first and simplest mode shape (Smith et al., 2007). The fundamental frequency paired with the first mode shape is what we call the first mode. Systems can have several modes, each with its frequency and corresponding mode shape. For every higher mode, the frequency is increased, and the mode shape is more complex. In general, the first mode is the most dominant concerning vibration energy, with decreasing energy for every higher mode. The first three mode shapes of a beam is shown in Figure 2-2. For elements with plate behaviour, e.g. floors, the modes become significantly more complex as they become two-dimensional, meaning that there are bending curves in both the longitudinal and the transversal direction.

The formulae from CEN (2023) for calculating the fundamental frequency of a single span floor that is approximately rectangular in plan and is one- or two-way spanning directly onto rigid supports, and primarily subject to uniform loading, are shown in equations (2.3) and (2.4).

$$f_1 = k_{e,2} \frac{\pi}{2l^2} \sqrt{\frac{(EI)_L}{m}} \tag{2.3}$$

With:

$$k_{e,2} = \sqrt{1 + \frac{\left(\frac{l}{b}\right)^4 (EI)_T}{(EI)_L}} \tag{2.4}$$

- $k_{e,2}$ is the frequency factor to consider the effect of the transverse floor stiffness taken as in equation (2.4) (in the case of a one way span floor: $k_{e,2}$ = 1,0)
- l is the floor span (the longer span in the case of double span floor)
- $(EI)_L$ is the floor bending stiffness in direction of the span per metre width as stated in 9.3.3(13) - (15) (in CEN (2023))
- m is the floor mass per unit area, as stated in 9.3.3(9) (in CEN (2023))
- b is the floor width
- $(EI)_T$ is the floor bending stiffness transverse to floor span per metre width as stated in 9.3.3(13) - (15) (in CEN (2023))

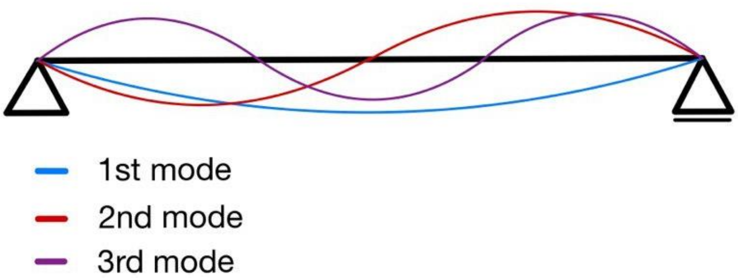


Figure 2-2. The first three mode shapes of a beam. Inspired by Smith et al. (2007).

2.2.2 Damping

Damping is the dissipation of vibration energy through different mechanisms either external or within the structure (Chopra, 2020). Damping attenuates the amplitude of the vibration, and can also delay the vibration movement. Damping occurs in all vibrating structures with different magnitudes.

The amount of damping is expressed with a damping ratio, which is the damping of the structure divided by the critical damping. Critical damping is the amount of damping needed for the system to come to rest after just one cycle of oscillation (Chopra, 2020). Basically, there is no oscillation for a system that is critically damped. A system can be overdamped, meaning that the time it takes for the system to come to rest without any oscillation corresponds to more than one oscillation with the fundamental frequency. Oscillating systems (which is commonly known as vibrating systems) are underdamped systems, meaning that it takes more than one oscillation cycle for the system to come to rest (Chopra, 2020). In that case, the damping ratio is lower than 1. The damping ratio can be stated in percent. Thus, a damping ratio of 0,05 correspond to a damping ratio of 5 %.

There may be many mechanisms contributing to damping, making it very difficult to differentiate the effects between them. Therefore, damping is often simplified with damping ratios defined for the type of structure analysed.

For design, the modal damping ratios for different floor types are recommended in the proposed new EC5 (CEN, 2023). They are listed below.

— ζ = 0,02 for joisted floors
— ζ = 0,025 for timber-concrete floors, rib type floors and slab type (e.g. CLT, LVL, GLVL, GL) floors
— ζ = 0,03 for joisted floors with a floating floor layer
— ζ = 0,04 for timber-concrete floors, rib type floors and slab type (e.g. CLT, LVL, GLVL, GL) floors with a floating floor layer.

2.2.3 Stiffness

As shown in equation (2.2), the stiffness is a governing factor concerning the frequency of the fundamental mode. For a simple beam, adjusting the stiffness (with mass held constant) will either increase or decrease the frequency of the modes. For plates, e.g. floors, the frequency and mode shapes are governed by an interplay of both the longitudinal and the transversal stiffness. If any of these two are changed, it may change the frequency of one or more modes and even the order of the modes.

2.2.4 Modal participation

How much the different modes of an object or a construction system participate to the overall vibration is called modal participation, often expressed as a percentage. For simple constructions such as a simply supported rectangular floor (vertical vibration) or a symmetric several story building (lateral vibration), the first mode is often the dominant mode with a modal participation well over 50 %. In theory, the modal properties of the modes with the highest modal participation will affect the overall vibration properties the most. Co-action of modes can happen as a result of so called mode clustering, meaning that the separation between natural frequencies is diminished. Mode clustering can adversely affect the vibration serviceability (Ussher et al., 2017; Weckendorf, 2009).

2.3 Excitation sources

There are many types of excitation forces to initiate vibration. Examples are human activities such as walking and jumping. Other sources include machinery, blast impacts and wind. Each carries its characteristics for exciting vibration. Blast impacts for example are characterized by instantaneous force duration. Machinery can have a rhythmic excitation. Walking excitation has a distinct force pattern which can be seen in the figures below. Walking frequency is normally taken to be 1,5Hz-2Hz (CEN, 2023).

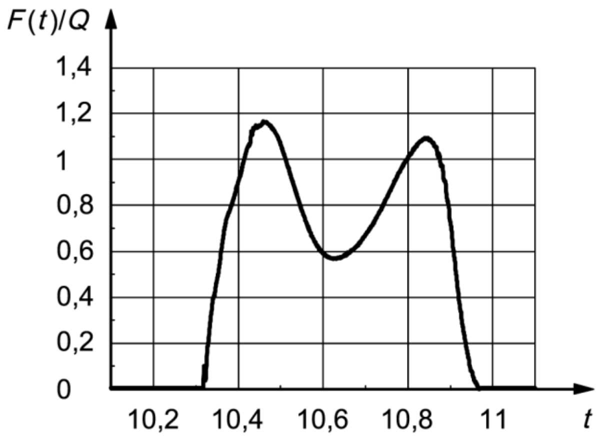


Figure 2-3. Example of vertical force against stiff ground for one walking step by one person. (ISO, 2007)

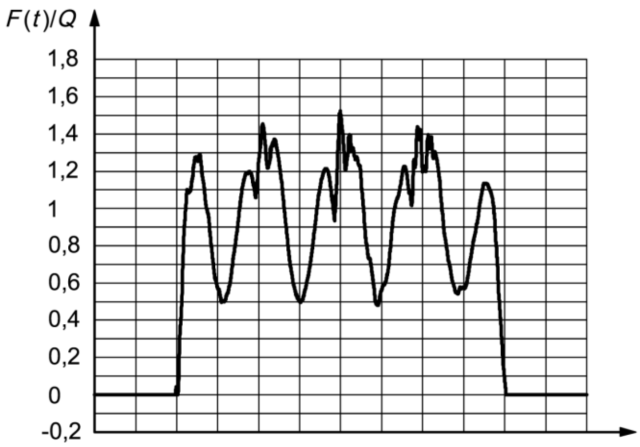


Figure 2-4. Example of the forcing function for one person walking across a 3 m long instrumented platform. (ISO, 2007)

2.4 Human perception of vibration

The perception of vibration depends on many factors, both for the objective characteristics of the vibration and the individual experiencing the vibration (ISO, 2007). The magnitude and direction of the vibration relative to the individual, the activity, position and posture of the individual, the subconscious expectations of comfort, the vibration frequencies, and whether the excitation source is visible or not. These are all factors that may affect the experienced discomfort of vibration .

From the literature, limited studies on how furniture affect floor vibration performance and the consequence on occupants is observed. Some only proposed a percentage of the imposed load as part of the mass to be accounted for in estimating vibration parameters in judging whether a floor is acceptable or not (CEN, 2023). It becomes necessary to assess the effect of furniture on floor vibration whilst providing the basis for quantifying some of the uncertainties associated with live load on human perception of floor vibrations.

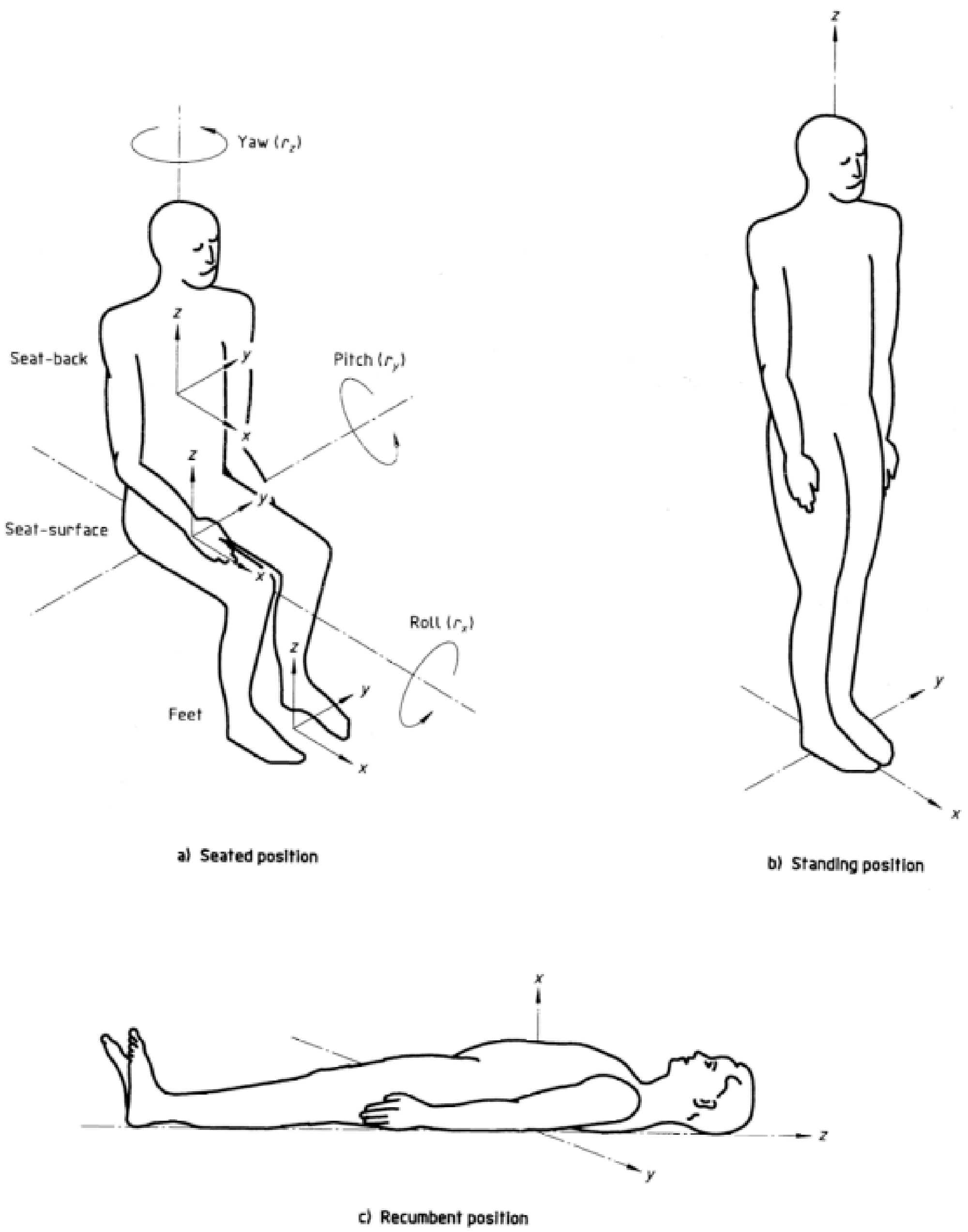


Figure 2-5. Basicentric axes of the human body. (ISO, 1997)

2.4.1 Frequency weighting

Humans are most sensitive to a specific frequency range, depending on position and posture. To take this into account when evaluating vibration comfort, the time history from an experiment is frequency weighted. This means that the parts of the signal containing frequencies humans are less sensitive to are attenuated. That way, the frequencies humans are most sensitive to carry more importance for the evaluation. Recommendations for frequency weighting are presented in ISO (1997).

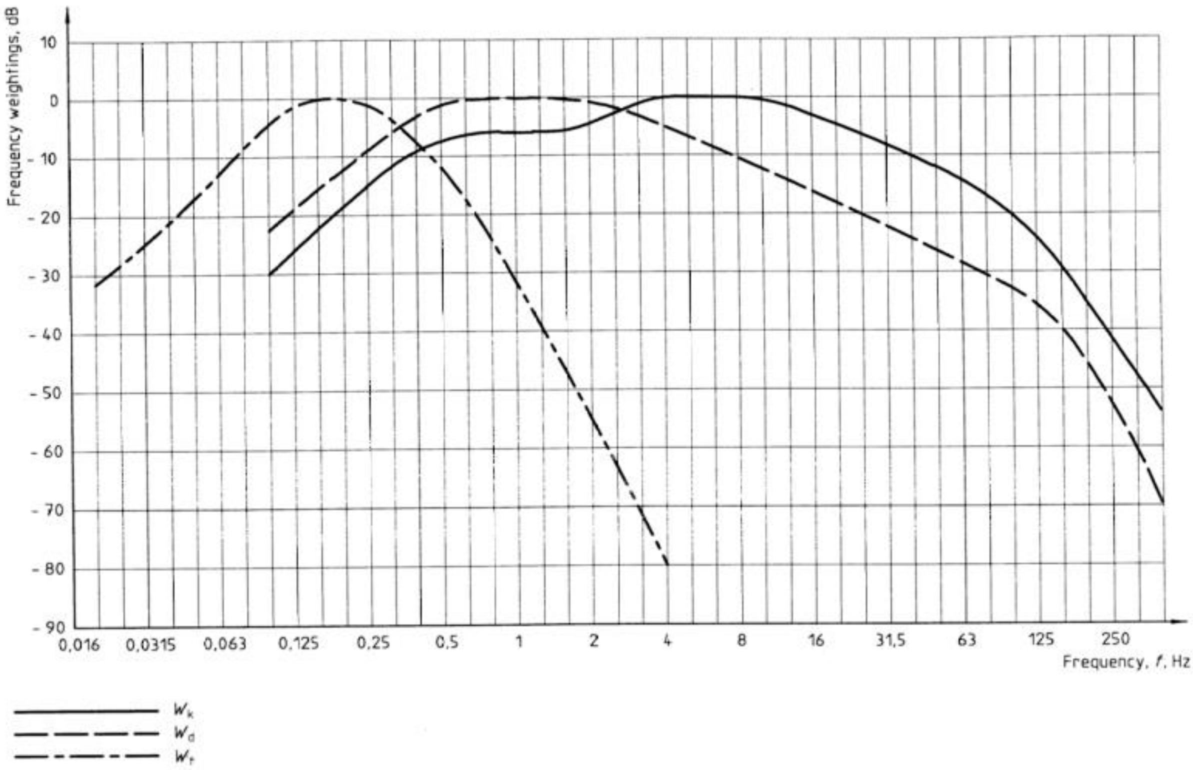


Figure 2-6. Frequency weighting curves for principal weightings (Schematic). (ISO, 1997)

- W_k is the weighting curve for z direction and for vertical recumbent direction (except head)
- W_d is the weighting curve for x and y directions and for horizontal recumbent direction
- W_f is the frequency weighting curve related to motion sickness

Table 2-1. Guide for the application of frequency-weighting curves for principal weightings. (ISO, 1997)

Frequency weighting	Health (see clause 7)	Comfort (see clause 8)	Perception (see clause 8)	Motion sickness (see clause 9)
W_k	z-axis, seat surface	z-axis, seat surface z-axis, standing vertical recumbent (except head) x-, y-, z-axes, feet (sitting)	z-axis, seat surface z-axis, standing vertical recumbent (except head)	—
W_d	x-axis, seat surface y-axis, seat surface	x-axis, seat surface y-axis, seat surface x-, y-axes, standing horizontal recumbent y-, z-axes, seat-back	x-axis, seat surface y-axis, seat surface x-, y-axes, standing horizontal recumbent	—
W_f	—	—	—	vertical

2.5 Parameters for evaluating vibration response

Several values are used to describe the magnitude of vibration and thus for the evaluation of vibration comfort. These include root mean square acceleration (a_{rms}), weighted root mean square acceleration (a_w), vibration dose value (VDV), velocity (v), fundamental frequency (f_1) and deflection (w). Each of these is briefly presented in the sections below. The term “root mean square” is shortened to “rms”.

2.5.1 Root mean square acceleration

The rms acceleration (a_{rms}) is a way of averaging the result (ISO, 2003), giving the higher peaks of acceleration more weight. Compared to the simplest averaging, a_{rms} will likely be a little higher if there are high peaks in the signal.

$$a_{rms} = \left[\frac{1}{T} \int_0^T a^2(t) dt \right]^{\frac{1}{2}} \tag{2.5}$$

- $a(t)$ is the acceleration as a function of time either in m/s^2 or rad/s^2
- T is the duration of the measurement in seconds

2.5.2 Weighted root mean square acceleration

For vibration evaluation, a weighted rms acceleration (a_w) is also calculated. ISO (1997) states that a_w “shall be determined for each axis (x, y and z) of translational vibration on the surface which supports the person.” Different weightings are done for different cases of evaluation, as indicated in Figure 2-6 and Table 2-1, in section 2.4.1. There are two ways of calculating the a_w. Both are presented in ISO (1997) and reiterated in this section. One involves the integration of the time history of the weighted acceleration, as shown in equation (2.6). Another involves the summation of bands of weighted acceleration using narrow or one-third octave bands, as shown in equation (2.7) for the use of one-third octave bands.

$$a_w = \left[\frac{1}{T}\int_0^T a_w^2(t)dt\right]^{\frac{1}{2}} \qquad (2.6)$$

- $a_w(t)$ is the acceleration as a function of time either in m/s^2 or rad/s^2
- T is the duration of the measurement in seconds

$$a_w = \left[\sum_i (w_i a_i)^2\right]^{\frac{1}{2}} \qquad (2.7)$$

- w_i is the weighting factor for the i-th one-third octave band given in ISO (1997), tables 3 and 4
- a_i is the rms acceleration for the i-th one-third octave band

2.5.3 Vibration dose value

The vibration dose value (VDV) is a method more sensitive to the peaks compared to the a_w, as it uses the fourth power instead of the second power. The formulas for calculating VDV are presented in ISO (1997) and reiterated in this section. VDV is given in m/s^{1,75} or rad/s^{1,75}.

$$VDV = \left\{\int_0^T [a_w(t)]^4 dt\right\}^{\frac{1}{4}} \qquad (2.8)$$

- $a_w(t)$ is the acceleration as a function of time either in m/s^2 or rad/s^2
- T is the duration of the measurement in seconds

If the vibration exposure consists of more than one period, with different magnitudes, the total VDV for the exposure should be calculated as shown below.

$$VDV_{total} = \left(\sum_i VDV_i^{\ 4}\right)^{\frac{1}{4}} \qquad (2.9)$$

- i is the number of the period

2.5.4 Velocity

The current EC5 (CEN, 2014) and the proposed new EC5 (CEN, 2023) have different formulas for approximating the velocity (v) and root mean square velocity (v_{rms}) respectively. Both take effects of modes higher than the fundamental mode into account, with formulas to predict this effect. There are several formulas needed to approximate the rms velocity. They will not be reiterated here. It is recommended to consult the appropriate standards for the details.

2.5.5 Fundamental frequency

The fundamental frequency (f_1) is mainly used to describe whether a floor will have a transient response or not. CEN (2023) has a lower limit of 4,5 Hz, and any floor with a lower fundamental frequency than that is not accepted, as it will most likely have a steady state response. Floors with fundamental frequencies over 7-10 Hz, depending on performance level and assumed walking frequency, are accepted if they satisfy criteria for deflection and velocity. These floors are defined as high frequency floors (HFF). Floors with fundamental frequencies between 4,5 and 7-10 Hz are defined as low frequency floors (LFF). These can also be accepted by satisfying an additional criterion regarding velocity. Generally, HFFs are opted for as they are considered to have better vibration performance. If needed, LFFs are also used.

The reasoning for these limits is that if the fundamental frequency of a floor is four times the excitation frequency, the response is considered to be transient. If the fundamental frequency is lower than four times the excitation frequency, transient response is still possible, but extra attention is needed for verification. For the case of walking excitation on a floor, transient response means that the vibration response dies out between every step. That way, there is no vibration buildup, avoiding steady state response.

2.5.6 Deflection

Deflection (w) is another criterion used for vibration verification, testing the general stiffness of the floor, since excessive deflection will cause discomfort regardless of the other criteria. In CEN (2023) the verification involves placing a force of 1 kN at the most unfavourable position (often at the centre of a one span floor), and calculating the resulting deflection. The deflection must be within the limit value corresponding to the decided performance level.

2.6 Data processing & analysis

Different methods are used to analyse and validate the vibration response of a structure, including Experimental modal analysis (EMA) and Operational modal analysis (OMA). For each of the techniques, the Fast Fourier Transform (FFT) and the Modal Assurance Criteria (MAC) are vital tools for the analysis and verification of results (Jacobsen et al., 2006; Weckendorf, 2009). Each of the concepts are briefly presented in the following sub-sections.

2.6.1 Fast fourier transform (FFT)

Fast Fourier Transform is an algorithm that converts time history of an oscillating signal into frequency domain, meaning that the oscillating signal is differentiated into waves, each having its specific frequency, with their magnitude. That way, one can sort out the frequencies that stands out (high peaks) to find modes and mode shapes.

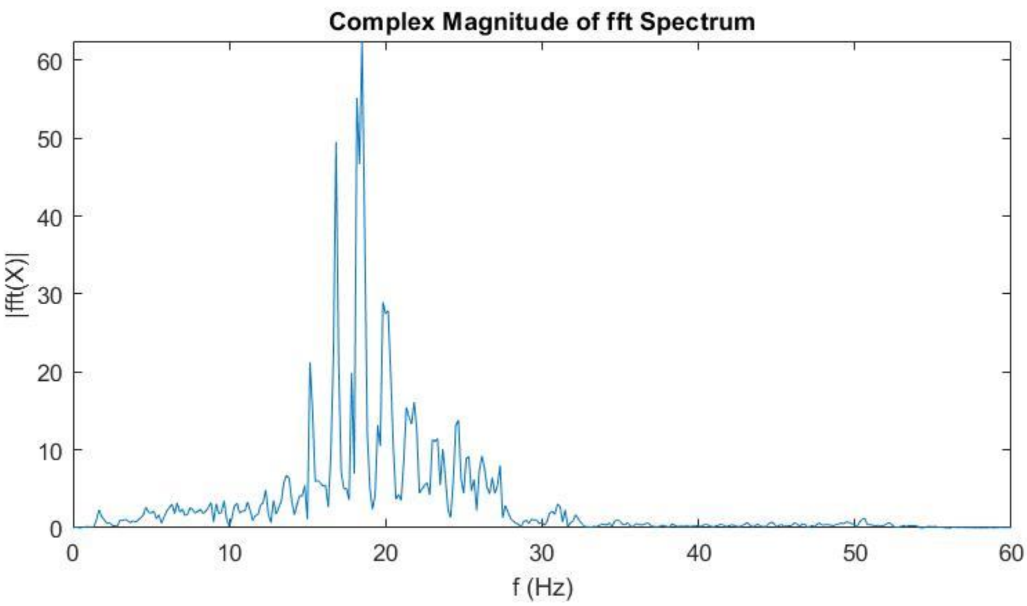


Figure 2-7. Example of an FFT diagram from Matlab using the fft()-function.

2.6.2 OMA & EMA

Operational modal analysis (OMA) is characterized by the fact that the input in the experimental test is unknown. An OMA often involves tests performed in more realistic, complex, in-situ environments. Additionally, since the input is unknown, any advanced and expensive equipment for controlled excitation is not needed. Simplifying the testing procedure and lowering the costs. One advantage of OMA is that one can investigate how a given object will behave in a real environment where knowing every input value is close to impossible. The downside is that not knowing the inputs prevents researchers finding clear correlations between input and output. If input is known, the method is called experimental modal analysis (EMA). EMAs are less “realistic” tests performed in laboratories or in other controlled environments, where both inputs and outputs are measured. The advantage with EMA is that one can quantify correlations or identify specific behaviours in a given subject. The downside is that the excitation is controlled and often fails to simulate operational conditions.

Enhanced frequency domain decomposition (EFDD) is an OMA method for analysing the frequency domain obtained by fourier transform of a given signal to identify modes with their frequency, mode shapes and damping. The method is an improved version of Frequency domain decomposition (FDD). FDD was first presented by Brincker et al. (2000), and introduced “a decomposition of the spectral density function matrix” to separate the response into single degree of freedom systems. One for each mode. This method can identify the frequencies and mode shapes of modes, but not damping. The method was further developed to identify damping as well as improving identification of natural frequencies (Brincker et al., 2001). “The individual SDOF auto spectral density functions are transformed back to time domain to identify damping and frequency” (Brincker et al., 2001). This updated method is called EFDD.

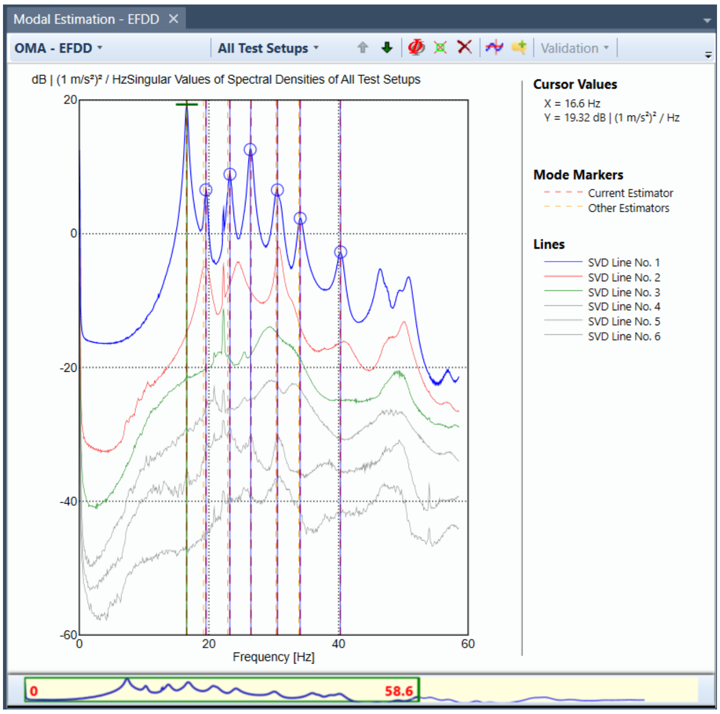


Figure 2-8. Mode selection in ARTeMIS Modal, using EFDD.

Stochastic system identification (SSI) is another OMA method of analysis using the time domain signal to identify modes, with frequency, mode shape and damping. Developed by De Moor et al. (1991) it involves a Block Hankel matrix and single value decomposition (Brincker & Andersen, 2006). The mathematics of SSI is complex and difficult to present. Thus, for more information on SSI, some useful references are the ones mentioned and Zahid et al. (2020).

2.6.3 Modal assurance criterion (MAC)

Modal assurance criterion is a validation method examining the similarities between the different modes. The similarity is quantified by calculating a MAC-value between zero and one. To validate the chosen modes, each mode should have a low similarity to the other modes, meaning that each mode should have a low MAC-value when compared to each of the other modes. As shown in Figure 2-9, both axes consist of all the selected modes, and the modes have MAC-values of 1 when compared to themselves (red columns), as it should be. In the figure, two separate modes have a high MAC-value (yellow column). This means that there are significant similarities between the two modes and one has to investigate whether they are separate modes or if one of them is caused by any secondary effects or noise. For more information on the MAC and its mathematics, see Pastor et al. (2012).

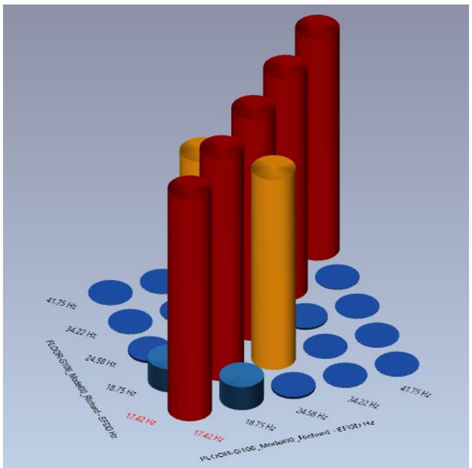


Figure 2-9. Diagram from ARTeMIS Modal displaying the MAC-values between the selected modes.

2.6.4 Software

ARTeMIS Modal (Structural Vibration Solutions, 2024a)
The software can be used to perform modal analysis of different objects.
In this software one can:

- Define a custom geometry.
- Assign acceleration data to point on the geometry.
- Process the data using OMA-methods (e.g. EFDD and SSI) to extract modes with modal parameters as frequency, mode shape and damping.
- Two frequency domain methods for EMA is also available.
- Validate the result by calculating MAC-values.

Several versions are available, and several plugins are supported. The most relevant features are mentioned above.

Matlab (MathWorks, 2024)
This software is a very versatile program with several areas of usage. By use of its programming language, it can perform many custom tasks defined by the user. The key feature of the software is its fast processing of matrix and array mathematics.

2.7 Guidelines/codes for vibration assessment

2.7.1 ISO 10137:2007

ISO 10137:2007 – *Bases for design of structures – Serviceability of buildings and walkways against vibrations.* "This international standard gives recommendations on the evaluation of serviceability against vibrations of buildings, and walkways within buildings or connecting them or outside of buildings." (ISO, 2007) The standard covers three recipients of vibration: Human occupancy, contents of the building and structure of the building. (ISO, 2007)

2.7.2 ISO 2631-1:1997

ISO 2631:1997 – *Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration – Part 1: General requirements.* This part of the standard "defines methods for the measurement of periodic, random and transient whole-body vibration. It indicates the principal factors that combine to determine the degree to which a vibration exposure will be acceptable." (ISO, 1997) The standard also presents current opinion, the effect of vibration on health, comfort, perception and motion sickness. Two frequency ranges are considered: 0,5-80 Hz for health, comfort and perception, 0,1-0,5 Hz for motion sickness. (ISO, 1997) Frequency weighting is defined for different postures of the occupant.

2.7.3 ISO 2631-2:2003

ISO 2631-2:2003 – *Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration – Part 2: Vibration in buildings (1 Hz to 80 Hz).* This part of the standard "concerns human exposure to whole-body vibration and shock in buildings with respect to comfort and annoyance of the occupants." (ISO, 2003) Methods for measurement and evaluation is specified. Frequency weighting applicable for the frequency range 1 Hz to 80 Hz is defined for when the posture of the occupant is undefined. (ISO, 2003)

2.7.4 EN 1995-1-1:2004

Eurocode 5: Design of timber structures. Part 1-1: General. Common rules and rules for buildings. (CEN, 2014) This code, published in 2004, has been the governing code for the design of timber structures for over two decades. It presents guidelines for most parts of the design process, including floor vibration. However, any guidelines for cross-laminated timber (CLT) are not included, and the guidelines for vibration are considered to be insufficient. This has led to other, more comprehensive methods being used for the verification of floor vibration.

2.7.5 prEN 1995-1-1:20XX (E)

CEN/TC 250/SC 5 "Eurocode 5: Design of timber structures". (CEN, 2023) This code has not been published as an official code yet. It is a proposal for an updated code for the design of timber structures, still in the works. At this moment, it is set to include significantly more than the existing Eurocode 5. Several topics, including vibration, have a renewed and a more comprehensive guidelines for design. Design of CLT is also included in this standard.

2.7.6 BS 6472-1:2008

BS 6472-1:2008 – *Guide to evaluation of human exposure to vibration in buildings. Part 1: Vibration sources other than blasting.* This British standard, published in 2008, gives guidance on how to predict the human comfort regarding vibration in buildings. Frequency weighting curves and advice on measurement methods is presented. The standard "describes how to determine the vibration dose value, VDV, from frequency-weighted vibration measurements. The vibration dose value is used to estimate the probability of adverse comment which might be expected from human beings experiencing vibration in buildings. Consideration is given to the time of day and use made of occupied space in buildings, whether residential, office or workshop." (BSI, 2008) The standard also provide limiting values, thus providing a basis for limit state design on vibration serviceability of floors.

Table 2-2. Assessment of VDV-values with regards to probability of adverse comments from occupants. (BSI, 2008)

Vibration dose value ranges which might result in various probabilities of adverse comment within residential buildings

Place and time	**Low probability of adverse comment** $m \cdot s^{-1.75}$ 1)	**Adverse comment possible** $m \cdot s^{-1.75}$	**Adverse comment probable** $m \cdot s^{-1.75}$ 2)
Residential buildings 16 h day	0.2 to 0.4	0.4 to 0.8	0.8 to 1.6
Residential buildings 8 h night	0.1 to 0.2	0.2 to 0.4	0.4 to 0.8

NOTE For offices and workshops, multiplying factors of 2 and 4 respectively should be applied to the above vibration dose value ranges for a 16 h day.

3 Methodology

The following sections present the approach adopted for this study. The test floors and the procedures for testing and analysis are described.

3.1 Test floors

Three floors were chosen to perform the vibration tests. The floors are from Støren Treindustri AS and are verified according to the “comfort criterion” regarding vibration. The criterion was instated by Homb (2007), but developed by Hu (2007).

The floors consist of timer joists known as “K-Beam Plus” and particleboards. Two of the floors namely Floor G101 and Floor G106 have perforated particleboards, while the other floor, Floor G105 has unperforated particleboards. The purpose of having perforated particleboards is sound insulation of floor dividers (Forestia, 2024). Floor G106 has transversal blocking in mid-span, also of the type “K-Beam Plus”. The joists are connected to end beams at each end, by nails. The particleboards are attached to the top of the joists by both glue and nails. The particleboards are mounted transversal to the longitudinal direction of the joists, as shown in Figure 3-1.

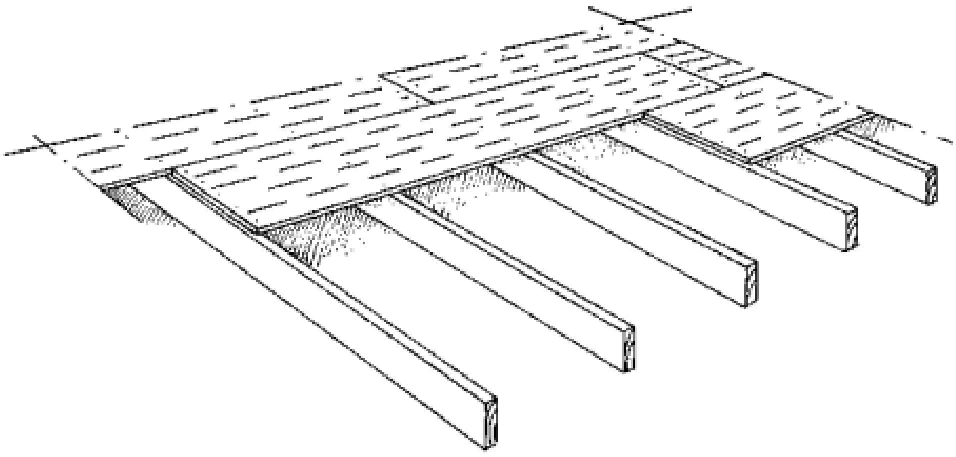


Figure 3-1. Mounting of particleboards. (Forestia, 2020b)

The outer dimensions of the floors, the joist dimensions and the joist spacings are the same on every floor, making any comparison between them more reliable. The only difference between them is whether they have perforated particleboard or not, and whether they have transversal blocking in mid-span or not. The naming and characteristics of the floors are specified in Table 3-1. Figure 3-2 shows floor G106 during testing, with sensors placed on the particleboard. Relevant material properties of the joists are presented in Table 3-2. Relevant material properties for the particleboards are presented in Table 3-3.

Table 3-1. Characteristics of the three test floors. Inspired by Kvinnesland (2018).

Floor	Joist	Joist spacing (cc)	Layout	Sheathing panel	Floor span	Floor length	Nr of joists	Floor width	Weight
G101	48x300 K-plus	600 mm	Joists & sheathing	Perforated particleboard	4,7m	4,9 m	5	2,4 m	363,3 kg
G105	48x300 K-plus	600 mm	Joists & sheathing	**Not** perforated particleboard	4,7m	4,9 m	5	2,4 m	380,3 kg
G106	48x300 K-plus	600 mm	Joists & sheathing + **blocking**	Perforated particleboard	4,7m	4,9 m	5	2,4 m	402,2 kg

Figure 3-2. Floor G106 during testing.

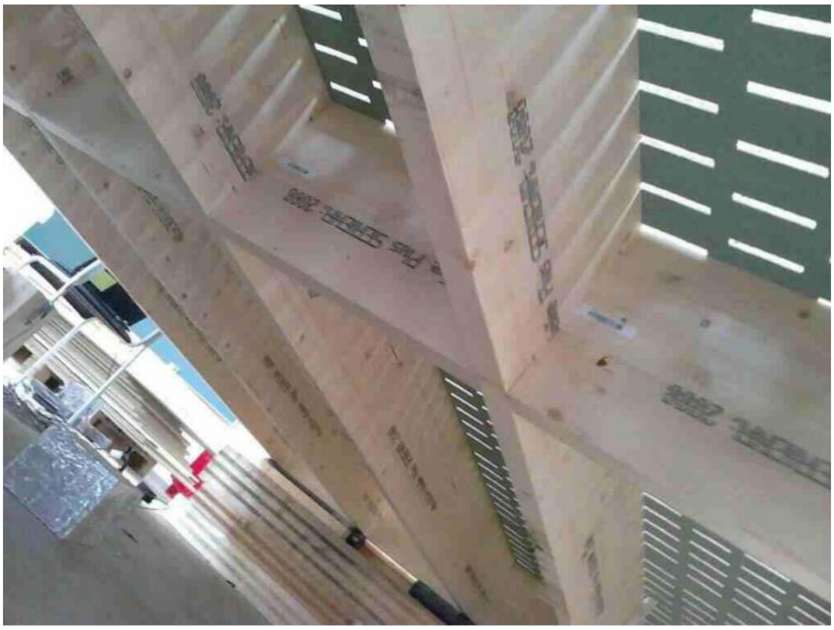


Figure 3-3. Transversal blocking on floor G106.(Kvinnesland, 2018)

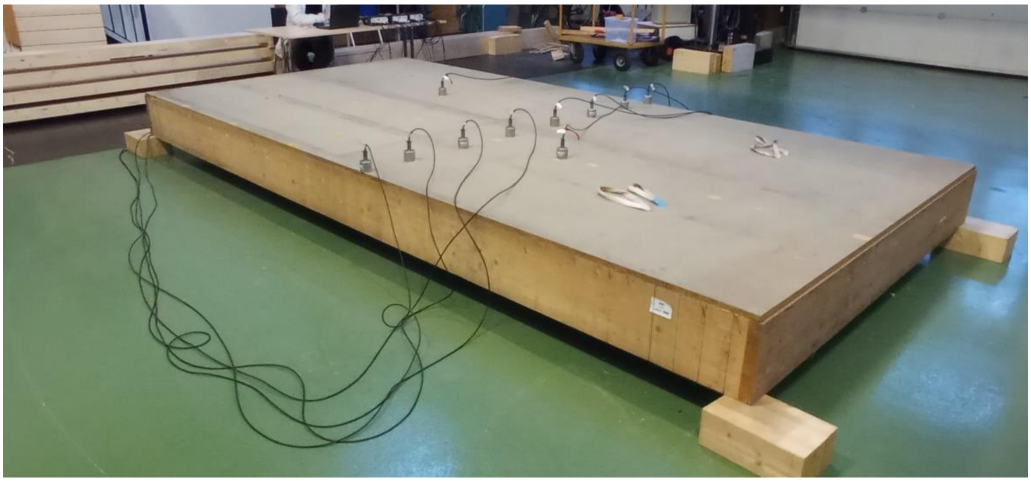


Figure 3-4. Floor G105 during testing.

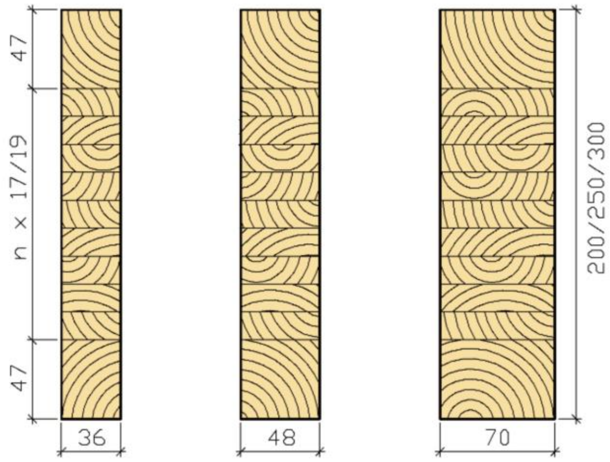


Figure 3-5. Available dimensions of the K-Beam. (SINTEF, 2023)

Table 3-2. Characteristic strength and stiffness properties in N/mm² for K-Beam and K-Beam Plus. (SINTEF, 2023)

		K-Beam	K-Beam Plus
Strength			
Bending strength			
- on edge and flatwise	$f_{m,k}$	24,0	33,0 [2)]
Tensile strength			
- in length of the beam	$f_{t,0,k}$	14,0	14,0
- perpendicular on fibres	$f_{t,90,k}$	0,4	0,4
Compression strength			
- in length of the beam	$f_{c,0,k}$	21,0	21,0
- perpendicular on fibres	$f_{c,90,k}$	5,3 [1)]	5,3 [1)]
Shear strength	$f_{v,k}$	3,5	3,5
Stiffness for calculation of stability			
Modulus of elasticity			
- bending and axial load	$E_{0,05}$	7400	9400
Stiffness for calculation of deformations			
Modulus of elasticity			
- bending and axial load	$E_{0,m}$	11000	14000
- perpendicular on beam edge	$E_{90,m}$	370	370
Shear modulus	$G_{0,m}$	690	690

Table 3-3. Material properties of the particleboards. Values obtained from Forestia (2020a).

Thickness	22 mm
Bending strength	16 MPa
Transversal tensile strength	0,4 MPa
E-modulus (longitudinal)	2550 MPa
Density	Ca. 670 kg/m^3

3.2 Testing procedure

Two types of test were carried out on the floors. One for capturing the modal properties of the floors; frequency, mode shape and damping. The other for measuring the time-history response of the floors from walking excitation. These two are referred to as "hammer test" and "walking test". How these tests were carried out are explained in the following sections. The setup of the technical equipment for data capturing is presented in Figure 3-6. A more specific description of the technical equipment is found in annex B on page 81.

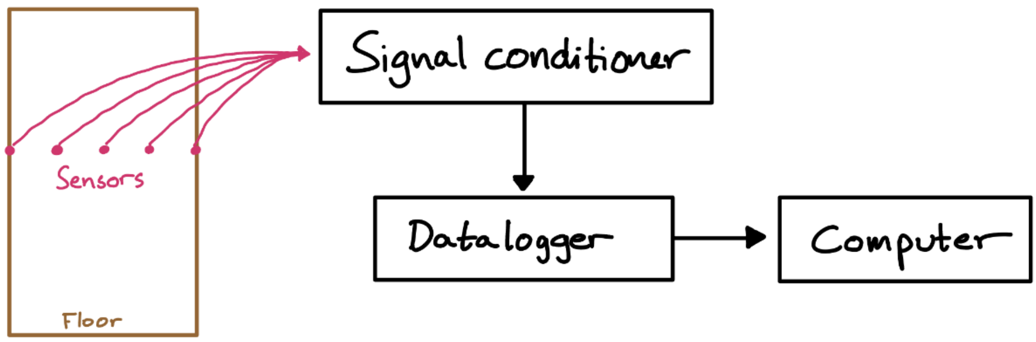


Figure 3-6. Setup for data capturing.

3.2.1 Hammer test

The hammer test involved placing accelerometers ("sensors", shown in Figure 3-7), measuring the acceleration in m/s^2 in the up-/downwards direction, on the floor. Then, the floor was excited using the hammer shown in Figure 3-7. A total of 10 sensors were used. An overview one of the test setups is shown in Figure 3-8. The first two were placed close to the centre of the floor as reference sensors, as one can see in Figure 3-9. These two sensors were not moved throughout the test. The remaining 8 sensors were placed in a line along one of the short sides of the floor, also shown in Figure 3-9. With a two minute recording time, the floor was excited around every 6 seconds using the hammer. The points where the floor was excited was spread out on the entire floor area so as to identify as many modes as possible.

This two-minute recording was repeated 8 times for every setup. For each repetition, the sensors were moved 70 cm. This way, after the 8 recordings, a grid of points with measurements enabled a modal analysis to be performed using suitable software (ARTeMIS Modal), and thus the modal properties could be found.

Figure 3-7. Rubber hammer and accelerometers used for testing.

Figure 3-8. Floor G101 during hammer test.

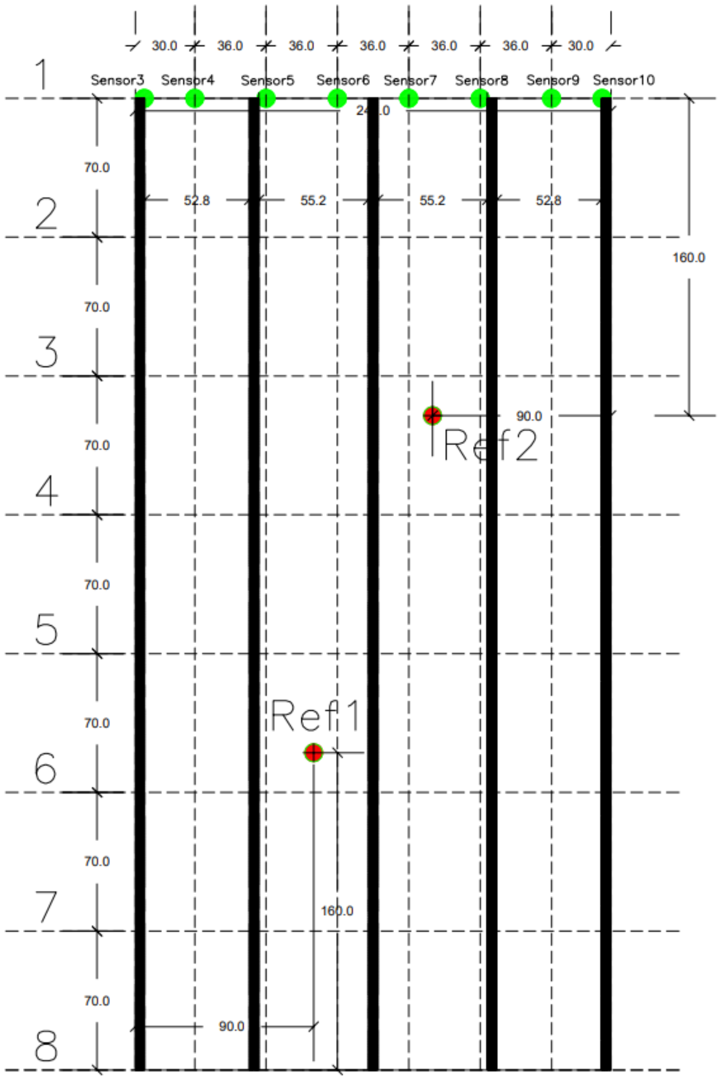


Figure 3-9. Sensor setup for hammer test.

3.2.2 Walking test

The walking test involved placing the sensors in different positions and having a person walk over the floor with different paths. The sensor arrangements are presented in Figure 3-10 with red points marking the sensor positions. The walking paths are presented in Figure 3-11, with a blue arrow marking their direction. An overview of all the combined sensor setups, furniture arrangements and walking paths used in the walking tests is presented in Annex A on page 77.

Walking tests for each setup were performed with walking frequencies of both 1,5 Hz and 2 Hz (denoted as “M” and “F”, respectively), each repeated 5 times. Time history data of the acceleration was captured and further processed and analysed in suitable software.

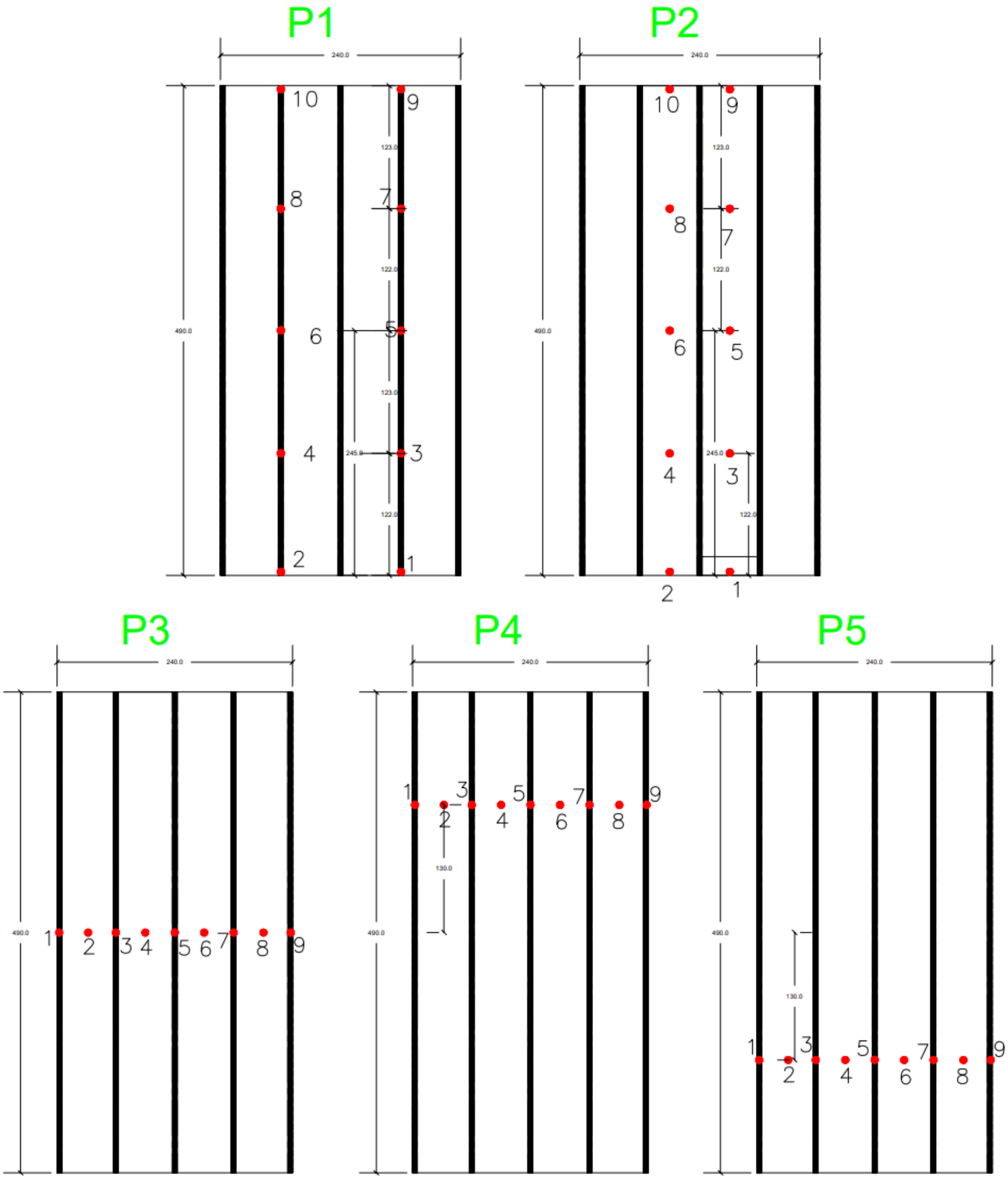


Figure 3-10. Sensor setups P1 to P5 used for walking tests.

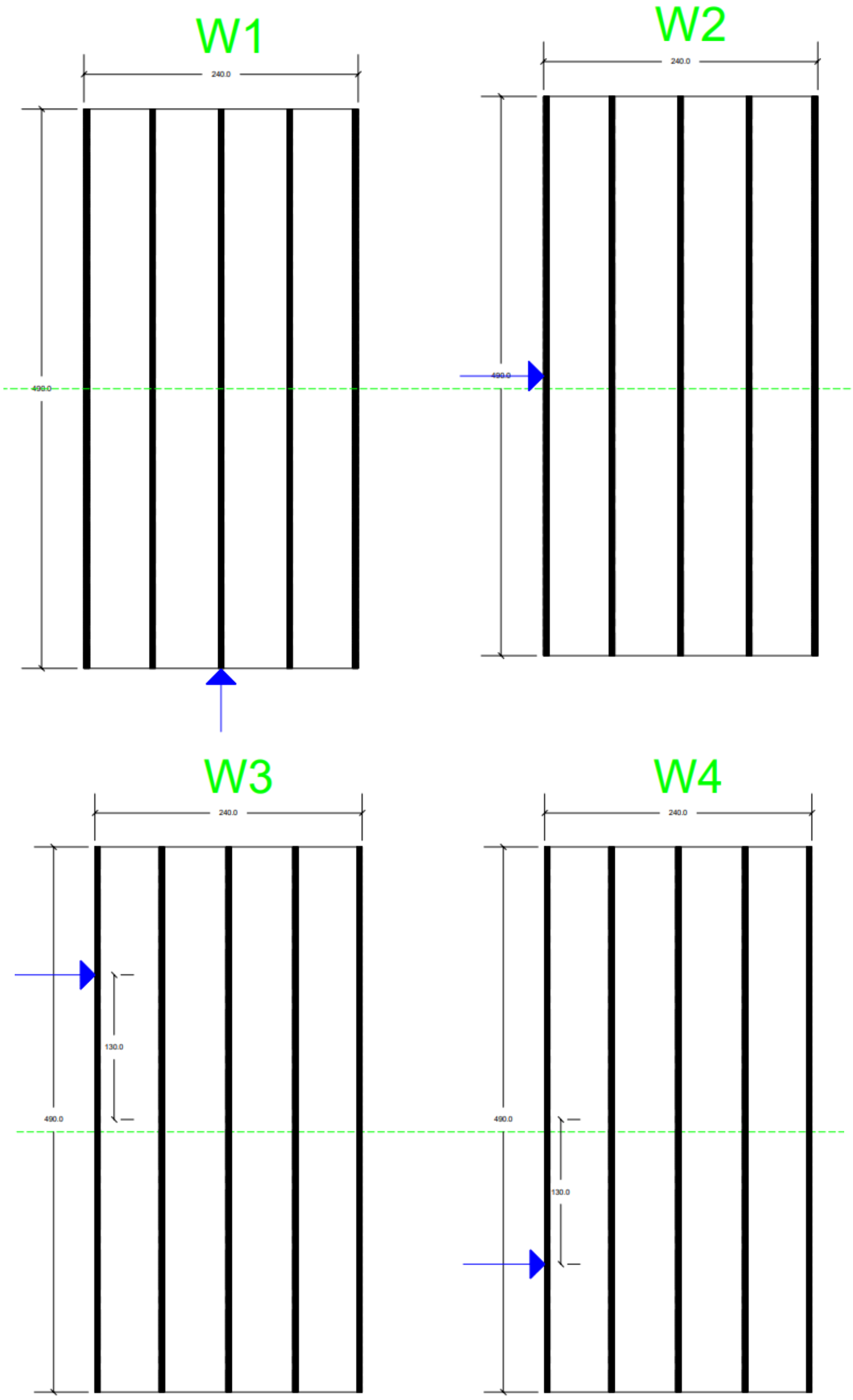


Figure 3-11. Walking paths W1 to W4 used for walking tests.

3.2.3 Vibration test with furniture

Five different test setups including floors with furniture arrangements were tested. One with no furniture, and four with furniture. The four setups with furniture are shown in the figures on the next page. The first setup, with no furniture, is called “Model00” and the other four is called “Model01” with the “1” increasing for every model to “Model04”.

The furniture was not fastened to the floor. It was simply placed on top of the floor, making sure the feet did not fall into any gaps in the floors with perforations. The feet of the desk were adjusted so that the desk stood steadily on all four feet, with no wiggling.

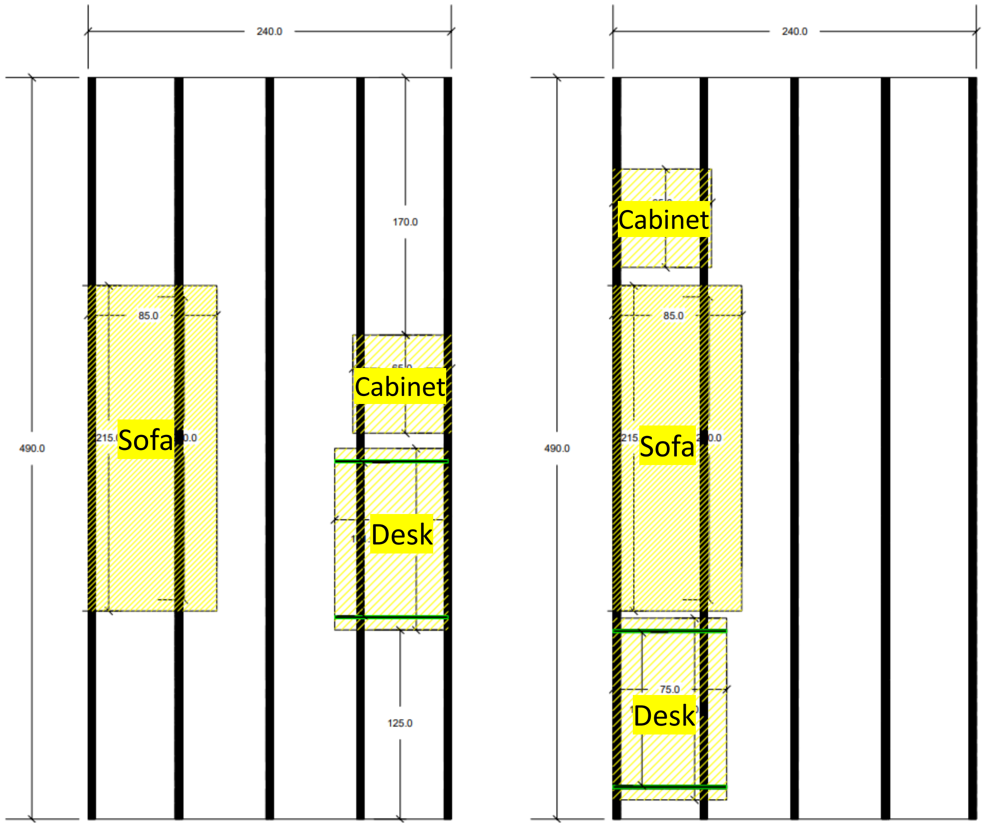


Figure 3-12. Model01 (left) and Model02.

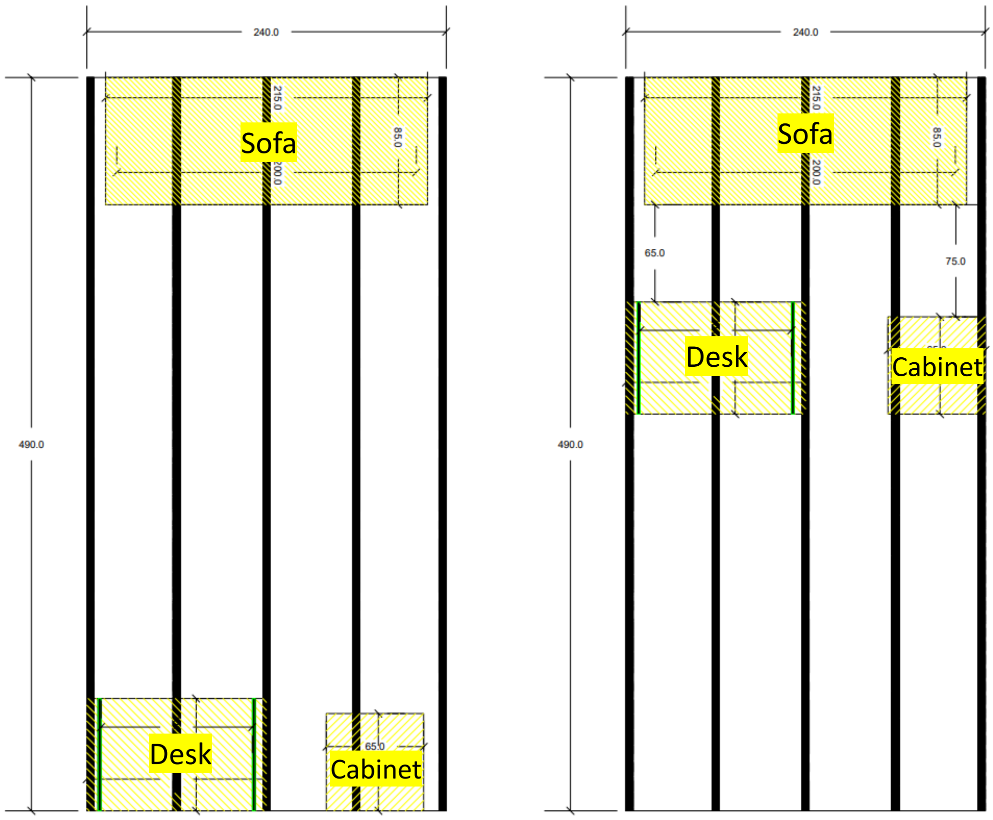


Figure 3-13. Model03 (left) and Model04.

The weights of the different furniture and the walking person are listed below. It's important to mention that the brown desk shown in Figure 3-8 was only used on floor G101. For the other floors, the white desk with the wooden blocks shown in Figure 3-14 were used. This was because of a logistics issue. The weight difference between the two desks is small (< 2%). This difference might impact the behaviour. If so, the impact is assumed to be minimal and of no significance.

Weight of furniture: (In total 122,7 kg when not including the brown desk)

- Sofa: 63,2 kg (17,5 kg on each back leg)
- Desk (brown): 16,7 kg
- Desk (white, with wooden blocks): 16,4 kg
- Cabinet: 23,8 kg
- Table (under the cabinet): 19,3 kg
- Walking person: 73,2 kg

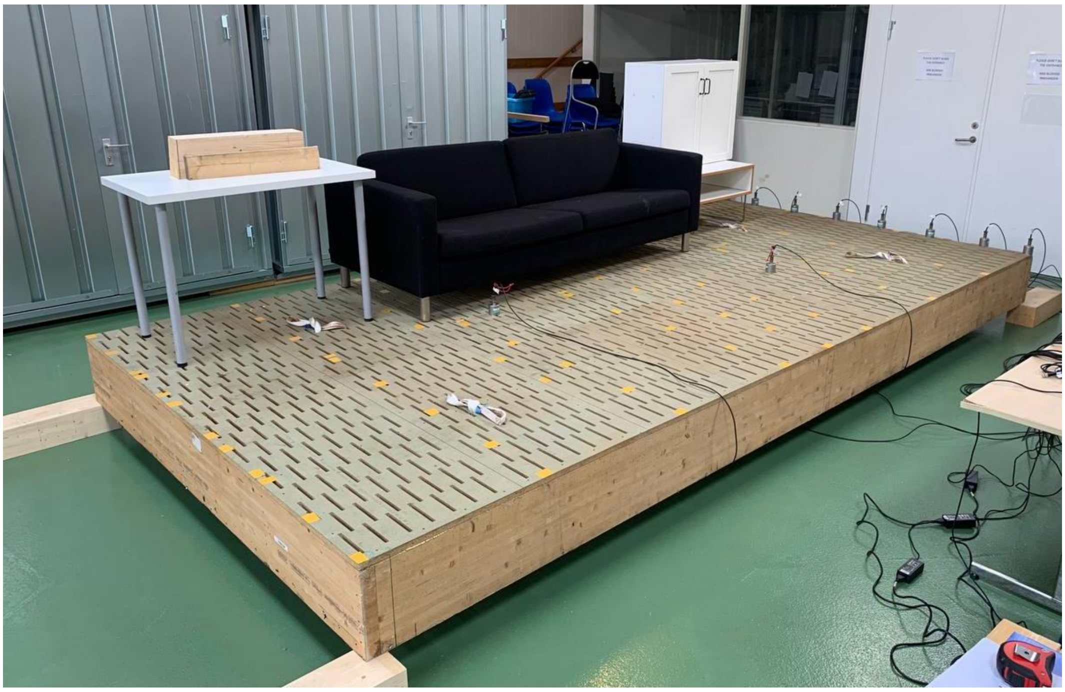


Figure 3-14. Model02 on floor G106.

3.2.4 Vibration test with sandbags

The hammer test was also performed using sandbags as the added live load instead of furniture. Floor G106 is the only floor tested with sandbags as live load. Tests with sandbags replacing the furniture were performed for all arrangements (Model01, Model02, Model03 and Model04). The purpose of the sandbags was for them to replace the furniture, having the same total mass but with a centre of mass close to the floor surface.

Figure 3-15. Model04 on floor G106 using sandbags.

The goal of this test was to investigate an effect Andersen et al. (2020) found by doing simulations on a finite element model of a joist floor with non-structural mass distributed over the floor. The non-structural mass was found to lower the natural frequencies of the floor, and even more so when the mass was elevated to the floor.

For the test with sandbags, the weight of the furniture was separated into bags, one for each leg on the furniture. For the sofa; 4 bags. For the desk; 4 bags. For the cabinet with table; 2 bags. The weight of the different bags are listed below.

Weight of sandbags: (total 101,2 kg)

- Sofa, front: 2 x 14,1 kg
- Sofa, back: 2 x 17,5 kg
- Desk: 4 x 4,1 kg
- Cabinet with table: 2 x 10,8 kg

Comparing the total weight of the sandbags to the total weight of the furniture, the sandbags weigh 21,5 kg less, due to an error in estimating an equivalent weight of the sandbags that replicates the furniture.

The weight ratio between the sandbags and the floor is 0,25, while the weight ratio between the furniture and the floor is 0,31.

3.3 Signal processing

To test the influence furniture and its placement have on the modal characteristics of a floor, a quasi-in-situ test was chosen to be performed. The floors were simply supported, as shown in Figure 3-2, not fully representative of an in-situ floor, but it is considered suitable for uncovering any significant effects. Performing the tests, we were not able to measure the input forces, making OMA the only option as we only have the output data.

Two methods were chosen to perform the OMA. One based on frequency domain called EFDD, and one based on time domain called SSI. This was to enable comparison between the results of the two methods. Thus, increasing the reliability of the end results.

All recorded data is in the form of time-history acceleration, meaning that the acceleration is measured over time. The sample rate used is 200 Hz, meaning that for every 0,005 second a measurement of the instantaneous acceleration was stored, adding up to 200 measurements per second. The time history acceleration can be plotted, as is shown in the figure below. The response clearly depicts decay of motion from time to time during the tests.

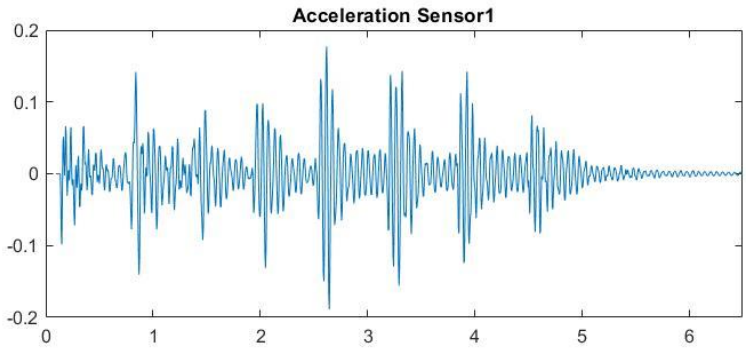


Figure 3-16. Time history acceleration from a walking test. Acceleration over time.

The time history acceleration data was analysed in two separate ways, one for each type of test. For the hammer test, the data was imported into the software, ARTeMIS Modal (see section 2.6.4), where the measurements were linked to their corresponding position on a geometry corresponding to the geometry of the floor. The software enables the processing of the data, and by using the methods EFDD and SSI (Structural Vibration Solutions, 2024b; Structural Vibration Solutions, 2024c), described in section 2.6.2, identifying and visualizing the modes was possible.

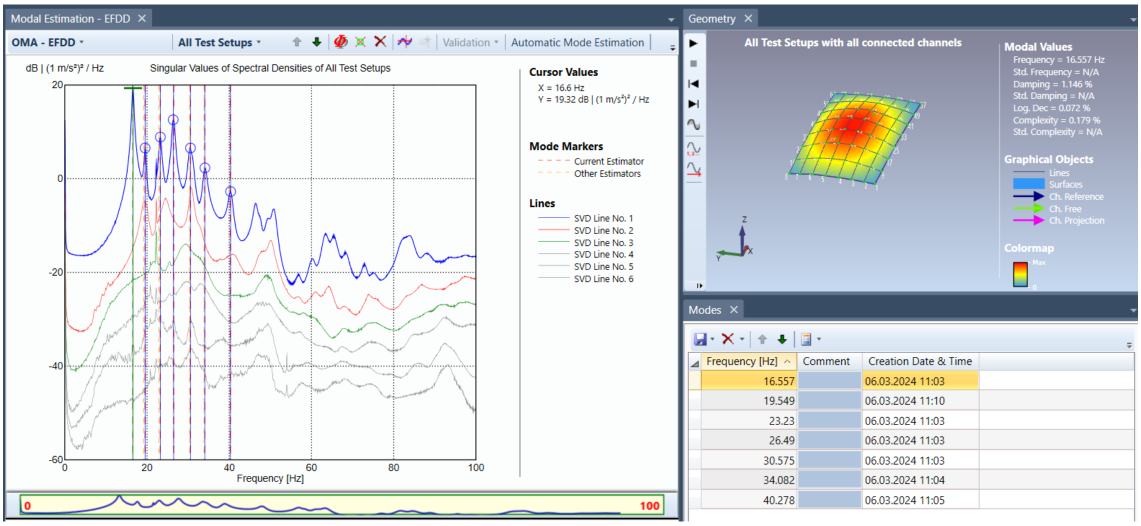


Figure 3-17. Seven modes selected manually using EFDD in ARTeMIS.

For the walking test, the data was processed in Matlab (See section 2.6.4). First, an appropriate length of the time history was extracted, called "windowing". The time windows have no tapering of the signal on either end, meaning the signal is simply cut off at the start and the end. The windows start right before the first response is recorded. The duration of the different time windows used is shown in the table below. Continuing, the maximum acceleration was found using the max()-function and the root mean square acceleration was calculated using the rms()-function. Furthermore, using a Matlab script, the time history acceleration of the sensors with highest rms acceleration was frequency weighted. Then this weighted time history acceleration was used to calculate a weighted rms acceleration and a vibration dose value for the exposure. This processing resulted in singular values used to evaluate the overall response of the floor. For the definition of these values, see section 2.5. For the definition of frequency weighting, see section 2.4.1. All values were stored in an excel sheet, where averages were calculated, the data was organized for easier analysis and then used to make figures to present results.

Table 3-4. Time windows used for analysis of the response from walking excitation.

	Duration	
Walk path \ Walking freq.	1,5 Hz (M)	2 Hz (F)
W1	6 s	4,7 s
W2	4 s	3,2 s
W3	4 s	3,2 s
W4	4 s	3,2 s

3.4 Data analysis

A lot of data was collected during the testing of the floors, and there are many interesting ways to use the data for analysis. Prioritizing had to be done, and the scope of the analysis was narrowed in to covering the research points mentioned in section 1.2. Analysis was divided into two main parts. First, analysis of the vibration performance of the different floors, and then analysis of furniture's effect on vibration performance. Additionally, comparison between the effect from using sandbags as the imposed mass and furniture was done.

Analysis involved investigating modal properties such as natural frequencies, damping and mode shapes. Higher modes were not as easy to capture as the first two. Thus, analysis involving comparison of the higher modes was relatively challenging.

The time history acceleration from walking tests were used to evaluate the vibration response using maximum acceleration and root mean square acceleration. To evaluate the vibration response in relation to human perception, weighted root mean square acceleration and vibration dose values were used.

The results from walking tests with walking frequency 1,5 Hz are mainly presented. Generally, the results from walking tests with walking frequency 2 Hz seem to have the same trends. To achieve a more covering analysis, the tests with 1,5 Hz were prioritized.

Charts with lines or columns in addition to tables were chosen to visualize the different values, simplifying analysis, comparison, and reading of the results.

4 Results

A lot of data was recorded as 19 hammer tests and 315 walking tests were performed, spread over three floors with five different furniture arrangements (model00 to model04) with one of the arrangements being “no furniture”. There are many ways to process, analyse the data and present the results. A selection of results to focus on had to be done, and the selected results are presented in this chapter. The presentation of the results is split into two parts, one for comparing the three floors without furniture, and the other for analysing the effects of adding imposed load in the form of furniture.

Through all the result sections, a colour code is used to differentiate the floors. Floor G101 is represented by the colour orange, blue for G105 and green for G106. The only exception is in section 4.2.2, where model00 is represented by blue columns for all floors, and orange and grey represent the two other models depending on the type of walking test.

An example of naming of a walking test is “P1W1”, where “P1” means sensor setup 1, and “W1” means walking path 1. The five sensor setups and four walking paths used during testing are presented in section 3.2.2.

4.1 Floors without furniture

This section first presents the mode shapes of modes up to about 45 Hz, with their denotation (Table 4-1). The denotation of the modes consists of two numbers, the first for the number of half-sine waves in the longitudinal (span) direction, and the second for the transversal number of half-sine waves.

Continuing, the modal properties, frequency and damping, of the captured modes are presented in tables and diagrams (Table 4-2 and Table 4-3, and Figure 4-1 and Figure 4-2). The values presented are the averages of the values found using both EFDD and SSI.

Lastly, the response in the floors from walking tests with path W1 is presented in the form of peak acceleration and RMS acceleration, for both 1,5 Hz and 2 Hz walking frequency (Figure 4-3 to Figure 4-6). The results from the remaining walking tests will not be presented, but the same trends are observed from them as well.

Table 4-1. Mode shapes with their corresponding denotation. Screenshots from ARTeMIS Modal.

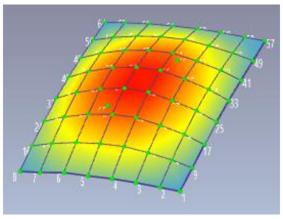
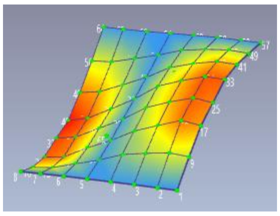
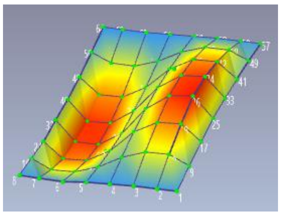
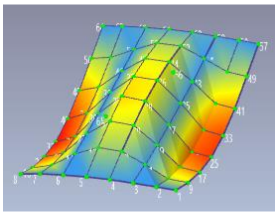
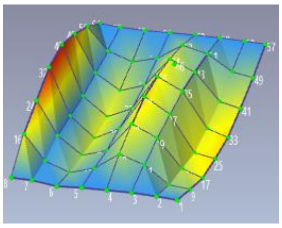
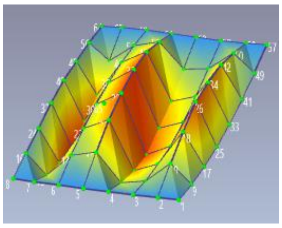
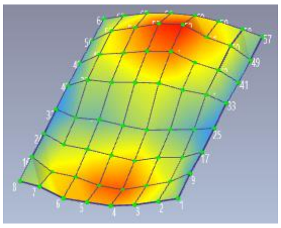
 (1,1)	 (1,2a)	 (1,2b)	 (1,3)
 (1,4a)	 (1,4b)	 (2,1)	

Table 4-2. Frequencies (Hz) of the modes up to around 45 Hz for all floors without furniture (Model00). (Average between EFDD and SSI)

Frequency	(1,1)	(1,2a)	(1,2b)	(1,3)	(1,4a)	(1,4b)	(2,1)
G101	16,6	19,4	23,1	26,5	30,5	34,0	40,3
G105	17,7	20,7	25,7	28,7	32,8	-	41,0
G106	17,4	18,8	24,6	34,2	-	-	41,6

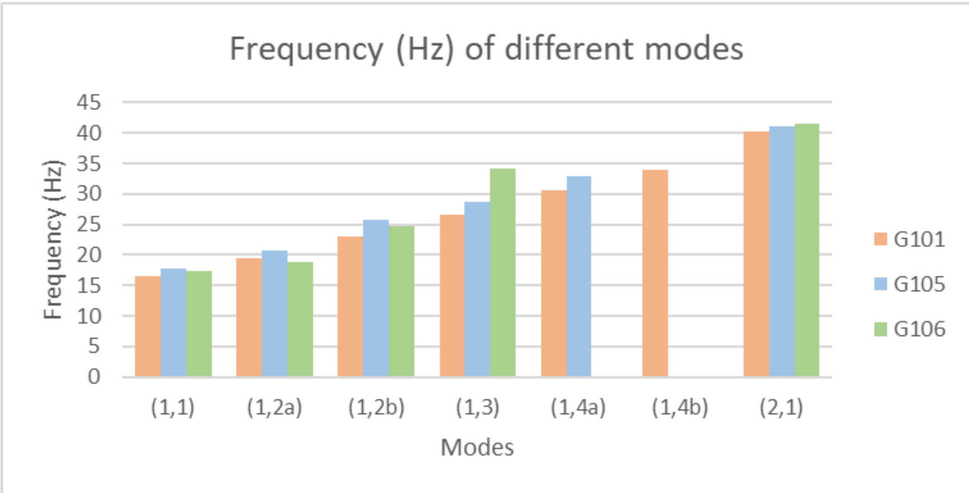


Figure 4-1. Frequencies (Hz) of the modes up to around 45 Hz for all floors without furniture (Model00).

Table 4-3. Damping ratio (%) of the modes up to around 40 Hz for all floors without furniture (Model00). (Average between EFDD and SSI)

Damping	(1,1)	(1,2a)	(1,2b)	(1,3)	(1,4a)	(1,4b)	(2,1)
G101	1,2	1,7	1,8	1,3	1,4	2,3	2,3
G105	1,1	2,6	2,2	1,0	1,3	-	1,5
G106	1,2	1,8	2,0	1,6	-	-	2,4

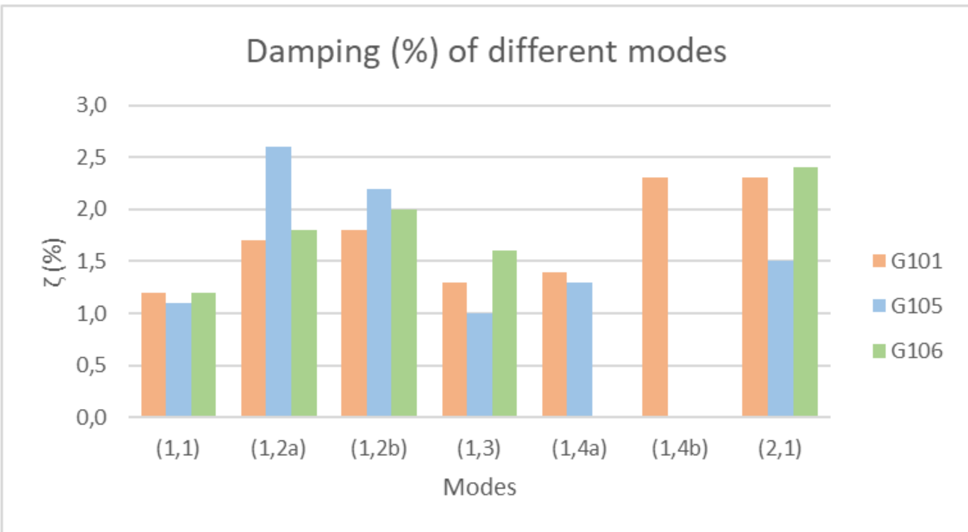


Figure 4-2. Damping ratio (%) of the modes up to around 45 Hz for all floors without furniture (Model00).

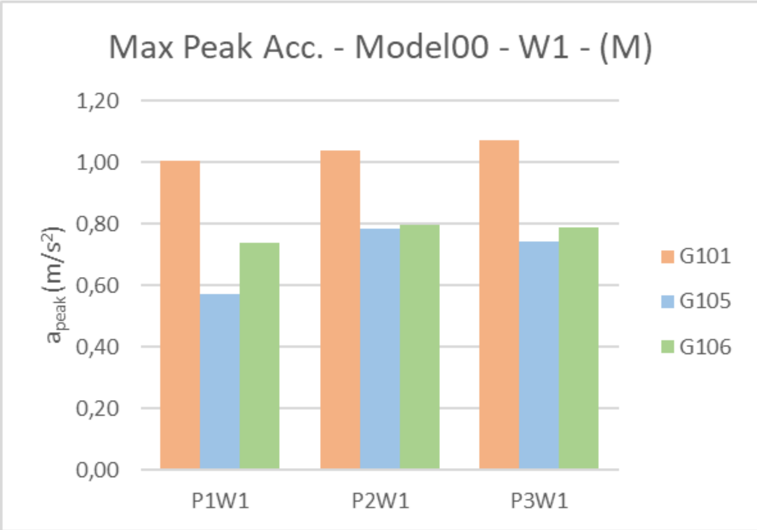


Figure 4-3. Maximum peak acceleration of all three floors during the walking tests (1,5 Hz) with walking path W1.

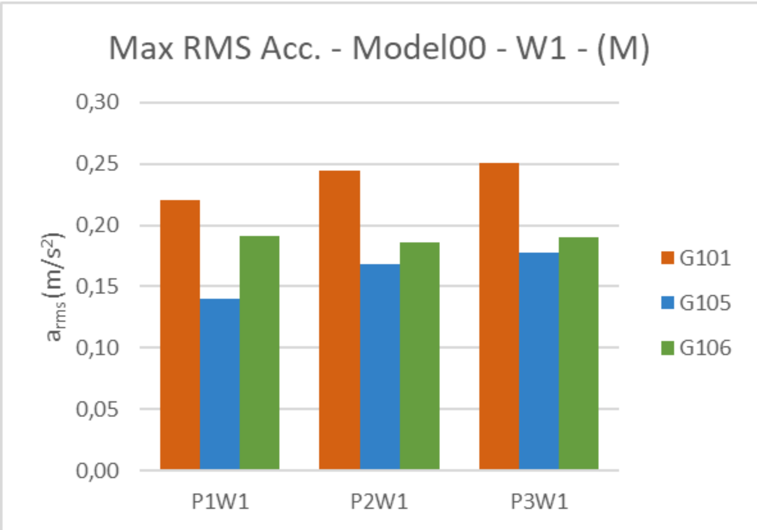


Figure 4-4. Maximum rms acceleration of all three floors during the walking tests (1,5 Hz) with walking path W1.

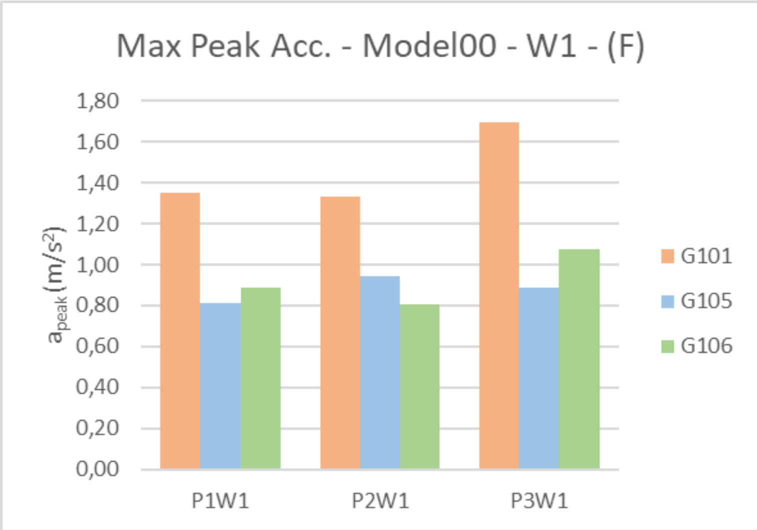


Figure 4-5. Maximum peak acceleration of all three floors during the walking tests (2 Hz) with walking path W1.

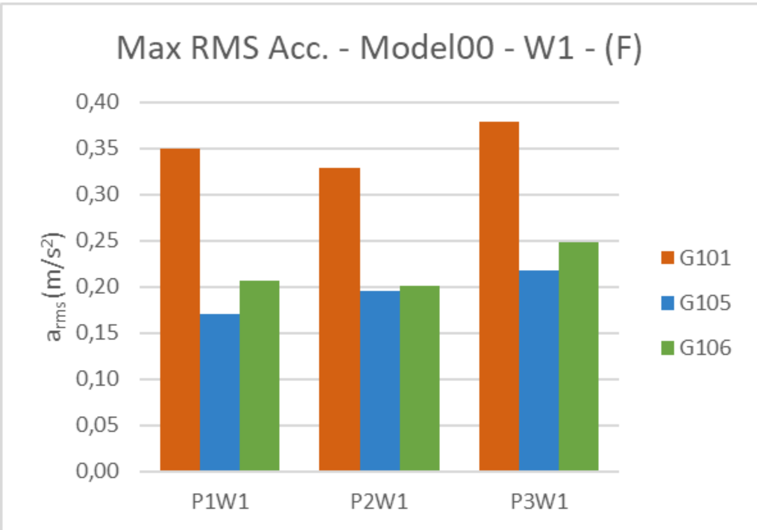


Figure 4-6. Maximum rms acceleration of all three floors during the walking tests (2 Hz) with walking path W1.

4.2 Floors with furniture

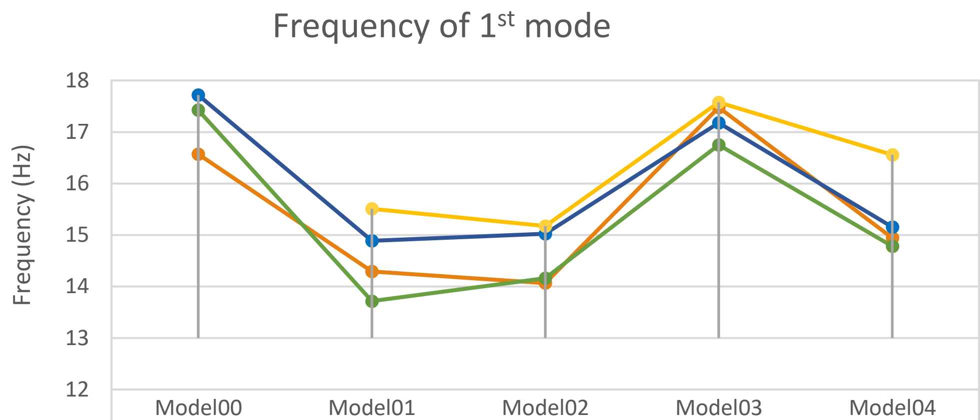
This section first presents the frequency and damping of the first and second mode for all models on all three floors (section 4.2.1). Then the average peak acceleration response and RMS acceleration response for each sensor in all walking tests, on all floors with walking frequency of 1,5 Hz (section 4.2.2). Furthermore, the maximum values of peak acceleration and RMS acceleration for every model on each floor, regardless of walking path and sensor setup, is presented, both for walking frequency 1,5 Hz and 2 Hz. Additionally, the weight ratio furniture-to-floor and the changes in maximum RMS acceleration for the models with furniture relative to model00, in percent, is presented (section 4.2.3). Lastly, weighted RMS acceleration and a vibration dose value for every model on each floor is presented (section 4.2.4). Those values are calculated from the same measurements giving maximum peak acceleration and RMS acceleration with 1,5 Hz walking frequency. See section 2.5.2 and 2.5.3 for definitions of weighted RMS acceleration and vibration dose value, respectively.

For an overview of the different sensor setups and walking paths, see section 3.2.2. For an overview of the combined sensor setups, furniture arrangements and walking paths, see annex A on page 77.

While performing the walking tests, the test was repeated five times for every combined sensor setup and walking path, for each walking frequency as explained in section 3.2.2. Section 4.2.2 (Figure 4-11 through Figure 4-16) shows the average peak acceleration and average RMS acceleration each sensor experienced through these five repetitions. The maximum response is generally around the centre sensors for sensor setups P1 and P2, while for the remaining sensor setups, the response has a more flat distribution. The similar values will not be presented for walking tests with walking frequency 2 Hz, but the same trends are observed for those tests as well.

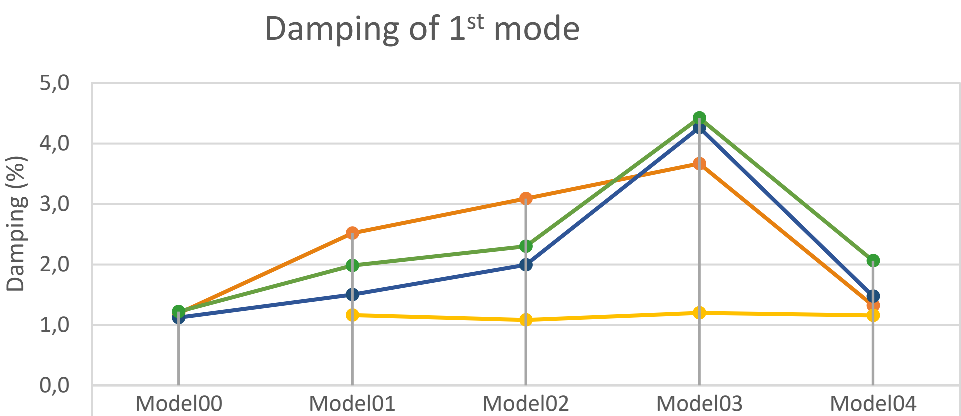
4.2.1 Frequency and damping

The following figures present the frequencies and damping for the fundamental mode and the second mode for every model on each floor. The mode shapes are (1,1) and (1,2a) from Table 4-1, respectively. The values presented are the averages between the values found using EFDD and SSI in ARTeMIS Modal. For the test with sandbags, finding the second mode was quite challenging for some models. Thus, the frequency and damping is only presented for the first mode for that case.



	Model00	Model01	Model02	Model03	Model04
G101	16,6	14,3	14,1	17,5	14,9
G105	17,7	14,9	15,0	17,2	15,2
G106	17,4	13,7	14,2	16,8	14,8
G106 (Sand)		15,5	15,2	17,6	16,6

Figure 4-7. Frequency of the fundamental mode for every model on all three floors, and with sandbags.



	Model00	Model01	Model02	Model03	Model04
G101	1,2	2,5	3,1	3,7	1,3
G105	1,1	1,5	2,0	4,3	1,5
G106	1,2	2,0	2,3	4,4	2,1
G106 (Sand)		1,2	1,1	1,2	1,2

Figure 4-8. Damping of the fundamental mode for every model on all three floors, and with sandbags.

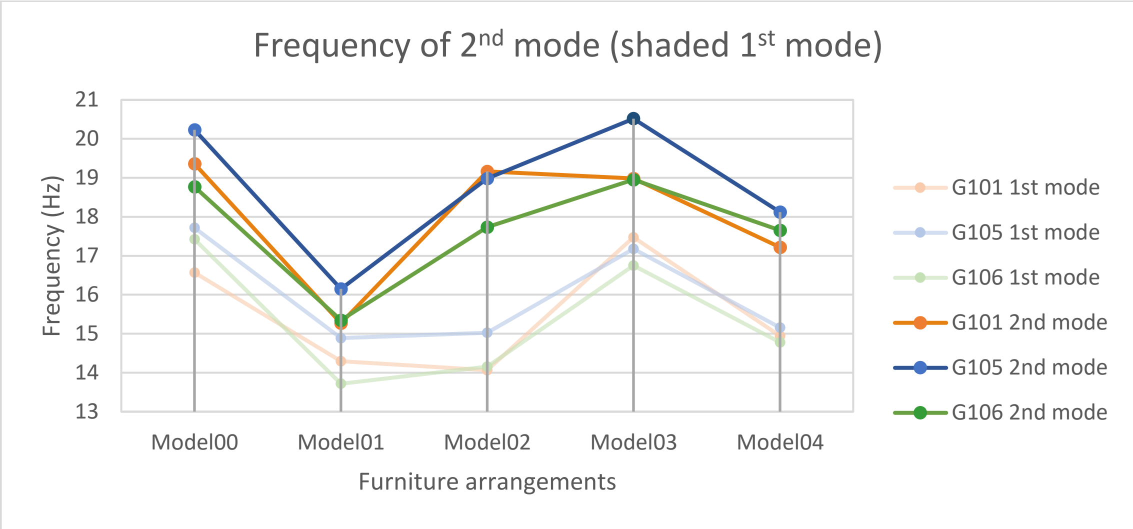


Figure 4-9. Frequency of the 2nd mode (shaded for 1st mode) for every model on all three floors.

Table 4-4. Frequencies of 2nd mode for every model on all floors.

Freq. (Hz) – 2nd mode	Model00	Model01	Model02	Model03	Model04
G101	19,4	15,3	19,2	19,0	17,2
G105	20,2	16,1	19,0	20,5	18,1
G106	18,8	15,3	17,7	19,0	17,7

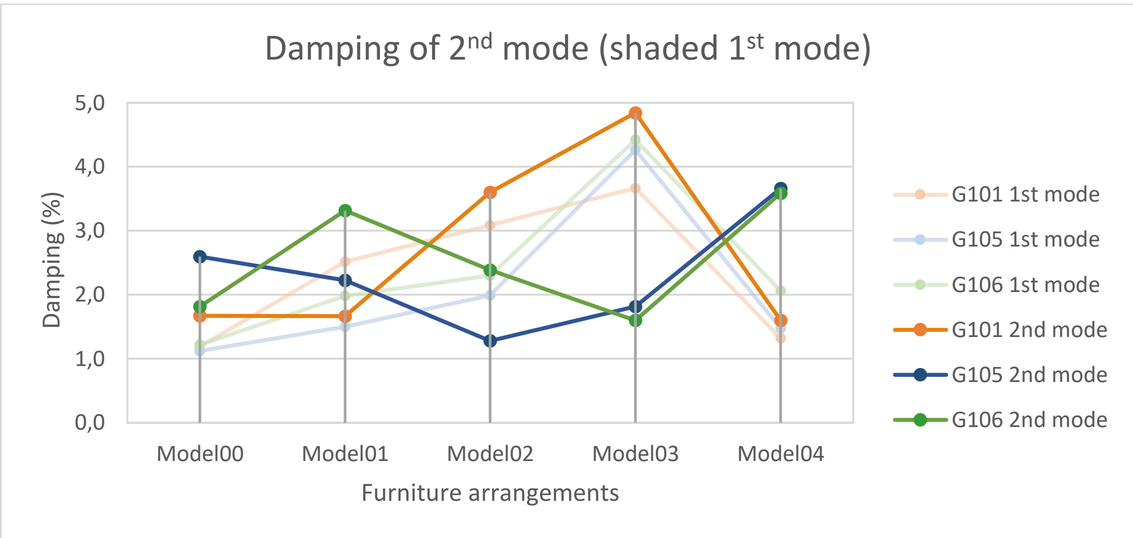


Figure 4-10. Damping of the 2nd mode (shaded for 1st mode) for every model on all three floors.

Table 4-5. Damping of 2nd mode for every model on all floors.

Damping (%) – 2nd mode	Model00	Model01	Model02	Model03	Model04
G101	1,7	1,7	3,6	4,8	1,6
G105	2,6	2,2	1,3	1,8	3,7
G106	1,8	3,3	2,4	1,6	3,6

4.2.2 A_{peak} & A_{rms}

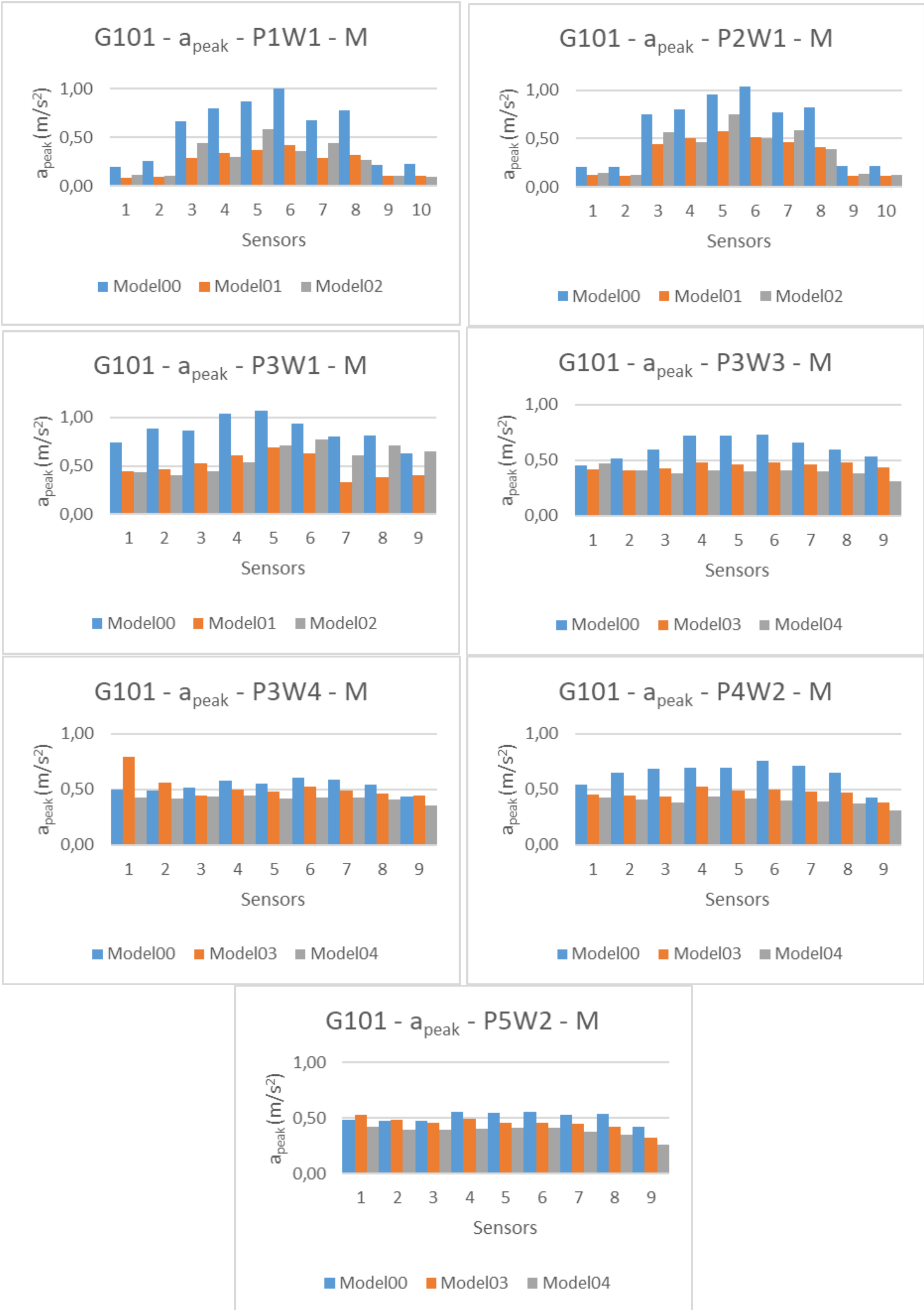


Figure 4-11. Average peak acceleration of each sensor for all the combined sensor setups and walking paths with 1,5 Hz walking frequency on floor G101.

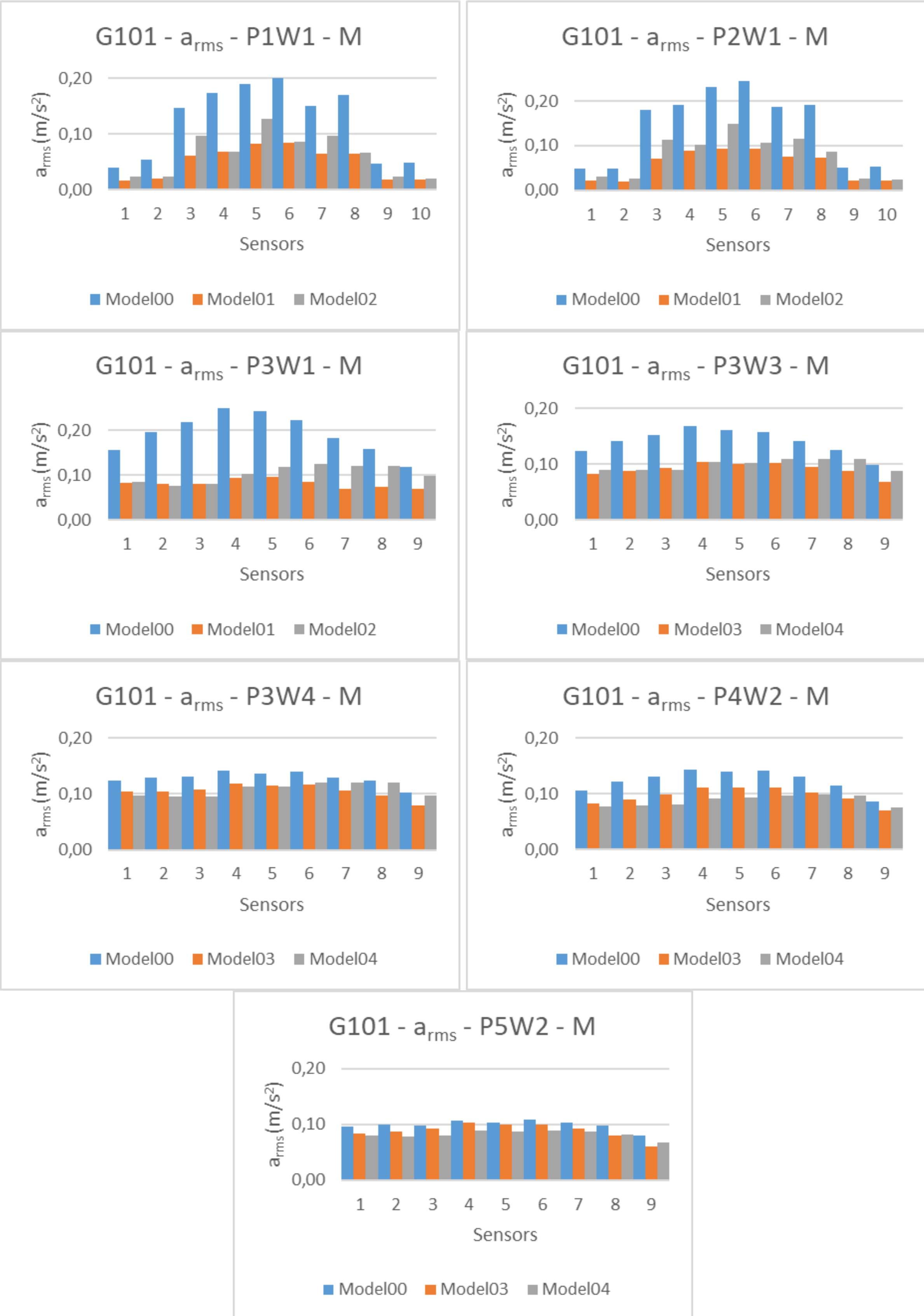


Figure 4-12. Average RMS acceleration of each sensor for all the combined sensor setups and walking paths with 1,5 Hz walking frequency on floor G101.

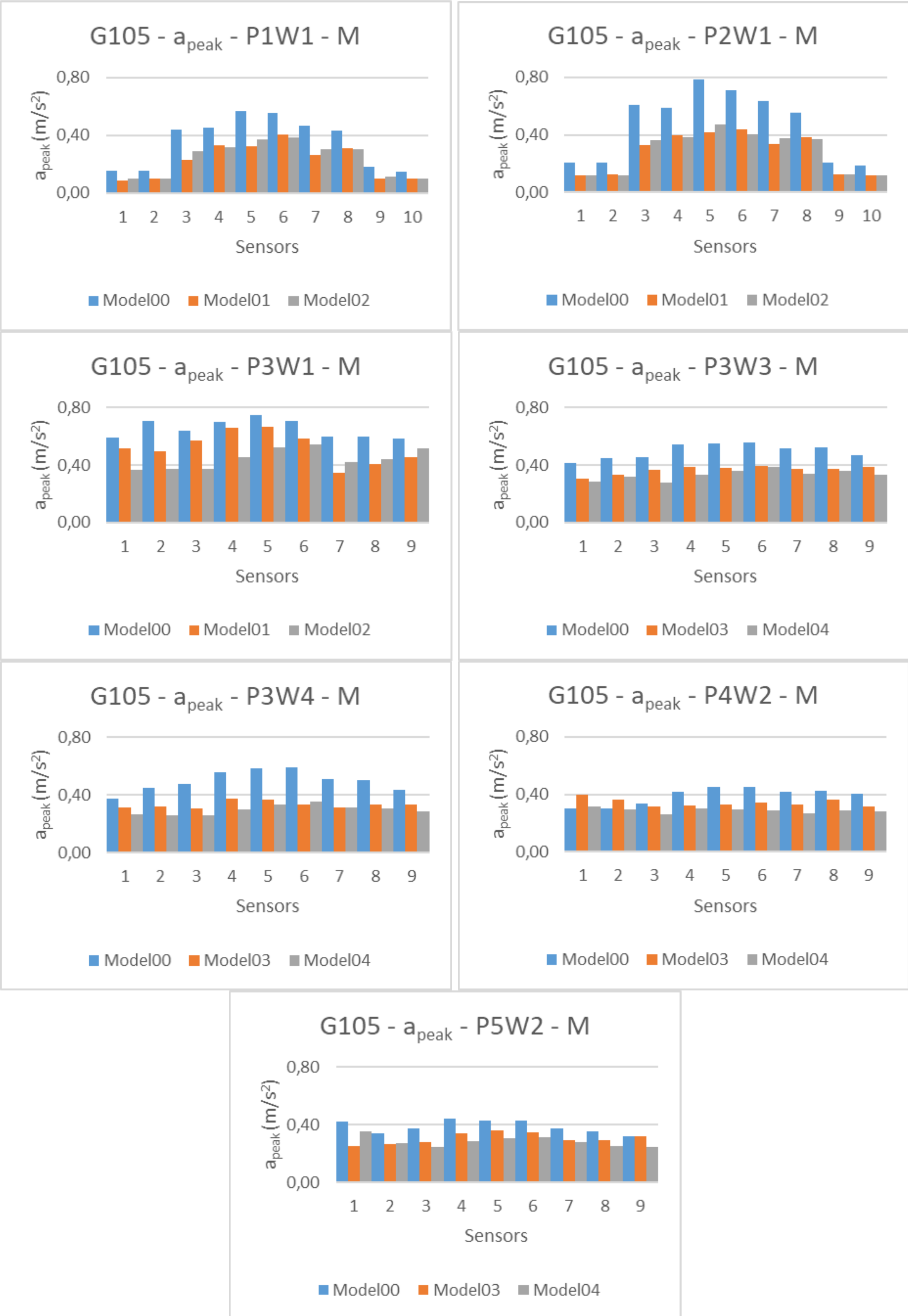


Figure 4-13. Average peak acceleration of each sensor for all the combined sensor setups and walking paths with 1,5 Hz walking frequency on floor G105.

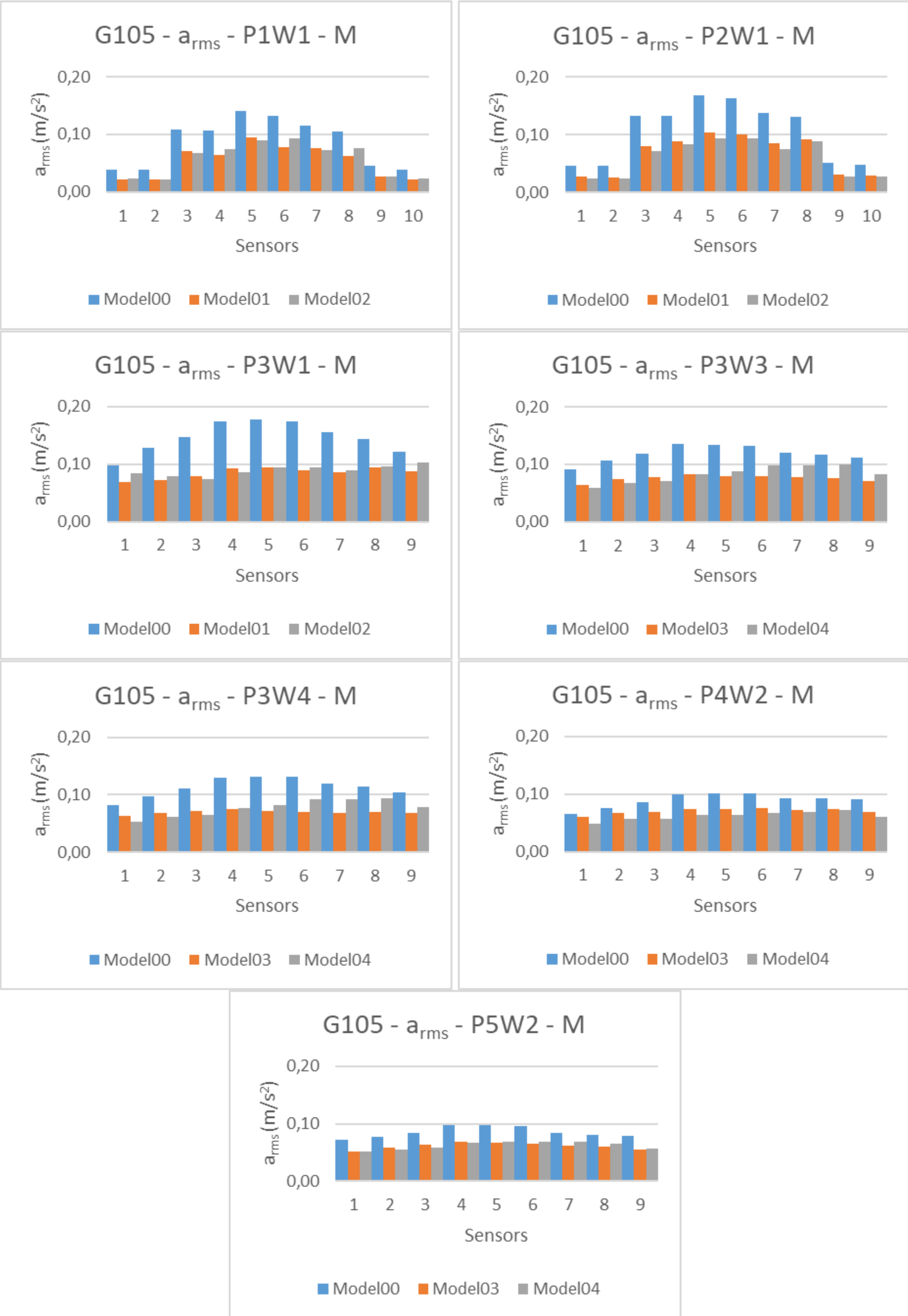


Figure 4-14. Average RMS acceleration of each sensor for all the combined sensor setups and walking paths with 1,5 Hz walking frequency on floor G105.

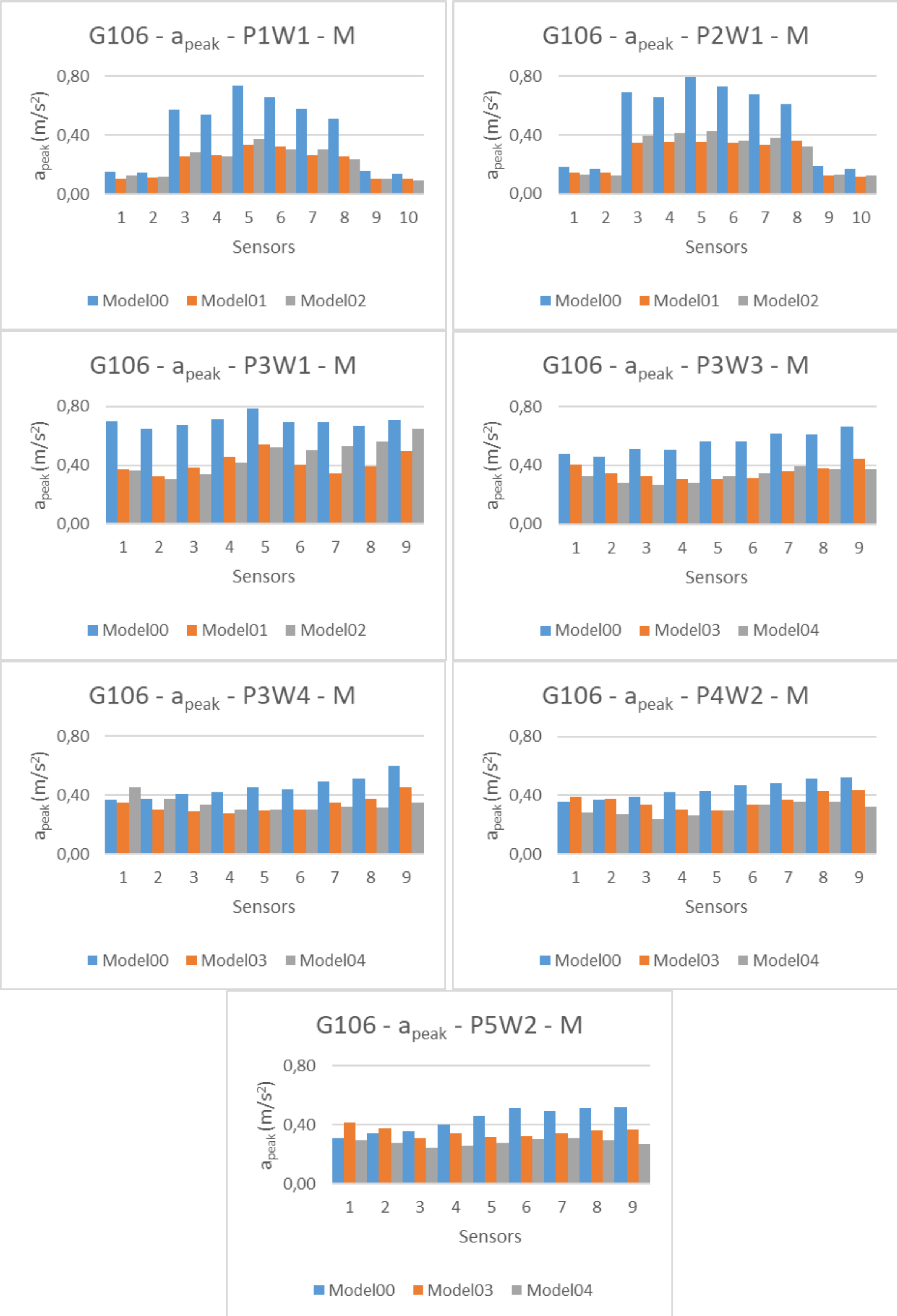


Figure 4-15. Average peak acceleration of each sensor for all the combined sensor setups and walking paths with 1,5 Hz walking frequency on floor G106.

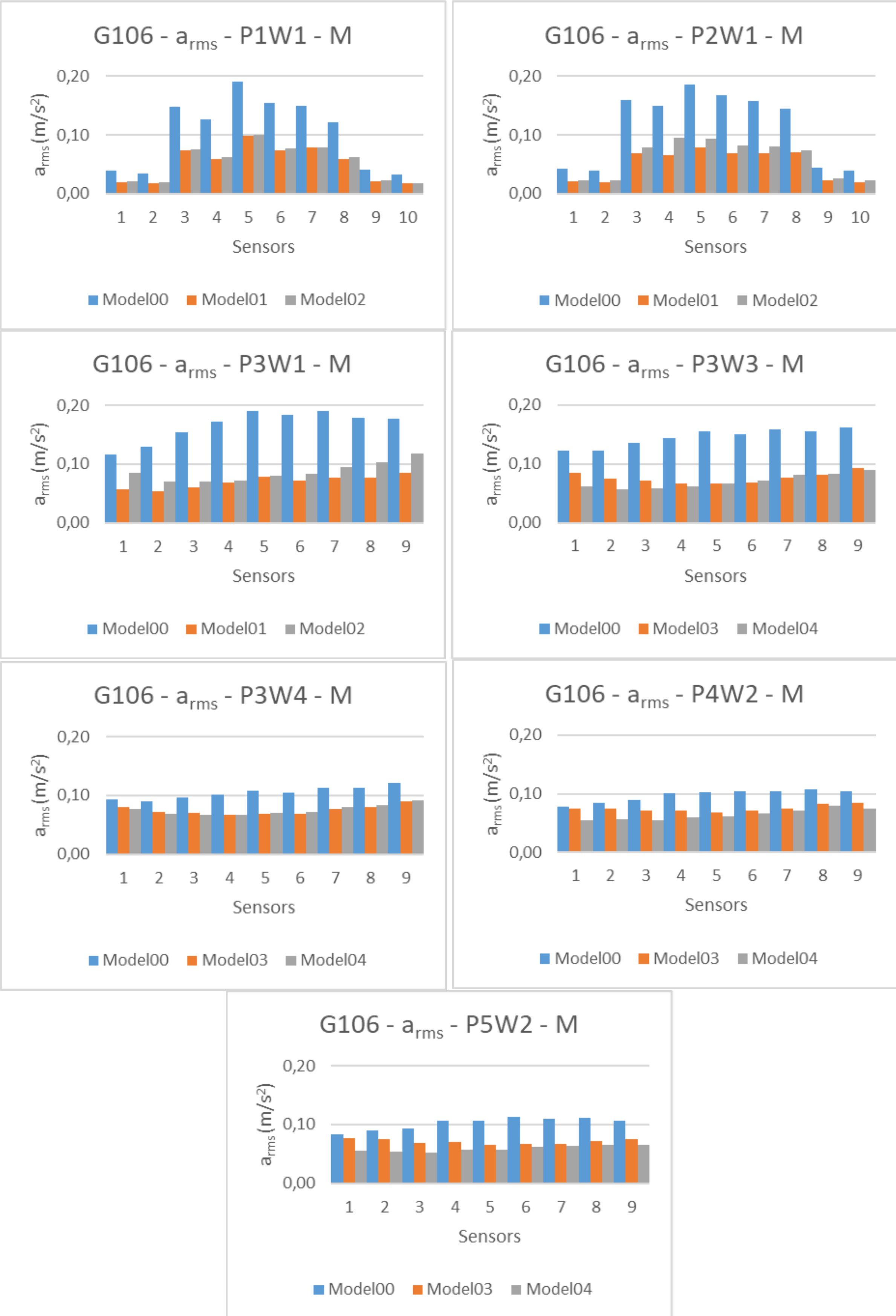


Figure 4-16. Average RMS acceleration of each sensor for all the combined sensor setups and walking paths with 1,5 Hz walking frequency on floor G106.

4.2.3 $A_{peak,max}$ & $A_{rms,max}$

Figure 4-17. Maximum peak acceleration and RMS acceleration (m/s2) for each model through all walking tests with 1,5 Hz walking frequency, for each floor.

Figure 4-18. Maximum peak acceleration and RMS acceleration (m/s2) for each model through all walking tests with 2 Hz walking frequency, for each floor.

Table 4-6. Weight ratio furniture-to-floor for each floor and the change in max a_{rms} relative to Model00. ***Walking frequency 1,5 Hz (M).***

Floor	Max a_{rms} Model00	Weight ratio furn./floor	Change in $a_{rms,max}$ relative to Model00			
			Model01	Model02	Model03	Model04
G101	0,25	0,34	-62 %	-41 %	-53 %	-52 %
G105	0,18	0,32	-41 %	-42 %	-53 %	-44 %
G106	0,19	0,31	-48 %	-38 %	-51 %	-52 %

Table 4-7. Weight ratio furniture-to-floor for each floor and the change in max a_{rms} relative to Model00. ***Walking frequency 2 Hz (F).***

Floor	Max a_{rms} Model00	Weight ratio furn./floor	Change in $a_{rms,max}$ relative to Model00			
			Model01	Model02	Model03	Model04
G101	0,38	0,34	-54 %	-47 %	-63 %	-66 %
G105	0,22	0,32	-26 %	-32 %	-44 %	-55 %
G106	0,25	0,31	-39 %	-32 %	-46 %	-58 %

4.2.4 A_w & VDV

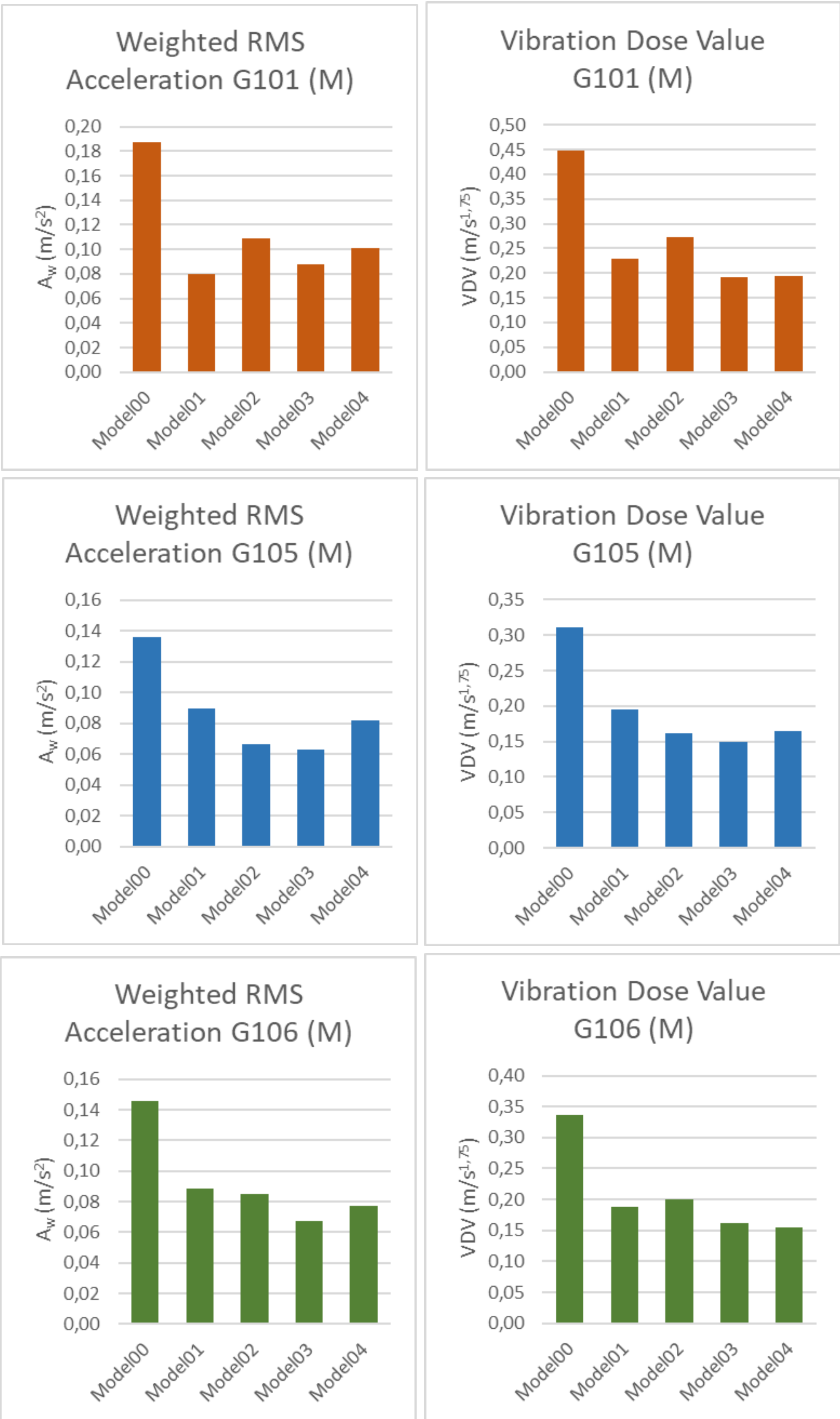


Figure 4-19. Weighted RMS acceleration and VDV for walking tests with 1,5 Hz walking frequency, calculated from the same measurements giving max RMS acceleration.

5 Discussion

Many interesting effects have been observed while visualizing and analysing the data, and covering all of the effects would take a lot of time and effort. Thus, the focus has been narrowed down to covering the scope of the study presented in section 1.2. The focus of this discussion is divided into three main parts; comparison of the floors without furniture, discussing the effect of adding furniture, and comparing the effect of furniture with the effect of sandbags as imposed load.

5.1 Floors without furniture

The characteristics of the floors are presented in Table 3-1. Key characteristics are listed below:

- G101 – Perforated particleboard – 363,3 kg
- G105 – Not perforated particleboard – 380,3 kg
- G106 – Perforated particleboard & blocking – 402,2 kg

Compared to G101, G105 is expected to have higher stiffness in both longitudinal and transversal direction. However, the mass is also a little higher. Considering the relationship between stiffness and mass demonstrated in equations (2.2) and (2.3), it's hard to predict whether the fundamental frequency will be higher or lower for G105. The same stands for G106 which is expected to have a higher transversal stiffness, but then also has even more mass than G105.

Looking at Table 4-1 and Table 4-2 presenting the mode shapes and frequencies, G101 has six modes before mode (2,1), with every mode having a more complex transversal mode shape than the previous. This indicates a higher stiffness in the longitudinal direction than in the transversal direction, which is expected. Furthermore, observing the fact that G105 has one less mode before (2,1) and G106 has two less modes before (2,1) indicates that the two floors have increased transversal stiffness, with G106 having the highest transversal stiffness, relative to the longitudinal stiffness.
Considering the overall stiffness, the frequency of the first three modes are higher for G105 compared to G106, suggesting a higher stiffness for G105 overall.

Figure 4-3 to Figure 4-6 present the maximum peak and RMS acceleration response in the floors from walking tests with walking path W1, both with walking frequency 1,5 Hz and 2 Hz. In all tests, except for P2W1 in Figure 4-5, the response in G105 is the lowest. Table 4-3 and Figure 4-2 shows that G105 has higher damping for the lower modes, while for the higher modes, G105 has lower damping. The combination of the lower response and damping distribution between the modes in G105, indicates that the modal participation is highest for the lower modes. G106 generally has more damping than G101, and higher damping than G105 for the higher modes, but since the damping of the lower modes are lower in G106 than G105, there is higher response in G106.

Overall, floor G105 seems to perform best. Both G105 and G106 perform better than G101, suggesting that non-perforated boards or transversal blocking in mid-span are two ways to improve the vibration performance. A combination of these two might be even better. This also suggests that perforating the boarding of bare joisted timber floors may reduce the modal stiffnesses to masses ratios of the system. Now, a floor in situ has more components on the floor surface and maybe under, that can have similar effects on the vibration performance. Investigation of a floor in situ is therefore suggested.

5.2 Floors with furniture

For this discussion it's recommended to have a clear understanding of what the different models are. Model00 is without furniture. The remaining models involve furniture and are presented in section 3.2.3. For a visual overview of the combined sensor setups, furniture models and walking tests performed, see appendix A on page 77.

5.2.1 Furniture's effect on frequency

The figures and tables in section 4.2.1 show that the frequency of the first mode is generally lowered around 15% when furniture is added, except with model03 where the frequency of the first mode do not change too much and is even increased for floor G101. This indicates that for models 01, 02 and 04, the added mass participate to lower the frequency and doesn't contribute to increase the stiffness to the same extent. With model03 on the other hand, the mass contributes almost equally to lower the frequency and increase the stiffness, resulting in an almost unchanged frequency. A possible explanation for this is that the furniture in model03 have a "clamping effect" on the floor.

For the second mode, the frequency is lowered the most with model01 (around 20%) and a little with model02 and model04. Again, model03 gives the highest frequencies, except for floor G101 where model02 gives a little higher frequency than model03.

Overall, considering the frequencies of the first two modes with the different models, it seems that placing the live load close to the centre of a floor will decrease the natural frequencies, while locating the live load closer to the edges does not affect the natural frequencies significantly, and can in some cases increase the natural frequencies.

Focusing on the fundamental frequency only, model03 stands out as the best alternative to mitigate vibration response. But then, model00 seems to perform as good as model03. However, as will be discussed further down, that does not seem to be the case. Higher fundamental frequency does not mean better vibration performance. Thus, considering the damping of the modes is necessary.

5.2.2 Effect of furniture on damping the tested floors

The damping of the first two modes, presented in figures and tables in section 4.2.1, does not change as uniformly across the floors and models as the frequencies do. Thus, considering each floor individually is necessary. As a base, the damping ratio across all floors with model00 range from 1,1% to 1,2% for the first mode, and from 1,7% to 2,6% for the second mode.

For floor G101, the damping of the first mode increase significantly with model01, model02 and model03, with maximum damping of 3,7% with model03. The damping is practically unchanged with model04. Damping of the second mode increase similarly with model02 and model03 to 3,6% and 4,8%, respectively. No change with model01 and model04. For floor G101, the damping of the two modes with model01, model02 and model03 suggest that the vibration performance is better, but not with model04. Any change in performance with model04 may then come from a changing effect of higher modes, which will not be covered in this thesis.

Considering floor G105, for the first mode, the damping increases a little with model01, model02 and model04. It increases significantly with model03 to a damping ratio of 4,3%. The damping of the second mode is decreased with model01, model02 and model03, from 2,6% with model00 to 1,3% at the lowest with model02. The damping is increased to 3,7% with model04. Any change in vibration performance could be caused by a change in modal participation between the two modes.

Floor G106 sees an increase in damping of the first mode with all models similar to floor G105, with model03 having the most significant damping of 4,4%. For the second mode, damping increases significantly with model01 and model04 to 3,3% and 3,6%, respectively. A little increase is observed with model02, but the damping remains practically unchanged with model03. Again, a change in the modal participation between the two modes could cause a change in vibration performance. Isolated, the damping of the two modes suggests a better vibration performance with every model on floor G106.

Overall, the furniture affects the damping. In some cases more and some cases less damping. Knowledge on any effect on higher modes and modal participation is needed to predict the effect of damping on vibration response.

It is important to note that the damping ratios presented in section 4.2.1 are from a modal analysis using the vibration response from a light excitation with a rubber hammer. Considering the vibration performance in relation to walking excitation, we're looking at a relatively greater impact force causing greater deformations in the floor. This might change the relative effect of damping with the different models, explaining any change in vibration performance.

5.2.3 Effect of furniture on vibration responses

The figures in section 4.2.2 show the average peak and RMS acceleration response measured by each sensor for every walking test with 1,5 Hz walking frequency. For the walking tests with walking path W1, the centre sensors generally measured the highest response. For the other walking tests, mostly with the sensors placed in a line across the floor in the transverse direction, the response is more evenly distributed with some of the highest responses occurring at the edges. This effect is more pronounced for the models with furniture (model01 to model04), and especially on floor G106 where the response in some cases obtains a "u-shape" distribution. The corresponding values for the tests with walking frequency 2 Hz are presented in appendix C from page 83. Similar trends are observed in the data from those tests as well.

From all the figures in section 4.2.2, we observe that the responses with model00 (blue columns) is generally higher than the other models. This indicates that the response is attenuated when furniture is placed on the floor. We also see from section 4.2.3, that the maximum responses in the floors are lowered when furniture is added, with model03 and model04 seemingly having the best performance overall.

Table 4-6 and Table 4-7 present the weight ratio furniture-to-floor for each floor and the change in maximum RMS acceleration with the four models with furniture relative to Model00. The weight ratio is ranging from 31% to 34%. The relative change in maximum RMS acceleration is ranging from -38% to -62% in the case of 1,5 Hz walking frequency, and from -26% to -66% in the case of 2 Hz walking frequency. Considering the spread in the relative response, both across the different floors and across the different models within each floor, a weight ratio furniture-to-floor seems to be a poor guide for estimating the effect of furniture on the dynamic properties of joisted timber floors. Again, the results suggest that adding furniture have an effect of attenuating the vibration response. Quantifying this effect in relation to the weight ratio furniture-to-floor, or imposed weight to floor weight, seems to be futile when not considering the arrangement of the imposed load and the floor characteristics. Further research is suggested on this topic, separating the different floor characteristics and arrangement of imposed load to describe the influence of the weight ratio of imposed weight to floor weight on the vibration response for each category.

Now, objectively saying that the response is lower doesn't necessarily mean that the experienced comfort regarding vibration is better. The two values weighted RMS acceleration and vibration dose value (VDV) are used to assess the perception of the vibration. Their definitions are presented in section 2.5. These two values are calculated and presented in section 4.2.4. They clearly show a lower response when furniture is added, in any configuration. With the different effects from the floor characteristics as well, the best configuration seems to be floor G105 with model03.

It should be noted that the values for weighted RMS acceleration and VDV presented in section 4.2.4 are calculated from the same measurements that gave the highest RMS accelerations presented in section 4.2.3. Also, only for the tests with walking frequency 1,5 Hz. With the frequency weighting (see section 2.4.1), and the fact that VDV is a fourth power version of the RMS, it is possible that one of the adjacent measurements could show a higher response than the ones presented in section 4.2.4. The reasoning behind not calculating these values for all measurements is that the calculation of these values is quite time consuming and prioritizing was deemed necessary.

The floors tested in this research were simply supported with a wooden block at every corner. For in-situ floors, the support conditions can be more influential, providing more resistance. In that case, the "clamping effect" observed from model03 might already be caused by the supports, making the effect of model03 less protruding compared to the other models. Additionally, some of the mode shapes captured involved bending along the floor edges. Mainly the edges in the longitudinal direction of the span. This type of free edges is rarely observed in situ except in the cases of balconies where floor edges may be left unsupported. In many cases, the edges are connected to the surrounding structure. That may change the modal properties and modal participation between the different modes, and thus the vibration performance. Research on the effect of furniture on in-situ joisted timber floors is therefore suggested.

With the effects found for placing furniture on joisted timber floors, it can improve the vibration performance, but also worsen the vibration performance if it leads to a fundamental frequency lower than 8 Hz. The significance of gaining knowledge on this specific topic can be argued both for and against. Introducing any new verification requirements on the effect of furniture is not considered wise as the variation in furniture arrangements is quite diverse and can change over time. Nevertheless, gaining knowledge on this topic could prove to be useful for mitigating vibration response in challenging cases or in the case of a constructed floor showing a poor vibration performance.

5.3 Furniture vs Sandbags

As suggested from the research of Andersen et al. (2020), performing a numerical analysis, live load placed on the floor surface may lower the first five natural frequencies of a floor. With that same mass elevated from the floor, the frequencies may be lowered even more. To investigate this effect, tests were performed using sandbags having around the same mass as the furniture. Only the fundamental frequency is considered in this discussion.

As mentioned in section 3.2.4, the total weight of the sandbags was 101,2 kg, while the total weight of the furniture was 122,7 kg. The mass of the sandbags was 21,5 kg less (17,5 %) than the furniture due to an error in estimating an equivalent weight of the sandbags that replicates the furniture. This difference in itself might cause the fundamental frequency to be a bit higher compared to the case with furniture. However, inspecting the equation for the fundamental frequency (equation (2.3), the weight of the whole floor should be considered. Considering the weight of both floor and furniture, the total weight is 524,9 kg, while the weight of the floor with sandbags is 503,4 kg. A reduction of only 4,1 %. Any effect from this difference is suspected to be small, but not necessarily insignificant.

Examining Figure 4-7, the fundamental frequencies of model01 to model 04 are all higher (5%-13%) for G106 with sandbags (yellow line) compared to G106 with furniture (green line). Model01 and Model04 both see an increase of 1,8 Hz with the use of sandbags (13% and 12%, respectively). Model 02 and model03 see an increase of 1,0 Hz (7%) and 0,8 Hz (5%), respectively. Arguing for the significance of these results is challenging, and drawing a definite conclusion is difficult. However, a conclusion is that these results seem to support the effect indicated by the research conducted by Andersen et al. (2020).

One important point to mention is that in the research by Andersen et al. (2020), the elevated mass was fixed to the floor, having a more direct connection to the floor. In this research the elevated mass is in the form of furniture, not as directly connected to the floor.

To investigate the effect elevating the centre of mass of imposed loads may have on the damping, the damping ratio for the fundamental frequency with model01 to model04, with sandbags, is presented in Figure 4-2. The damping seems to be almost unchanged compared to model00 (floor G106). But, considering the nature of a bag of sand compared to furniture and how differently they may respond to vibration over time, it is deemed improper to make any suggestions regarding the damping.

In the research from Andersen et al. (2020) the fundamental frequency is lowered around 16,7 % when the mass is elevated (using the centres of the cumulative distribution functions in Figure 1-5 and Figure 1-6), and in that case the non-structural mass equals 144% of the floor mass. In the research conducted here, the fundamental frequency is lowered 4,5%-11,6 %, depending on the arrangement of the live load, and in this case the live load equals 25,2 % (sandbags) and 30,5 % (furniture) of the floor mass. The relation between weight ratio and decreased frequency depends on other factors. Boundary conditions, floor finishing, type of live loads (furniture and equipment), centre of gravity from the floor surface and more. Any relation between the mass ratio (imposed mass over floor mass) and the impact of elevating the centre of mass is not possible to define in this research as there are many factors that can affect this phenomenon.

For further work with defining guidelines to predict vibration performance, an important point to note is that in general, elevated live load tends to affect vibration response more than the same load concentrated at the floor surface. To define the amount of mass to use in vibration calculations, the EC5-proposal (CEN, 2023) states in point 9.3.3 (8):

"The floor mass used for the vibrational calculations should be a unique value including the sum of the mass caused by permanent loads, the self-weight of the floor as well as all supported or suspended horizontal structural layers, the self-weight of partition walls and an additional mass equivalent to 10 % of the characteristic imposed loads."

It is stated that permanent loads, self-weight of partition walls as well as 10 % of the characteristic imposed loads should be included in the calculations. For the residential category, the characteristic loads is taken as 2 kN/m^2 (Standard Norge, 2008). 10 % of the characteristic imposed load converted to kg/m^2 is 20,39 kg/m^2. For the tested floors, the area is 11,76 m^2 (2,4 m x 4,9 m). That gives a total imposed load of approximately 240 kg. In our case, the imposed load by furniture was 122,7 kg. The furniture used in the test is considered to be light as there are no content in the shelf, empty desk, and no chair. But then the floor is considered to be light, as there are no roofing or floor finishing layers. Thus, the weight ratio between the imposed load and the floor can be argued to be representative for in-situ floors. As a result of this, the definition of mass to be included in the vibration calculations in the EC5-proposal may be conservative enough to cover this effect.

6 Conclusions

Conclusions are presented below:

- Non-perforated particleboard may improve the vibration performance of joisted timber floors exposed to walking excitation by increasing the frequency and damping of the lower modes, compared to perforated particleboard.
- Transversal blocking in mid-span of joisted timber floors may improve the vibration performance during walking excitation by increasing the frequency and damping of most modes.
- Placing live load on joisted timber floors can lower the natural frequencies of the first two modes significantly, or in some cases increase the natural frequency of one of the first two modes slightly, depending on the arrangement of the live load.
- Placing live load on joisted timber floors can increase the damping of the fundamental mode significantly. The damping of the second mode can be both increased and decreased significantly, depending on the arrangement of the live load and floor characteristics.
- Live load placed close to the floor centre of joisted timber floors seems to be more likely to decrease the natural frequency of the lower modes, compared to placing live load along the edges of a floor.
- The vibration performance of joisted timber floors seems to be improved by placing live load, e.g. furniture, on them. This effect varies with different arrangements.
- Exposed to walking excitation, the best configuration for vibration performance of joisted timber floors with furniture, out of the variables in this study, seems to be transversal blocking at mid-span and furniture placed at the ends of the span.
- Using the ratio of imposed weight to floor weight to predict the effect of adding furniture on the vibration performance of joisted timber floors is challenging when not differentiating both the furniture arrangements and floor characteristics.
- Introducing any verification requirements regarding vibration of joisted timber floors with furniture is not recommended. However, gaining knowledge on this topic could prove to be useful for mitigating vibration response in challenging cases or in the case of a constructed floor showing a poor vibration performance.
- Results suggest that elevating the centre of gravity of the imposed mass amplifies the effect of lowering the fundamental frequency of joisted timber floors. The tests in this study is deemed improper to assess the effect on damping.

Suggestions for further research:

- Investigating the effect of furniture on cross-laminated-timber floors having a slab-type behaviour with higher transversal stiffness.
- Investigating the effect of higher modes with different furniture arrangements (difficult to capture and analyse).
- Investigating the influence of furniture on modal participation.
- Investigating the damping effect from furniture on a floor with an initial deflection caused by an imposed load corresponding to a person standing on the floor.
- Investigating the effect of furniture on the vibration performance of joisted timber floors in situ.
- Performing numerical studies on the effect of furniture on vibration characteristics of joisted timber floors.
- Finding the ratio of imposed weight to floor weight that will significantly influence vibration performance of joisted timber floors, differentiating floor characteristics and arrangement of imposed load.

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Appendix A:
Combined Sensor Setups, Furniture Arrangements & Walking Paths

Model01

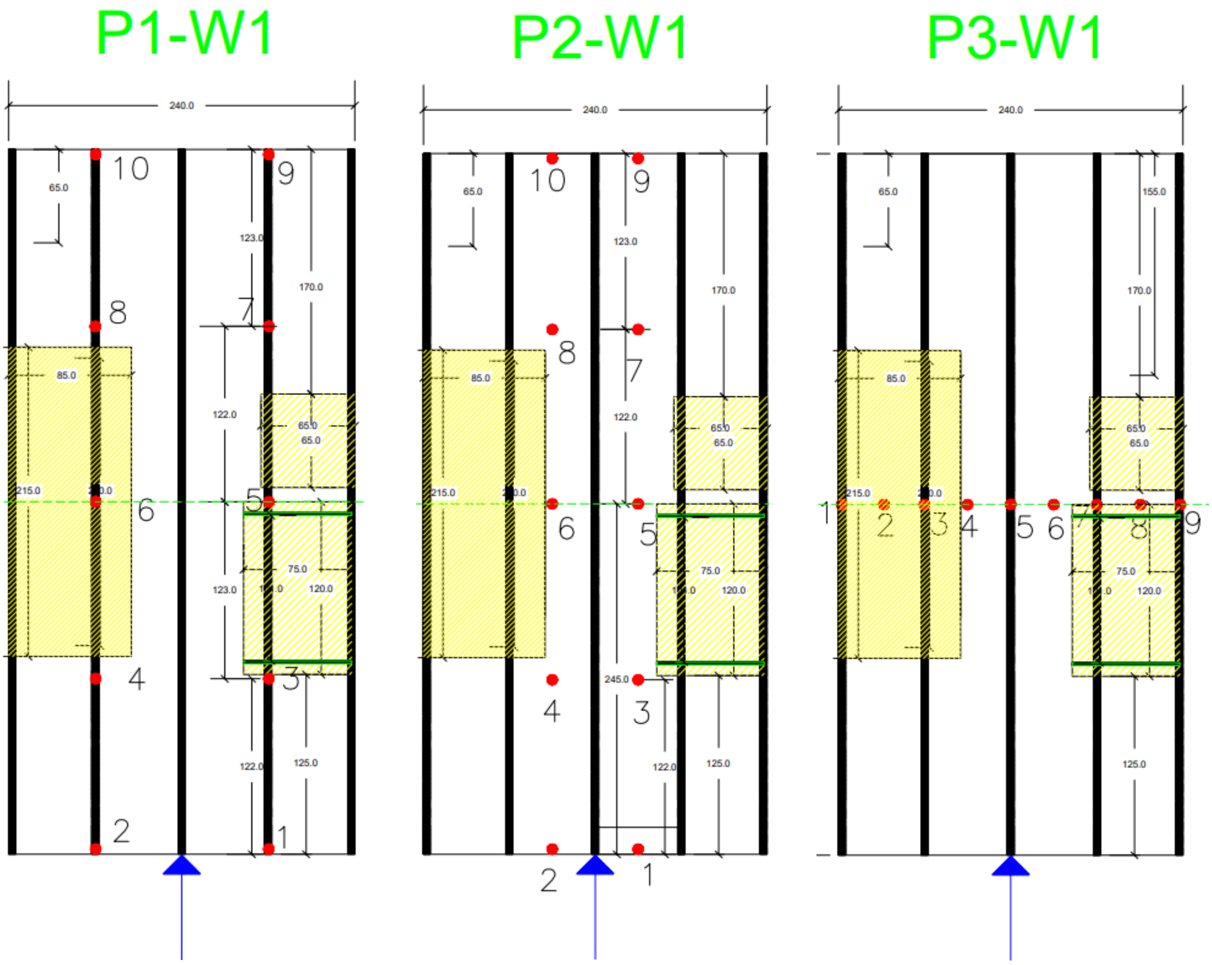

Figure A-1. Test setups for model01 (walking).

Model02

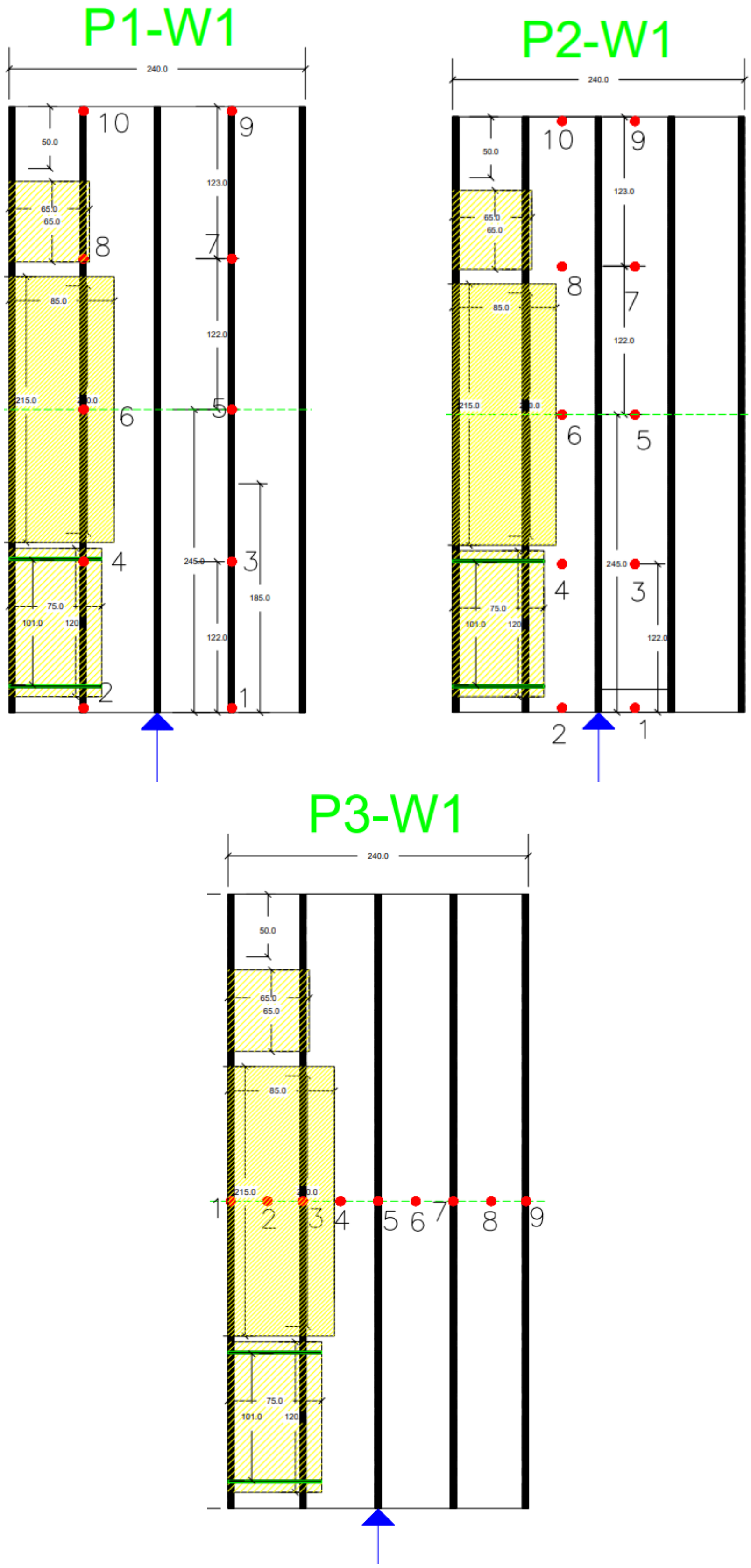

Figure A-2. Test setups for model02 (walking).

Model03

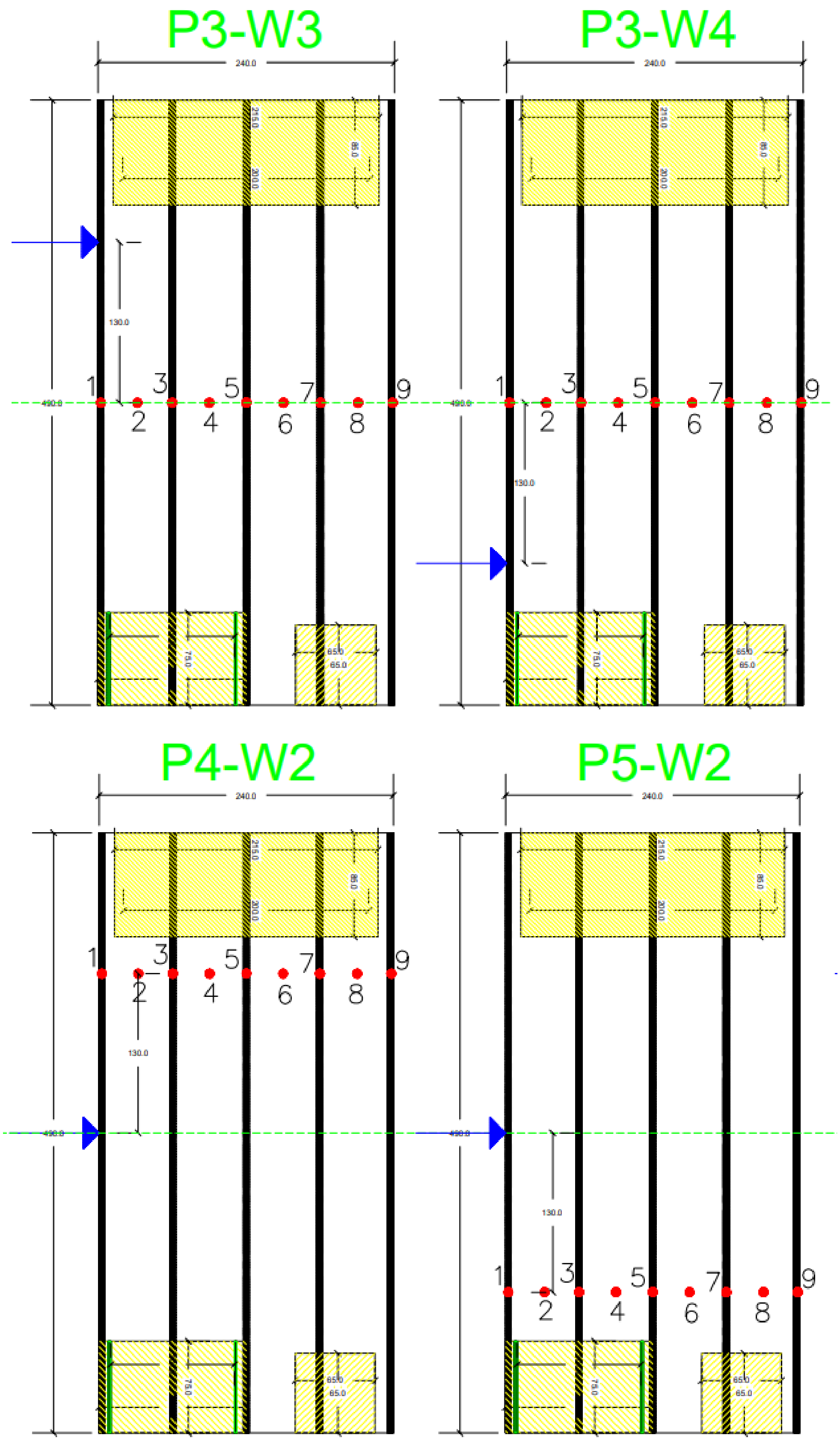

Figure A-3. Test setups for model03 (walking).

Model04

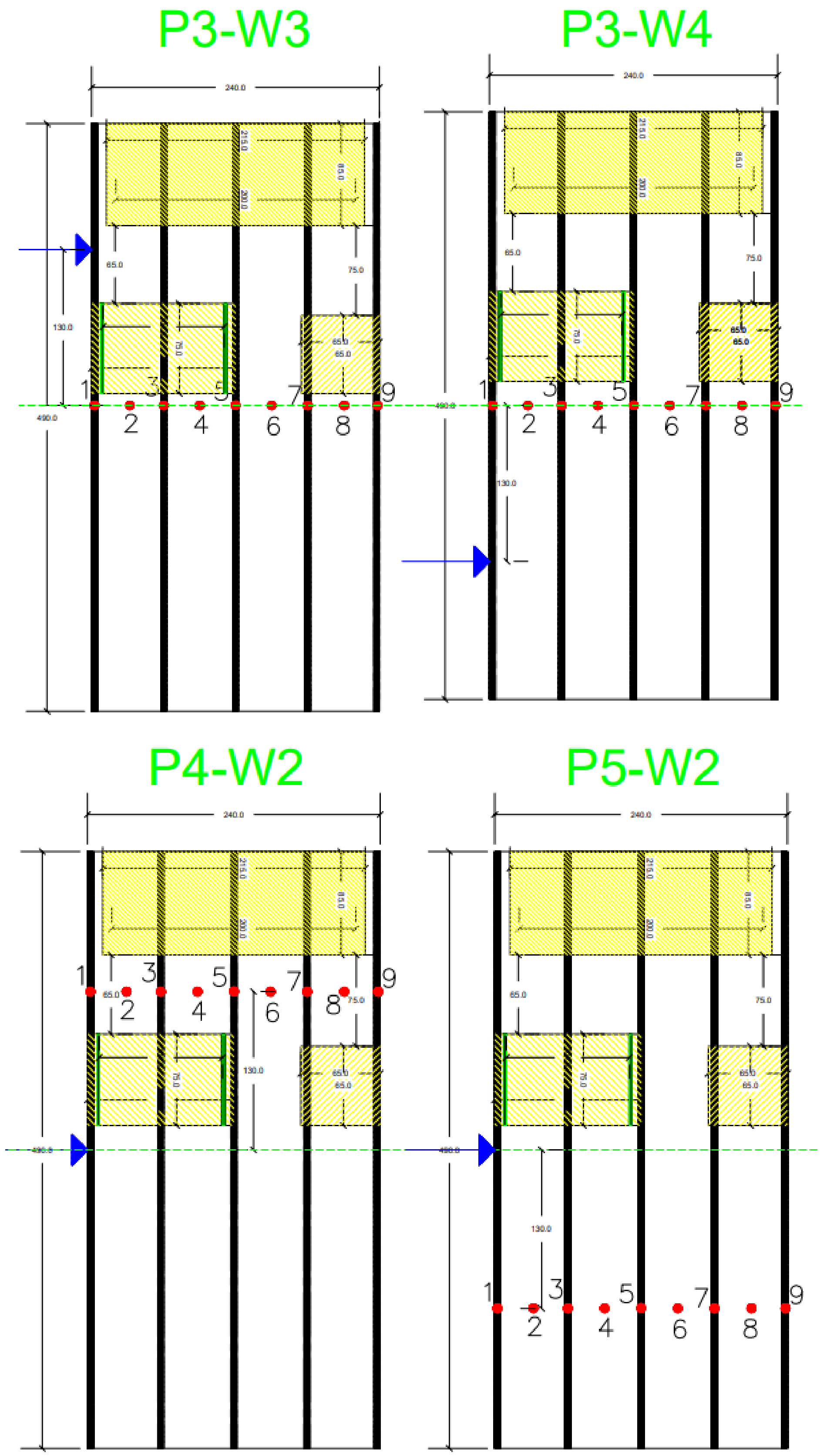

Figure A-4. Test setups for model04 (walking).

Appendix B:
Technical equipment for vibration measurement

The technical equipment used for data capturing is presented below:

- **ACCELEROMETER, ICP®, SEISMIC** *Model 393B12*
  Seismic, high sensitivity, ceramic shear ICP® accelerometer, 10 V/g, 0.15 to 1000 Hz, 2-pin top connection.
- **PCB Piezotronics 482C05 Four-channel, ICP sensor signal conditioner**
- **Datalogger, MX1601B universal amplifier**
  16-channel amplifier of the QuantumX family
- **CatmanEasy V5.2.1** (Software)

Appendix C:

A_{peak} & A_{rms} – All floors – All walking tests – 2 Hz (F)

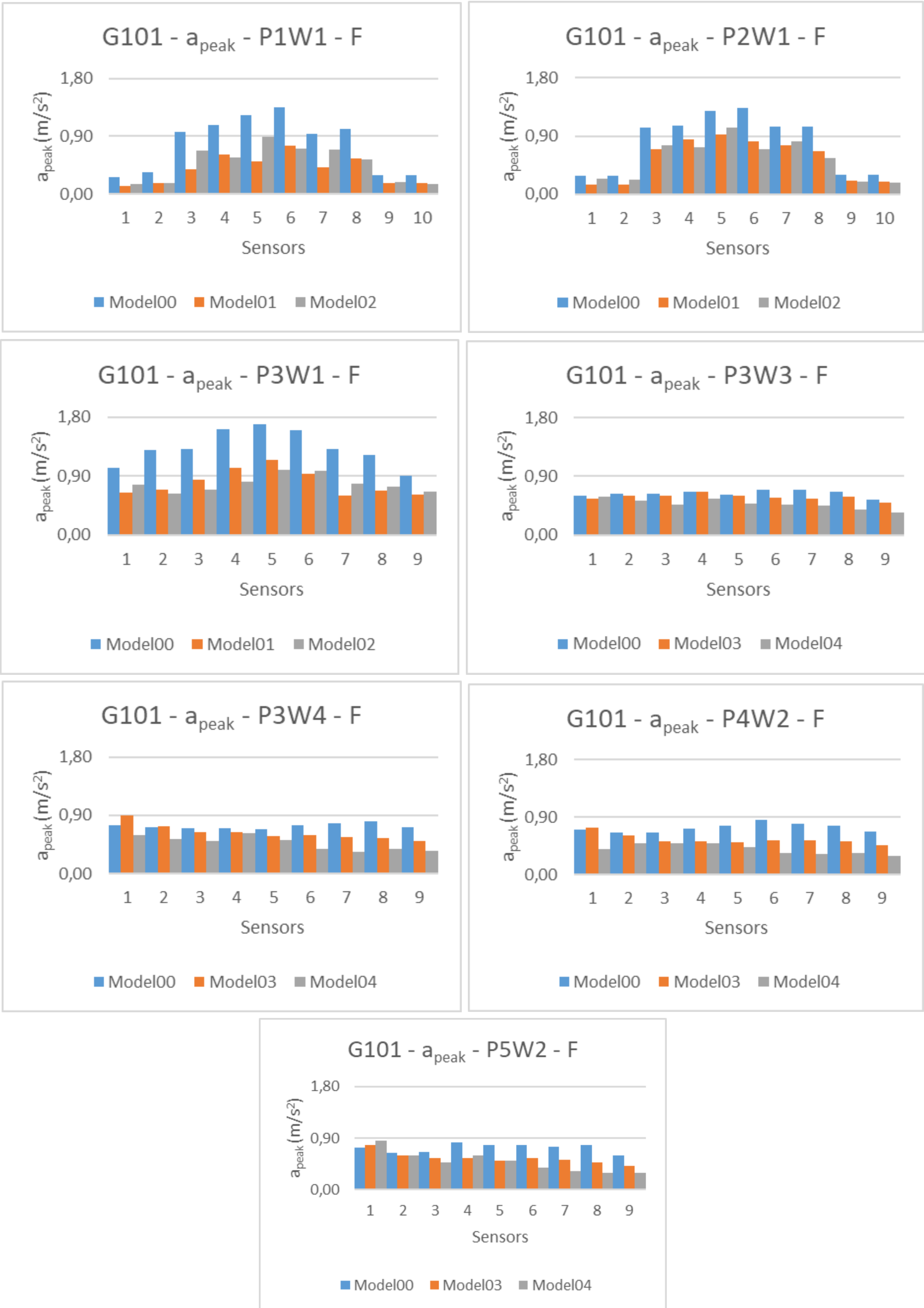

Figure C-1. Average peak acceleration of each sensor for all the combined sensor setups and walking paths with 2 Hz walking frequency on floor G101.

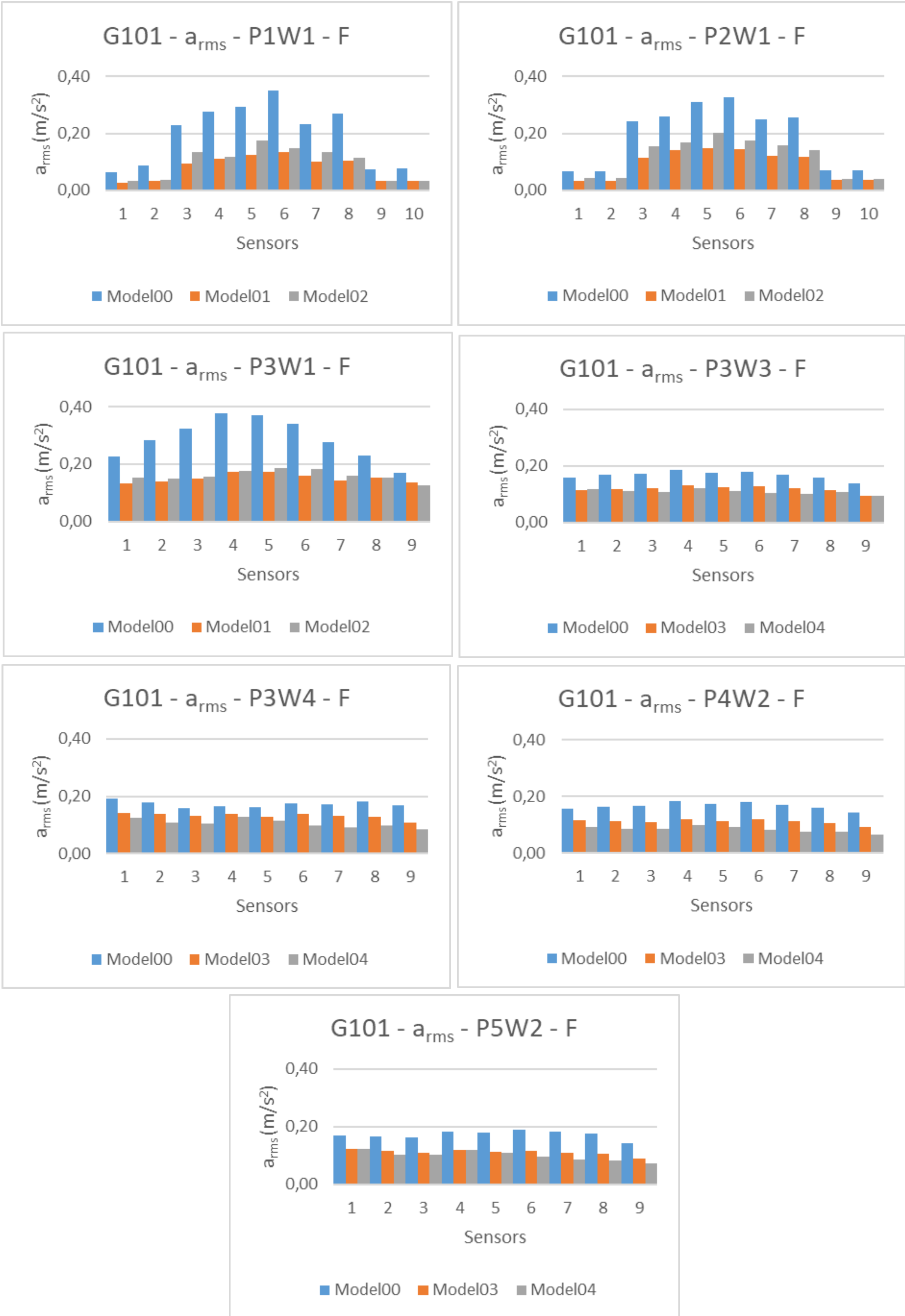

Figure C-2. Average RMS acceleration of each sensor for all the combined sensor setups and walking paths with 2 Hz walking frequency on floor G101.

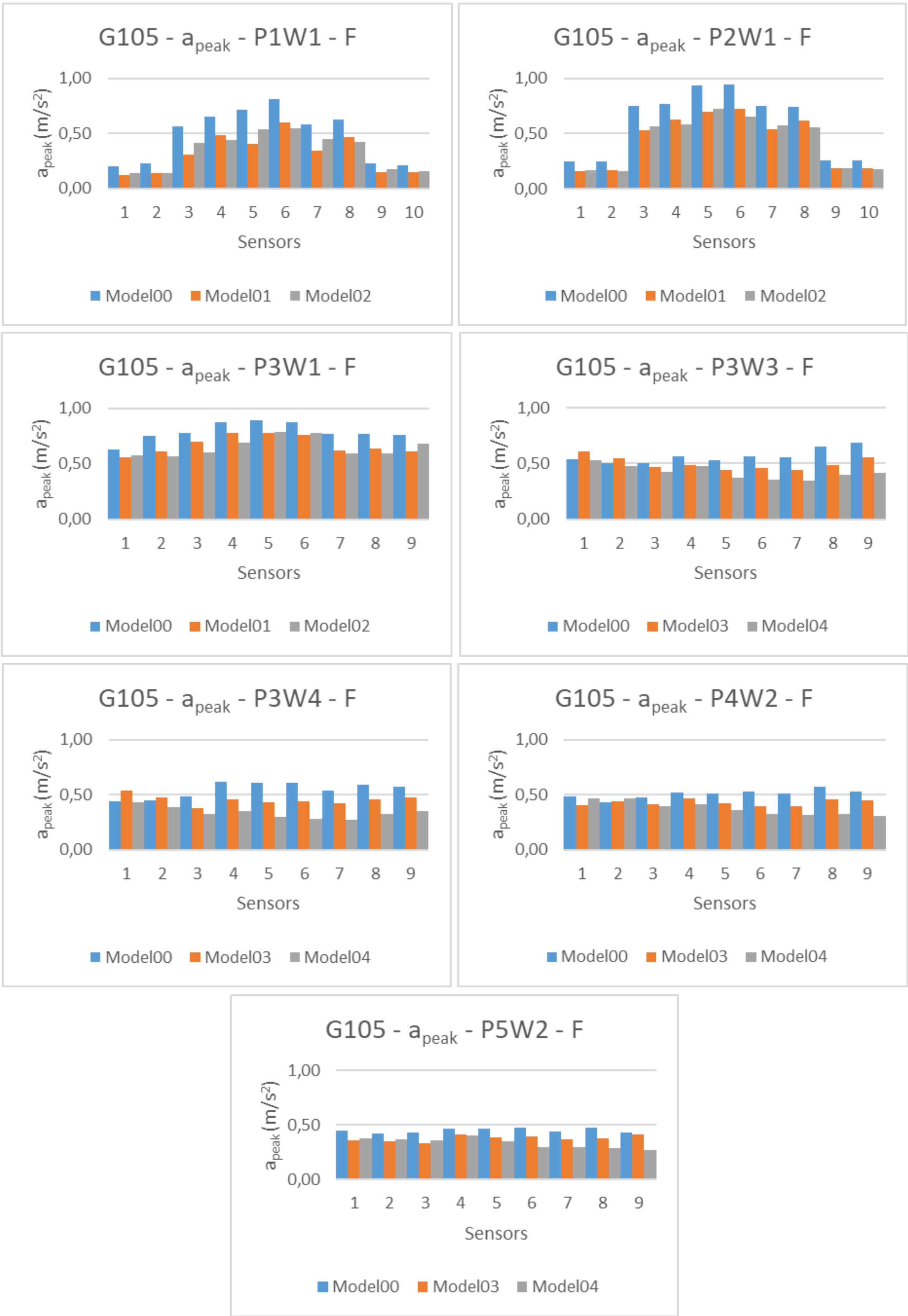

Figure C-3. Average peak acceleration of each sensor for all the combined sensor setups and walking paths with 2 Hz walking frequency on floor G105.

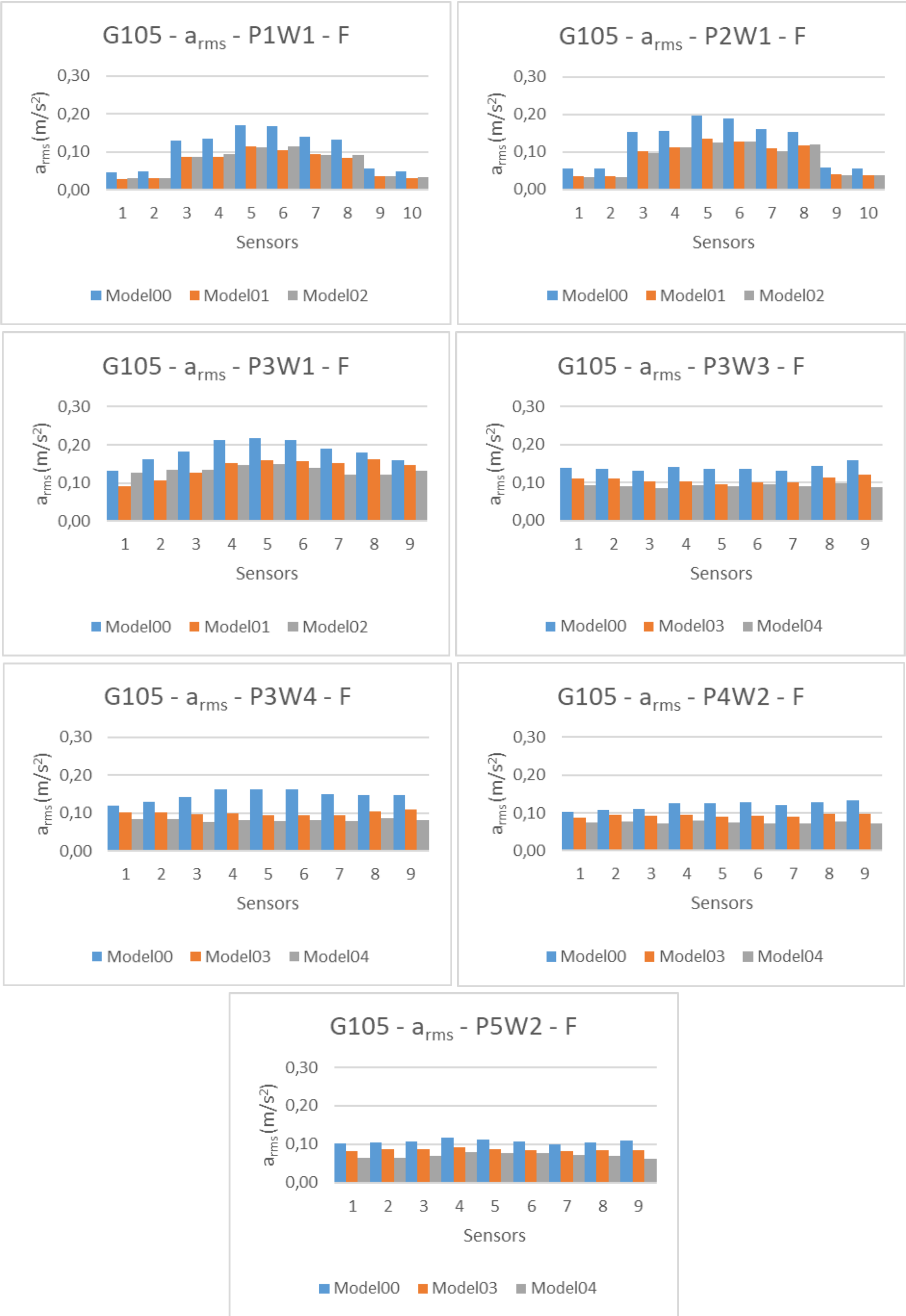

Figure C-4. Average RMS acceleration of each sensor for all the combined sensor setups and walking paths with 2 Hz walking frequency on floor G105.

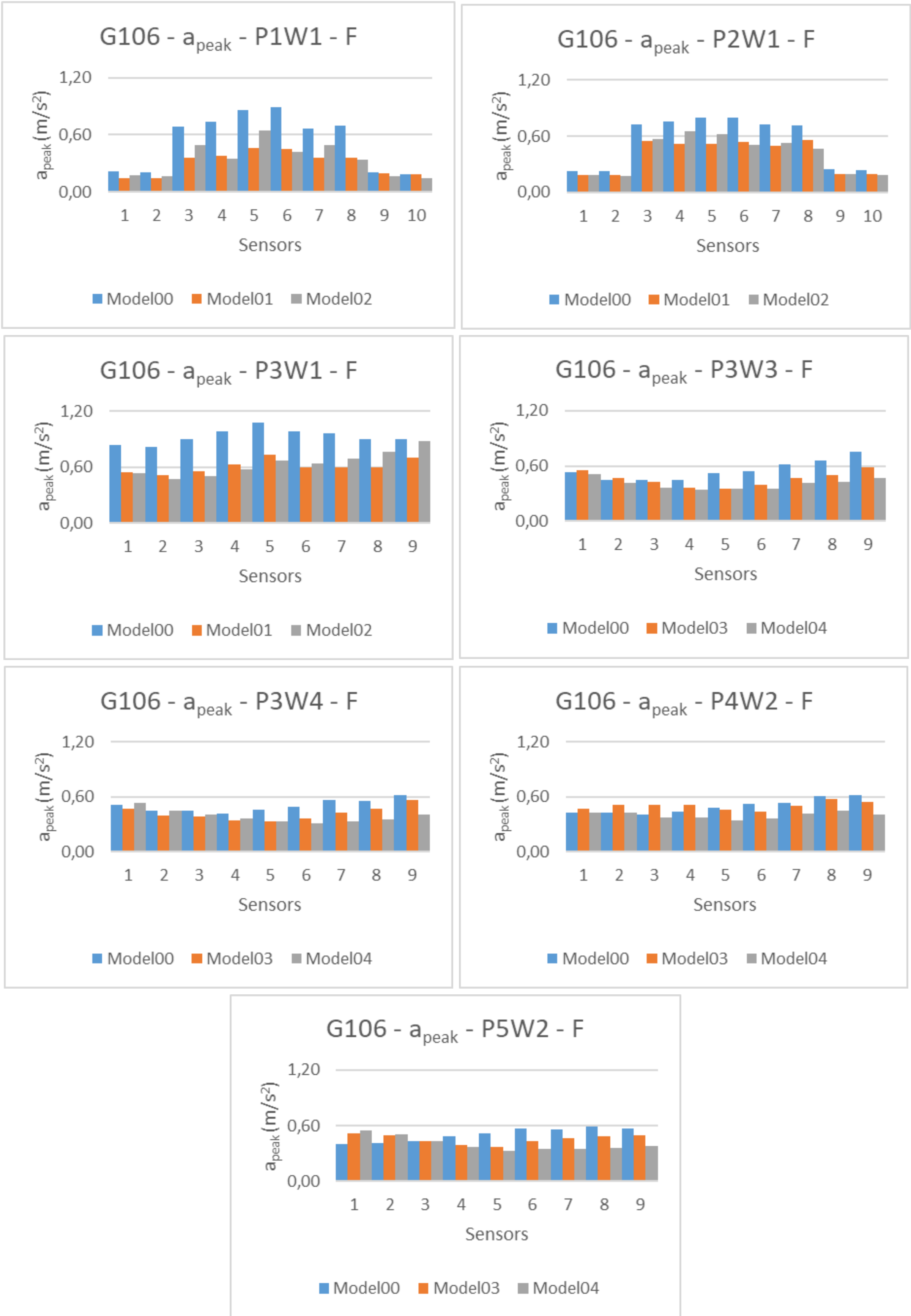

Figure C-5. Average peak acceleration of each sensor for all the combined sensor setups and walking paths with 2 Hz walking frequency on floor G106.

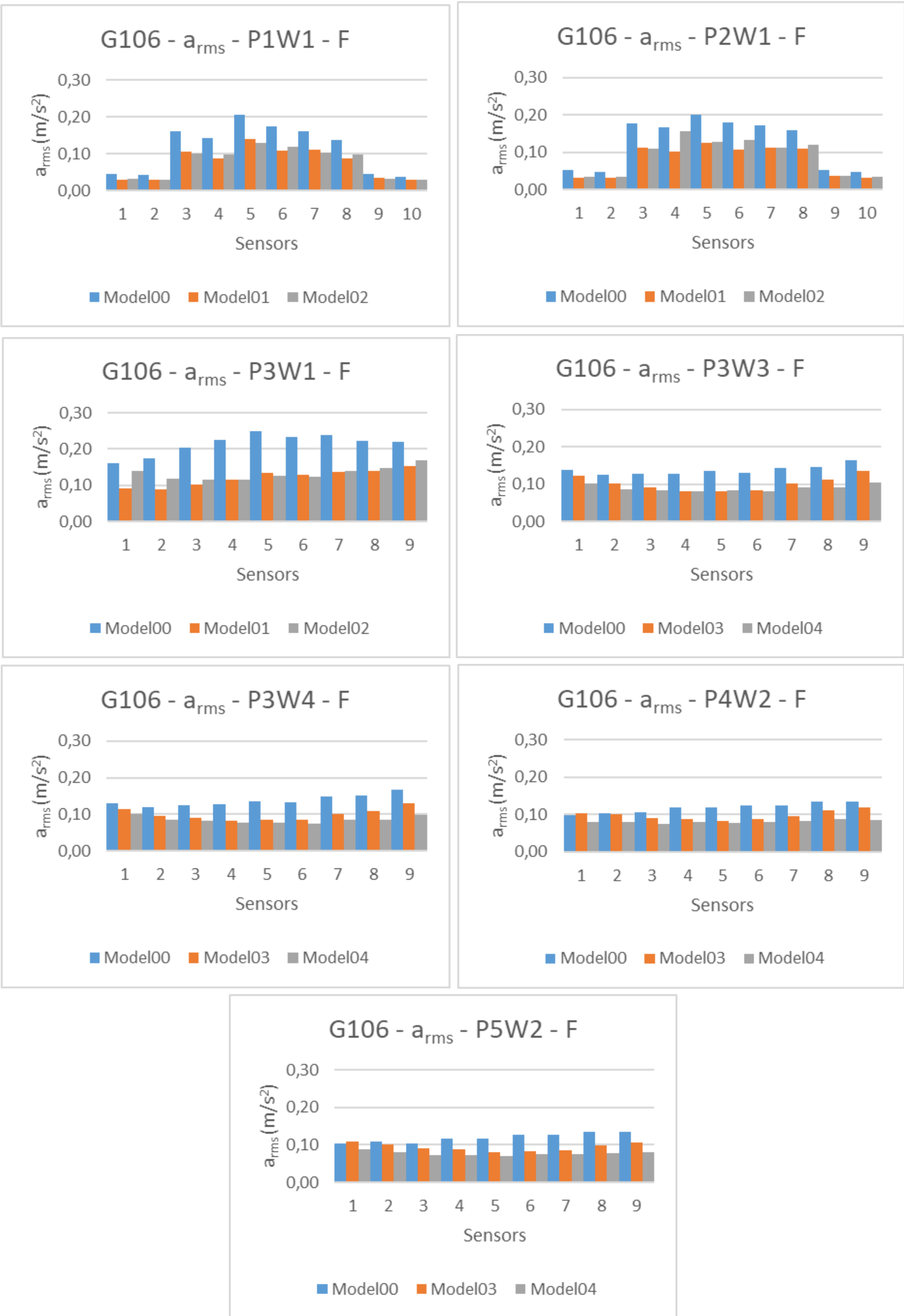

Figure C-6. Average RMS acceleration of each sensor for all the combined sensor setups and walking paths with 2 Hz walking frequency on floor G106.

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