Vibration of Hollow Core Concrete Elements Induced by Walking

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Vibrationer i HDF-bjälklag orsakade av en gående person

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Preface

The work presented in this master thesis was carried out at the Division of Structural Engineering and the Division of Engineering Acoustics, at Lund Institute of Technology, during the period September 2008 to March 2009.
There are many persons that I would like to thank for their help, guidance and support:

First of all I would like to thank my supervisor Dr. Sc. Delphine Bard for her great assistance during this work. I would also like to thank Ph.D. Kent Persson, at the Division of Structural Mechanics, and Johan Kölfors, Head of Software Department at Scanscot Technology, for their help and guidance during the FE-simulations. Furthermore, I would like to thank Prof. Sven Thelandersson for his guidance throughout this thesis.
A special thanks to STARKA for delivering the HD elements that were used to build the experimental floor structure, and Per-Olof Rosenkvist for all the help with casting, and other laboratory work.
Another special thanks goes to my fellow students that I shared an office with; I would like to thank them for all the help during the measurements and all the interesting conversations during coffee breaks and lunches.

It has been a pleasure; throughout the course of this work I have learnt a lot, and I have made many new friends.

Lund, March 2009

Pia Johansson

Abstract

Historically, traditional concrete floors have performed well with regard to vibration serviceability. This is much due to their heavy weight. However, the use of stronger concrete materials and prestressing has resulted in slender cross sections and the possibility to build long-span floor elements. The combination of long span and relatively light weight means that the floor element is more sensitive to vibrations.

This thesis investigates vibration in hollow core concrete elements induced by human walking. One of the objectives of the thesis was to establish a maximum span with respect to vibration serviceability for the smallest HD elements in the series, HD/F 120/20. Another objective was to investigate how the dynamics of a floor structure is affected when different types of connections are used, when different spans are used, or when a concrete topping is cast.

An experimental floor structure made of three hollow core elements was built in a laboratory. The floor was simply supported and the span of the floor was 8 m, which is within the recommended limits. Subjective tests were performed before and after a concrete topping was cast. The results from the subjective tests showed that a large majority of the test persons found the experimental floor structure unacceptable with regard to vibrations induced by another person walking. The results from the subjective tests indicated that a concrete topping improved the vibration performance slightly, but the vibrations were still classified as clearly perceptible or strongly perceptible.

Accelerometers were used to measure the accelerations of the slab induced by a number of different persons walking, one at a time. For offices many researchers propose a single person walking to be the governing load case when checking the vibration serviceability of a floor structure. This is also the load case that was used in this study. A limitation of this master thesis is however that only one walking line was examined.

From the measurements the dynamic properties of the test floor, such as damping and natural frequencies, could be determined. The improvement of the vibration performance of the experimental floor structure after a concrete topping was cast could also be seen in the measurements; in this case in the form of slightly reduced average values of overall weighted acceleration.

The measured acceleration magnitudes were also evaluated according to the former ISO standard ISO 2631-2:1989 and a method proposed by Talja & Toratti. Both methods indicated the same as the subjective tests: the experimental floor structure is unacceptable with regard to vibrations. When the vibration signals were filtered and plotted in 1/3 octave bands it could be seen that the highest acceleration magnitudes were found in the frequency interval of maximum human sensitivity.

A finite element model of the experimental floor structure was built in *Abaqus*. In order to decrease computational time and cost of each analysis the three-dimensional structure was replaced by a shell with the same stiffness properties and density as the hollow core elements. The results from the measurements were used to validate the FE-model of the floor, and then a number of simulations of different boundary conditions and different spans were performed.

During the simulations it was found that the frequency content of the applied load function affected the resulting accelerations significantly. This sensitivity made it difficult to draw any clear conclusions about the maximum possible span, based on only the three different load functions that were used. However, it was concluded that supports with some rotational resistance, or a shorter span will improve the vibration performance. The calculations also showed that there is a probability of adverse comment in the case of simply supported slabs with spans of 6 or 7 m.

In order to investigate if the problem with annoying vibrations in HD elements is widespread, a handful of interviews were performed with structural designers. Only one of the interviewed persons had come into contact with a case where people were complaining about annoying vibrations induced by human walking. However, one must keep in mind that only structural engineers were interviewed, and the picture might have been another if occupants of different office buildings had been interviewed.

Contents

1 Introduction

1.1 Background

Historically, traditional concrete floors have performed well with regard to vibration serviceability. This is much due to their heavy weight. However, the use of stronger concrete materials and prestressing has resulted in slender cross sections and the possibility to build long-span floor elements. The combination of long span and relatively light weight means that the floor element is more sensitive to vibrations, induced by for instance a walking person.

A common type of prestressed floor element used in Sweden is the hollow core element (HD element). These elements are frequently used in office buildings, where a long span often is required.

Modern-day offices are often sparsely furnished with few permanent partitions to get a flexible building. This along with the relatively small weight of the HD elements has led to a handful of HD floors failing their vibration serviceability, i.e. people are complaining about disturbing vibrations. In general, the cause of the annoying vibrations in offices and similar buildings is human walking.

According to the Swedish design code (*BKR*, the Construction Code of *Boverket*) different parts of a building shall be designed so that disturbing vibrations do not occur. Since vibration serviceability traditionally has been an issue for light-weight floors, as for example floor structures made of wood, the Swedish design code does not include any general rules about designing with respect to vibration; it only contains some advice for wooden floors.

Furthermore, in the current situation there is a lack of unanimous vibration criteria and vibration limits in the case of whole-body vibration in buildings. The lack of clear dose-response relationships can be explained by the complexity of human response to vibration. Since how humans perceive vibration is highly subjective, and the response depends on a large number of variables, there are huge inter- and intra-subject differences in the response to nominally the same vibration. In other words, different people will react differently to the same whole-body vibration, and the same person may respond differently to the same vibration exposure under different circumstances. Therefore, in the current ISO standard concerning whole-body vibration in buildings, no guidance values regarding acceptable magnitudes of vibration are included since their possible range is too widespread to be reproduced in an International Standard.

1.2 Objective

The aim of this master thesis is to investigate vibrations in hollow core elements caused by human walking. One of the objectives is to establish a maximum span with respect to vibration serviceability for the smallest HD element in the series, HD/F 120/20. Another objective is to investigate how the dynamics of a floor structure is affected when different types of connections are used, or when a concrete topping is cast.

1.3 Method

A test floor structure made of three hollow core elements was built in a laboratory. Accelerometers were used to measure the accelerations of the slab induced by human walking or a tapping machine. From the measurements the dynamic properties of the test floor, such as damping and natural frequencies, could be derived. The measurements were complemented with subjective tests, where a number of persons were asked to evaluate the intensity and acceptability of the vibrations of the experimental floor structure induced by human walking. Measurements and subjective tests were performed before and after a concrete topping was cast, which made it possible to investigate the effect of a topping on the dynamic properties of the floor. The results from the measurements and the subjective tests were also used to evaluate some of the existing methods for evaluating the vibration serviceability of a concrete floor structure.

A FE-model of the test floor structure was built in the finite element software *Abaqus.* The computer model was validated by the measurements on the experimental floor structure, and then used for investigating the effect of different boundary conditions and determining the maximum span with regard to vibration serviceability.

Furthermore, a small number of interviews were performed in order to investigate to which extent there is a problem with annoying vibrations of hollow core elements in existing buildings. All the interviewed persons were structural designers.

1.4 Scope

This master thesis is restricted to examining vibrations induced by walking. The main load case is assumed to be a single person walking. This is the load case proposed by a number of researchers to be the governing load case in an office when checking vibration serviceability. The report is focused on the smallest hollow core element in the series, HD/F 120/20.

1.5 Disposition

The report includes the following chapters:

- In chapter 2 concrete hollow core elements are described.
- Chapter 3 contains an introduction to basic vibration theory.
- In chapter 4 human perception of, and response to, whole-body vibrations is described.
- In chapter 5 some of the existing criteria and limit values concerning whole-body vibration in buildings are presented.
- In chapter 6 walking excitation is presented. This chapter describes forcing patterns for walking, and different methods to model the footfall load.

- In chapter 7 the experimental floor structure is described, and the subjective tests and measurements performed in this study are presented. This chapter also contains the results from the subjective tests and the measurements. Furthermore, the vibration serviceability of the floor structure is evaluated according ISO 2631-2:1989 and the vibration classes suggested by Talja & Toratti.
- In chapter 8 the FE-model of the floor structure is presented. The results from the simulations of other boundary conditions, and other spans, are also presented.
- Chapter 9 summarizes the interviews that were performed.
- Chapter 10 describes the parameters that influence the dynamic behavior of a floor structure, and presents methods to counteract high vibration magnitudes in existing floor structures. This chapter also discusses the differences between laboratory measurements and in situ measurements.
- In chapter 11 the results from the subjective tests, the measurements, and the FE-analysis are discussed and conclusions are drawn.

2 Concrete hollow core elements

As the name reveals, concrete hollow core elements, or HD elements, are hollow with channels in the lengthwise direction. They can either be made of prestressed concrete or normal reinforced concrete. One big area of use is as floor structure in office buildings, where a long span often is required. In that case, the hollow core elements consist of prestressed concrete of a rather high strength class.
The hollow core elements are manufactured in factories mainly by continuous casting (Bygga med prefab 2008). A typical cross section can be seen in figure 2.1.
According to the Swedish Concrete Industry the HD elements have a low self weight relative to their carrying capacity. In general, the use of stronger concrete materials and prestressing has resulted in slender cross sections and the possibility to build long-span floor elements.

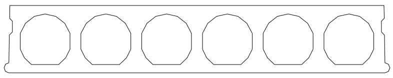


Figure 2.1. Cross section of a HD element.

2.1 Dimensions and spans

HD elements are available with the four standard cross-sectional heights: 200 mm, 265 mm, 320 mm and 380 mm. The width is 1200 mm. Table 2.1 shows the names and the cross-sectional heights of the standard dimensions.

Name of the HD element	**HD/F 120/20**	**HD/F 120/27**	**HD/F 120/32**	**HD/F 120/38**
Cross-sectional height [mm]	200	265	320	380

Table 2.1. The denotation of the four standard dimensions of HD elements.

Hollow core elements can be used for spans in the range 5-18 m. The maximum span depends on the strength class of the concrete, the number and the size of tendons, height of the cross section and, of course, the magnitude of the imposed load.
STARKA is one of the manufacturers of HD elements in Sweden. Figures 2.2 and 2.3 show the maximum span, in the ultimate limit state and the serviceability limit state, of Starka's HD/F 120/20 with three different reinforcement options. The vertical axis shows the design load in excess of the self weight and the corresponding maximum span can be read on the horizontal axis.

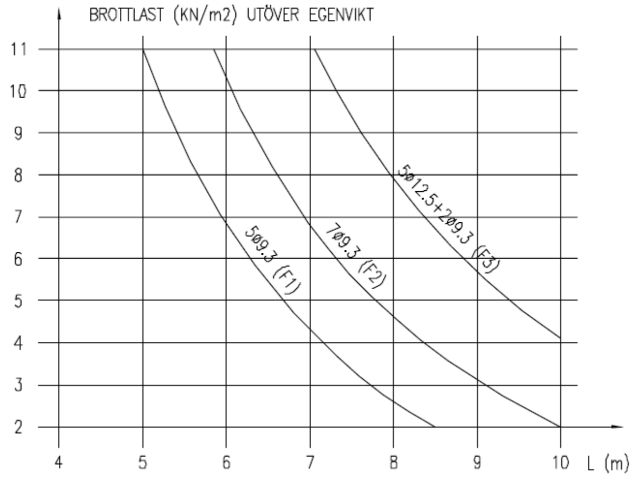


Figure 2.2. Maximum span in the ultimate limit state for HD/F 120/20 (Starka Prefab Handbok 2008).

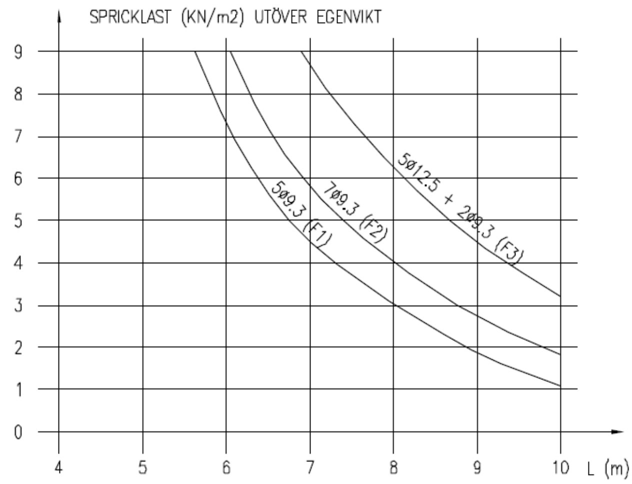


Figure 2.3. Maximum span in the serviceability limit state for HD/F 120/20 (Starka Prefab Handbok 2008).

2.2 Framework and connections

The HD elements can be used together with a steel frame, concrete columns and beams, or concrete walls. There are a number of standard connections for these situations, see figure 2.4 for some examples.

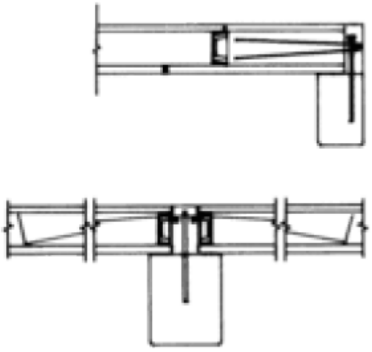


Figure 2.4. Examples of connections between HD elements and concrete beams (Bygga med prefab 2008)

The load-carrying capacity of the HD elements is slightly reduced when they are placed on beams compared to support on concrete walls. The reason for this is the transversal stresses that occur in the elements when they follow the deformation of the beam (Bygga med prefab 2008).

The joints between the HD elements in the lengthwise direction are filled with grout. The Swedish Concrete Industry recommends using at least a concrete of the strength class C20/25, often a concrete of a higher strength class is chosen (Bygga med prefab 2008). One of the manufacturers of HD elements, *STARKA,* recommends its customers to use a concrete of the strength class K40 in the lengthwise joints (Persson 2008). K40 is an older strength class, which can be translated to the newer strength class C30/37 (Betongbanken 2008).The concrete should have a high flowability, and is poured into the joints. To make the concrete fill out the space completely it is recommended to puddle the concrete with a bar.
In order to keep the lengthwise joints together reinforcement is placed in the transverse joints over the beams or concrete walls, this transverse reinforcement ensures some shearing strength in the lengthwise joints (Bygga med prefab 2008).

According to the Swedish design regulations (*Boverket 2003*) the HD elements have to be anchored to the supports in order to minimize the risk for a progressive collapse. For example, this anchorage can be made of dowels and bent reinforcement bars that are cast together with the hollow core elements see figure 2.5 (Bygga med prefab 2008).

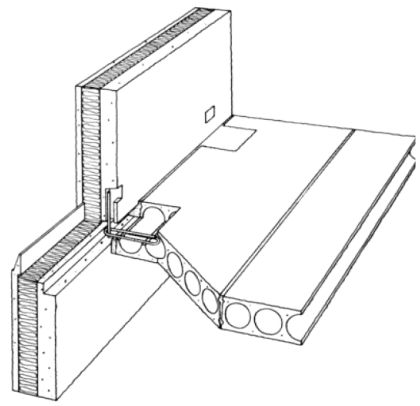


Figure 2.5. The picture shows an example of the anchorage of a HD element to a concrete wall (Bygga med prefab).

In the interior of the building, HD elements in adjacent spans are often connected with reinforcement bars, as shown in figure 2.6, to prevent progressive collapse (Bygga med prefab 2008).

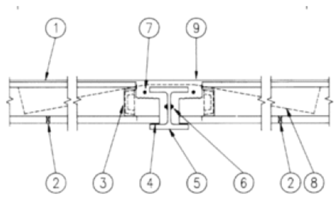


Figure 2.6. The picture shows an example of the connection between two adjacent HD elements in the lengthwise direction (Bygga med prefab 2008).
8: Reinforcement bar.7 and 9: Transverse reinforcement.

It is recommended that the support width is at least 60 mm for the two smallest hollow core elements, HD/F 120/20 and HD/F 120/27 (Bygga med prefab 2008). *STARKA* recommends its customers to use at least a support width of 70 mm for the HD/F 120/20 elements, and in the case of a long span they often recommend wider supports (Persson 2008).

2.3 Concrete topping

The prestress causes the concrete elements to bend upwards. In order to get a plane floor area a concrete topping is often cast on site. Because of the floor structure's excess height the thickness of the topping will vary across the floor. A strength class between C25/30 and C30/37 is often used and the thickness of the concrete layer is often 30-70 mm. There are also other materials that can be used to make the floor area plane.

In order to be able to account for interaction between the precast floor element and the concrete topping reinforcement is often needed. This kind of interaction is however seldom used in the case of HD elements (Bygga med prefab 2008).

3 Introduction to basic vibration theory

Vibration can be described or measured as displacements, velocities or accelerations. The vibration signal can be presented in the *time domain,* as accelerations plotted against time, see figure 3.1. Or it can be presented in the *frequency domain* as amplitude plotted against frequency. This kind of plot is called a response spectrum, it shows the frequency content of the oscillation, see figure 3.2. The two concepts above are equivalent and either one can be chosen to describe a vibration signal. The signal can be transferred between the time domain and the frequency domain by using methods from the Fourier Analysis, such as FFT, the Fast Fourier Transform (Bodén et al. 2001).

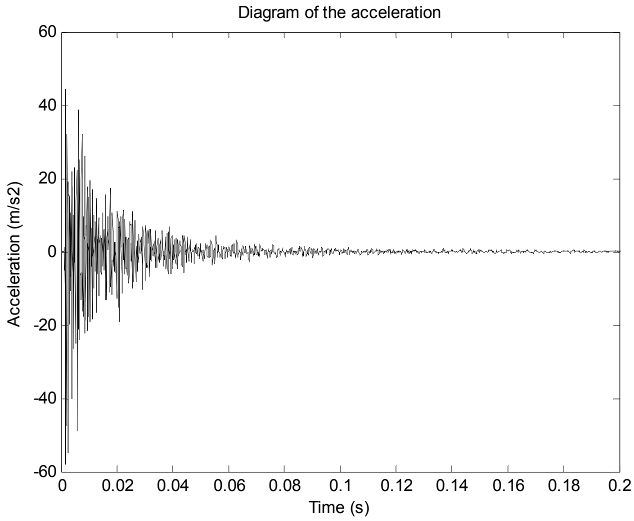


Figure 3.1. The vibration presented in the time domain as accelerations plotted against time.

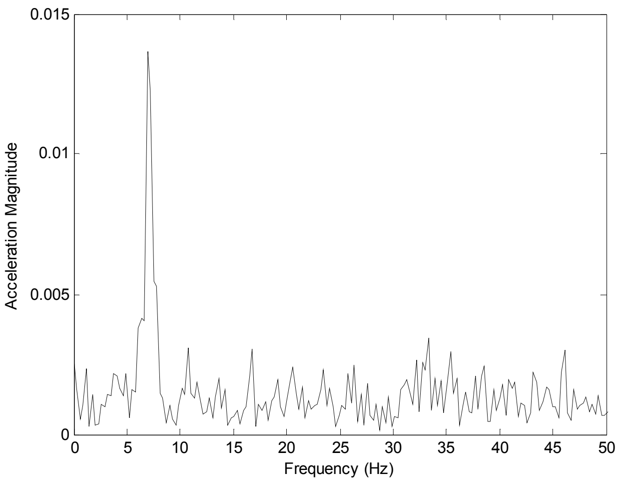


Figure 3.2. The vibration signal presented in the frequency domain as amplitude plotted against frequency.

3.1 Dynamics of structures: Single-degree-of-freedom-system

As a first rough model of a floor structure a SDOF model can be used to determine the displacements, velocities and accelerations of the slab caused by a dynamic force. SDOF stands for single-degree-of-freedom and means that the motion of the structure is defined in only one direction, *u* in figure 3.3.

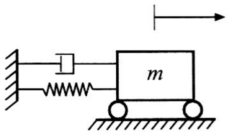


Figure 3.3. SDOF model (Heyden et al. 2005).

A SDOF model consists of three components: mass component, stiffness component and damping component. In a SDOF model the mass is concentrated at one point and the model is therefore an idealization when modeling a floor structure (Heyden et al. 2005).
For an object with the mass *m* which is subjected to an external time varying force *p(t),* all the forces acting on the mass at some instant of time can be seen in figure 3.4. The external force is acting in one direction and the resisting force and the damping resisting force are acting in the opposite direction.

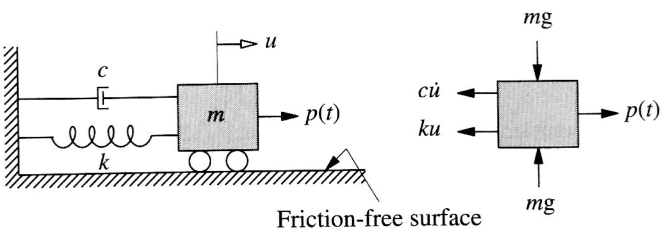


Figure 3.4. Forces acting on a mass subjected to an external dynamic force (Chopra 2001).

When the deformations are small, as they would be in the case of vibrations in a floor structure induced by human walking, the force-displacement relation will be linear. This means that the resisting force can be modeled by a linear spring (Chopra 2001):

$$f = ku$$

k= stiffness of the system [N/m]

In reality some damping is always present in structures, which makes the free vibration of a structure steadily diminish in amplitude. The reason for this is that energy is dissipated by various mechanisms when the structure is vibrating.
This energy dissipation is modeled by a damper; in many cases a linear viscous damper can be used. This means that the damping force is proportional to the velocity across the damper (Chopra 2001):

$$f_D = c\dot{u}$$

c= viscous damping coefficient [Ns/m]

Using Newton's second law of motion (F=ma) on the mass-spring-damper system in figure 3.4 gives:

$$p(t) - ku - c\dot{u} = m\ddot{u}$$

After rearranging the terms this can be written as:

$$m\ddot{u} + c\dot{u} + ku = p(t)$$

This is the equation of motion from which the displacements of the object, *u(t)* can be calculated.

3.2 Dynamics of structures: Multi-degree-of-freedom-systems

In order to describe the motion of a floor structure in a more realistic way, a MDOF (multi-degree-of-freedom) model can be used. This means that the slab is divided into smaller parts, making it possible to calculate the different displacements of the different parts that occur in reality.

The equation of motion for a MDOF system can be written:

$$\mathbf{M}\ddot{\mathbf{u}} + \mathbf{C}\dot{\mathbf{u}} + \mathbf{K}\mathbf{u} = \mathbf{f}(t)$$

M is a mass matrix and **C** is a damping matrix. **K** is a stiffness matrix; it contains the geometry and the material properties of the structure analyzed. **u**, $\dot{\mathbf{u}}$ and $\ddot{\mathbf{u}}$ are the displacement vector, the velocity vector and the acceleration vector. **f** contains the external dynamic forces (Chopra 2001).

The early methods for assessing floor vibration serviceability were developed for hand calculations and therefore used simple models of the floor structure. The development of more powerful computers, however, made FE modeling an affordable design tool in the 1990s (Pavic & Reynolds 2002b). In the finite element method the structure is divided into smaller parts and multiple degrees of freedom are used to model the behavior of the structure.

3.3 Natural vibration frequencies and mode shapes

When a structure is disturbed from its static equilibrium position and is allowed to oscillate without any external dynamic excitation it will vibrate with certain frequencies, its natural frequencies. The natural frequencies are a property of the structure and in principle they depend on the mass, the distribution of mass and the stiffness of the structure (Heyden et al. 2005).

A structure has an unlimited number of natural frequencies and to each of these frequencies a specific deformed shape of the structure belongs, called mode shape or mode. If the finite element method is used to model the structure it will have as many natural frequencies and corresponding mode shapes as there are degrees of freedom (Chopra 2001).
The natural frequencies of a damped system differ somewhat from the natural frequencies of the same system without damping. But, for lightly damped structures with damping ratios below 20 %, the natural frequencies of damped vibration are approximately the same as the natural frequencies of the structure without damping. Buildings typically have a damping ratio less than 10 % (Chopra 2001).

3.3.1 Resonance

If a structure is subjected to a dynamic force with a frequency close to one of its natural frequencies the response can be strongly enhanced, this is called resonance. Without damping the deformation amplitude will gradually grow bigger and bigger. In reality some damping is always present preventing the vibrations going unbounded.
Figure 3.5 shows the effects of various damping ratios on the resonant response. The deformation response factor R_d on the y-axis is the ratio of the dynamic deformation to the static deformation (Chopra 2001).

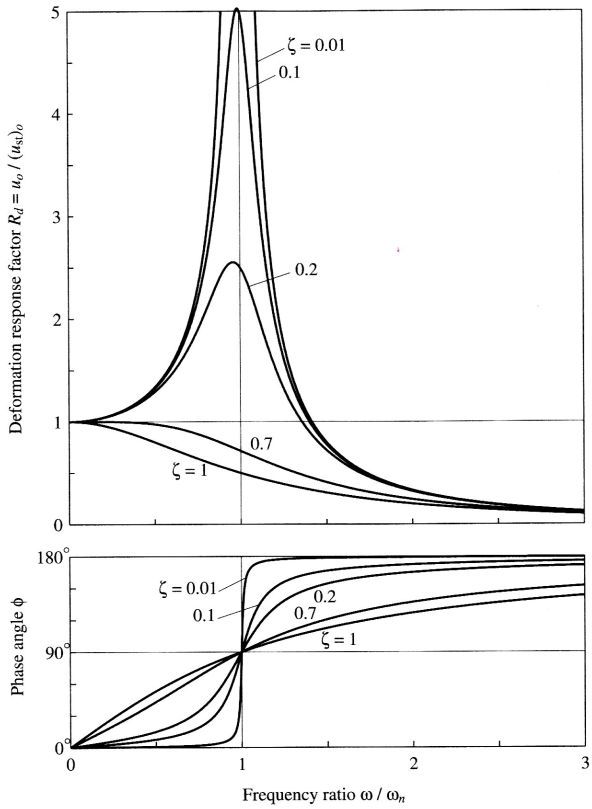


Figure 3.5. Deformation response factor for a damped system excited by harmonic force (Chopra 2001).

According to figure 3.5 the presence of damping significantly reduces the resonant and near resonant responses. As the response becomes more non-resonant, however, the stiffness and mass of the structure becomes more important to the response of the system (Pavic & Reynolds 2002b).

3.3.2 Modal analysis

With the fact in mind that for lightly damped structures the natural frequencies of damped vibration are approximately the same as without damping, finding the natural frequencies of a MDOF system is the same as solving an eigenvalue problem:

Free vibration of a system without damping is governed by the equation of motion with $\mathbf{f}(t) = 0$:

$$\mathbf{M}\ddot{\mathbf{u}} + \mathbf{K}\mathbf{u} = \mathbf{0}$$

The solutions to this equation are of the form:

$$\mathbf{u} = A\cos\omega t\,\mathbf{\Phi}$$
$$\ddot{\mathbf{u}} = -\omega^2 A\cos\omega t\,\mathbf{\Phi}$$

If the solution is inserted into the equation of motion:

$$(\mathbf{K} - \omega^2\mathbf{M})\mathbf{\Phi} = \mathbf{0} \qquad \text{(Eigenvalue problem)}$$

The eigenvalue problem has nontrivial solutions if:

$$\det(\mathbf{K} - \omega^2\mathbf{M}) = 0$$

$$\Rightarrow \omega_1, \omega_2, \omega_3 \ldots\ldots\ldots \omega_N$$

N is the number of DOFs.
ω is the natural circular frequency [rad/s]

When a natural frequency ω_i is known the corresponding eigenvector or natural mode $\mathbf{\Phi_i}$ can be calculated from the eigenvalue equation (Austrell 2008).

The modal eigenvectors turn out to be an orthogonal base, which means that any displacement vector, **u**, of the system can be expressed in this base:

$$\mathbf{u} = \sum_{r=1}^{N} \phi_r q_r$$

q_r are scalar multipliers

This so called modal expansion of the displacement vector u can be used when solving the equation of motion for a MDOF system (thereby the name modal analysis); often it leads to simple uncoupled equations that are easy to solve (Austrell 2008). Because of superposition is used, modal analysis is restricted to linear systems (Chopra 2001).

Tests performed by Hanagan & Murray (1997) showed that the response of a floor structure subjected to human walking is dominated by the lower-frequency modes of vibration. Consequently it would be a good approximation to include only these modes of vibration in the model when performing modal analysis.

3.4 Damping

As mentioned earlier, in reality some damping is always present in structures, which makes the free vibration of a structure steadily diminish in amplitude. The cause of the decreasing vibrations is a loss of energy in the system.
The energy is dissipated by many different mechanisms. In buildings these mechanisms can be for example friction at connections, the opening and closing of microcracks in concrete, or friction between a floor structure and nonstructural elements such as partition walls and furniture.
Under the particular circumstances of laboratory testing the main energy dissipation mechanisms presumably are internal friction in the material and the thermal effect of repeated elastic straining of the material (Chopra 2001).

Today there is a lack of knowledge of the actual physical phenomena and mechanisms which cause damping. Therefore, in the current situation it is not possible to calculate or describe mathematically the individual contributions from the various energy dissipating mechanisms in a building. The consequence of this is that the modeling of damping is not as exact as the modeling of mass or stiffness (Pavic & Reynolds 2002b). The damping can either be measured, estimated by comparing with similar existing structures, or estimated by using Rayleigh damping. Rayleigh damping means that the damping matrix is constructed by assuming a mass- and stiffness-proportional damping; see for example Chopra (2001) for more information.

Measurements of damping will measure the combined effects of all the different energy dissipating mechanisms. For a SDOF model it is therefore, in many cases, practical to idealize damping by a linear viscous damper that combines the effects of the different mechanisms into one (Chopra 2001):

$$f_D = c\dot{u}$$

c= viscous damping coefficient [Ns/m]

f_D = damping force

3.4.1 Damping ratio, ζ

It is common to use the damping ratio ζ, instead of the damping constant c, to describe damping in a structure. The damping ratio is a dimensionless measure of damping. It shows the ratio of the actual damping in the structure, in terms of the damping constant c, to the critical damping coefficient c_{cr}. The critical damping coefficient is the smallest value of c that makes the system return to its equilibrium position without oscillating.
It is possible to divide structures into three categories: underdamped, critically damped, and overdamped systems (Chopra 2001):

$$\zeta = \frac{c}{c_{cr}} = \frac{c}{2\sqrt{km}}$$

ζ= damping ratio
c= viscous damping coefficient
c_{cr}= critical damping coefficient
k= stiffness of the system
m= mass of the system

Underdamped system:	$c< c_{cr}$,	$\zeta<1$
Critically damped system:	$c= c_{cr}$,	$\zeta=1$
Overdamped system:	$c> c_{cr}$,	$\zeta>1$

Free vibration of underdamped, critically damped, and overdamped systems is shown in figure 3.6.

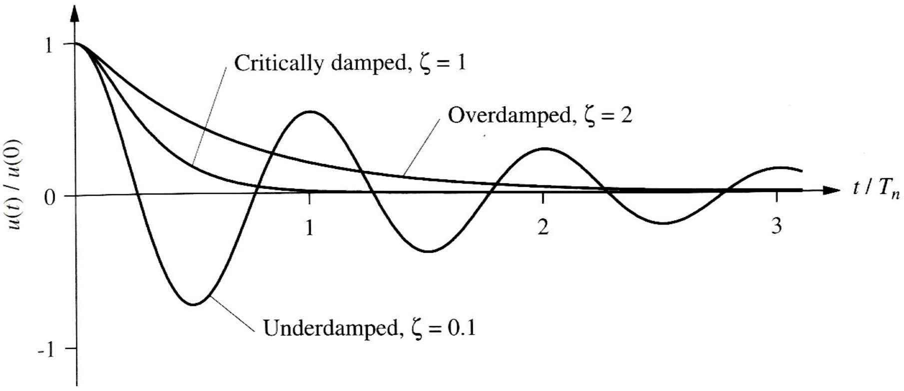


Figure 3.6. Free vibration of underdamped, critically damped, and overdamped systems (Chopra 2001).

Buildings and building components are typically underdamped structures, with damping ratios less than 0.10. For calculations Chopra (2001) recommends a damping ratio of 2-3 % for prestressed concrete with a stress level no more than half of the yield stress. Eriksson (1994) has performed field measurements of dynamic properties such as damping on a number of prestressed concrete floors. The measurements showed that the damping ratio varied from 0.5-2 %.

Furthermore, the damping ratio does not only vary between different floors, it also varies between the different modes of one floor structure.

To sum up, the amount of damping that is present in a floor structure in a real building depends on among other things the type of connections used, the amount of furniture and nonstructural elements, the number of humans on the floor, etc.
It has for instance been shown that humans are good dampers (Johansson 1999).

3.4.2 Experimental evaluation of damping ratios: Half-power bandwidth

Since it is not possible to calculate the damping coefficient of a system from the dimensions of the structure, measurements must be performed in order to evaluate the damping of a structure. One method that can be used to determine the damping ratios of the different modes of a structure is half-power bandwidth. By plotting the acceleration signal in the frequency domain, the damping ratio corresponding to a certain mode can be estimated according to the following equation:

$$\zeta = \frac{f_b - f_a}{2f_n}$$

f_n= resonant frequency
f_b, f_a= frequencies on either side of the resonant frequency, where the amplitude is $1/\sqrt{2}$ times the resonant amplitude, see figure 3.7.

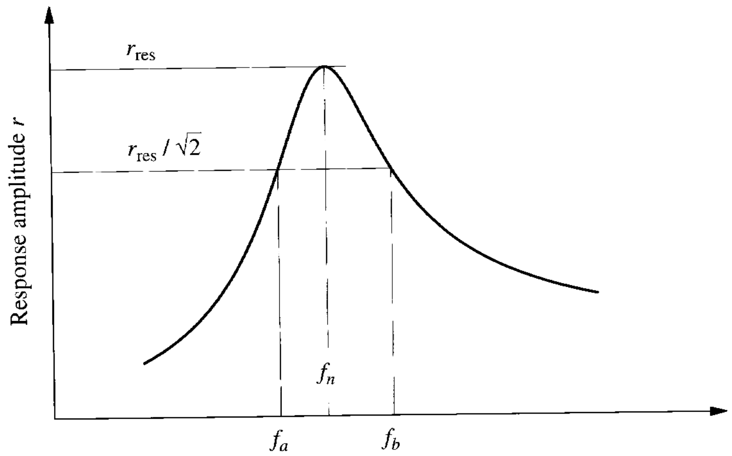


Figure 3.7. Definition of half-power bandwidth (Chopra 2001).

The half-power bandwidth equation is valid for small values of ζ, and means that the damping ratio can be determined without knowing the applied force (Chopra 2001).

3.5 Terms

Fundamental frequency
The lowest natural frequency.

Harmonics
Integer multiples of the fundamental frequency.

Footfall induced vibrations
The floor vibration source and receiver are different persons (Pavic & Reynolds 2002b).

Springiness
The person causing vibrations feels them as well, i.e. acts as the source and receiver at the same time (Pavic & Reynolds 2002b). This is typical for light-weight floors.

Steady-state and transient vibrations
The response of a damped system subjected to a harmonic force consists of two different components: steady-state vibration and transient vibration. Steady-state vibration means vibration at the frequency of the applied force and transient vibration means vibration at the natural frequency of the system. The transient part of the total response decays with time, leaving essentially the forced response, as can be seen in figure 3.8 (Chopra 2001).

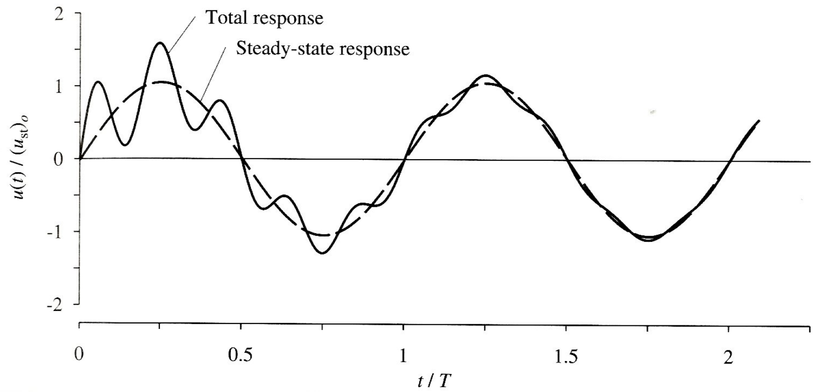


Figure 3.8. Response of a damped system to harmonic force (Chopra 2001).

Low-frequency floors vs. high-frequency floors
Floors are usually divided into low-frequency floors and high-frequency floors. Low-frequency floors have a fundamental frequency below 7-8 Hz, and high-frequency floors have a fundamental frequency above 7-8 Hz (Eriksson 1994). This limit is set to 10 Hz by Talja and Toratti (2006). Low-frequency floors are generally heavy structures such as concrete floors.
This classification of floors into low-frequency and high-frequency ones has its origin in the different responses of the floor types to human walking. For low-frequency floors the low frequency parts of human walking (the continuous parts) are the most

important because they cause a resonant response of the floor. This means that a person staying still may feel this resonance vibration. A high-frequency floor is more responsive to the impulsive parts of human walking. In this case a person standing still might feel the impacts caused by another person walking by, and the walking person might get a feeling of springiness (Eriksson 1994, Talja & Toratti 2006, Pavic & Reynolds 2002b).

r.m.s. acceleration

r.m.s. acceleration (root mean square) is a measure of the intensity of a vibration signal. Since the accelerations of a structure constantly are changing sign, the mean value is not a good description of the intensity of vibration; instead the r.m.s. value is used:

$$a_{rms} = \sqrt{\frac{1}{\Delta t}\int_{t_0}^{t_0+\Delta t} a^2(t)dt} \qquad \text{(Nilsson et al. 2005 \& ISO 2631-1:1997)}$$

Octave bands and 1/3 octave bands

An octave band is an interval of frequencies; it consists of all the frequencies between a lower limit and an upper limit. The ratio of the upper limit frequency and the lower limit frequency in an octave band is two, i.e. an octave means a doubling of the frequency. The frequency in the middle of the interval is often used to name the octave band. Every octave band is divided into three intervals called 1/3 octave bands. These frequency intervals and their mid frequencies are standardized.

Octave bands or 1/3 octave bands are used to analyze the frequency content of a vibration or sound signal. An octave band filter lets all the frequencies between a lower limit frequency and an upper limit frequency pass; this is done by amplifying all the frequencies in that specific range and excluding all the others (Nilsson et al. 2005), see figure 3.9.

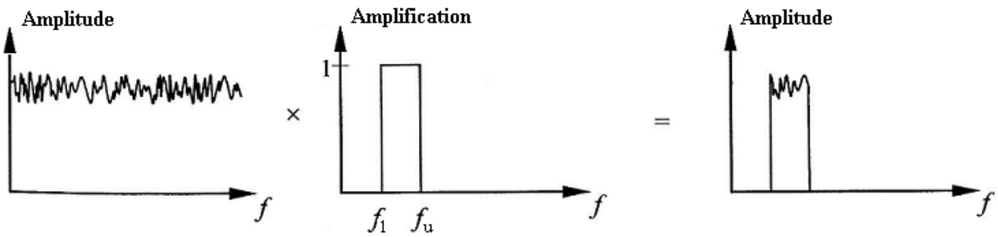


Figure 3.9. An example of a signal that is filtered by an octave band filter (Nilsson et al. 2005).

4 Human perception of whole-body vibration, and human response to whole-body vibration

A lot of research has been performed and is being performed in the area of human perception of whole-body vibration, and human response to whole-body vibration. According to Holmlund (1998) human response to whole-body vibration can be divided into five categories; perception, degraded comfort, interference with activities, impaired health and occurrence of motion sickness. In the case of vibration in buildings the main response is degraded comfort or annoyance.

Despite the vast research efforts that have been made there are in the current situation no clear limits for acceptable magnitudes of vibration in buildings (ISO 2631-2:2003). The reason for this lack of universally recognized dose-response relationships is the fact that the human body is a very complex and sensitive receiver of vibration. The response of a human to vibration is highly subjective and depends on a large number of variables. This means that there are huge inter- and intra-subject differences in the response to nominally the same vibration. For example, different people will react differently to the same whole-body vibration (inter-subject differences), and the same person may respond differently to the same vibration under different circumstances (intra-subject differences) (Pavic & Reynolds 2002a).

4.1 Whole-body vibrations

Vibration of the human body can be caused by a number of sources: hand-held power tools, vehicles, vibrations in buildings, etc. The vibrations can be divided into whole-body vibrations, e.g. vibrations in buildings or vehicles, and vibrations that influence only a part of the body, e.g. vibration caused by tools.

According to Meixner (2008) a lot of industrialized countries have standards for vibrations caused by power-tools and similar machines, which include vibration limits for acceptable magnitudes. These type of standards and vibration limits are easier to establish since the input is better known and easy to measure; the exposure time is often the same as the working time and the frequencies created by a motor are often easy to calculate. In these standards the vibration criteria is mostly impaired health.

When it comes to whole-body vibrations in buildings the vibration criteria is degraded comfort and annoyance. In this case the vibration limit is harder to establish since human perception of and response to whole-body vibration is highly subjective. Furthermore, the input such as exposure times and frequencies of the load show substantial variation.

4.2 Perception threshold

Many modern vibration assessment guidelines recognize the perception thresholds to be the limit for acceptance of vibration. ISO 2631-1:1997 states that: “Experience in many countries has shown that occupants of residential buildings are likely to complain if the vibration magnitudes are only slightly above the perception threshold.” However, there are many factors that influence the sensation limit, and it

has proven to be difficult to predict in which way these factors will affect the perception (Pavic & Reynolds 2002a).
One of the first studies of human sensitivity to whole-body vibration was performed by Reiher and Meister in 1931. They published the so called Reiher-Meister scale, which contains a vibration perception threshold, and also limits for when the vibration is perceived as annoying, unpleasant or painful, see figure 4.1.

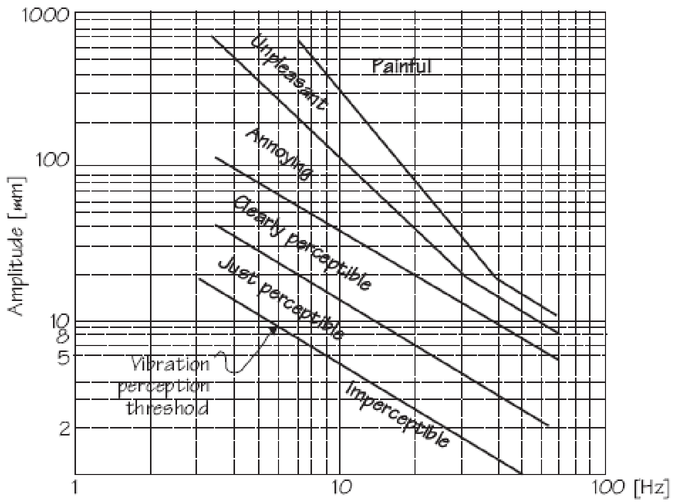


Figure 4.1. The Reiher-Meister scale (Pavic & Reynolds 2002a).

Since then, a lot of researchers have carried out tests in order to determine the perception threshold. Griffin (1990) has presented an overview of the results from some of these studies, see figure 4.2.

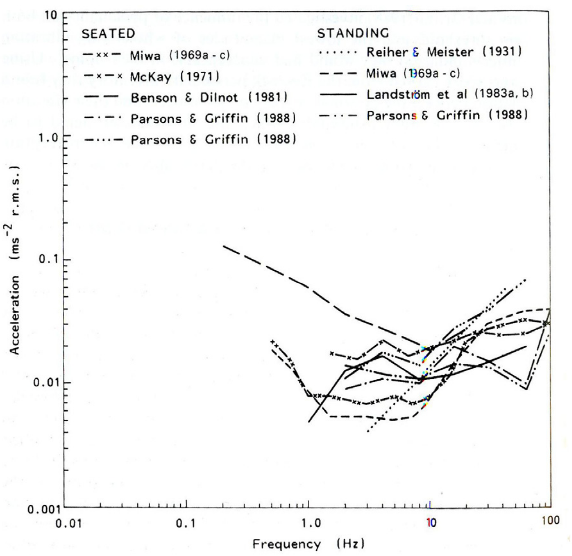


Figure 4.2. Perception thresholds for vertical whole-body vibration of seated and standing persons (Griffin 1990).

Figure 4.2 shows that there is some diverseness between the obtained perception thresholds. These differences may be explained by differences in test set-up, variation in posture, inter-subject differences such as age and gender of the test persons, or the characteristics of the vibration stimuli (Griffin 1990).
According to ISO 2631-1:1997 fifty percent of alert, fit persons can just detect a W_k weighted vibration (see chapter 5.3) with a peak magnitude of 0.015 m/s^2. It is also recognized that there is a large difference between humans in their ability to perceive vibrations. This is shown by the fact that the median value for the perception threshold is 0.015 m/s^2, and the interquartile range is between 0.01 m/s^2 and 0.02 m/s^2 (interquartile range is the area where 25 to 75 % of the test subjects can sense the vibration).

4.3 Variables that affect the response

The matter of determining an acceptance limit is complicated by the fact that the perception of vibration is not just a function of "feeling the vibration". Vibrations can be sensed and detected by a number of sensory systems; the visual-, the auditory-, the vestibular- and the somatic system. In other words, vibrations can be detected by seeing the movements, it can be heard, it might affect the balance sense organs, or it can be felt (Griffin 1990). Furthermore, some researchers hold that human reactions to whole-body vibration in buildings are more psychological than physiological (Pavic & Reynolds 2002a).
Some examples of variables that affect the response are presented below:

Human response to whole-body vibration depends on the characters of the vibration, i.e. amplitude, frequency, duration, direction, and so on. The response is also influenced by the inter- and intra-subject differences, as for example age, gender, posture, fitness, type of activity, attitude, or motivation. To illustrate this, there is a difference in perception thresholds for standing and sitting persons, and heavy people are more sensitive to higher frequencies and less sensitive to lower frequencies than a lighter person. Also, just bending your knees will change the vibration transmission drastically.
Furthermore, it has been found that if people are expecting vibrations, or know that they are present, they will discover them earlier, i.e. the perception threshold will be lower than in the case when they do not expect vibrations to exist (Johansson 1999). Another way of seeing it is that people are particularly sensitive to the existence of vibrations in buildings since they do no expect large, heavy objects to move.
It has also been shown that the presence of noise may reduce the acceptable vibration magnitudes (Pavic & Reynolds 2002a).

Some researchers claim that the duration of exposure to vibration is a very important factor. According to Griffin prolonged exposure to vibrations increase discomfort. Other studies have shown that the amount of damping in a structure has an effect on the response to vibrations, especially in the case of transient vibrations. It was found that people generally rate transient vibrations that decrease quickly as more acceptable.

Another interesting thing that must be mentioned is that the perception of vibration depends on whether the person is moving or stationary when subjected to the vibration. During the process of walking the human body is subjected to accelerations as high as 3 m/s^2. However, the nervous system and the brain are used to these types of accelerations and are capable of disregarding them. Therefore, when walking over a floor structure, small vibrations of the floor structure might not be perceived (Pavic and Reynolds 2002a).
An example of a psychological factor that can affect the response is whether the person knows the vibration source or not. If the vibration is caused by their own children it might not be perceived as annoying as vibration caused by the children in the neighbouring apartment (Johansson 1999).
The response to whole-body vibrations also depends on the frequency content of the vibration signal. Humans are more sensitive to accelerations in the frequency range 4-8 Hz (Pavic & Reynolds 2002a)

4.4 The natural frequencies of the human body

The human body can be regarded as one mass when it is subjected to vibrations consisting of frequencies smaller than 2 Hz. During higher frequencies the human body can be described as a lumped mass model, in which the different parts of the body have different resonance frequencies (Bodén et al. 2001), see figure 4.3.

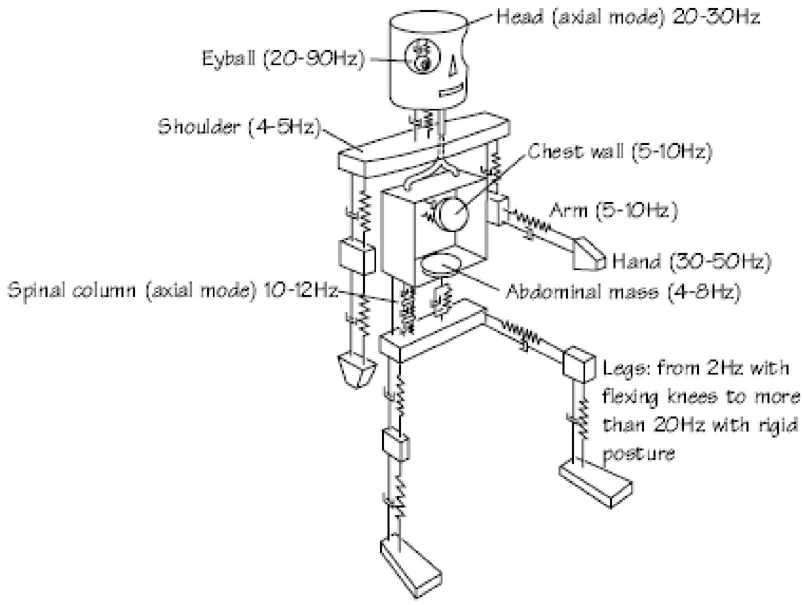


Figure 4.3. Lumped mass model of a human body (Pavic & Reynolds 2002a).

The different natural frequencies of the human body are the reason for the frequency dependence of human sensitivity to vibrations. People are more sensitive to vibrations in the range of 4-8 Hz since vibrations with this frequency content cause resonance of some internal organs (Pavic & Reynolds 2002a).

4.5 Frequency weighting and equal comfort contours

Because of the frequency dependence of human sensitivity to vibration so called equal comfort contours can be drawn. These curves show the accelerations at different frequencies which cause the same sensation.
To account for this frequency dependence some standards and vibration assessment guidelines practice the method of frequency weighting when evaluating a vibration signal. Frequency weighting means that vibration magnitudes where the equal comfort contour is low (e.g. 4-8 Hz) are left unchanged, and the vibration magnitudes at the frequencies to which humans are less sensitive are attenuated. Thereby the vibration signal is "normalized" to the same sensation level (Pavic & Reynolds 2002a).
When evaluating vibration with respect to limits there are two possibilities; one can compare the vibration magnitude in each 1/3 octave band separately to the limit value for each band, or one can frequency weigh the magnitudes in each band (multiply them by weights) and compare them to only one value, the limit value for the band of maximum sensitivity (4-8 Hz in the case of vertical vibration). Therefore, frequency weighting makes the evaluation process simpler and it enables the determination of a single parameter that characterizes the vibration, the weighted r.m.s. acceleration (Griffin 1990).

An example of a equal comfort contour and frequency weighting curve can be seen in figure 4.4. In ISO 2631 the frequency weighting curves are named W.

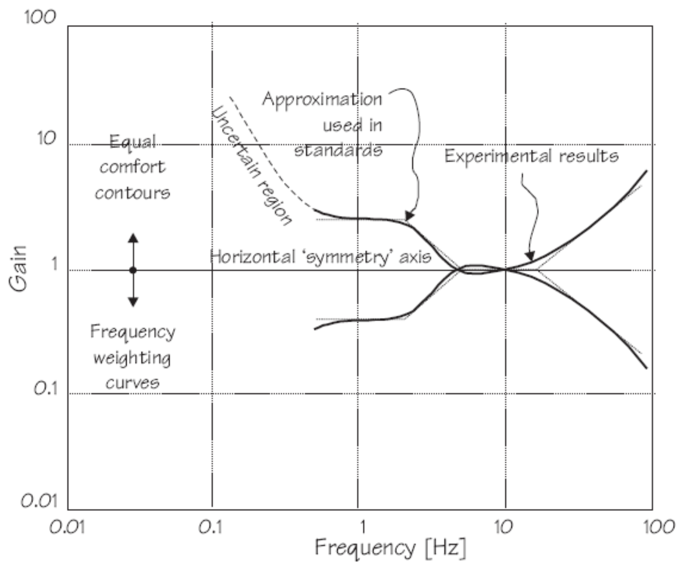


Figure 4.4. Relationship between equal comfort contours and frequency weighting curves (Pavic & Reynolds 2002a).

4.6 The effect of whole-body vibrations on health and performance

According to ISO 2631-1:1997, long-term high-intensity whole-body vibrations can result in an increased health risk to the lumbar spine and the connected nervous system of the segments affected. There is also a risk that the digestive system, the genital/urinary system, or the female reproductive organs can be affected. These effects are valid for seated persons, since there has not been any corresponding research performed on standing or recumbent persons. It is also stated that it normally takes several years for the health changes to occur.
There is also a part in the standard that concerns the incidence of motion sickness, which can be produced by vibration at frequencies below 0.5 Hz.

When it comes to the effects of vibration on performance and task capability the standard does not contain any guidelines. The reason for this is the dependence on the ergonomic details, the activity, etc (ISO 2631-1:1997).

5 Existing criteria and limit values

In the current situation there is a lack of unanimous vibration criteria and vibration limits in the case of whole-body vibration in buildings. The reasons for this lack of clear dose-response relationships are among other things the inter-subject differences, i.e. different people will react differently to the same vibrations, and the complexity of human response to vibration.

5.1 The design regulations of the Swedish Board of Housing, Building, and Planning

According to the Swedish design regulations, BKR, construction parts shall be designed so the oscillation that might occur will not be perceived as annoying. More guidance on how to design floor structures in order to avoid annoying vibration, or limiting values are not stated, except for the case of timber slabs. In the case of floor structures made of wood the design regulations advises the designer to use a handbook called *Svängningar, deformationspåverkan och olyckslast* in order to evaluate the tendency to oscillate (Boverket 2003).
The first part of this handbook is based on the work of Sven Ohlsson and deals with vibration of floor structures caused by human walking. When designing a slab with respect to vibration serviceability the handbook uses a static criterion, where the maximum deflection is checked, and a dynamic criterion. The method is valid for different types of slabs, but the fundamental frequency of the floor structure must be higher than 8 Hz and the span must be shorter than 4 m (Boverket 1994).
These limitations implicates that the method is not valid for the experimental floor structure used in this study, or for hollow core elements in general. Furthermore, calculations performed by Meixner (2008) showed that the method did not correlate well with subjective opinions regarding the vibration performance of a test floor made of HD elements.

5.2 Eurocode

Just like in the Swedish design regulations, there is no chapter concerning vibration serviceability of concrete floors in Eurocode. There is, however, some design rules regarding the vibration serviceability of timber structures. Similar to the Swedish design regulations, a static and a dynamic criterion must be fulfilled in the case of high-frequency timber floors in residential buildings (EN 1992-1-1 & EN 1995-1-1).

5.3 ISO 2631-1:1997

The International Standard ISO 2631-1:1997 has the status of a Swedish Standard. The title of this standard is *Vibration and shock- Evaluation of human exposure to whole-body vibration- Part 1: General requirements.* As the name reveals this standard is applicable to vibration transmitted to the human body as a whole, which is typical for vibration in buildings. This type of vibration can also be found in vehicles and certain types of machinery.

ISO 2631-1:1997 provides guidelines on how to perform vibration measurements, what to report, and how to evaluate the measurement results in order to standardize the reporting and simplify comparison. The standard does not include any vibration exposure limits for whole-body vibrations. The reason for this is the complexity of human physiological/pathological and behavioral response to vibration, and the lack of clear, universally recognized dose-response relationships in this case. However, the standard provides three annexes with information on the current opinion on the possible effects of vibration on health, comfort and perception, and motion sickness.

According to the standard, vibration magnitude shall be presented as acceleration, or more precisely root-mean-square acceleration. Since how vibration affects health, comfort, perception and motion sickness depends on the frequency content of the vibration, the measured accelerations should also be frequency weighted. There are different frequency weightings for different situations, for example for different directions of vibration. In the case of a multi-frequency vibration signal it is recommended to determine the overall weighted acceleration:

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

a_w is the frequency-weighted acceleration
W_i is the weighting factor for the *i* th one-third octave band
a_i is the r.m.s. acceleration for the *i* th one-third octave band

Furthermore, the duration of the measurement shall be reported as well as other factors that may affect human response to vibration, for example the frequency content of the vibration, the vibration direction, how conditions change over time, population type, expectations, activities and so on.

In Annex C of ISO 2631-1:1997 the following sentences can be found:
"With respect to comfort and/or discomfort reactions to vibration in residential and commercial buildings, ISO 2631-2 should be consulted. Experience in many countries has shown that occupants of residential buildings are likely to complain if the vibration magnitudes are only slightly above the perception threshold." Furthermore, it is stated that 50 % of alert, fit persons can just detect a W_k weighted vibration with a peak magnitude of 0.015 m/s^2 (SS-ISO 2631-1:1997).

5.4 ISO 2631-2:2003

The title of the second part of ISO standard 2631 is *Mechanical vibration and shock-Evaluation of human exposure to whole-body vibration- Part 2: Vibration in buildings (1 Hz o 80 Hz).* This standard is applicable to the evaluation of vibration in buildings with respect to comfort and annoyance of the occupants; it is not applicable when investigating the effects of vibration on human health and safety.

In this edition of the standard, limit values have been excluded, since research findings in the area of acceptable magnitudes of vibration are too widespread to be presented as guidance values in an international standard. Instead the standard recommends a method for measurement and evaluation of whole-body vibrations in buildings in order to encourage a uniform collection of data, which will facilitate the establishment of limit values in the future.

For the evaluation of the measured accelerations the standard recommends using overall weighted values, see ISO 2631-1:1997. A frequency weighting W_m is defined and recommended to be used irrespective of measurement direction or posture of an occupant. This frequency weighting curve is the same as the curve called W_k in ISO 2631-1:1997. The standard also states that it is enough to consider and evaluate vibration in the direction with the highest frequency-weighted vibration magnitude (ISO 2631-2:2003). Since the experimental floor structure in this study is subjected to human walking, the main vibration direction will be the vertical direction, which means that only the accelerations in this direction must be measured.

The standard emphasizes that human response to building vibration is in many cases not only a function of vibration magnitude, but also depends on secondary effects such as noise, expectations, and economic, social or other environmental factors. Temporary disturbances such as construction work and transient events are given as examples of situations where significantly higher vibration magnitudes can be tolerated. If vibration last during a long period, the occupants might get familiarized and the adverse comment threshold might change. Another example is that adverse comment may arise due to secondary effects that are associated with vibration, such as the rattling of windows or ornaments or other visual effects that may emphasize the disturbance.
For this reason, guidelines for collecting data concerning human response to building vibration are given in an annex. These guidelines encourage users to not only measure vibration magnitudes but also collect data about all the other factors in a building that might affect human response to vibration. Parameters that should be reported are among others the character of the vibration, i.e. continuous, intermittent or impulsive vibration, the exposure time, measured noise level related to the vibration, and visual effects such as swinging of suspended features (ISO 2631-2:2003).

5.5 ISO 2631-2:1989

This version of ISO standard 2631-2 has been cancelled and replaced by the newer edition ISO 2631-2:2003. However, the former edition is interesting because in this edition tentative vibration limits are given in the form of base curves.
There is one base curve for vibration in the foot-to-head direction. This base curve represents vibration magnitudes that cause approximately the same annoyance. When evaluating the vibration serviceability of a structure the base curve should be used together with multiplication factors. These multiplication factors take into consideration the time of day and the use made of the occupied space, i.e. office,

residential, etc. The multiplication factors are given in an annex, and they are a result of a number of investigations of satisfactory magnitudes of building vibration with respect to human response, i.e. the multipliers are based on the state-of-the-art information present at that time.
For offices the base curve should be multiplied with 4. The base curve and the curve for evaluating vibration serviceability in offices can be seen in figure 5.1. In offices the probability of adverse comment is low if the vibration magnitudes are below the curve that is valid for offices (ISO 2631-2:1989).

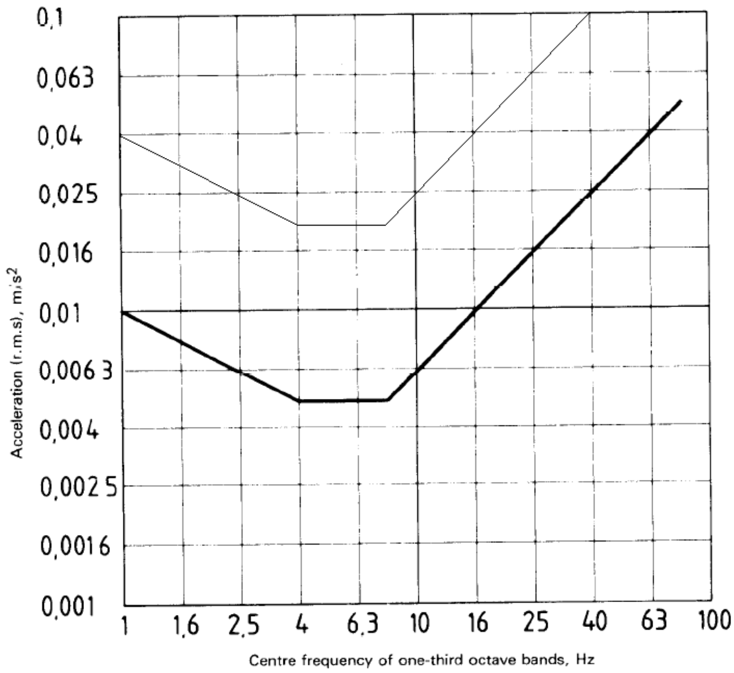


Figure 5.1. Building vibration z-axis base curve for acceleration. The thin line is valid for offices (ISO 2631-2:1989).

It is also recognized in the standard that the satisfactory magnitudes depends on the circumstances and the expectations, which means that it is possible that values below the curve could give rise to annoyance, or values above the curve might not give rise to complaints. However, in general for magnitudes below the curve no adverse comments had been reported at the time of the publication of this edition of the standard (ISO 2631-2:1989).

When evaluating a structure's vibration performance by using the base curve presented in ISO 2631-2:1989 the vibration signal can be filtered in 1/3 octave bands and then the value in each band shall be compared to the limit at the centre frequency of that band. The other possibility is to frequency weigh the accelerations and calculate an overall weighted value. In this case the overall weighted value shall be compared to the limit magnitude in the frequency band of maximum sensitivity, i.e. 4-8 Hz (ISO 2631-1:1985). The frequency weighting curve in the first edition of the standard ISO 2631-2 is the same as the frequency weighting curve in the second edition, i.e. it has not been changed.

According to ISO 2631-2:1989 it has been shown that there are some summation effects, or interaction, for vibration consisting of different frequencies compared to vibration at one frequency at a time. Therefore, it is preferred that overall weighted values are used in the case of multi-frequency vibration.

Ljunggren (2006) has shown that human perception of vibration is greatly affected by the vibration signal's composition in terms of number of frequency components and also their frequency separation. He has come to the conclusion that the frequency weighting of ISO 2631-2 and the overall weighted value works well to describe the annoyance for a single sinusoidal, but is less accurate when it comes to a signal consisting of a limited number of discrete frequencies. Instead he has developed a prediction model where both the weighted total amplitude and the fundamental frequency are considered. He also refers to the work of other researchers that indicate that the use of the base curve in ISO 2631-2:1989 will either overestimate the effects of low-frequency vibration or underestimate the effects of high-frequency vibration, depending on the multiplication factor that is used:
Figure 5.2 shows the results from Griffin and Parson's (1988) experiments regarding whole-body vibration perception thresholds of sitting and standing subjects exposed to vertical sinusoidal vibration compared with the base curve of ISO 2631-2:1989.

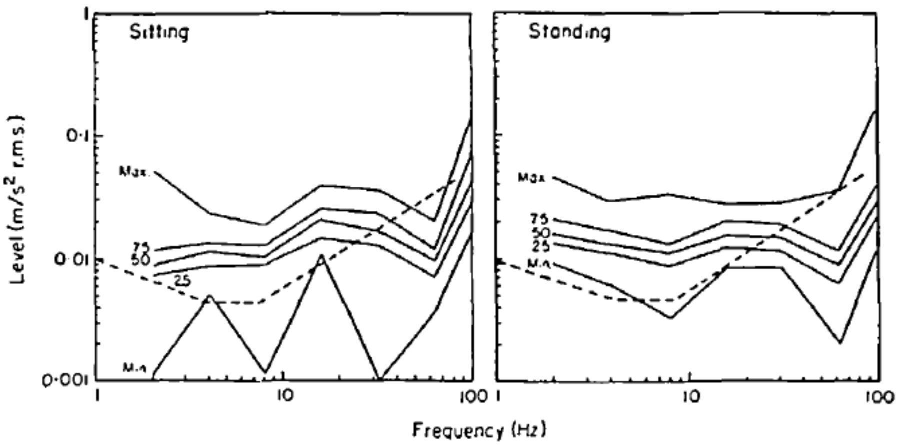


Figure 5.2. Results from experiments by Griffin & Parsons. Percentiles and range of vibration thresholds for 36 sitting and standing subjects exposed to vertical vibration, compared with the z-axis base curve as proposed in ISO 2631 (Griffin & Parsons 1988).

The base curves of ISO 2631-2:1989 have been withdrawn in the latest edition of the standard, the motivation is:
"Guidance values above which adverse comments due to building vibration could occur are not included any more since their possible range is too widespread to be reproduced in an International Standard." (ISO 2631-2:2003)

5.6 Classification and acceptance limits of human induced floor vibrations according to Talja and Toratti

Tomi Toratti and Asko Talja are two researchers that have spent more than the last 10 years to study human perception of floor vibration. They have performed subjective tests and measurements on a number of different floor structures during those years. The projects have involved timber-, steel- and concrete floors. More than half of the tests were performed in a laboratory and the rest were performed in buildings just after construction. Their research has resulted in a proposed method for the assessment of vibration serviceability of floors. Also, suggested criteria and limiting values are given (Toratti & Talja 2006). This method is recommended in a number of reports by the Swedish Steel Institute, *Stålbyggnadsinstitutet* (Lennartsson 2007 & Wang et al. 2003).

For high-frequency floors (f_0 >10Hz) they have found that point load deflection is the best indicator when designing with respect to floor vibration. For low-frequency floors (f_0 <10Hz) the recommended parameter to use is acceleration, because of its good correlation with subjective ratings.
Talja and Toratti propose a classification of floors into five classes, see table 5.1. This classification presumes human walking to be the designing load case and it is valid for floors in residential and office buildings. It is based on the sense perception of a sitting person and the sense perception from vibrations of objects (Toratti & Talja 2006).

A	Special class for vibrations inside one apartment. Normal class for vibrations transferred from another apartment. The vibration is usually imperceptible.
B	Higher class for vibrations inside one apartment. Lower class for vibrations transferred from another apartment. The vibration may be perceptible but usually it is not annoying (inside one apartment).
C	Normal class for vibrations inside one apartment. The vibration is often perceptible and some people may feel it annoying (inside one apartment).
D	Lower class for vibrations inside one apartment. For example attics and holiday cottages. The vibration is perceptible and most people feel it annoying (inside one apartment).
E	Class without restrictions.

Table 5.1. Vibration classes in office and residential buildings (Toratti & Talja 2006).

5.6.1 Subjective tests

The method proposed by Toratti and Talja involves among other things subjective tests. During the subjective tests a walker weighing 80 kg is supposed to walk back and forth across the floor and each round one of the footprints should be placed on a reference point. The reference point is the point on the floor with the largest deformation. In the case of a rectangular floor the midpoint can be taken as the reference point.
The observer is placed on an uncovered foot stool at the observation point, which is a point where the maximum vibration will occur. In the case of a rectangular floor the observation point can be placed 600 mm from the reference point (Talja & Toratti 2004). An example of a test set up is shown in figure 5.3.

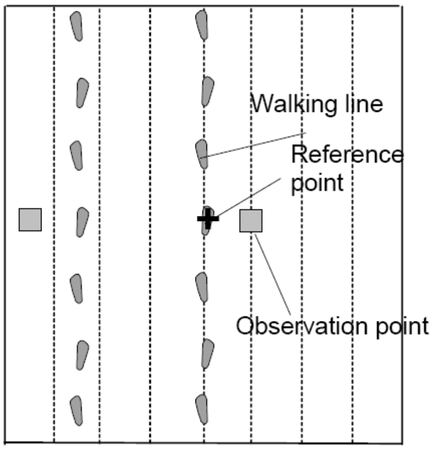


Figure 5.3. Examples of a walking line, reference point and observation point (Talja & Toratti 2004).

For low-frequency floors the walker should walk with a step frequency that is proportional to the fundamental frequency of the floor. The step frequency is determined by dividing the fundamental frequency by an integer, it should be less than 2 Hz, but as close as possible to 2 Hz.
A test subject sitting at the observation point is asked to rate the intensity and acceptability of the vibrations induced by the walker:
The walker passes the observer three times and then the observer is asked to fill out a form, where each test subject is asked to classify the intensity of vibration as:

- imperceptible,
- barely perceptible,
- clearly perceptible or
- strongly perceptible.

The test subject is also asked to form an opinion of the acceptability of the vibration in a newly built living room as:

- absolutely acceptable,
- acceptable,
- unacceptable or
- absolutely unacceptable.

The ratings above are based on the body feeling of a sitting test person. Talja and Toratti also recommend letting the test subjects rate the vibration of objects. In this case the observer stands on the observation point when the walker passes by, and the vibration of a number of articles placed on a special tripod is supposed to be classified the same way as above (Talja & Toratti 2004). An example of a form used when classifying floor vibration is shown in figure 5.4. Talja (2000) states that it is a good idea to also let the test persons evaluate the vibration when they themselves walk on the floor.

INTENSITY OF VIBRATIONS
The vibrations are
- imperceptible **(No)**
- barely perceptible **(B)**
- clearly perceptible **(C)**
- strongly perceptible **(S)**

ACCEPTABILITY OF VIBRATIONS

Is the floor acceptable in a newly built living room ?
+ yes **++** absolutely acceptable
- no **- -** absolutely unacceptable

Test 1	Intensity				Acceptability			
	No	B	C	S	++	+	-	- -
Body perception								
Clinking of a coffee cup								
Leaf movements of a pot plant								
Water rippling in a glass bowl								
Chinking of a glass pane								

Figure 5.4. Assessment form for rating vibrations (Talja & Toratti 2004).

5.6.2 Measurements

Measurements should be performed using an accelerometer placed on the observation point used in the subjective tests. The source of the vibration should be the same walker as during the subjective tests.
It is recommended to filter the samples in 1/3 octave bands, and to weigh the accelerations by the weighting function W_k according to ISO 2631-1:1997. The acceptance limit used is the weighted r.m.s. acceleration of all frequency bands:

$$a_w = \sqrt{\sum_i (W_{k,i} a_i)^2} \qquad \text{(Talja \& Toratti 2004).}$$

5.6.3 Acceptance limits

The acceptance criterion proposed by Talja and Toratti is when the majority of the observers find a floor acceptable based on body perception. They also recognize that it can seem to be a too loose criterion classifying a floor acceptable with regard to vibration when only 50 % of the occupants find it acceptable. However, they argue that the test looks at the worst point of the floor and in a test situation the observers are likely to be more critical (Talja & Toratti 2004).

Based on a number of measurements and subjective tests, during a 10-year period, limiting values for all the vibration classes have been retrieved, see table 5.2. The time period for the weighted r.m.s. acceleration is T=1s (Talja & Toratti 2006).

	Dynamic vibration values				**Static deflection values**	
	$f_0 < 10$ **Hz**		$f_0 > 10$ **Hz**		$f_0 > 10$ **Hz**	**Floor plate or superstructure**
	a_{wrms} [m/s^2]	v_{max} [mm/s]	v_{rms} [mm/s]	$\lvert u_{max} \rvert$ [mm]	Global deflection [a)] δ_0[mm/kN]	Local deflection [b)] δ_1[mm/kN]
A	≤ 0.03	≤ 4	≤ 0.3	≤ 0.05	≤ 0.12	≤ 0.12
B	≤ 0.05	≤ 6	≤ 0.6	≤ 0.1	≤ 0.25	≤ 0.25
C	≤ 0.075	≤ 8	≤ 1.0	≤ 0.2	≤ 0.5	≤ 0.5
D	≤ 0.12	≤ 10	≤ 1.5	≤ 0.4	≤ 1.0	≤ 1.0
E	> 0.12	> 10	> 1.5	> 0.4	> 1.0	> 1.0

[a)] Deflection of main beams

[b)] Deformation caused by floor tops (measured at a distance of 600 mm, Figure 1) which are deformations of top plate, floating floor or raised floor.

Table 5.2. Tentative acceptance limits for vibration classes (Talja & Toratti 2006).

6 Walking excitation

There are many examples of sources that can cause vibrations in buildings: traffic, blasts of wind, earthquakes, machines with rotating masses, humans that are moving, construction work, and so on. However, the most important source of annoying vibrations in residences and office buildings is human walking (Heyden et al. 2005 & Ohlsson 1984). Footfall forces are a major source of floor vibration disturbance, since walking happens frequently and is difficult to isolate (Pavic & Reynolds 2002a).

6.1 Forcing patterns for walking

Walking, or more precisely the gait cycle of one footstep, consists of three phases. During the first phase both feet are in contact with the floor. This is the time period just after the heel strikes the floor. During phase 2 the trailing leg swings past the leading leg and the ground reaction force declines. In the third phase the body is supported only by the toes of the trailing leg and the rear foot pushes the body forward, this cause the force to increase again (Lievens & Brunskog 2007).
The gait cycle of one footstep and the corresponding vertical component of the ground reaction force are shown in figure 6.1. The figure shows the typical "two peak" forcing pattern for walking. A floor structure is also subjected to horizontal force components from human walking, but according to Eriksson (1994) these forces are of little importance when studying floor vibrations.

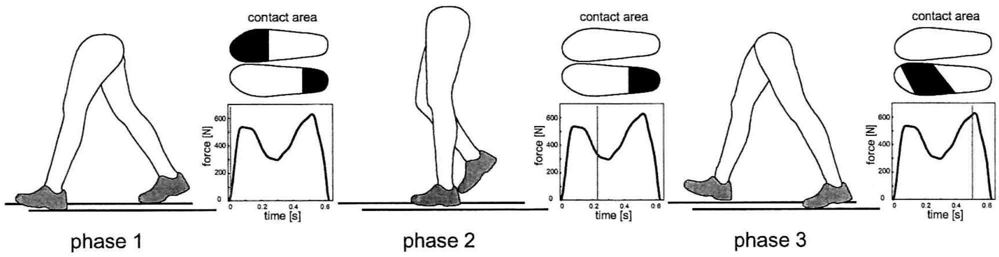


Figure 6.1. Different phases during the gait cycle of one footstep (Lievens & Brunskog 2007).

Forcing patterns for walking at different paces and running are shown in figure 6.2. As can be seen, there is a difference in the forcing pattern for walking and running. Running creates a force that is shorter in duration and greater in magnitude compared to walking, and in running there are time periods when both feet are off the ground. The entity on the y-axis in the diagrams is force/weight, since the weight of a person does not significantly affect the shape of the force patterns; it only affects the magnitude of the force (Pavic & Reynolds 2002a).

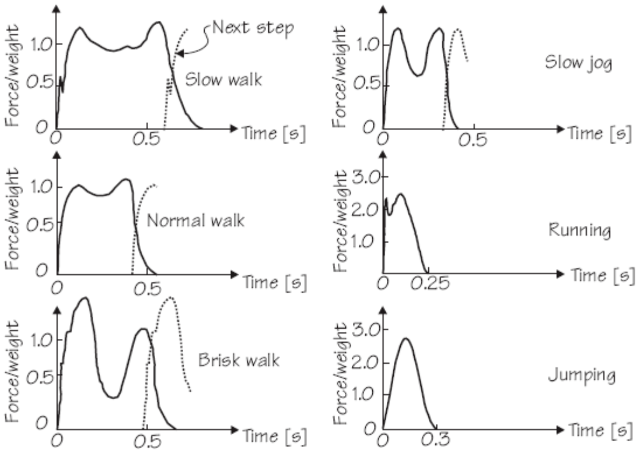


Figure 6.2. Forcing patterns for walking, jogging and running (Pavic & Reynolds 2002a).

As mentioned above, in walking there is always one foot touching the ground, and during a short period of time both feet are on the ground. This means that the forces induced by the left and the right leg overlap, which can be seen in figure 6.2 and 6.3.

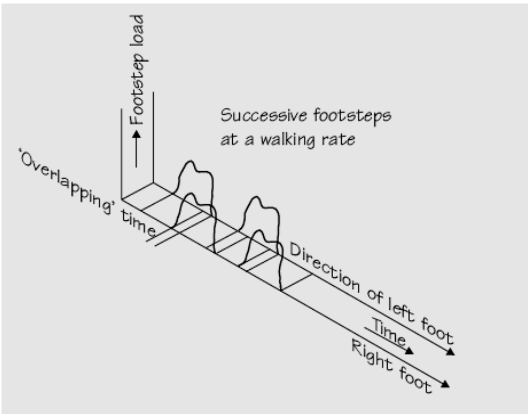


Figure 6.3. Forcing patterns for walking (Pavic & Reynolds 2002a).

6.1.1 Step frequencies

Walking is a periodic excitation and a number of researchers have reported step frequencies between 1.5 and 2.5 Hz (steps per second) for normal walk (Pavic & Reynolds 2002a). The step frequency naturally depends on the activity. Step frequencies for different activities are displayed in table 6.1.

Activity	Steps/second
Walking	1,7- 2,3
Running	2,0- 3,5
Jumping	1,8- 3,0
Sports activity	2,0- 3,0
Dancing	1,9- 3,3

Table 6.1. Step frequencies for different activities (Meixner 2008)

Moreover, among others Eriksson (1994) has shown that forces due to walking consist of higher harmonics of the step frequency in addition to the fundamental step frequency. Consequently, walking consists of a low frequency part from the successive footsteps and a higher frequency part from the initial impact of the foot on the floor. This is why human walking can excite the fundamental frequency or other natural frequencies of a floor structure, thereby causing resonant vibration (Pavic & Reynolds 2002 a&b).
Furthermore, Eriksson (1994) concludes that the type of footwear does not have a major effect on the low-frequency parts of walking. But according to Lievens and Brunskog (2007) it will affect the high-frequency components.

6.2 Footfall load simulations

For offices a single person walking is proposed by many researchers to be the governing load case when checking the vibration serviceability of a floor structure. For other buildings, e.g. gymnasiums, the governing load case will be another, for instance a group of people moving (Pavic & Reynolds 2002a).
Historically it has been very popular to apply the footfall loading at the worst possible point of the floor structure when modeling loading due to walking. Consequently human walking is modeled as treading in place at the worst point of the floor structure. The main reason for this approach is the simplification of the calculations. However, modern-day computer capacity and FE-modeling makes it justifiable to model the load due to walking as a moving load (Pavic & Reynolds 2002b).

6.2.1 Walking modeled as Fourier series

One way of modelling a single person walking is to assume that walking is a perfectly periodic activity, which makes is possible to describe it as a sum of Fourier components. According to Pavic & Reynolds (2002b) Bachmann et al. proposed an expression $F_p(t)$ for the vertical footfall load from a single person walking:

$$F_p(t) = G + \alpha_1 G \sin(2\pi f_s t) + \alpha_2 G \sin(4\pi f_s t - \varphi_2) + \alpha_3 G \sin(6\pi f_s t - \varphi_3)$$

G = the weight of the person
$\alpha_i G$ = the loading amplitude corresponding to the ith harmonic
f_s = the pacing rate
φ_2, φ_3 = the phase angles of the second and third harmonics

In this expression of the force the fundamental frequency is equal to the pacing rate and the frequencies of higher harmonics are integer multiples of the fundamental frequency. This is exactly what Eriksson (1994) observed in his studies.
The load function according to Bachmann et al. for a person weighing 80 kg and walking at a pacing rate of 2 steps per second can be seen in figure 6.4.

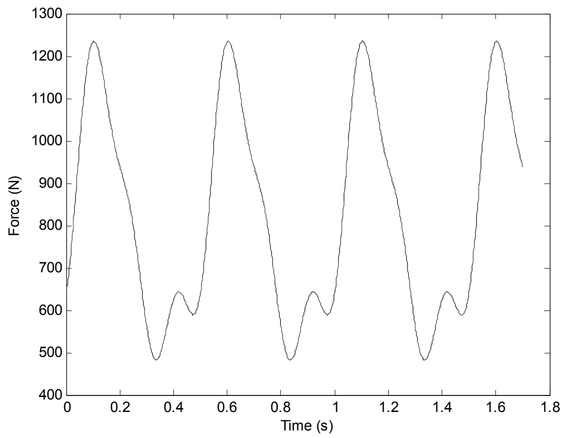


Figure 6.4. Single person walking excitation. Load function according to Bachmann et al. (Meixner 2008)

Meixner (2008) used the load function above in order to determine the maximum span of hollow core elements with respect to vibration serviceability. The load was applied at the midpoint of the floor model.

6.2.2 Heel-drops

Another type of load that has been used to check vibration serviceability of floor structures is a single heel-drop or multiple heel-drops. A heel-drop is when a person standing on their toes drops their heels to impact the floor (Hanagan & Murray, 1997). According to Hanagan and Murray heel-drop impacts are for example useful when evaluating the transient response of a floor structure. However, multiple heel-drops are not a realistic form of walking excitation in residential buildings or offices (Pavic & Reynolds 2002b).

6.2.3 FE analysis

The recent advances in the computer area have made it justifiable to model human walking as a moving load. If modeling the floor structure in a finite element program the load due to walking can be applied as a moving load.

For example, Xing, Xiong and Tan (2007) have used the available experimental results on footfall load time history to create an approximate load function, which can be seen in figure 6.5. They apply this load function successively at every point a walking person would place their feet. The load is applied at nodes, and the overlap in forces when both feet are on the ground is considered.

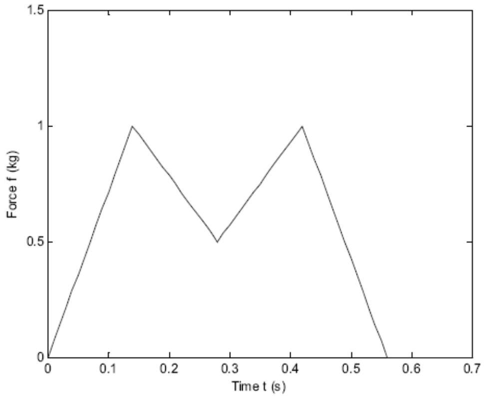


Figure 6.5. The time history of human walking impact load function (Xing et al. 2007).

Similarly, in their work Bard, Persson and Sandberg (2008) have used a load function based on the measurements, made by other researchers, of the time history of the reaction forces from human walking. The reaction force of a gait cycle consisting of two steps can be seen in figure 6.6.

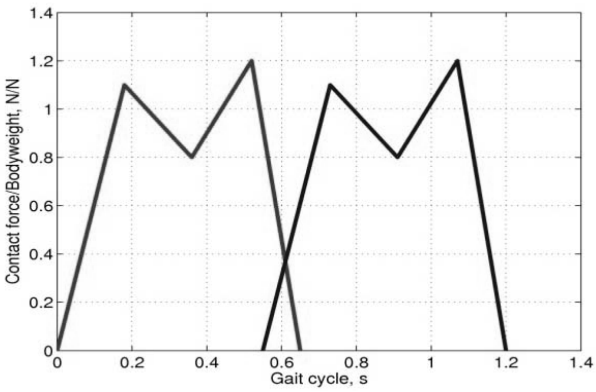


Figure 6.6. The reaction force of a gait cycle for two steps (Bard et al. 2008).

For each foot step they apply the load on two discrete circles, which represent the heel and the forefoot. The reaction force time history for one step is therefore divided into one time history for the heel and one for the forefoot, see figure 6.7. In their calculations they have used a gait speed of 1.3 m/s and the parameters concerning stride length, etc are from a master thesis processing statistics on walking patterns (Bard et al. 2008).

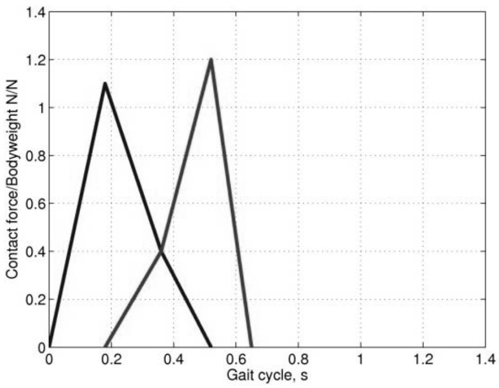


Figure 6.7. The reaction force time history for one step divided into separate time histories for the heel and the forefoot (Bard et al. 2008).

7 Subjective tests and laboratory measurements

In a study performed by Meixner (2008) a number of people were asked to rate the vibration serviceability of a slab consisting of three hollow core elements, HD/F 120/20, cast together. In that study, the elements were used without any concrete topping. The span of the floor was 8 m, and therefore within the recommended limits for this type of hollow core element. The survey showed that most of the test persons found the floor unacceptable with regard to vibrations.
However, in reality it is customary to cast a topping on site to get a plane surface. This will of course affect the vibration properties of the floor structure and will probably improve the vibration serviceability of the floor.

Therefore, in order to investigate the effect of a concrete topping on the dynamic properties of a slab consisting of HD elements, an experimental floor structure was built in a laboratory. Measurements of the vibration properties were carried out before and after a concrete topping was cast. Moreover, subjective tests were performed, where a number of people were asked to evaluate the vibration serviceability of the floor structure with and without the topping.

7.1 Experimental floor structure

The experimental floor structure consisted of three hollow core elements of the dimension HD/F 120/20. These HD elements are the smallest elements in the series of standard dimensions for hollow core elements. The elements were cast together with a concrete of strength class C25/30. The experimental floor structure can be seen in figure 7.1.

Figure 7.1. Experimental floor structure.

The span of the floor was 8 m. According to the handbook of prefabricated concrete elements (*Bygga med prefab*) the recommended bearing lengths for this type of hollow core elements is between 6 and 10.5 m. These spans are valid for slabs with moderate loads, for example slabs in office buildings, schools, residential buildings and lighter industries. Diagrams from the manufacturer of the HD elements used in this study also show possible bearing lengths between 6 and 10 m, depending on the imposed load. Since the load imposed on the experimental floor structure was rather small, a span of 8 m is well within the recommended limits.

The elements were simply supported on 60 mm wide supports. The width of the supports was chosen that small in order to make the floor structure resemble a simply supported slab as much as possible. A simply supported beam is characterized by the fact that it is free to rotate at the supports, and the shorter the support the easier it is for a beam or a slab to rotate at the supports. The reason for wanting it to resemble a simply supported slab is that it makes it easier to make an analogous FE-model of the floor structure. Wider supports would have caused some rotational resistance that can be difficult to estimate, and therefore making it hard to create a consistent FE-model that will behave the same way as the real floor structure.
Furthermore, in reality hollow core elements are often placed on supports that are only 80-90 mm wide. The manufacturer recommends using at least 70 mm supports for this type of HD element and span (Persson 2008). The Swedish Concrete Industry specifies that HDF 120/20 elements should be placed on at least 60 mm wide supports (Bygga med prefab 2008).

As Meixner (2008) states in his report, in reality a floor structure usually consists of far more elements than the three elements used to build the experimental floor structure in this study. This will increase the mass that will be brought to oscillate, but in turn it will be possible for more people to walk on the floor at the same time. Therefore, the experimental floor structure can be regarded as a reasonable approximation of reality.

7.1.1 Concrete topping

As mentioned above, in reality a concrete topping is often used to make the floor surface plane. With the intention of investigating the effect of such a topping on the vibration properties of the experimental slab a concrete layer was cast on site. A concrete of strength class C25/30 was used in this study. The mean value of the thickness of this topping was 30 mm.

7.2 Subjective tests

Subjective tests were performed in order to evaluate the vibration serviceability of the experimental floor structure. The purpose of the subjective tests was also to be able to evaluate some of the existing methods for evaluating the vibration serviceability of a concrete floor structure. Consequently, the results from the subjective tests, concerning the acceptability of the floor structure with regard to vibrations, were compared to the classification obtained by different methods, such as the former ISO standard ISO 2631-2:1989, and the method proposed by Talja and Toratti.

The setup of the subjective tests was inspired by a method proposed by Talja and Toratti, see chapter 5.6.1. First the test subjects were asked to walk across the floor structure themselves, and then they were asked to rate the intensity of the vibrations as; strongly perceptible, clearly perceptible, barely perceptible or imperceptible. They were also asked to form an opinion about the acceptability of the floor structure if it would have been installed in a newly built office building. They could choose between; absolutely unacceptable, unacceptable, acceptable or absolutely acceptable.

In the second part of the test the participants were seated on a chair placed on the observation point, i.e. 600 mm from the midpoint of the floor. A walker weighing 60 kg walked back and forth on the floor structure, and when the walker had passed the observation point three times the test subject was asked to rate the intensity of the vibrations and the acceptability of the floor structure in a newly built office. The walker walked with a step frequency of about 1.8 Hz, and to make sure a uniform walking pattern was used for all test situations, foot prints were marked on the floor surface.

In both the first part and the second part of the test the participants were asked to rate the vibration performance of the floor structure on a scale from 1 to 10, were 1 means “very poor” and 10 means “very good”.

The third part of the test was intended to investigate the impact the vibrations had/ will have on working efficiency. In this case, the test subject was seated on a chair by a desk, and was asked to fill out a form at the same time as the walker walked back and forth on the floor. The test subjects were then asked to rate the effect the vibrations had/will have on working efficiency on a scale from 1 to 10, were 1 means “very much” and 10 means “not at all”.

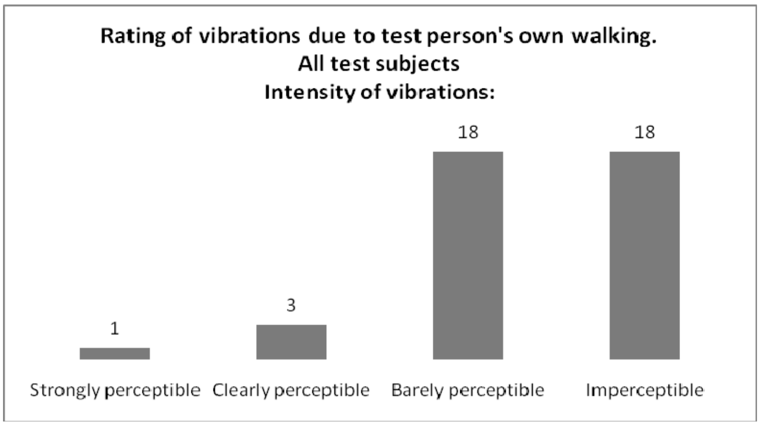
The questionnaires used in the subjective tests can be found in appendix 1.

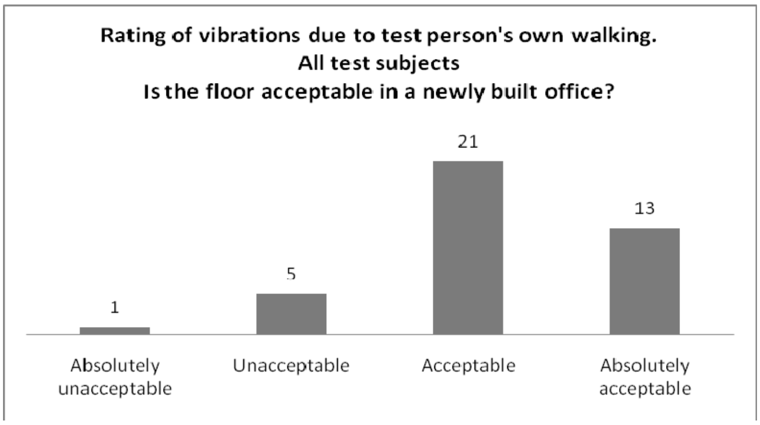
According to Talja and Toratti (2004) a floor structure is acceptable with regard to vibrations when the majority (at least 50 %) of the test subjects find the floor acceptable.

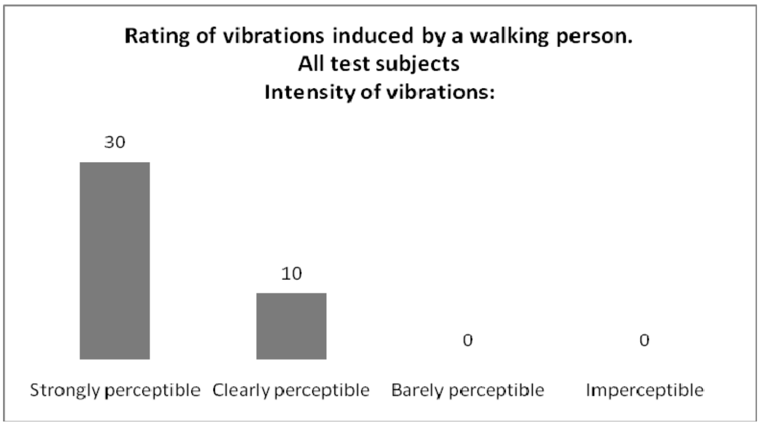
7.2.1 Results: Evaluation of the vibration serviceability of the experimental floor structure, before a concrete topping was cast

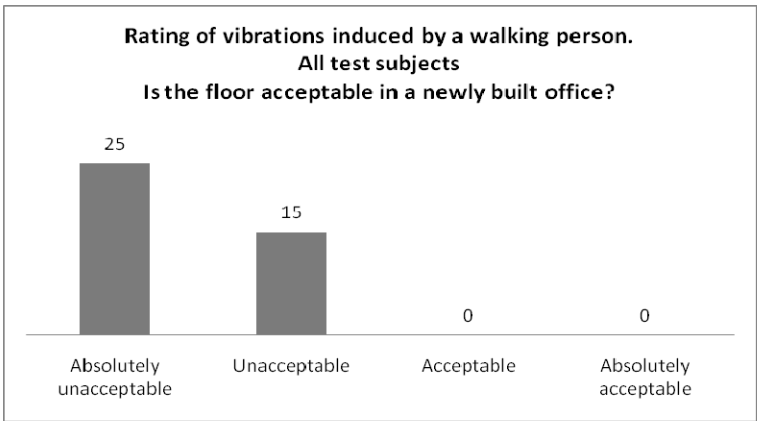
40 persons, 16 women and 24 men, participated in the subjective tests before a concrete topping was cast. 8 of them had participated in a similar test performed by Meixner (2008). The results from the subjective tests can be found in a graphical form below and in table 7.1.

When it comes to vibrations caused by the test persons walking themselves the majority of the test group found the vibrations barely perceptible or imperceptible. The majority also found the floor acceptable with regard to vibrations from this point of view.
However, in the case of vibrations induced by another person walking by, the majority of the test persons found the vibrations strongly perceptible and the floor absolutely unacceptable.
The big differences in perception between the two cases might be explained by how the human brain works: During the process of normal walking the human body is subjected to accelerations. Therefore, the nervous system and the brain are used to these types of accelerations and are capable of disregarding them. This means that when walking over a floor structure, small vibrations of the floor structure might not be perceived.









	Age [years]	Weight [kg]	Test 1	Test 2	Test 3
Mean value	26.5	73.1	7.2	1.9	2.4
Standard deviation	7.7	12.4	2.5	1.1	1.7

Table 7.1. Rating of the vibration performance of the floor.
Test 1: Vibrations due to test person's own walking. 1=very poor, 10=very good.
Test 2: Vibrations due to another person walking by. 1=very poor, 10=very good.
Test 3: Effect on working efficiency. 1=very much, 10=not at all.

The results in table 7.1 are in agreement with the results obtained by Meixner (2008). In his study, however, the effect on working efficiency was rated as slightly more significant, with a mean value of 1.58. The difference might be explained by that different chairs or different desks were used in the two studies. Ergonomic details such as type of chair can have a great impact on the effect vibrations have on working efficiency.

In appendix 2 the results from the subjective tests are displayed for the four groups; men, women, persons who had not participated in a similar test, and persons who had

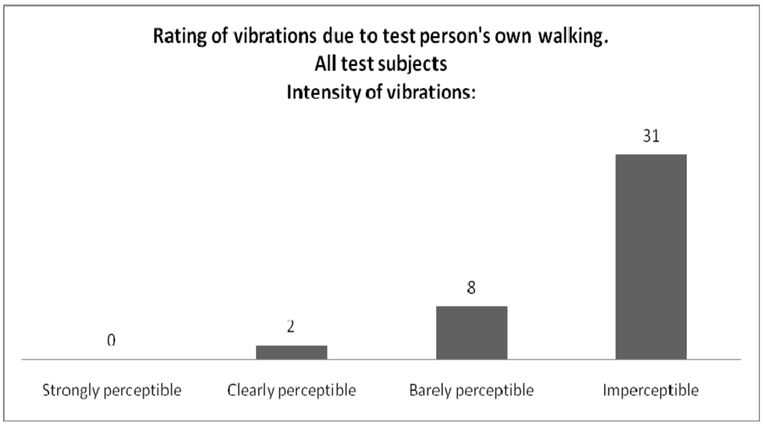
participated in a similar test. This division was made since human perception of vibration depends on, among other things, gender and expectations. Some differences between the groups can be distinguished; men rated the vibrations caused by the test person's own walking as more perceptible, and the floor more often as unacceptable, than women did. A possible explanation for these differences is that generally men are heavier than women; thereby they cause higher amplitudes of vibration.
In the second test, women rated the vibrations as more perceptible, and the floor more often as absolutely unacceptable, than men did. These differences might also be contributed to the heavier weight of men, since heavy people are more sensitive to higher frequencies and less sensitive to lower frequencies than a lighter person.
People who had not participated in a similar test rated the floor structure as absolutely not acceptable more often than people who had participated in a similar study. This might be contributed to the lack of expectations of the people who never had been in a similar study before. Probably they just did not expect a heavy concrete structure to vibrate that much.

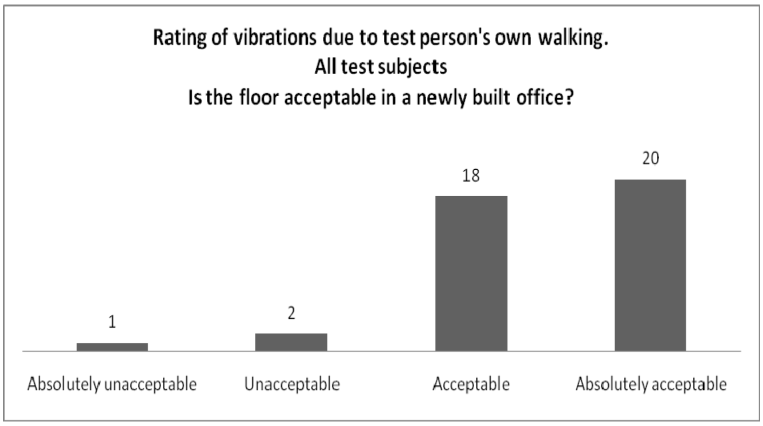
To sum up, the majority of the test persons found the experimental floor structure unacceptable or absolutely unacceptable with regard to vibration performance. When it comes to vibrations induced by another person, not one of them found the floor structure acceptable.

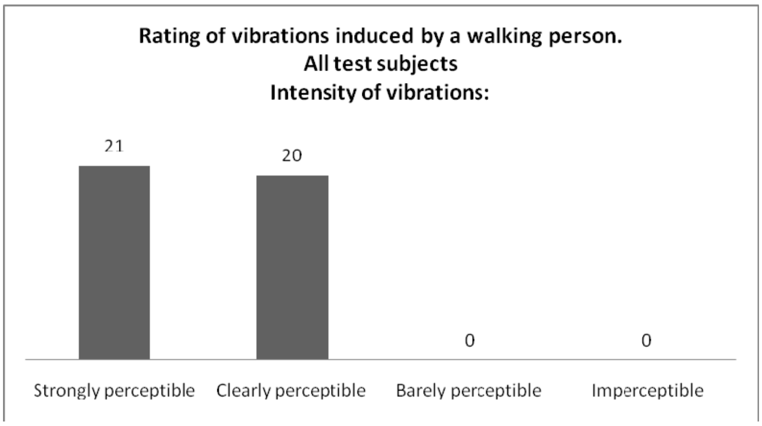
7.2.2 Results: Evaluation of the vibration serviceability of the experimental floor structure, after a concrete topping was cast

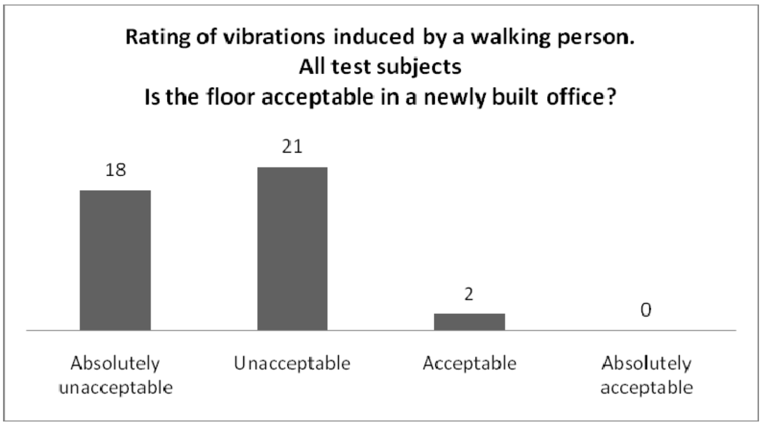
41 persons, 18 women and 23 men, participated in the subjective tests after a concrete topping was cast. 19 of them had participated in the tests performed before a concrete topping was cast. The results from the subjective tests can be found in a graphical form below and in table 7.2.

When it comes to vibrations caused by the test persons own walking a large majority of the test group found the vibrations imperceptible. In this case, the majority also found the floor absolutely acceptable with regard to vibrations.
In the second test, where the test subjects were asked to rate the intensity of the vibrations induced by another person, all of the test persons found the vibrations strongly perceptible or clearly perceptible. In this aspect most of the test persons found the floor structure unacceptable.


Rating of vibrations due to test person's own walking.
All test subjects
Intensity of vibrations:
0
2
8
31
Strongly perceptible
Clearly perceptible
Barely perceptible
Imperceptible


Rating of vibrations due to test person's own walking.
All test subjects
Is the floor acceptable in a newly built office?
1
2
18
20
Absolutely unacceptable
Unacceptable
Acceptable
Absolutely acceptable


Rating of vibrations induced by a walking person.
All test subjects
Intensity of vibrations:
21
20
0
0
Strongly perceptible
Clearly perceptible
Barely perceptible
Imperceptible



	Age [years]	Weight [kg]	Test 1	Test 2	Test 3
Mean value	31.8	74.3	8.4	2.5	2.7
Standard deviation	12.4	14.7	1.8	1.4	1.6

Table 7.2. Rating of the vibration performance of the floor.
Test 1: Vibrations due to test person's own walking. 1=very poor, 10=very good.
Test 2: Vibrations due to another person walking by. 1=very poor, 10=very good.
Test 3: Effect on working efficiency. 1=very much, 10=not at all.

In appendix 2 the results from the subjective tests are displayed for the four groups; men, women, persons who had not participated in a similar test, and persons who had participated in a similar test.

Just like in the subjective tests performed before a concrete topping was cast, men rated the vibration caused by the test person's own walking as more perceptible, and the floor more often as unacceptable, than women did. Women tended to rate the intensity of vibrations induced by another person as strongly perceptible more often than men did.

People who did not participate in the subjective tests before a concrete topping was cast, rated the self-induced vibrations more often as imperceptible, and the vibrations caused by another person more often as strongly perceptible, than people who participated in the tests before the topping was cast. People who had not participated in the tests performed before the concrete topping was cast also tended to rate the floor structure more often as absolutely unacceptable, when it came to vibrations induced by another person. These differences might be explained by the lack of expectations of the people who never had participated in a similar test, as opposed to the knowledge of the vibrations that persons who had participated in a similar test had.

People who had not participated in a similar test probably did not expect a heavy structure such as a concrete floor to vibrate that much, and therefore the degree of adverse comment was higher for this group. Also, a contributing factor to the differences might be that people who had participated in a similar test expected the vibration performance to have improved because of the added concrete topping, and therefore rated the vibration intensity and the acceptability of the floor structure more favourably.

To sum up, in spite of the added concrete topping a large majority of the test persons still found the experimental floor structure absolutely unacceptable or unacceptable with regard to vibrations induced by another person.

7.2.3 Results: Comparison of before and after a concrete topping was cast

If the results from the subjective tests before- and after a concrete topping was cast are compared, it can be concluded that the concrete topping improved the vibration performance of the experimental floor structure slightly. All categories (men, women, people who had not participated in a similar test, people who had participated in a similar test) rated the vibration performance more favourably after a concrete topping was cast. This goes for both vibrations due to the test person's own walking, the vibrations due to another person walking, and the effect the vibrations have on working efficiency.

When it comes to the intensity of the vibrations and the acceptability of the floor structure with regard to vibrations, the weight shifted over from barely perceptible vibrations to imperceptible in the case of self-induced vibrations. In this aspect, more people also found the experimental floor structure absolutely acceptable after a concrete topping was cast.
In the case of vibrations induced by another person, fewer people found the vibrations strongly perceptible after a concrete topping was cast. The weight shifted over from strongly perceptible to clearly perceptible compared to the floor structure without a concrete topping. The weight also shifted from absolutely unacceptable to unacceptable after a topping was cast. Without the concrete topping the majority found the experimental floor structure absolutely unacceptable in a newly built office, with the concrete topping the majority found the floor unacceptable.

In conclusion, adding the concrete topping improved the vibration performance of the experimental floor structure used in this study. However, not a single one of the test subjects found the floor acceptable with regard to vibration performance before a concrete topping was cast. The picture was about the same after a concrete topping was cast; a large majority still found the experimental floor structure unacceptable as a floor in a newly built office.

7.3 Measurements

One of the objectives with the measurements was to determine the damping ratios, since damping is a complex mechanism that cannot be calculated. Another important piece of information that was extracted from the measurement data is the natural frequencies of the floor structure and the response of the floor structure when subjected to a walking person. This information was used to validate the FE-model.

The equipment used during the measurements was accelerometers, *ADXL 202*, with a bandwidth of 0-5 kHz, and the computer program *TracerDAQ 2.0 pro*, which presents the data graphically as vibration magnitudes plotted against time. The accelerometers were mounted on small metal plates that were glued to the concrete surface. These metal plates were placed evenly spaced over the floor, see figure 7.2. Since only 15 accelerometers were available a number of different set-ups were used to be able to measure the accelerations across the whole floor structure.

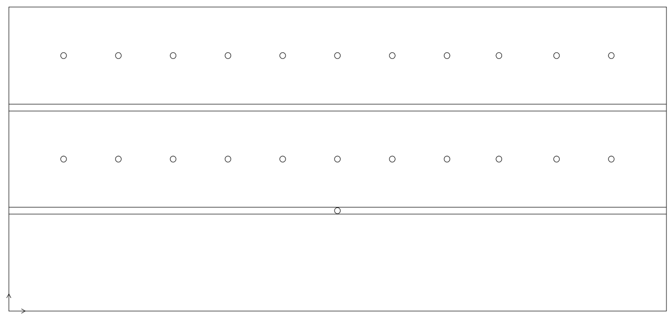
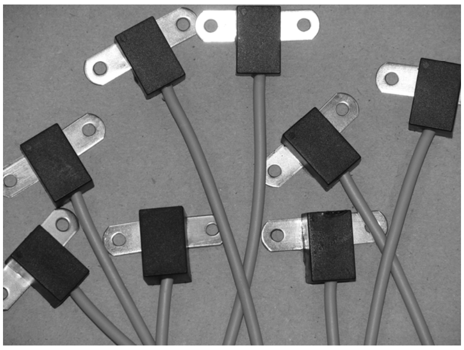


Figure 7.2. Measurement set up. The figure shows where the accelerometers were placed.

The floor structure was excited by either a tapping machine or a walking person.
The tapping machine is a standardized piece of equipment that is used in acoustical measurements. It consists of 5 hammers that each taps the floor twice every second, which means that the tapping machine has a working frequency of 10 Hz. Each hammer is weighing 0.5 kg and drops from a height of 40 mm. In this case only one of the hammers was used, which means that the floor was excited by a force with a frequency of 2 Hz.
The test person walked in the centre element in the lengthwise direction. A number of measurements were performed with the same walker as in the subjective tests. In this case the walker placed the feet beside the accelerometers when walking, which were the same foot prints that were used in the subjective tests. Also, a number of other persons were asked to walk across the floor, one at a time, in order to measure the induced vibrations. In this case the walk was more free, i.e. the walker did not have to place the feet beside the accelerometers.
It took the walkers about 6-7 s to walk across the floor, and the duration of the measurements was chosen to 10 s.

7.3.1 Accelerometers

An accelerometer is an electromechanical device that measures acceleration forces. When the floor structure is set to vibrate the accelerometer sends an electrical signal that is proportional to the acceleration the accelerometer is subjected to. A picture of some accelerometers can be seen in figure 7.3.



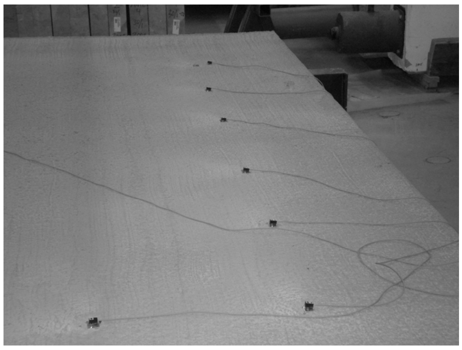


Figure 7.3. Accelerometers.

The result of the measurements is a data file for each accelerometer containing time and the magnitude of the electrical signal. In order to convert the electrical signal into acceleration values a computer programme called *Accelero* was used. The code in this programme is written by Dr.Sc. Delphine Bard. This programme also FFT transforms the measured data, which means that the vibration signal can be plotted in the frequency domain.

7.3.2 Determining the natural frequencies of the experimental floor structure from the measurement data

The natural frequencies of the floor structure can be seen as spikes in a response spectrum, where amplitude is plotted against frequency. It has been shown by a number of researchers that the response of a floor structure subjected to human walking is dominated by the lower-frequency modes of vibration. Since only the lowest natural frequencies of the system are of interest in this case, the response spectrum has been limited to show frequencies between 0 and 50 Hz.

Before a concrete topping was cast

The following diagrams show response spectra for different accelerometers and different loads. In this case the acceleration magnitudes are arbitrary, since the sensitivity of the accelerometers has not been considered. This means that the magnitudes shown in the diagrams below cannot be compared to the magnitudes shown in the diagrams from after the concrete topping was cast. However, a peak in a response spectrum shows a natural frequency of the system, despite if the accelerometer sensitivity is considered or not.

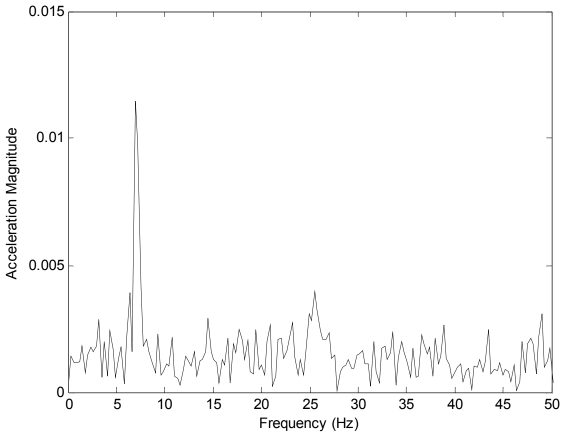


Figure 7.4. Response spectrum. Accelerometer placed at a quarter of the span on the side element. Test person walking.

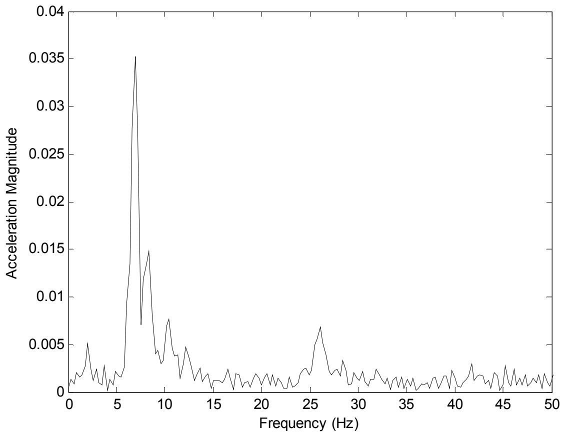


Figure 7.5. Response spectrum. Accelerometer placed at a quarter of the span on the center element. Test person walking.

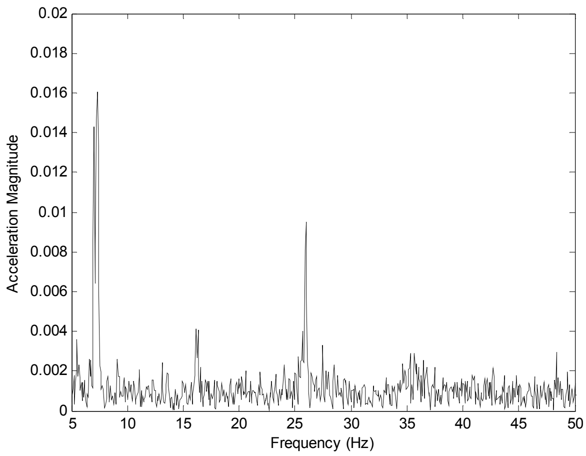


Figure 7.6. Response spectrum. Accelerometer placed 0.75m from the edge on one side element. Test person walking.

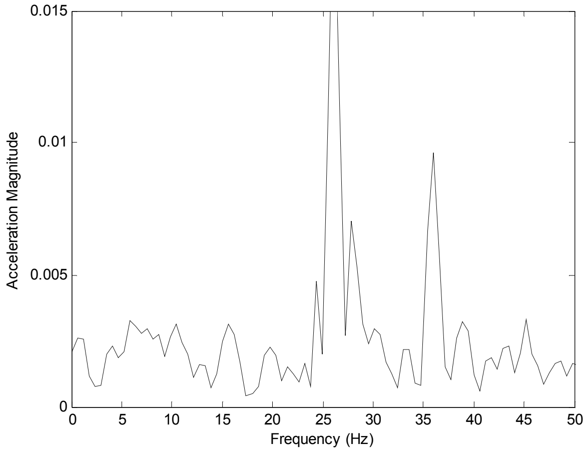


Figure 7.7. Response spectrum. Accelerometer placed at a quarter of the span on one side element. Tapping machine placed at corner point on the opposite side element.

From the response spectra above the following natural frequencies can be identified:

f_1= 7 Hz
f_2= 16 Hz
f_3= 26 Hz
f_4= 36 Hz

These frequencies are approximately the same natural frequencies that Meixner (2008) found for a similar slab.

After a concrete topping was cast

Some of the response spectra that have been used to identify the natural frequencies of the floor structure are shown below.

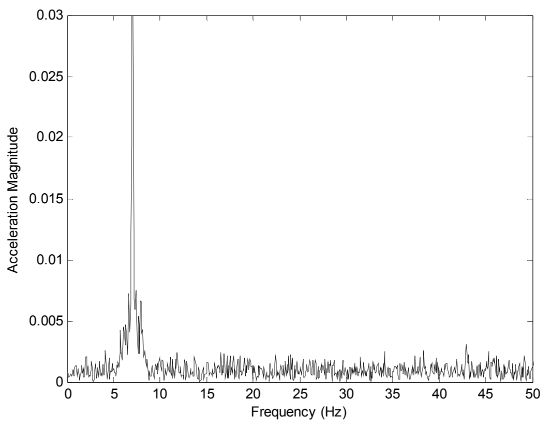


Figure 7.8. Response spectrum. Accelerometer placed at midpoint. Test person walking.

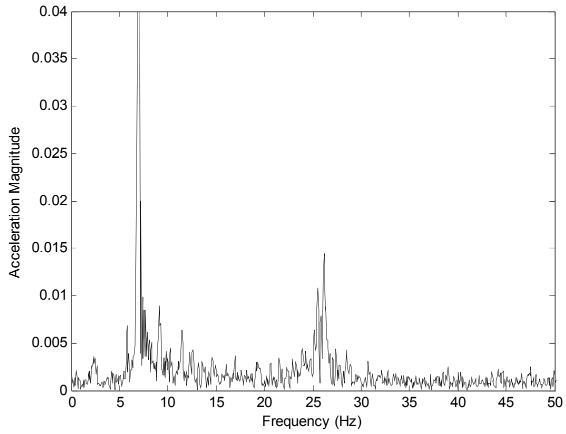


Figure 7.9. Response spectrum. Accelerometer placed 2m from the edge on the center element. Test person walking.

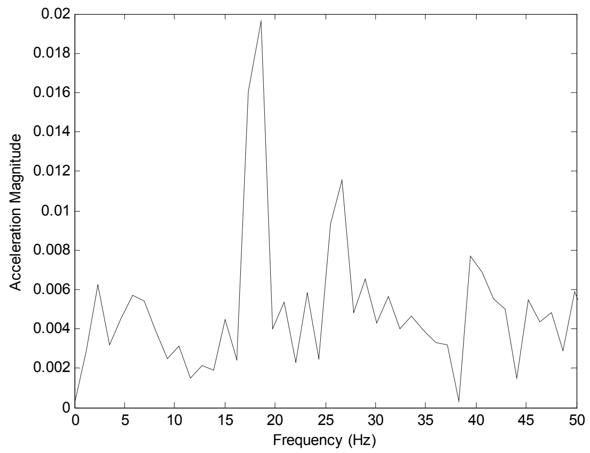


Figure 7.10. Response spectrum. Accelerometer placed 2.6m from the edge on one of the side elements. Tapping machine placed at corner point on the opposite side element.

From the response spectra above the following natural frequencies can be identified:

f_1= 7 Hz
f_2= 19 Hz
f_3= 26 Hz

Discussion

In some of the response spectra a peak could be seen at a frequency of about 2 Hz. Calculations of the natural frequencies of the experimental floor structure showed that the first natural frequency should be around 7 Hz for both before and after a concrete topping was cast. Since walking is a periodic activity with step frequencies of 1.5-2.5 Hz, the peak at 2 Hz might be explained by the walking.

From the response spectra it could be seen that it was mainly the first and the third mode that was excited by walking. As a remark for future work, the measurements with the tapping machine placed in the middle of the floor did not produce any response spectra that could be used for evaluating the natural frequencies of the floor. From this point of view, the best response spectra was obtained with the tapping machine placed at a corner point and measurements performed at the opposite side of the floor.

The natural frequencies of the experimental floor structure before and after a concrete topping was cast can be seen in table 7.3.

	f_1 [Hz]	f_2 [Hz]	f_3 [Hz]
Before	7	16	26
After	7	19	26

Table 7.3. Natural frequencies of the experimental floor structure, before and after a concrete topping was cast.

7.3.3 Determining the damping ratio, ζ, from the measurement data

The damping ratios of the three first modes were determined by using half-power bandwidth. For each mode, the damping ratio was determined as an average of damping ratios calculated using the vibration signals from a number of different accelerometers.
The damping ratios of the experimental floor structure, before and after a concrete topping was cast, can be seen in table 7.4. It can be seen that the concrete topping increased the damping slightly.

	Mode 1: ζ	Mode 2: ζ	Mode 3: ζ
Before	0.0064	0.0027	0.0024
After	0.0115	0.0040	0.0035

Table 7.4. Damping ratio of the experimental floor structure, before and after a concrete topping was cast.

7.3.4 Overall weighted acceleration

Both ISO 2631-1:1997 and ISO 2631-2:1989 recommend determining the overall weighted acceleration. This is also the quantity used in the method, proposed by Talja and Toratti, for evaluating the vibration serviceability of a floor structure.
The overall weighted value of acceleration, calculated from the recorded vibration signal in a point, provides a single number that quantifies the effects of vibration. The alternative is to filter and present the unweighted vibration signal in 1/3 octave bands.

In this study, the recorded vibration signals were weighted according to the weighting curve W_m in ISO 2631-2:2003. The resulting overall weighted values are presented in appendix 3. In the appendix overall weighted values are presented for the vibrations caused by a number of different walkers. Since 15 accelerometers were used to record the vibrations, overall weighted values could be calculated in 15 points distributed

over the floor surface. This measurement set-up gave a picture of how the magnitudes of vibration varied across the floor structure, and furthermore a minimum value, a maximum value, and an average value for each walk could be determined.
Matlab code for frequency weighting and calculation of overall weighted values can be found in appendix 4. This code was written by Dr.Sc. Delphine Bard.

One factor that has a great impact on the magnitude of the overall weighted value, or more precisely the magnitude of the r.m.s. acceleration, is the averaging time used for calculation of r.m.s. acceleration. In the method proposed by Talja and Toratti it is stated that t=1s shall be used. On the contrary, in ISO 2631-2:1989 there is no clear averaging time stated that should be used together with the base curves for evaluation of the vibration performance of a structure. For example, in this study an averaging time of both 1s and 10s were tested. For t=1s the floor was found unacceptable when using the base curve for offices, which is consistent with the subjective tests that were performed. However, using an averaging time of 10s resulted in an absolutely acceptable floor structure if evaluated according to the base curve for offices in ISO 2631-2:1989. This shows the importance of the averaging time chosen.
When calculating the overall weighted acceleration with an averaging time of 1 s, *Accelero* was used to isolate the second with the largest impact.

According to Pavic and Reynolds (2002a) the used averaging time differs between different researchers. For instance, Eriksson proposes a 10s averaging time for the calculation of r.m.s. acceleration, which he thinks is more appropriate than the 1s often used. Consequently, in the past there has been a lack of a commonly used averaging times in the area of floor vibration, which has made it difficult to compare the results from different investigations. The lack of information about the averaging time, in for instance the ISO standards, is a big problem.

Since one of the goals of the measurements and the subjective tests was to evaluate the existing vibration criteria, such as ISO 2631-2:1989 and the method proposed by Talja and Toratti, it is the measured overall weighted values of acceleration at the location of the chair, that was used in the subjective tests, that are interesting. These values and also the minimum- and maximum magnitudes across the floor are presented in table 7.5-7.8. Table 7.5-7.8 only contain the overall weighted values caused by the same walker as in the subjective tests, since it was these magnitudes the participants in the subjective test were exposed to. Overall weighted values at other locations on the floor surface and magnitudes caused by other walkers can be found in appendix 3.

Before concrete topping	Averaging time (s)	Min (across the floor)	Max (across the floor)	Average (across the floor)	Under the chair that was used in the subjective tests
Pia_Walk_1	1	0,009	0,0922	0,047447	0,0922
Pia_Walk_2	1	0,0155	0,0669	0,040053	0,0363
Pia_Walk_3	1	0,0137	0,1045	0,066967	0,1045
Pia_Walk_4	1	0,0122	0,1024	0,046413	0,096
Pia_Walk_5	1	0,0095	0,0935	0,05202	0,0935
Pia_Walk_6	1	0,0479	0,1656	0,11502	
				Average value under the chair:	0,0845

Table 7.5. Before a concrete topping was cast. Overall weighted values of acceleration (m/s^2) caused by the same walker as in the subjective tests. 6 different walks. Averaging time used for calculation of r.m.s. acceleration: T= 1s. Accelero was used to isolate the second with the largest impact.

Before concrete topping	Averaging time (s)	Min (across the floor)	Max (across the floor)	Average (across the floor)	Under the chair that was used in the subjective tests
Pia_Walk_1	10	0,0019	0,0048	0,00338	0,0048
Pia_Walk_4	10	0,0017	0,004	0,0028	0,004
Pia_Walk_5	10	0,0018	0,005	0,00354	0,0048
				Average value under the chair:	0,004533

Table 7.6. Before a concrete topping was cast. Overall weighted values of acceleration (m/s^2) caused by the same walker as in the subjective tests. 3 different walks. Averaging time used for calculation of r.m.s. acceleration: T= 10s.

After concrete topping	Averaging time (s)	Min (across the floor)	Max (across the floor)	Average (across the floor)	Under the chair that was used in the subjective tests
CT_Pia_Walk_1	1	0,0092	0,1945	0,044453	
CT_Pia_Walk_2	1	0,0087	0,1241	0,076813	0,1079
CT_Pia_Walk_3	1	0,0101	0,0941	0,052267	0,0908
CT_Pia_Walk_4a	1	0,007	0,0583	0,030513	0,0426
CT_Pia_Walk_4b	1	0,0071	0,0857	0,04376	0,0554
CT_Pia_Walk_5	1	0,0148	0,0689	0,034907	0,0515
CT_Pia_Walk_6	1	0,0106	0,0662	0,03974	0,045
				Average value under the chair:	0,065533

Table 7.7. After a concrete topping was cast. Overall weighted values of acceleration (m/s^2) caused by the same walker as in the subjective tests. 7 different walks. Averaging time used for calculation of r.m.s. acceleration: T= 1s. Accelero was used to isolate the second with the largest impact.

After concrete topping	Averaging time (s)	Min (across the floor)	Max (across the floor)	Average (across the floor)	Under the chair that was used in the subjective tests
CT_Pia_Walk_1	10	0,0023	0,0039	0,0030	
CT_Pia_Walk_2	10	0,0016	0,0043	0,0033	0,0041

Table 7.8. After a concrete topping was cast. Overall weighted values of acceleration (m/s^2) caused by the same walker as in the subjective tests. 2 different walks. Averaging time used for calculation of r.m.s. acceleration: T= 10s.

Comparison of overall weighted values before and after a concrete topping was cast

If the calculated average values of the overall weighted acceleration at the location of the chair are compared for the two cases with- and without concrete topping, it can be seen that the magnitude decreased slightly after a concrete topping was cast. The same goes for the average of the maximum values across the floor.

In order to investigate if the reduction in magnitude was valid for all the points on the floor surface a comparison of the magnitudes, before and after, caused by the same walker and measured by the same measurement set-up was performed, see appendix 3. A small majority of the investigated points on the floor showed a reduction in magnitude of the overall weighted acceleration when the extra mass in form of a concrete topping was placed on the floor structure. At the remaining investigated locations on the floor structure the magnitudes increased after a concrete topping was cast, or remained the same. However, one has to keep in mind the possibility of human error, i.e. despite of the marked footprints on the floor structure there is a possibility that the gait was slightly different during the different measurements.

7.3.5 Evaluation of the vibration serviceability of the experimental floor structure according to ISO 2631-2:1989 and the vibration classes suggested by Talja & Toratti

To examine if it would be adequate to use the base curve of ISO 2631-2:1989 or the method proposed by Talja and Toratti when investigating the vibration serviceability of a floor structure made of hollow core elements, the results from the measurements were evaluated according to the two criteria. The classifications of the experimental floor structure were then compared to the results obtained in the subjective tests.

Talja and Torattis classification of floor structures into different vibration classes is based on overall weighted values of the acceleration, with an averaging time of 1 s. The different vibration classes and the corresponding limits are presented in chapter 5.6.
ISO 2631-2:1989 defines a base curve that should be multiplied by 4 in the case of offices. For magnitudes below this curve the probability of adverse comments is low. The vibration signal can either be filtered in 1/3 octave bands and the result plotted in the same diagram as the curve for offices, or overall weighted values of the acceleration can be calculated and compared to the limit value of the frequency band of maximum sensitivity. For foot-to-head vibration the frequency band of maximum sensitivity is 4-8 Hz, and for offices the limit value in this interval is 0.02 m/s^2, see figure 5.1.

Before concrete topping

Average value of the overall weighted acceleration at the location of the chair that was used in the subjective tests:

$$a_{w,rms} = 0.085 m/s^2$$

1. Talja & Toratti

$a_{w,rms} = 0.085 m/s^2$ → Vibration class D (see table 5.2)

Vibration class D is characterized by: “The vibration is perceptible and most people find it annoying”. This is in agreement with the subjective tests performed.

2. ISO 2631-2:1989, t=1s

$a_{w,rms} = 0.085 m/s^2 > 0.02$ m/s^2 → There is a probability of adverse comment.

Since the overall weighted value of acceleration is much higher than the limit, the probability of adverse reaction is high. This is in agreement with the subjective tests performed.

The vibration signal was also filtered in 1/3 octave bands and the magnitude in each band were plotted in a diagram together with the base curve of ISO 2631-2:1989. A representative plot of the acceleration magnitudes caused by the same walker as in the subjective tests, at the location of the chair that was used in these tests, can be seen in figure 7.11. Diagrams of the magnitudes at other locations on the floor structure, and magnitudes induced by other walkers can be seen in appendix 5.
As can be seen in figure 7.11, the highest acceleration magnitudes are found in the frequency interval of maximum human sensitivity. Furthermore, the magnitudes in this interval are much higher than the curve for satisfactory magnitudes in offices.

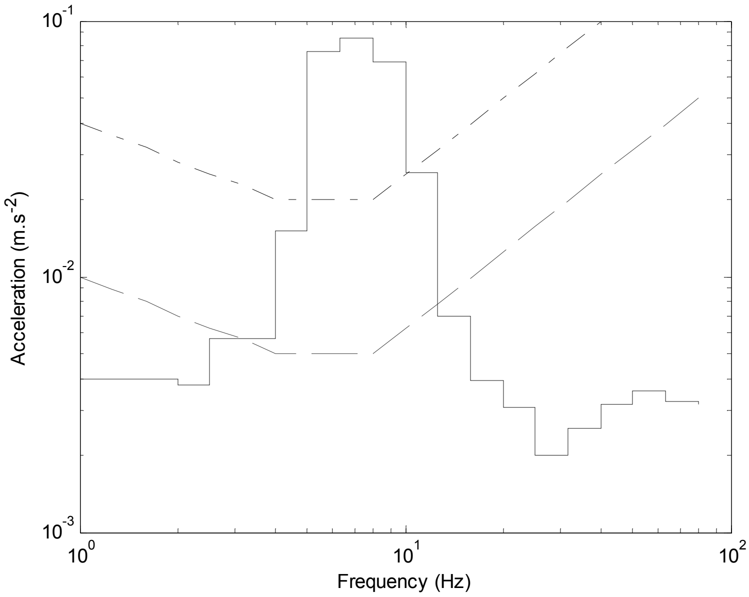


Figure 7.11. Acceleration magnitudes in 1/3 octave bands at the location of the chair, caused by the same walker as in the subjective tests. Averaging time 1s. The diagram also shows the base curve of ISO 2631-2:1989, and the curve that is valid for offices.

3. ISO 2631-2:1989, t=10s

$a_{w,rms} = 0.0045 m/s^2 < 0.02$ m/s^2 → The probability of adverse comments is low.

The magnitudes of acceleration in 1/3 octave bands caused by the same walker as in the subjective tests, at the location of the chair, can be seen in figure 7.12. In this case the magnitudes are well below both the base curve and the curve for offices. This is not in agreement with the subjective tests performed, and it can be concluded that an averaging time of 10 s cannot be used together with the curves of ISO 2631-2:1989.

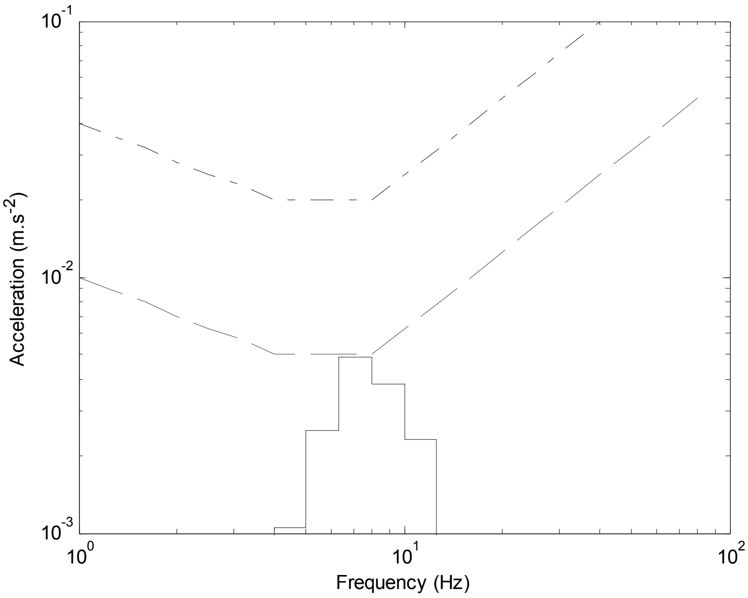


Figure 7.12. Acceleration magnitudes in 1/3 octave bands (t=10s) at the location of the chair, caused by the same walker as in the subjective tests. The diagram also shows the base curve of ISO 2631-2:1989, and the curve that is valid for offices.

After concrete topping

Average value of the overall weighted acceleration at the location of the chair that was used in the subjective tests:
$a_{w,rms} = 0.066m/s^2$

1. Talja & Toratti

$a_{w,rms} = 0.066m/s^2$ → Vibration class C (see table 5.2)

Vibration class C is characterized by: “The vibration is often perceptible and some people may feel it annoying”. This is partly in agreement with the subjective tests performed. In the subjective tests most of the test persons found the floor not acceptable with regard to vibrations, instead of just some of the people as stated in vibration class C.

2. ISO 2631-2:1989, t=1s

$a_{w,rms} = 0.066m/s^2 > 0.02$ m/s^2 → There is a probability of adverse comment.

Since the overall weighted value of acceleration is much higher than the limit, the probability of adverse reaction is high. This is in agreement with the subjective tests performed.

A representative plot of the acceleration magnitudes in 1/3 octave bands caused by the same walker as in the subjective tests, at the location of the chair that was used in these tests, can be seen in figure 7.13. The highest acceleration magnitudes are still found in the frequency interval of maximum human sensitivity. Furthermore, the magnitudes in this interval are much higher than the curve for satisfactory magnitudes in offices.

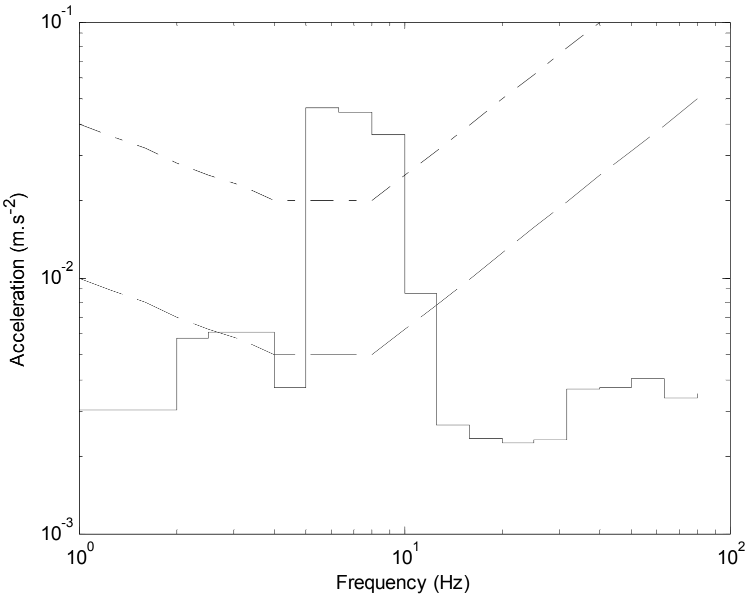


Figure 7.13. Acceleration magnitudes in 1/3 octave bands at the location of the chair, caused by the same walker as in the subjective tests. The diagram also shows the base curve of ISO 2631-2:1989, and the curve that is valid for offices.

7.3.6 Discussion

If the vibration serviceability of the experimental floor structure is evaluated according to Talja and Torattis vibration classes, or the curve of ISO 2631-2:1989 (with an averaging time of 1s), the same results are obtained as in the subjective tests: In the subjective tests a majority of the test persons found the floor structure unacceptable with regard to vibrations, the classification according to Talja and Toratti indicates that most people will find the vibration annoying, and according to ISO 2631-2:1989 the probability of adverse comment is high.
Therefore, either one of the methods can be used to process the results from the FE-analyses performed in this study.

8 FE model of the experimental floor structure

The goal of a finite element model of the experimental floor structure was to be able to investigate the effect that other types of boundary conditions, and other spans, have on the vibration performance of the floor structure. Therefore, a FE-model of the experimental floor structure was built in the finite element software *Abaqus 6.7-1*.
In order to decrease the computational cost and the computational time of each analysis the three-dimensional structure was replaced by a shell with the same stiffness properties and the same density as the hollow core elements. Consequently, the first step was to find the equivalent properties of the shell structure.
It should be noted that the use of a shell is a simplification, and it is possible that some of the dynamic properties might be lost in the transition from a complex three-dimensional structure to a plain shell.

8.1 Equivalent properties

The dynamic behaviour of the shell should correspond as much as possible to the behaviour of the original three-dimensional structure. This can be achieved by calculating the stiffness properties and the mass properties of the three-dimensional floor structure, and then assign them to a shell.
The hollow core elements are not homogenous building parts, instead the cavities makes the bending stiffness in the lengthwise direction differ from the bending stiffness in the short direction. Therefore, it was assumed that a shell consisting of an orthotropic material would be appropriate to use.
The strategy to find the equivalent properties consisted of modelling a small piece of a hollow core element in *Abaqus* using 3D solid elements, and by bending, shearing and tensioning that part the equivalent properties that produced the same response in a shell could be determined. The strategy was inspired by work performed by Holterman and Petersson (2008).

The prestressing tendons were not included in the model, because the tendons only affect the static deflection and not the oscillation around an equilibrium position. Furthermore, it has been shown that the amount of prestressing does not affect the dynamic behaviour of a floor structure in any significant way (Pavic & Reynolds 2002a).

In table 8.1 some properties of HD/F 120/20 elements can be seen. The data was retrieved from the manufacturer of the HD elements. The cross section of a HD/F 120/20 element, and measurements can be seen in figure 8.1.

Height of cross section [m]	0.2
Moment of inertia, I [m^4]	0.59e-3
Self weight [kN/m]	2.9
Type of concrete	C50/60

Table 8.1. Properties of one HD/F 120/20 element.

Concrete of the strength class C50/60 has an average value of the Young's modulus of 37 GPa. In the case of vibrations it is recommended to use a dynamic Young's modulus, which is 1.2 times larger than the static modulus (Boverket 2004). For concrete C50/60 the dynamic modulus of elasticity is thereby 44.4 GPa.

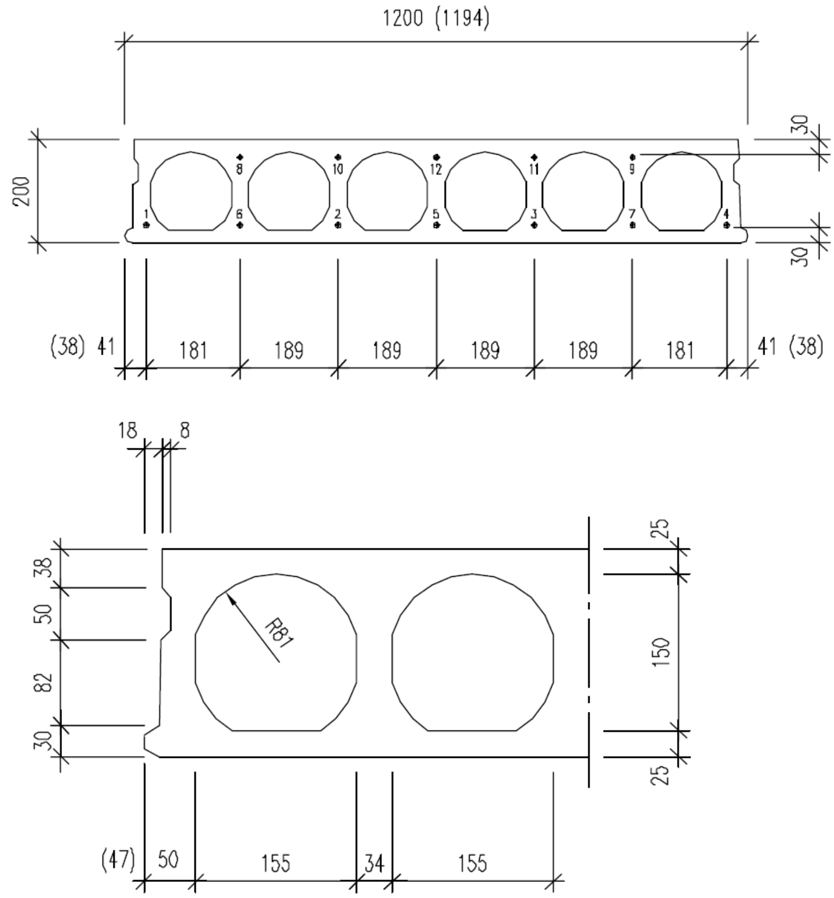


Figure 8.1. Cross section of a HD/F 120/20 element (Starka 2008).

8.1.1 Young's modulus

Since a shell with an orthotropic material was chosen to model the behaviour of the slab, two moduli of elasticity had to be determined, one in the lengthwise direction (E1) and one in the short direction (E2).

E1

The starting point was that E1 of the shell model was assigned the same value as the dynamic Young's modulus of concrete C50/60, i.e. E1=44.4 GPa. After that a thickness, *t*, of the shell elements could be calculated, which produced a structure with the same moment of inertia in the lengthwise direction as a HD/F 120/20 element:

$$I_{shell} = I_{HD/F-120/20}$$

$$I_{shell} = \frac{bt^3}{12} = 0.59e-3m^4 \Rightarrow t_{shell} = 0.183m$$

b= width of one HD element

E2

The bending stiffness of a HD/F 120/20 element in the weak direction was calculated by modelling a one meter long piece of an element in *Abaqus,* see figure 8.2, and subjecting it to bending in the weak direction. The part was modelled with CPE8R elements with a size of 0.01m, and it was assigned an elastic, isotropic material with a Young's modulus of 44.4 GPa. Poisson's ratio was set to zero, since bending of a beam was considered. A pressure load of 1000 N/m^2 was applied on top of the part, and as a boundary condition two of the sides of the part were fixed, causing beam bending in the weak direction, see figure 8.3.

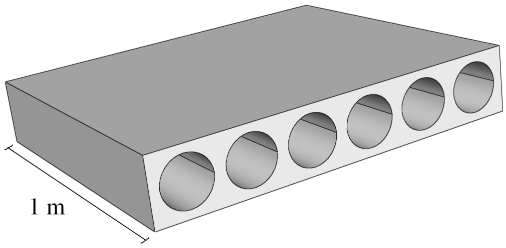


Figure 8.2. Model of a HD/F 120/20 element.

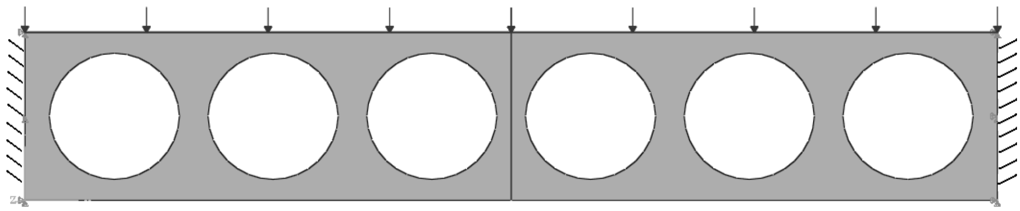


Figure 8.3. Model of one HD/F 120/20 element. The short sides of the cross section were fixed in order to model beam bending in the weak direction.

The mid-deflection of the part was calculated, and an equivalent shell should deflect as much as the three-dimensional structure when subjected to the same load:

The mid-deflection, *u*, of a beam which is fixed in both ends and subjected to a line load, *q*, can be calculated according to:

$$u = \frac{qL^4}{384EI}$$

$$I_{2,shell} = \frac{1*t^3}{12}$$

$$\Rightarrow E2_{shell} = \frac{qL^4}{384uI_{2,shell}} = 8.7GPa$$

L= beam length=width of one HD element

8.1.2 Shear modulus

The shear modulus of the shell, G12, was determined by modelling a one meter long piece of a HD/F 120/20 element in *Abaqus* and subjecting it to shearing:

The 3D part was assigned an elastic, isotropic concrete material with a Young's modulus of 44.4 GPa, and a Poisson's ratio of 0.2. The part was meshed with C3D20R elements, with a size of 0.01m, and it was subjected to shearing by fixing one of the ends and applying a force of 1000 N at the opposite surface, see figure 8.4.

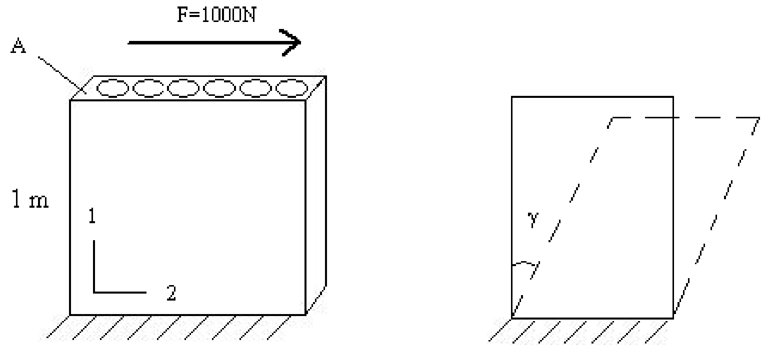


Figure 8.4. Shearing of a one meter long piece of a HD/F 120/20 element.

When subjected to the same load and boundary conditions the shell should show the same amount of shear strain, γ:

$$\tau_{12} = \frac{F}{A}$$

$$\tau_{12} = G_{12}\gamma$$

$$\Rightarrow G_{12,shell} = \frac{F}{A_{shell}\gamma} = \frac{F}{t_{shell}b\gamma} = 3.92GPa$$

b= width of one HD element

8.1.3 Poisson's ratio

The equivalent Poisson's ratio of the shell structure was calculated by a tension analysis. In this case surface forces were applied to two opposite sides of the one meter long piece of HD/F 120/20 element that was used in the shearing analysis, see figure 8.5.

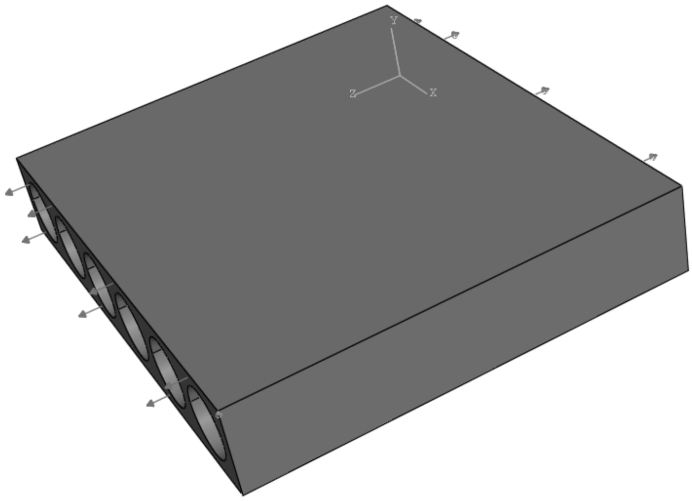


Figure 8.5. Tension analysis.

One degree of freedom was fixed in order to avoid a singular stiffness matrix. Otherwise the part was free to deform in all directions. The strain in the lengthwise direction (the direction of the cavities), ε_{11}, and the strain in the direction perpendicular to the main direction, ε_{22}, were determined, and the equivalent Poisson's ratio of the shell could be calculated according to:

$$\nu_{12} = -\frac{\varepsilon_{22}}{\varepsilon_{11}} = 0.39$$

8.1.4 Density of the shell

In dynamic analysis the density of the material, that forms the structure, is needed as input in order to be able to construct the mass matrix that is used in the calculations. One HD/F 120/20 element weighs 2.9 kN/m, and the shell should weigh the same:

$$\rho_{shell} = \frac{m_{shell}}{t_{shell} * b} = \frac{\frac{2900N/m}{9.81N/kg}}{t_{shell} * b} = 1395 kg/m^3$$

ρ_{shell}= density of the shell
t_{shell}= thickness of the shell
b= width of one HD element

8.2 FE-model of the floor structure using shell elements

A FE-model of the experimental floor structure was built in *Abaqus* using shell elements. As mentioned above, the use of a shell structure instead of a complicated three-dimensional structure saves computational time and cost.
The shell was assigned a thickness of 0.183 m, and the HD part of the model was assigned an orthotropic material (material behaviour elastic, type lamina in *Abaqus*) with the equivalent properties calculated above:

E1= 44.4 GPa
E2= 8.7 GPa
G12= 3.92 GPa
ν12= 0.39
ρ= 1395 kg/m^3

In reality the joints between the HD elements in the lengthwise direction were filled with a concrete of the strength class C25/30. In *Abaqus* these joints were modelled as 40 mm wide, with 0.183 m thick shell elements, and they were assigned an elastic isotropic material with an equivalent Young's modulus of 48.6 GPa and an equivalent density of 2623 kg/m^3. Poisson's ratio was set to 0.2. The equivalent Young's modulus of the joints was calculated according to:

$(EI)_{real\ joint} = (EI)_{shell\ joint}$

(EI)=bending stiffness

A picture of the model of the experimental floor structure can be seen in figure 8.6.

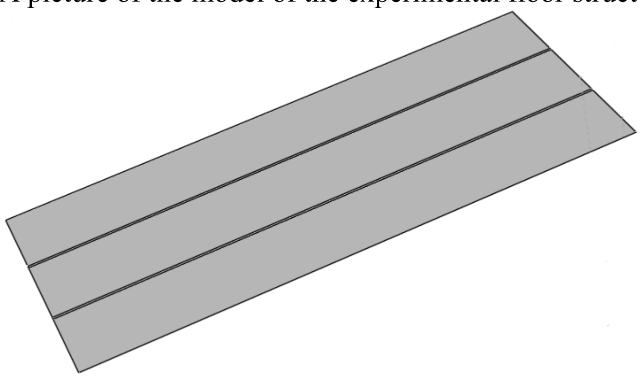


Figure 8.6. Model of the experimental floor structure.

In reality the experimental floor structure was placed on 60 mm wide supports along the short sides of the floor structure. In *Abaqus* the supports were modelled as a pin support and a roller support, making the floor structure simply supported. In the FE-model of the floor structure these boundary conditions were applied along a line 30 mm from the edge, i.e. along a line in the middle of the real supports.
The part was meshed with S8R5 elements with a size of 0.1m.

8.2.1 Modelling of the concrete topping

As a first assumption it was assumed that adding a concrete topping will not significantly increase the stiffness of the floor structure, but it will increase the mass. This assumption was based on the relatively thin layer of concrete that was added, and the lack of reinforcement that could ensure some interaction between the slab and the concrete topping. Therefore, the elastic moduli and the shear modulus were kept the same as without the topping, and only the density of the material was increased:

Thickness of the concrete topping: 30mm (average)
$\rho_{concrete\ topping} = 2308\ kg/m^3$

- ➔ $\rho_{shell,\ C25/30} = 3005\ kg/m^3$ *(Joints)*
- ➔ $\rho_{shell,\ C50/60} = 1773\ kg/m^3$ *(HD elements)*

8.2.2 Natural frequencies and mode shapes

The first step of the FE-analysis was to determine the natural frequencies of the floor structure and the corresponding mode shapes. The calculated natural frequencies of the floor structure, with and without a concrete topping, can be seen in table 8.2. The corresponding mode shapes can be seen in figures 8.7-8.9. The mode shapes are practically the same for before and after a concrete topping was added.

	f_1 [Hz]	f_2 [Hz]	f_3 [Hz]	f_4 [Hz]
Without a concrete topping	7.4	13.1	29.5	36.7
With a concrete topping	5.9	13	23.6	-

Table 8.2. Natural frequencies of the FE-model of the experimental floor structure.

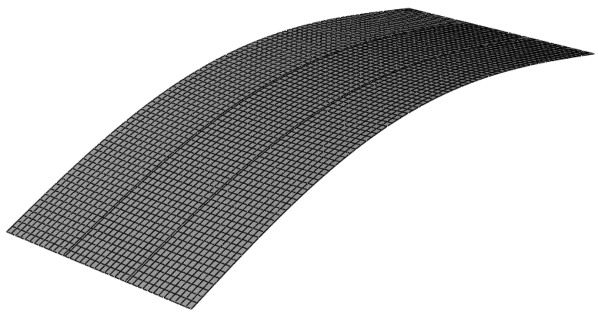


Figure 8.7. Mode shape 1.

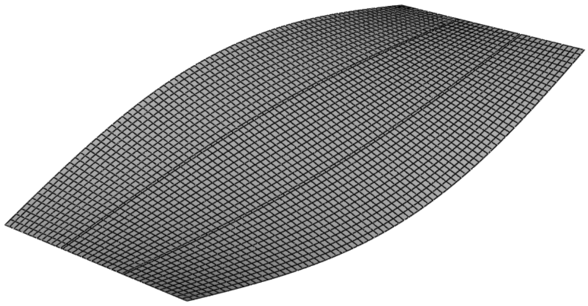


Figure 8.8. Mode shape 2.

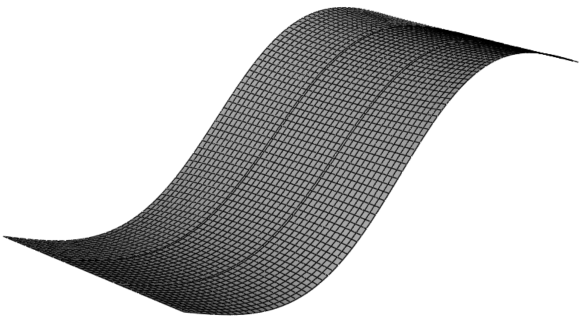


Figure 8.9. Mode shape 3.

8.2.3 Comparison of the natural frequencies obtained by the FE-model and the results from the measurements

The calculated natural frequencies of the floor structure were compared with the natural frequencies obtained from the measurements:

Before a concrete topping was cast
The calculated natural frequencies and the measured ones can be seen in table 8.3.

	f_1 [Hz]	f_2 [Hz]	f_3 [Hz]	f_4 [Hz]
Measured	7	16	26	36
Calculated	7.4	13.1	29.5	36.7

Table 8.3. Measured- and calculated natural frequencies of the experimental floor structure, before a concrete topping was cast.

As can be seen in table 8.3 both the second and the third natural frequency differs slightly between the measurements and the calculations. A possible explanation for these differences can be the contingency in the material parameters. For example, during the initial FE-calculations, where the goal was to find equivalent stiffness properties to use in a model of the floor consisting of shell elements, the Young's modulus of the concrete was set to 44.4 GPa. This value is the dynamic Young's modulus, and it is obtained by multiplying the static modulus of elasticity by 1.2. The static modulus of elasticity was not determined by testing; instead the value that was used is a 50 %- fractile. This means that it is possible that the Young's modulus of the concrete in the elements in this study deviated slightly from the value used in the calculations. Furthermore, the number 1.2 that was used to obtain the dynamic modulus is not an exact number, but a recommendation of the Swedish concrete design rules (BBK 04). Pavic and Reynolds (2002b) have reviewed relevant literature and found the recommended increase of the static modulus to be between 10-25 %. To sum up, the Young's modulus is an uncertain parameter in the FE-analysis.

In order to obtain a better correspondence between the FE-model and the experimental floor structure a parameter study was performed. One at a time, the modulus of elasticity in the lengthwise direction (E1), the modulus of elasticity in the short direction (E2), and the shear modulus (G12) were varied to investigate the impact they have on the natural frequencies. A 50 % reduction, a 50% increase, and a 100% increase of the parameters were investigated and compared to the initial case which resulted in the natural frequencies in table 8.3 above. The results of the parameter study can be seen in figure 8.10-8.12.

Parameters in the initial case:
E1=44.4 GPa
E2=8.7 GPa
G12=3.92 Gpa

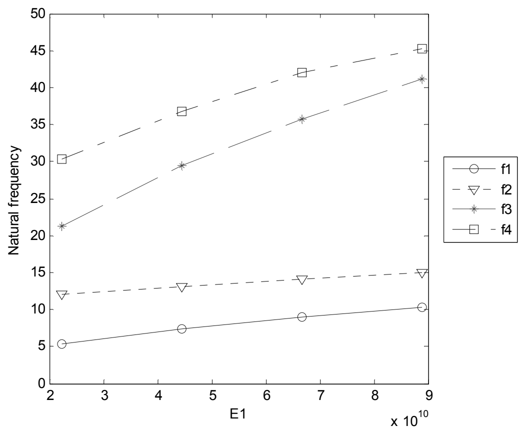


Figure 8.10. The figure shows how E1 influences the first four natural frequencies if everything else is kept constant.

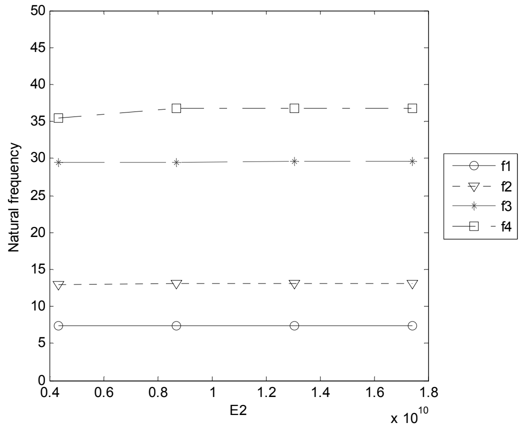


Figure 8.11. The figure shows how E2 influences the first four natural frequencies if everything else is kept constant.

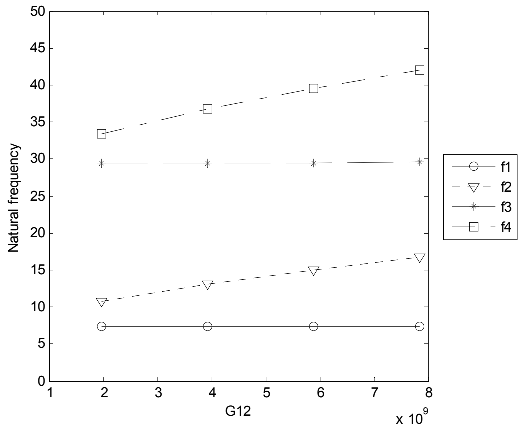


Figure 8.12. The figure shows how G12 influences the first four natural frequencies if everything else is kept constant.

Based on the parametric study a new calculation was performed with the shear modulus increased by 50%, and the elastic modulus in the lengthwise direction reduced by 20%:

E1=35.52 GPa E2=8.7 GPa G12=5.88 GPa

This change in material parameters resulted in a better consistency between the natural frequencies obtained by measurements and the natural frequencies obtained in the FE-calculations, see table 8.4. Therefore, in the following FE-calculations these material parameters were used.

	f_1 [Hz]	f_2 [Hz]	f_3 [Hz]	f_4 [Hz]
Measured	7	16	26	36
Calculated	6.6	14.7	26.6	37.3

Table 8.4. Measured- and calculated natural frequencies of the experimental floor structure, before a concrete topping was cast.

After a concrete topping was cast

The starting-point for a FE-model of the floor structure including the concrete topping was the material parameters obtained by the parametric study above. To model the concrete topping it was first assumed that the topping did not contribute significantly to the stiffness of the slab, that it only contributed to increasing the mass. The assumption was based on the relatively thin layer of added concrete and the lack of reinforcement that could ensure interaction between the slab and the topping. It is also difficult to estimate to what degree the elements and the concrete topping will interact. Therefore, the elastic moduli and the shear modulus were kept the same as without the topping, and only the density of the material was increased. The calculated natural frequencies and the measured ones can be seen in table 8.5.

	f_1 [Hz]	f_2 [Hz]	f_3 [Hz]
Measured	7	18.6	26
Calculated	5.9	13	23.6

Table 8.5. Measured- and calculated natural frequencies of the experimental floor structure, after a concrete topping was cast.

It can be concluded from table 8.5 that the topping did affect the stiffness. Therefore, another parameter study was performed in order to obtain a better consistency between the measured natural frequencies and the calculated ones. As before, one at a time, the modulus of elasticity in the lengthwise direction (E1), the modulus of elasticity in the short direction (E2), and the shear modulus (G12) were varied to investigate the impact they have on the natural frequencies. The results from the parametric study can be seen in figure 8.13-8.15.

Parameters in the initial case:
E1=35.52 GPa
E2=8.7 GPa
G12=5.88 GPa

Also the density was increased, compared to the case without a concrete topping, to account for the increase in mass.

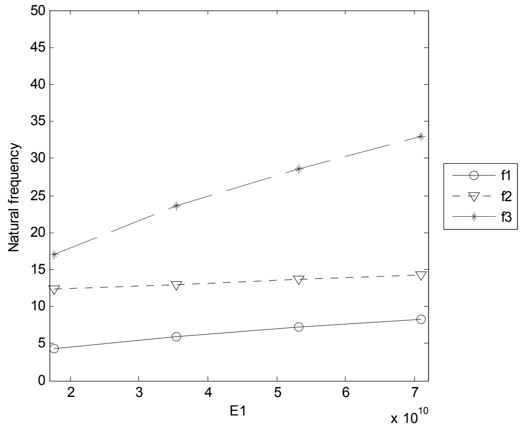


Figure 8.13. The figure shows how E1 influences the first three natural frequencies if everything else is kept constant.

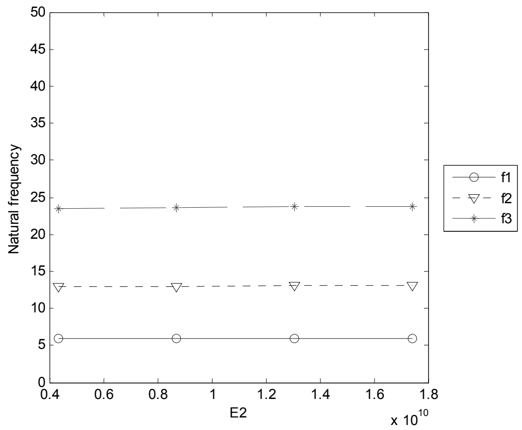


Figure 8.14. The figure shows how E2 influences the first three natural frequencies if everything else is kept constant.

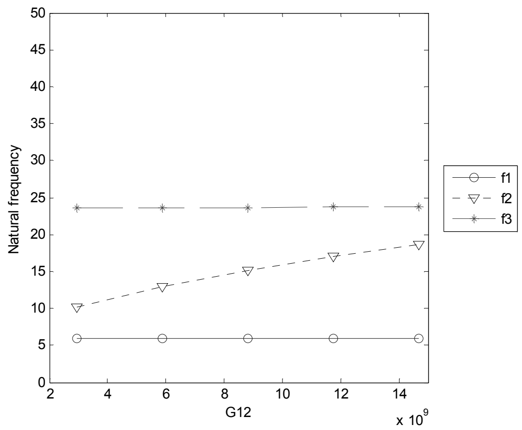


Figure 8.15. The figure shows how G12 influences the first three natural frequencies if everything else is kept constant.

Based on the parametric study a new calculation was performed with the shear modulus increased by 100%, and the elastic modulus in the lengthwise direction increased by 25%:

E1= 44.4 GPa
E2= 8.7 GPa
G12= 11.76 GPa

The increase in shear modulus is consistent with what could be expected; adding a 30mm lamina to an existing structure will increase the equivalent shear modulus.
The change in material parameters resulted in a better consistency between the natural frequencies obtained by measurements and the natural frequencies obtained in the FE-calculations, see table 8.6. Therefore, in the following FE-calculations these material parameters were used.

	f_1 [Hz]	f_2 [Hz]	f_3 [Hz]
Measured	7	18.6	26
Calculated	6.6	17.3	26.3

Table 8.6. Measured- and calculated natural frequencies of the experimental floor structure, after a concrete topping was cast.

8.3 Modeling of human walking

The load due to human walking was modeled as a moving load. The same walking line as in the subjective tests was used, i.e. the load was applied along a line in the middle of the floor structure, in the lengthwise direction. For each footstep the load was applied on two discrete circles, which represents the heel and the forefoot, see figure 8.16.

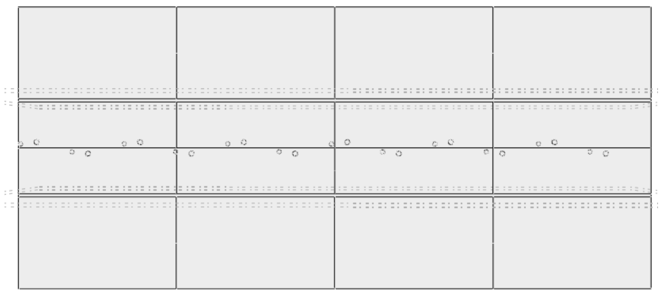
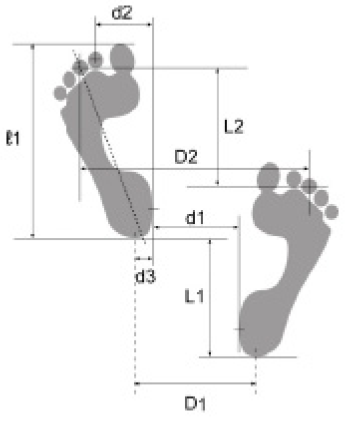


Figure 8.16. Model of the experimental floor structure. The circles indicate the position of the load due to walking.

In order to validate the FE-model of the experimental floor structure first a simulation of the gait load due to the walker (weighing 60 kg) that walked in the subjective tests was performed. In this case the exact position of the footsteps was known, which means that the load could be applied at the same position in the computer model of the floor, and the calculated overall weighted accelerations could be compared to the measured overall weighted accelerations.

Simulations were also performed with a more general human walking pattern, and in this case the weight of the walker was chosen to 80 kg.
The walking pattern in the general case was constructed from average values of gait parameters, which were retrieved from a master thesis concerning the geometric walking pattern of men. In this thesis Claesson (2008) examined the gait pattern of 150 men, the different parameters that were recorded can be seen in figure 8.17, and to the right of the figure the corresponding average values are presented.



*l*1= 26.5 cm
L1= 65 cm
L2= 65 cm
d1= 5 cm
d2= 5 cm
d3= 2.2 cm
D1= 10 cm
D2= 19 cm

Figure 8.17. Gait parameters (Claesson 2008).

In the case of a lightweight floor structure the presence of humans can change the structural dynamic properties of the floor; a stationary person can change the structural mass, stiffness, or damping, but a moving human has little influence on the dynamic properties. Therefore, when the mass of the humans is substantial compared to the mass of the floor structure, the humans should be modeled as a mass-spring-damper system that is connected to the floor structure (Pavic & Reynolds 2002a). In this case, the human-structure interaction was not taken into account. The decision was based on the heavy weight of the concrete floor compared to the weight of a human, and the fact that only one moving person loaded the floor structure.

8.3.1 Load function

Three different load functions, or in other words three different step frequencies, were used in the calculations; f_{walk}= 1.67 Hz, f_{walk}= 1.8 Hz, and f_{walk}= 1.9 Hz.
The starting point was the reaction force time history for one footstep that was constructed by Bard, Persson and Sandberg (2008), see chapter 6.2.3 and figure 8.18 and 8.19. In that case the overlap in time when both feet are on the ground is 0.1 s, and the total time of the gait cycle of one footstep is 0.65 s. This reaction force creates a step frequency of f_{walk}= 1.8 Hz:

$$f_{walk} = \frac{1}{(0.65 - 0.1)s} = 1.8 Hz$$

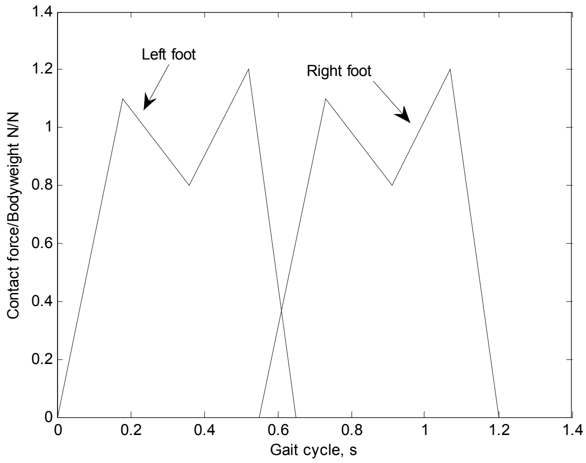


Figure 8.18. Reaction force time history for two footsteps. f_{walk}*= 1.8 Hz.*

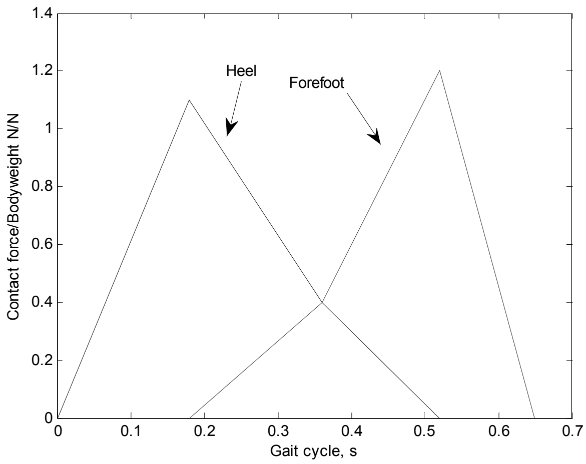


Figure 8.19. Reaction force time history for one foot step divided into separate time histories for the heel and the forefoot. f_{walk}*= 1.8 Hz.*

The other two load functions were constructed accordingly:

The overlap in time when both feet are on the ground was kept the same, i.e. 0.1s.

The total time of the gait cycle of one footstep was either decreased or increased to get a higher or lower step frequency respectively. This was done by leaving the middle part of the load function, between the two peaks, the same, and either increase or decrease the slope of the first and last part of the original load function, see figure 8.20 and 8.21.

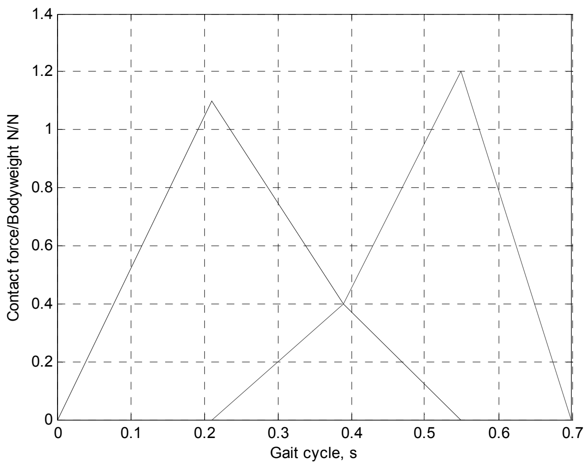


Figure 8.20. Reaction force time history for one footstep divided into separate time histories for the heel and the forefoot. f_{walk}= 1.67 Hz.

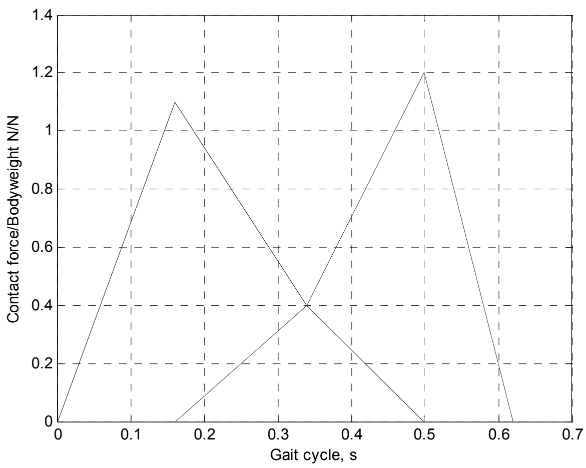


Figure 8.21. Reaction force time history for one footstep divided into separate time histories for the heel and the forefoot. f_{walk}= 1.9 Hz.

Measurements of reaction forces due to walking were not performed in this study. Therefore, in order to investigate if the time histories of the two constructed load functions are reasonable, they were compared to the results from measurements performed by Chao et al. (1983). Chao et al. measured among other things the vertical ground reaction forces in adult walking. The basic parameters can be seen in figure 8.22, and measurements of these parameters are presented in table 8.7. The parameters T_1-T_3 of the constructed load functions were compared to the values in table 8.7, and it was found that the constructed load functions are reasonable in relation to the measurements performed by Chao et al., i.e. T_1-T_3 of the constructed load functions lie within the intervals in table 8.7.

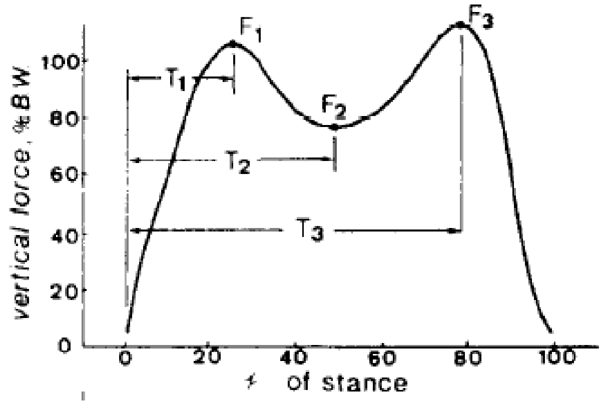


Figure 8.22. Parameters used to describe the foot-floor reaction forces (Chao et al. 1983).

Parameter (% stance)	Men (n = 52) I (n = 32)	III (n = 20)	Total	Women (n = 55) I (n = 37)	III (n = 18)	Total
T_1*	25 ± 3	24 ± 4	24 ± 3	27 ± 4	25 ± 3	27 ± 3
T_2	47 ± 6	46 ± 4	47 ± 5	49 ± 5	50 ± 9	49 ± 6
T_3	79 ± 4	77 ± 2	78 ± 3	78 ± 4	78 ± 3 *	78 ± 3

Table 8.7. Measured values of the parameters T_1-T_3 , in percent of the total time of the load function for one footstep (Chao et al. 1983).

8.3.2 Frequency content of the load functions

During the simulations it was found that the choice of load function affected the resulting accelerations significantly. Therefore, the three different load functions were FFT transformed in order to examine the frequency content of each load.

Figure 8.23 shows an example of a load function, consisting of several steps, that was FFT transformed to the frequency domain. Figures 8.24-8.26 show the frequency content of the three different load functions.

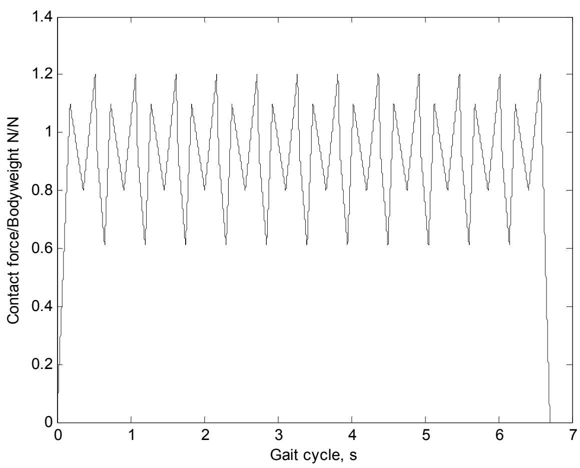


Figure 8.23. Reaction force time history for 12 footsteps. f_{walk}= 1.8 Hz.

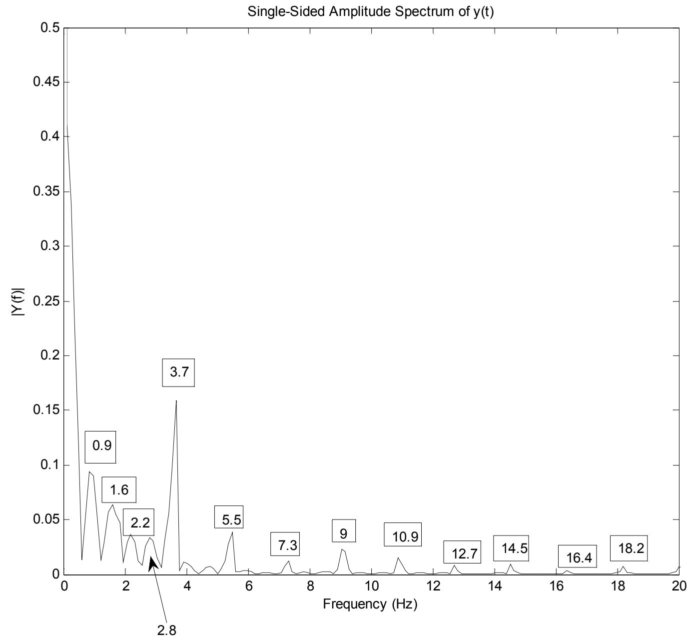


Figure 8.24. Frequency content of the load function f_{walk}= 1.8 Hz.

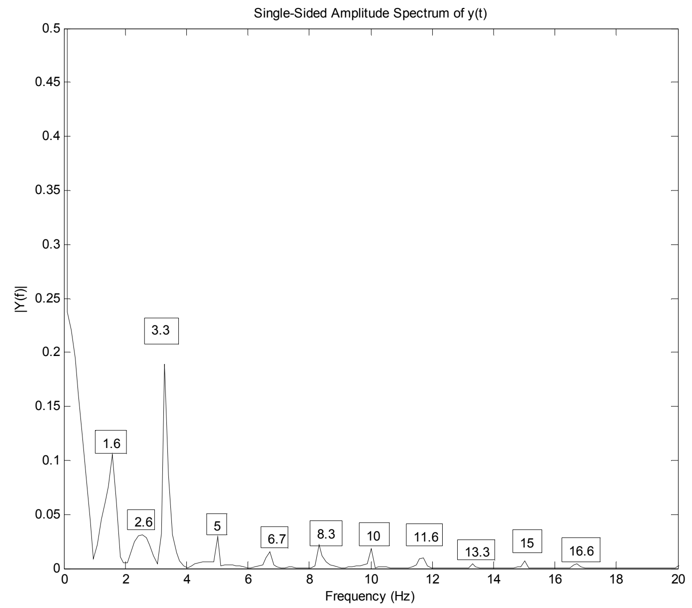


Figure 8.25. Frequency content of the load function f_{walk}= 1.67 Hz.

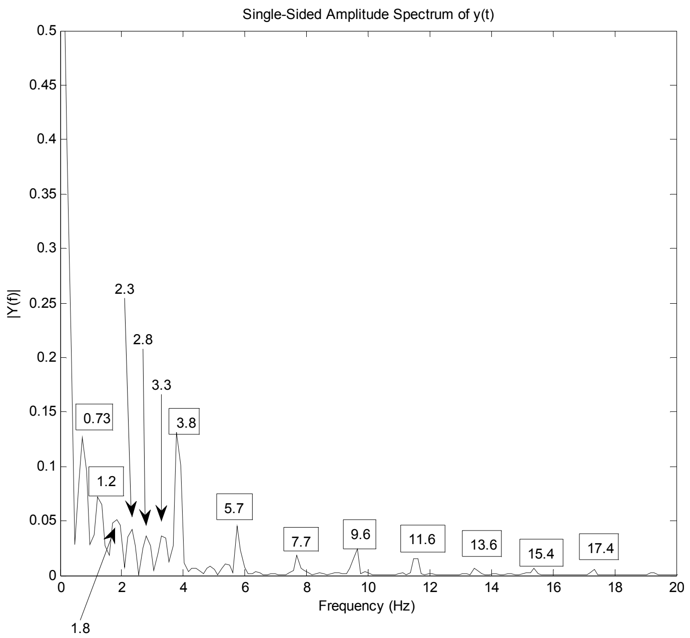


Figure 8.26. Frequency content of the load function f_{walk}= 1.9 Hz.

8.4 Modal analysis

The measurements showed that it was mainly the three first modes of the experimental floor structure that were excited when a person walked across the floor. Therefore, it was concluded that it would be a good approximation to perform modal analysis with the three first modes as a mode base.

In *Abaqus* a linear perturbation- and modal dynamics step was created for simulating the human walking across the floor. The total time of the step was chosen to 10 s, since this was the time period used in the measurements, and the time increment was set to 0.001 s. The measured damping ratios of each mode were used as input, since the damping ratios cannot be calculated.

8.5 Overall weighted values of acceleration

Accelerations were registered and saved for 7 different locations on the model of the floor structure, see figure 8.27.

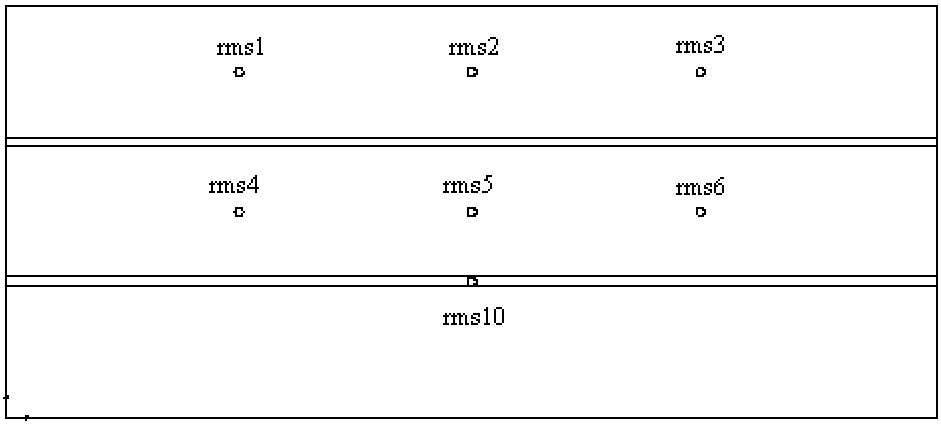


Figure 8.27. Locations on the model were the accelerations due to walking were registered and saved.

In order to validate the FE-model of the experimental floor structure first a simulation of the gait load due to the walker (weighing 60 kg) that walked in the subjective tests was performed. The results, in terms of overall weighted acceleration values for the structure without a concrete topping, can be seen in table 8.8. The averaging time for the overall weighted values of acceleration is 1 s, and *Accelero* was used to pick out the second with the highest acceleration.

As can be seen in table 8.8, f_{walk}= 1.67 Hz resulted in values that are close to the measured values of overall weighted acceleration; for example the average measured overall weighted acceleration at location rms10 was 0.085 m/s^2. There are however significant differences between f_{walk}= 1.67 Hz and f_{walk}= 1.8 Hz; the later one resulted in overall weighted accelerations that are much smaller than the measured.
The substantial differences in acceleration magnitudes between the two step frequencies may be explained by the frequency content of the two load functions; f_{walk}= 1.67 Hz contains frequencies that match the first natural frequency of the model (6.6 Hz), which means that this load function hits the resonant frequency of the model spot on, causing resonant vibration. f_{walk}= 1.8 Hz contains frequencies that are not as close to the first natural frequency, therefore the vibration magnitudes are smaller.

	rms1	**rms2**	**rms3**	**rms4**	**rms5**	**rms6**	**rms10**
pia walk 1.67 Hz	0.061	0.087	0.061	0.059	0.085	0.059	0.086
pia walk 1.8 Hz	0.015	0.021	0.015	0.014	0.021	0.014	0.021

Table 8.8. Overall weighted values of acceleration [m/s^2], without a concrete topping. Averaging time 1s.

The vibration signal at location rms10, which is the location where the chair was placed in the subjective tests, was also filtered in 1/3 octave bands and the magnitude in each band were plotted in a diagram together with the curves of ISO 2631-2:1989. The shape of the graph is approximately the same as the graph obtained from the measurements, see figure 8.28.

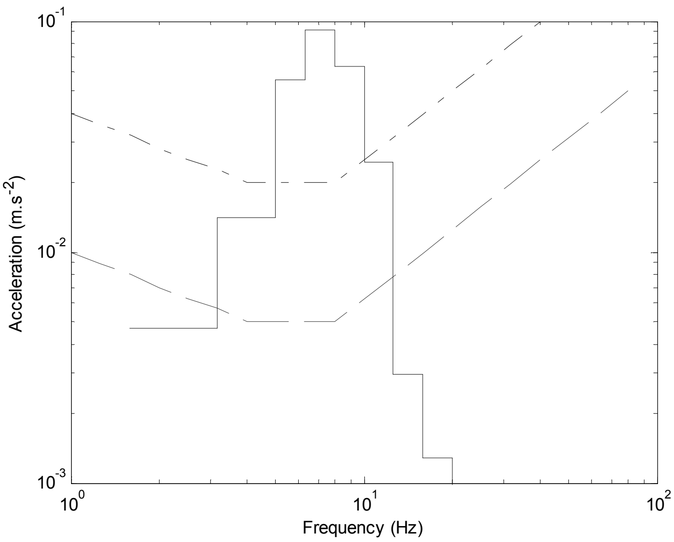


Figure 8.28. Acceleration magnitudes in 1/3 octave bands at the location rms10, without a concrete topping. The diagram also shows the base curve of ISO 2631-2:1989, and the curve that is valid for offices.

Since it was established that the load function with a step frequency of 1.67 Hz caused overall weighted acceleration magnitudes that were similar to the measured ones, this step frequency was used in the more general case with a human weighing 80 kg walking across the floor. The resulting overall weighted values of acceleration can be seen in table 8.9.

	rms1	**rms2**	**rms3**	**rms4**	**rms5**	**rms6**	**rms10**
human walk 1.67 Hz	0.081	0.116	0.080	0.078	0.113	0.080	0.114

Table 8.9. Overall weighted values of acceleration [m/s^2], without a concrete topping. Averaging time 1s.

When the concrete topping is included in the model the first natural frequency of the floor is the same as without the concrete topping, i.e. 6.6 Hz. Therefore, based on the conclusions above the load function f_{walk}= 1.67 Hz was applied to the model to simulate walking. The results can be seen in table 8.10.

The used load function resulted in too low values of overall weighted acceleration compared to the measurements, for example at the location rms10 an average value of 0.066 m/s^2 was measured for the walker in the subjective tests, which should be compared to the calculated value of 0.041m/s^2. These differences may be explained by the uncertainty in the modeling of the load; in reality the reaction forces due to walking perhaps contained higher amplitudes of the resonant frequencies.

	rms1	**rms2**	**rms3**	**rms4**	**rms5**	**rms6**	**rms10**
pia walk 1.67 Hz	0.027	0.041	0.029	0.029	0.040	0.029	0.041
human walk 1.67 Hz	0.039	0.055	0.036	0.038	0.053	0.038	0.054

Table 8.10. Overall weighted values of acceleration [m/s^2], with a concrete topping. Averaging time 1s.

8.6 Modeling of different types of connections and boundary conditions

The experimental floor structure used in this study was placed on thin supports and therefore assumed to be a simply supported slab. In real buildings, the hollow core elements are connected to the walls and beams through reinforcement bars, and the connections are filled with concrete. This is done in order to prevent a progressive collapse. Typical connections between HD elements and concrete walls or steel beams can be seen in chapter 2.

Consequently, in reality the connections between HD elements and walls/beams have some rotational resistance and cannot be compared to a roller support or a pinned support, since these kinds of supports allow a beam or slab to rotate freely.
At the other extreme there is the fixed support, which is not a good description of how the connections work either, since they are not that stiff. In reality, the function of the connections is somewhere in between the two extremes, i.e. somewhere between a fixed support and a roller/pin support.

The type of boundary condition will of course affect the dynamic properties of a slab. A number of simulations of different boundary conditions were performed in *Abaqus* to investigate how the dynamic properties and the vibration performance of the floor are changed compared to the simply supported floor structure.
Simulations were only performed for the floor structure without a concrete topping.
Another type of connection might increase the energy dissipated and therefore the damping ratio. However, since the damping ratios cannot be calculated, they were kept the same as in the simply supported case.

8.6.1 Fixed ends

Calculations were performed in *Abaqus* with fully fixed supports instead of the roller- and pin support that was used to model the experimental floor structure. The natural frequencies of the slab, when the short sides of the floor are fully fixed, are presented below:

f_1= 15.1 Hz
f_2= 21.0 Hz
f_3= 41.4 Hz

The mode shapes that belong to the first three natural frequencies are approximately the same as in the simply supported case. There is only a difference in shape near the supports.

After looking at the frequency content in the different load functions it was decided that f_{walk}= 1.67 Hz or f_{walk}= 1.9 Hz would be most suitable to use, since they contain frequencies that are the closest to the first natural frequency of the floor model. The resulting overall weighted values of acceleration due to these two gait loads, with a walker weighing 80 kg, can be seen in table 8.11.

	rms1	**rms2**	**rms3**	**rms4**	**rms5**	**rms6**	**rms10**
human walk 1.67 Hz	0.011	0.021	0.011	0.011	0.020	0.011	0.020
human walk 1.9 Hz	0.006	0.010	0.006	0.006	0.012	0.006	0.012

Table 8.11. Overall weighted values of acceleration [m/s^2]. Model without a concrete topping, and with fixed supports. Averaging time 1s.

A step frequency of 1.67 Hz resulted in higher values of overall weighted acceleration than a step frequency of 1.9 Hz. If the acceleration at the midpoint of the model, for the case of 1.67 Hz, is filtered and presented in 1/3 octave bands it can be seen that the area of maximum magnitude has shifted to the right of the frequency interval of maximum human sensitivity, see figure 8.29.

An overall weighted value of acceleration of 0.02 m/s^2 is just at the limit for acceptable magnitudes of vibration in offices according to ISO 2631-2:1989. The value also classifies the floor as belonging to vibration class A according to the method proposed by Talja & Toratti, in this class the vibrations are usually imperceptible.

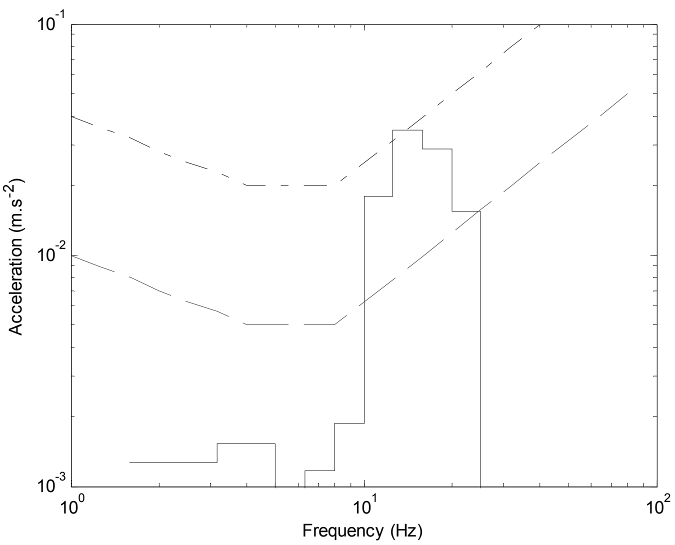


Figure 8.29. Acceleration magnitudes in 1/3 octave bands at the midpoint of the floor, without a concrete topping, and with fully fixed supports. The diagram also shows the base curve of ISO 2631-2:1989, and the curve that is valid for offices.

8.6.2 Midsupport

In the interior of a building, where two hollow core elements in adjacent spans meet, it is common to connect the two elements with reinforcement in order to prevent a progressive collapse, see chapter 2.2 and figure 2.6. This type of connection has some rotational resistance, and in order to estimate the rotational resistance it was assumed that two elements in adjacent spans could be viewed as one continuous beam, see figure 8.30. To model this type of connection in *Abaqus* a rotational spring was connected to one of the short sides of the floor. Consequently, in this simulation the boundary conditions consisted of a pin support along one of the short sides of the model, and a roller support along the other short side including a rotational spring connected to that side.

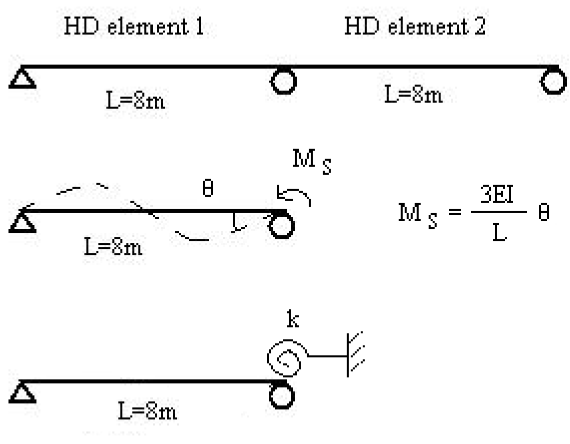


Figure 8.30. Modeling of the midsupport.

The stiffness of the rotational spring was set to:

$$k = \frac{3E_1 I}{L} = \frac{3*35.52e9*3*0.59e-3}{8} = 23.6MNm$$

The calculated natural frequencies of the model are presented below:

f_1= 7.9 Hz
f_2= 17.4 Hz
f_3= 28.1 Hz

Based on the frequency content in the different load functions it was decided that f_{walk}= 1.67 Hz or f_{walk}= 1.9 Hz would be most suitable to use, since they contain frequencies that are the closest to the first and the second natural frequency of the floor model. The resulting overall weighted values of acceleration due to these two gait loads, with a walker weighing 80 kg, can be seen in table 8.12.

	rms1	**rms2**	**rms3**	**rms4**	**rms5**	**rms6**	**rms10**
human walk 1.67 Hz	0.025	0.031	0.019	0.023	0.030	0.020	0.031
human walk 1.9 Hz	0.034	0.054	0.035	0.033	0.053	0.034	0.053

Table 8.12. Overall weighted values of acceleration [m/s²], without a concrete topping. Averaging time 1s. Midsupport.

The step frequency f_{walk}= 1.9 Hz resulted in the highest magnitudes of overall weighted acceleration. In figure 8.31 the acceleration at the midpoint of the model, filtered and presented in 1/3 octave bands, can be seen together with the base curve of ISO 2631-2:1989 and the curve that is valid for offices. As can be seen there is a probability of adverse comments according to ISO 2631-2:1989.

A value of 0.053 m/s^2 classifies the floor as belonging to vibration class C according to the method proposed by Talja and Toratti. This vibration class is characterized by that the vibration is often perceptible and some people may feel it annoying (inside one apartment).

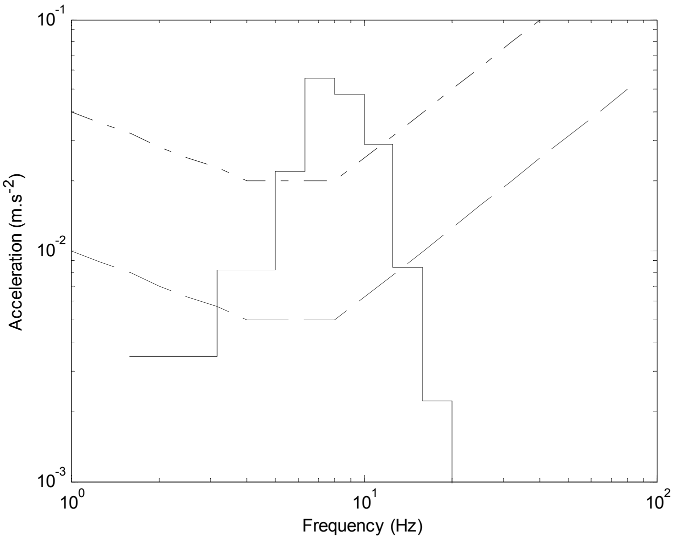


Figure 8.31. Acceleration magnitudes in 1/3 octave bands at the midpoint of the floor, without a concrete topping, and with a midsupport. The diagram also shows the base curve of ISO 2631-2:1989, and the curve that is valid for offices.

8.7 Modeling of different spans

Changing the span of the floor structure will also change the dynamic properties of the floor. In order to investigate how the vibration performance of the floor structure is affected when a shorter span is used, two models with a span of 7 m and 6 m respectively were constructed.
Simulations were only performed for a floor structure without a concrete topping, and the models were simply supported.

8.7.1 L= 7 m

A simply supported slab with a span of 7 m resulted in the following natural frequencies:

f_1= 8.7 Hz
f_2= 17.3 Hz
f_3= 34.8 Hz

Since the load functions f_{walk}= 1.67 Hz and f_{walk}= 1.8 Hz contains frequencies that are the closest to the first natural frequency of the floor structure, two different simulations were performed with these loads. The resulting overall weighted values of acceleration caused by a walker weighing 80 kg can be seen in table 8.13.

	rms1	rms2	rms3	rms4	rms5	rms6	rms10
human walk 1.67 Hz	0.025	0.038	0.026	0.025	0.036	0.026	0.036
human walk 1.8 Hz	0.026	0.037	0.026	0.025	0.036	0.025	0.036

Table 8.13. Overall weighted values of acceleration [m/s^2], without a concrete topping. Averaging time 1s. L= 7m.

An overall weighted acceleration value of 0.037 m/s^2 means that the floor structure belongs to vibration class B according to Talja & Toratti's method. Vibration class B is characterized by that the vibration may be perceptible but usually it is not annoying (inside one apartment).

According to ISO 2631-2:1989 the probability of adverse comments in offices is low if the overall weighted acceleration is below 0.02 m/s^2.

In figure 8.32 the acceleration at the midpoint of the model, filtered and presented in 1/3 octave bands, can be seen together with the base curve of ISO 2631-2:1989 and the curve that is valid for offices. As can be seen there is a probability of adverse comments.

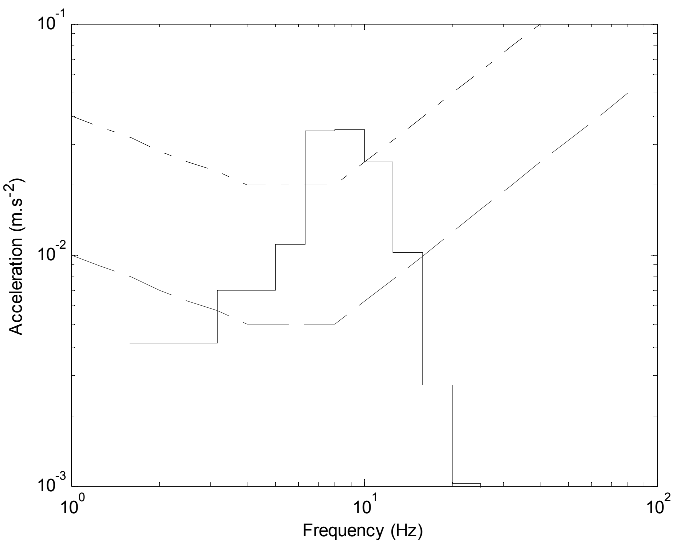


Figure 8.32. Acceleration magnitudes in 1/3 octave bands at the midpoint of the floor, without a concrete topping. Span of the floor: 7m. The diagram also shows the base curve of ISO 2631-2:1989, and the curve that is valid for offices.

8.7.2 L= 6 m

A simply supported slab with a span of 6 m resulted in the following natural frequencies:

f_1= 11.9 Hz
f_2= 21.1 Hz
f_3= 47.4 Hz

Since the load functions f_{walk}= 1.67 Hz and f_{walk}= 1.9 Hz contains frequencies that are the closest to the first natural frequency of the floor structure, two different simulations were performed with these loads. The resulting overall weighted values of acceleration caused by a walker weighing 80 kg can be seen in table 8.14.

	rms1	**rms2**	**rms3**	**rms4**	**rms5**	**rms6**	**rms10**
human walk 1.67 Hz	0.022	0.031	0.022	0.021	0.030	0.021	0.030
human walk 1.9 Hz	0.022	0.031	0.022	0.021	0.030	0.022	0.031

Table 8.14. Overall weighted values of acceleration [m/s^2], without a concrete topping. Averaging time 1s. L=6m.

The maximum value of overall weighted acceleration is 0.031 m/s^2, which means that according to ISO 2631-2:1989 there is a probability of adverse comments. In figure 8.33 the acceleration at the midpoint of the model, filtered and presented in 1/3 octave bands, can be seen together with the base curve of ISO 2631-2:1989 and the curve that is valid for offices. It can be seen that the area of maximum magnitude has shifted to the right of the frequency interval of maximum human sensitivity compared to the original simply supported floor structure with a span of 8 m.

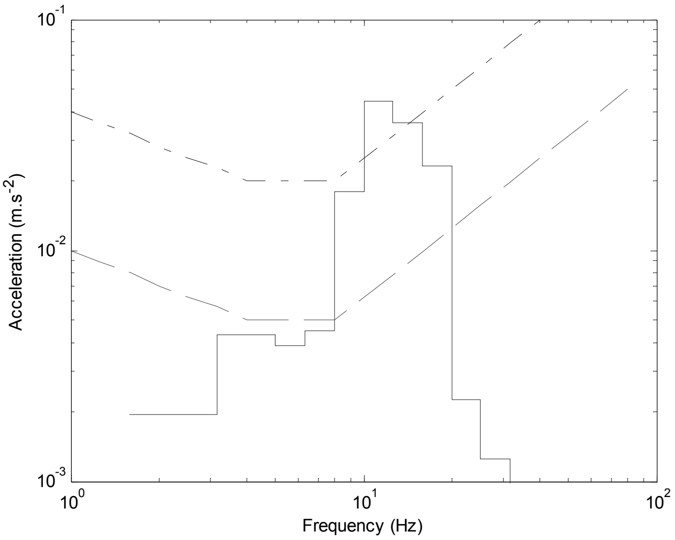


Figure 8.33. Acceleration magnitudes in 1/3 octave bands at the midpoint of the floor, without a concrete topping. Span of the floor: 6 m. The diagram also shows the base curve of ISO 2631-2:1989, and the curve that is valid for offices.

8.8 Discussion

During the simulations it was found that the choice of load function affected the resulting accelerations significantly. For example, a load function that had a frequency content that matched the first natural frequency of the floor structure resulted in overall weighted values of acceleration that were in accord with the results from the measurements. A load function that had a frequency content that differed only slightly from the fundamental frequency of the floor structure resulted in significantly lower magnitudes of acceleration compared to the average of the measurements.

This sensitivity to the frequency content of the applied load means that it is difficult to draw any clear conclusions based on the three different load functions that were used in this study. For instance, another choice of load function may result in higher magnitudes of acceleration. Therefore, as a suggestion for further work, and when designing for vibration serviceability, it is recommended that many different load functions are tested, and the one that results in the highest acceleration magnitudes is chosen to be the governing load case. Another approach would be to design a load function that contains the natural frequencies of the floor structure, for instance by using Fourier series. Of course, the constructed load function must be within reasonable limits compared to results from measurements of the reaction force time history of gait loading. Because of the limited time frame of this master thesis it was not possible to try these approaches.

Since the FE-model of the floor structure showed a significant sensitivity to the frequency content of the applied load, the results from the measurements were reviewed in order to investigate if the same tendency applied to the real floor structure. In the results from the measurements it can be seen that the overall weighted values of acceleration varies between different measurements of the same person walking. This may be a result of that humans are not perfect exciters, in general they are not able to maintain the same pacing frequency for the whole walk, and it is not likely that they will walk with the exact same step frequency in subsequent measurements. The differences in acceleration magnitudes between two walks may also be explained by the narrowness of the peaks around resonances for lightly damped structures, i.e. if the load contains resonant frequencies it will cause large response amplification, but only a slight off-resonance will result in a great reduction in response. Consequently, the differences in acceleration magnitudes between different walks indicate that the real floor structure is sensitive to the frequency content of the gait load, however the differences in magnitudes are not as big as in the FE-simulations, see appendix 3. Perhaps the human brain and the nervous system unconsciously modifies the step frequency in order to match the natural frequency of the floor structure and frequency of the vibration, since it is more comfortable to walk in time with vibrations.

To sum up, from the simulations performed in this study it can be concluded that fully fixed supports will improve the vibration performance of the floor structure compared to the simply supported case. Fixed supports cause the natural frequencies of the floor structure to rise, and the frequency content of the vibration due to walking is shifted out of the interval of maximum human sensitivity. The same is valid for shortening of the span.

9 Interviews

The results from the subjective tests in this study indicate that vibration in hollow core elements very well could be a problem that could cause adverse comments in real buildings. A majority of the test persons found the experimental floor structure absolutely not acceptable with regard to vibration. The strongly perceptible vibration of the test floor came as a surprise to many of the test subjects. With these results in mind, the author of this master thesis found it interesting to perform a small survey in order to investigate if there are any existing buildings where people are complaining about annoying vibration in HD elements.
Interviews with six structural engineers were performed. One of them was working in Stockholm, the rest of them in Malmö or Lund. They were working at five different companies in the construction business, one of the companies was a construction company and the rest of the companies were in the consultant business. The structural engineers were chosen because of their long experience in the construction area or because of their long experience of prefabricated concrete elements.

They were asked the following two questions:

- Do you know of any case where people are/were complaining about annoying vibrations in hollow core elements?
- How do you think when you are choosing the span or size of a hollow core element? (Do you choose the maximum possible span or do you choose a span in the middle of the possible span?)

If they answered yes on the first question a longer interview was performed with questions about the activity in the building, the size and span of the HD elements, which kind of load-bearing elements were used in the building frame, and so on.

9.1 Results

Three of the structural engineers did not know any cases were people are or have been complaining about disturbing vibrations in hollow core elements. However, one of them talked about two cases where the involved persons realized from the beginning that vibration could become a problem. In both cases it was disturbing vibration from fan rooms they were afraid could occur and not vibration caused by human walking. They solved the possible problem by talking to the structural engineers working for the element supplier, by choosing a thicker dimension of HD elements and by casting a thick concrete layer on top of the HD elements.

9.1.1 Case 1: Extensive vibrations caused by an extreme load in an assembly hall

One of the interviewed structural engineers had spent a major portion of his working life working with prefabricated concrete elements. He knew of one case where

disturbing vibrations had occurred in hollow core elements. This was, however, a one-time extreme case; the load was on the verge of extraordinary and the span of the floor was long. It was the top floor in a concrete building with concrete walls. The top floor accommodated an assembly hall, which was used for dancing at the time of the occurrence of the disturbing vibrations. Otherwise, he had not experienced any reported problems with annoying vibrations in normal office buildings with HD floors, not as reported damage cases anyway.
Generally he avoids using maximum spans because of the risk of significant vibrations and the risk of disturbing excess height of the floor structure. He usually chooses a HD element with a span that is 75-80% of the maximum possible span.

9.1.2 Case 2: Extensive vibrations caused by too heavy trucks

One of the interviewed structural engineers had come into contact with a case where extensive vibrations in HD elements had occurred, but it turned out that too heavy trucks were driven over the floor structure. The hollow core elements were not designed to carry such heavy trucks. Otherwise, the structural engineer had not heard about or received any complaints about annoying vibration in HD elements. He has reviewed cases in the planning stage and pointed out that they will not work in view of vibration, but in all these cases the dimensions were adjusted before they were built, and did not lead to any problems.
As a rule this structural engineer checks the deflection of the floor structure when choosing the span and dimensions of the HD elements. He also calculates the natural frequency of the floor, with simple formulas for beams or plates, and compares it to the frequency of the load that will be applied.

9.1.3 Case 3: Extensive vibrations in an office building caused by human walking

One of the interviewed structural engineers gave two examples of buildings where extensive vibrations occur. According to this structural engineer, when talking to his colleagues about the matter of vibration in prefabricated concrete elements, they all say that it is best to go to a certain furniture store in Malmö to experience the problems by oneself. The author of this report did of course visit this furniture store, and experienced the vibrations when another person walked by. However, the floor structure seemed mostly to consist of another type of prefabricated concrete elements and not HD elements.

The other case, where people had complained about annoying vibration, was in a two-storey office building in Älmhult. The occupants complained about annoying vibrations when another person walked by, not when they themselves walked on the floor structure. In this office the second smallest HD element had been used, HD/F 120/27 with a thickness of 265 mm. The span was 11-12 m, which is in the upper region of the possible span in serviceability limit state. According to the handbook of prefabricated concrete elements, *Bygga med prefab,* the maximum span for this type of hollow core element in serviceability limit state is 13 m.

The building frame consisted of steel beams and steel columns, and a concrete topping was used to make the floor surface plane. The connections were performed according to the prescription of the manufacturer, and no mistakes in the design could be found. The office was sparsely furnished and open-plan. According to the structural engineer, this is one of the things the manufacturers of the elements always refer to; today the office environment is not like in the past. In the past, more interior walls were used which could stabilize the floor structure, and before the computer age more furniture were used, which added mass.
As far as the structural engineer knew no steps have been taken in order to solve the vibration problem. The suggestion that had been put forward was to apply more concrete to increase the mass.

After this incident, with the annoying vibrations in the office building, the structural engineer and his colleagues have always chosen a smaller span, and they usually have a dialogue with the manufacturer of the elements whenever they are prescribing a size of a HD element.

9.2 Discussion

The survey carried out indicates that the problem with annoying vibration in hollow core elements caused by human walking is currently not widespread. However, one must keep in mind that only a few people were interviewed and all of them were structural engineers. The picture might have been another if occupants of different office buildings had been interviewed. Generally, the construction business is not very good at feedback and the information might not reach the structural engineers, or the vibration caused by human walking might not be seen as a damage case and is therefore not reported.

Of course, there are big differences between the experimental floor structure used in this study and floor structures in real buildings. The experimental floor structure was a worst-case scenario; it was simply supported, very sparsely furnished and consisted only of three hollow core elements. But still, the remarkable results from the subjective tests performed in this study are reason to believe that in some cases vibration in hollow core elements caused by human walking could be a problem in real buildings.

10 Vibration control

If an existing floor structure is found not acceptable with regard to vibration there are a number of possible measures to counteract high vibration magnitudes; tuned mass dampers, active control, visco-elastic dampers, increasing the mass, etc. However, they all seem to have large drawbacks such as extensive cost, the need for extra space for the equipment, etc. The methods and some of their disadvantages are described below.
Another interesting fact is that results from measurements in laboratory conditions can differ markedly from in situ measurements on floor structures in real buildings. Some possible explanations for these differences are presented below.

10.1 Parameters that influence the dynamic behavior of floor structures

The parameters that influence the dynamic behavior of a floor structure are stiffness, mass and damping. A high stiffness means small deflections when subjected to a force, which in turn means that the stiffness decides the springiness of a floor structure. High stiffness can be achieved by increasing the dimensions (I) or choosing a stronger material (E), if the span is constant.
When it comes to vibration serviceability a high mass is often favorable. Increased mass has a positive effect on vibration performance by lowering the amplitudes of vibration (Ljunggren 2006). Therefore, it can be a good idea to engage larger floor area in vibration by increasing the lateral stiffness of the floor or by using continuity. However, continuity between spans means that there is a possibility of transmission of the vibrations to another room (Pavic & Reynolds 2002b & Ohlsson 1984).
High damping has been found to have a positive effect on human acceptance of vibrations (Ljunggren 2006).

Another dynamic property of a floor structure is the fundamental frequency, i.e. the lowest natural frequency. The fundamental frequency of a floor structure is recognized to have an effect on how humans perceive vibrations, and thereby the division into high-frequency floors and low-frequency floors.
The natural frequencies of a structure are mainly determined by the mass of the structure, the distribution of mass, and the stiffness (Heyden et al. 2005).
For example, the fundamental frequency of a simply supported element can be estimated according to:

$$f_1 = \frac{\pi}{2}\sqrt{\frac{E_{c,dyn} \cdot I}{m \cdot l_{red}^4}} \qquad \text{(Eriksson 1988)}$$

I = moment of inertia
m = weight (kg/m)
$E_{c,dyn}$ = dynamic modulus of elasticity
l_{red} = free span width considering the support width

From the formula above it can be concluded that an increase of the mass does not only reduce the vibration amplitude but also the fundamental frequency.
A higher frequency is normally less annoying because humans are more sensitive to lower frequencies. Therefore, it has been proposed by some researchers to eliminate the problem with resonance vibrations due to walking by shifting the floor's fundamental frequency above 9 Hz. Consequently, they suggest using a frequency tuning method in the design stage (Pavic & Reynolds 2002b).

10.2 Methods to counteract high vibration magnitudes in existing floor structures

There are a number of methods to reduce resonant floor vibration; tuned mass dampers, active control, or visco-elastic dampers. The vibrations can also be reduced by adding concrete thickness to the floor structure, i.e. increase the mass. However, the strength of the floor and the building frame must be checked to conclude if the additional weight can be supported. This method also means a disruption in an occupied building.
Non- structural components such as partition walls can bring some damping to the system; they also provide support to the floor structure. The drawback in this case is the possibility of transmission of vibrations to other parts of the building (Hanagan & Murray 1997). It has been found that non-structural components such as raised or false floors add very little damping to bare long-span concrete floors (Pavic & Reynolds 2002a).

Tuned mass dampers (TMD) can be used to add damping to a system. A tuned mass damper consists of a mass that is connected to the floor structure. This additional mass has its natural frequency slightly below the natural frequency of the floor structure. And when the floor is vibrating at its natural frequency the energy is transmitted to the TMD and dissipated. A model of the floor structure and the TMD can be seen in figure 10.1 (Ljunggren 2006).
One of the drawbacks with tuned mass dampers is that one TMD only damps one mode of vibration. Furthermore, TMDs cannot be mass produced since the dynamic properties of a floor are highly dependent on the environment. Measurements have to be performed on each individual floor structure so that the TMD can be tuned to the natural frequency of that individual floor. Also, the natural frequency of the floor may change, due to for example a change in load, leaving the TMD useless or maybe even worsening the response (Ljunggren 2006).

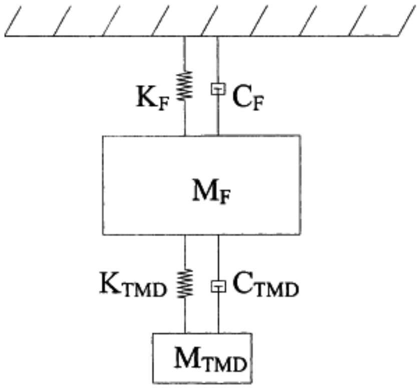


Figure 10.1. Model of a floor structure and a tuned mass damper. The parameters K_{TMD}, C_{TMD} and M_{TMD} must be carefully chosen (Ljunggren 2006).

Another way of adding damping to a system is to use an active control approach. In the active control approach a force controlled by a computer is applied to the floor structure in order to reduce the amplitudes of vibration. However effective, the major disadvantage of this type of system is the cost (Hanagan & Murray 1997).

In the current situation there is research in the area of using visco-elastic materials to bring some additional damping to a structure (Ljunggren 2006).

10.3 Laboratory measurements vs. in situ measurements and FE calculations vs. in situ vibration performance

Results from measurements in laboratory conditions can differ markedly from in situ measurements on floor structures in real buildings. The same way, results from FE calculations can differ markedly from the dynamic behavior of an in situ floor structure. These differences can be explained by the fact that the dynamic response of a floor structure is a combination of the dynamic properties of the floor structure and the interaction with its surroundings. For example, the boundary conditions affect the natural frequencies and play an important role in the response to a dynamic force. In the laboratory environment it is possible to control these boundary conditions, but for in situ floor structures the exact boundary condition is usually unknown.
Furthermore, real buildings can be loaded by line loads from partitions, which can change the natural frequency compared to the calculated one or measured one.
To sum up, the response of a floor structure subjected to a dynamic force is a result of a complicated interaction between the floor and exterior walls, partitions, etc. Therefore, results from measurements will depend on the set up of partitions and so on. Moreover, the damping is normally higher for in situ floors compared to a floor in a laboratory (Ljunggren 2006).

There is always a question about how to model the boundary conditions in a FE-model; one can treat them as being simple pin supports or fully fixed supports, or maybe something in between. An interesting illustration of the fact that the exact in situ boundary conditions usually are not known, is one building found in a case study by Bachmann and Ammann:

In this building they had a vibration serviceability problem. The vibrations were transmitted down through the building when people were exercising on the top floor. In the design stage the floor was estimated to have a natural frequency of 10 Hz, probably by assuming some ideal pin- or fixed support. However, the top floor was supported by long columns, which in reality acted as vertical springs, thereby reducing the fundamental frequency of the floor to only 4.4 Hz (Pavic & Reynolds 2002b).

11 Discussion and conclusions

The results from the subjective tests showed that a large majority of the test persons found the experimental floor structure unacceptable or absolutely unacceptable with regard to vibrations induced by another person. Before a concrete topping was cast not a single test person found the floor acceptable in this regard. Adding a concrete topping of 30 mm thickness resulted in that the weight was shifted from absolutely unacceptable to just unacceptable. Only a small percentage of the test group found the floor acceptable in a newly built office after a concrete topping was cast. The results from the subjective tests indicated that a concrete topping improved the vibration performance of the floor structure slightly, but the intensity of the vibrations induced by another person was still classified as clearly perceptible or strongly perceptible.

The slight improvement of the vibration performance of the experimental floor structure after a concrete topping was cast could also be seen in the measurements, in this case in the form of reduced average values of overall weighted acceleration.
The results from the measurements were also evaluated according to the method proposed by Talja and Toratti, and the former ISO standard ISO 2631-2:1989. Both methods indicated that the probability of adverse comments is high, which was in agreement with the subjective tests that were performed. When the vibration signal was filtered and plotted in 1/3 octave bands it could be seen that the highest acceleration magnitudes were found in the frequency interval of maximum human sensitivity, which explains the results from the subjective tests.
During the measurements 15 accelerometers were placed across the floor, and the results from the measurements showed that it was not only in the midsection of the floor that the vibration magnitudes were high. Based on the results from the subjective tests and the evaluation of the measurements it can be concluded that a span of 8 m is not advisable for a simply supported floor structure made of HD/F 120/20 elements, not even if a concrete topping with a thickness of 30 mm is cast.

It can be argued that in real buildings more furniture and perhaps partition walls would be used, which would increase the mass that must be set to oscillate, and thereby reduce the magnitudes of acceleration. Friction between the floor structure and nonstructural elements such as furniture and partition walls also brings damping to the system, which has the possibility to reduce resonant vibration. Furthermore, in real buildings the connections between hollow core elements and other structural parts cannot be classified as pin- or roller supports, instead the connections have some rotational resistance. The rotational resistance of the connections has a positive effect on the vibration performance of the floor structure in terms of an increase in the natural frequencies of the floor structure, compared to the simply supported slab.
However, in the designing stage of the building process a worst case scenario is typically used to determine the appropriate dimensions of a structure. In this case the worst case scenario corresponds to a simply supported floor structure without nonstructural elements, and in that case a span of 8 m for HD/F 120/20 elements does not work with regard to vibration serviceability.

The goal of the finite element simulations that were performed was to investigate the effect that other types of boundary conditions, and other spans, have on the vibration performance of the floor structure. One of the original goals was also to establish a maximum possible span of HD/F 120/20 elements with regard to vibration serviceability.
During the simulations it was discovered that the frequency content of the applied load function affected the resulting accelerations significantly. A load function that contained frequencies that matched the first natural frequency of the floor structure resulted in the highest magnitudes of overall weighted acceleration, and it was also this load that resulted in magnitudes that were consistent with the results from the measurements.
The sensitivity of the model to the frequency content of the applied load made it difficult to draw any clear conclusions about the maximum possible span with regard to vibration serviceability based on only the three load functions that were used in this study. Another load function would perhaps have resulted in higher magnitudes of vibration.
Therefore, it is suggested to further investigate this sensitivity of the model to the frequency content of the load, and when designing for vibration serviceability it is recommended to use one of the following methods:
The first approach would be to test many different load functions, and choose the one that result in the highest acceleration magnitudes to be the governing load case. The other alternative is to design a load function that contains the natural frequencies of the floor structure, for instance by using Fourier series. Because of the limited time frame of this master thesis it was not possible to try either one of these methods.

From the simulations performed in this study it can be concluded that fixed supports, or supports with at least some rotational resistance, will improve the vibration performance of the floor structure compared to the simply supported case. The improvement has its origin in the rise of the natural frequencies of the floor structure compared to the simply supported slab; higher natural frequencies means that the frequency content of the vibrations due to walking is shifted out of the frequency interval of maximum human sensitivity. The same is valid for shortening of the span.
Based on the three load functions that were used in this study, it can be determined that a simply supported slab with a span of 7 m will at least belong to vibration class B, i.e. the floor will not belong to a better vibration class, but there is a possibility that it will belong to a worse vibration class. Vibration class B is characterized by the vibration may be perceptible but usually it is not annoying
A simply supported slab with a span of 6 m resulted in slightly lower values of overall weighted acceleration compared to a span of 7 m. If the vibration magnitudes are compared to the vibration classes proposed by Talja and Toratti the floor will also be classified as belonging to vibration class B, but in this case the acceleration values are on the verge to vibration class A.

The sensitivity of the FE-model to the frequency content of the applied load could also be distinguished in the real experimental floor structure, when looking at the results from the measurements. The acceleration magnitudes varied between different measurements of the same person walking, even when the same footprints were used. Since humans are not perfect exciters, i.e. in general they are not able to maintain the same pacing frequency for subsequent walks, the varying results from the measurements indicate sensitivity to the frequency content of the load. However, the differences in acceleration magnitudes that can be seen in the measurements are not as big as the differences in the calculations. A possible explanation for this discrepancy is that perhaps the real reaction force due to walking contains more or higher frequencies that are able to cause resonant vibration, compared to the constructed load functions, which are simplified. Furthermore, perhaps the human brain and the nervous system unconsciously modifies the step frequency in order to match the natural frequency of the floor structure and the frequency of the vibration, since it is more comfortable to walk in time with vibrations.

Another restriction of this master thesis is that only one walking line was considered. It could be interesting to investigate how another walking line would affect the resulting vibrations. Also, in reality a floor structure usually consists of far more elements than the three elements that were used to build the experimental floor structure in this study. Therefore, it could be interesting to see how much the vibration magnitudes are changed if a larger floor area is modeled and subjected to a single person walking. In this thesis it was assumed that the experimental floor structure made of three hollow core elements could be regarded as a reasonable approximation of reality. This assumption was based on that a floor structure made of more than three elements will increase the mass that must be brought to oscillate, but on the other hand it will be possible for more people to walk on the floor at the same time.

In conclusion, this master thesis has shown that a simply supported floor structure made of HD/F 120/20 elements with a span of 8 m is not acceptable with regard to vibration serviceability. The calculations have also shown that there is a small risk of adverse comments with regard to vibrations in the case of simply supported floor structures with spans of 6 or 7 m.

The interviews that were performed indicated that the problem with annoying vibrations in hollow core elements induced by human walking is currently not widespread. However, the results from the subjective tests and FE-calculations performed in this study gives a reason to believe that in some cases vibration in hollow core elements caused by human walking could be a problem in real buildings. The risk of adverse comments is the highest for sparsely furnished spaces. The use of long and slender columns or beams in the building frame could also increase the risk of adverse comments; for example there is a possibility that the columns can act as vertical springs and reduce the fundamental frequency of the floor system.

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Appendix 1: Questionnaire used in the subjective tests

Questionnaire

Test person no.______

Male [ ]
Female [ ]

Age _____

Weight _____

Did you participate in a similar test carried out last autumn and in springtime?

Yes [ ]
No [ ]

Test 1: Rating of vibrations due to test person's own walking

Walk back and forth on the floor structure and evaluate the vibration serviceability/performance of the floor.

1.1 Please, classify the ***intensity*** of the vibrations.

Strongly perceptible	Clearly perceptible	Barely perceptible	Imperceptible

1.2 Is the floor ***acceptable*** in a newly built office?

Absolutely unacceptable	Unacceptable	Acceptable	Absolutely acceptable

1.3 On a scale from 1 to 10, rate the vibration serviceability/performance of the floor.

1 2 3 4 5 6 7 8 9 10
Very poor Very good

Test 2: Rating of vibrations induced by a walking person

Sit down on a chair placed on the floor structure and evaluate the vibration serviceability/performance of the floor when another person is walking by.

2.1 Please, classify the ***intensity*** of the vibrations.

Strongly perceptible	Clearly perceptible	Barely perceptible	Imperceptible

2.2 Is the floor ***acceptable*** in a newly built office?

Absolutely unacceptable	Unacceptable	Acceptable	Absolutely acceptable

2.3 On a scale from 1 to 10, rate the vibration serviceability/performance of the floor.

1	2	3	4	5	6	7	8	9	10
Very poor									Very good

Test 3: Rating of the effect vibrations have on working efficiency

To what extent will vibrations in the desk affect your work efficiency?

1	2	3	4	5	6	7	8	9	10
Very much									Not at all

Thank you for participating!

If you have anything to add, please write it below:

Questionnaire used in the subjective tests, Swedish version

Frågeformulär

Testperson nr.______

Man [ ]
Kvinna [ ]

Ålder _____

Vikt _____

Deltog du i ett liknande försök förra hösten eller i våras?

Ja [ ]
Nej [ ]

Test 1: Utvärdering av golvets egenskaper med hänsyn till svikt vid gång över bjälklaget

Gå över golvet och bedöm hur du uppfattar golvets egenskaper med hänsyn till svikt och vibrationer.

1.1 Bedöm vibrationernas ***intensitet***.

Starkt märkbara	Tydligt märkbara	Knappt märkbara	Ej märkbara

1.2 Är golvet ***acceptabelt*** i ett nybyggt kontor?

Absolut oacceptabelt	Oacceptabelt	Acceptabelt	Absolut acceptabelt

1.3 På en skala mellan 1 och 10, bedöm hur du uppfattar golvets egenskaper med hänsyn till svikt.

1	2	3	4	5	6	7	8	9	10
Dåligt									Bra

Test 2: Utvärdering av golvets egenskaper med hänsyn till vibrationer då en annan person går över bjälklaget

Bedöm golvets egenskaper med hänsyn till vibrationer då du sitter på en stol och en annan person går förbi.

2.1 Bedöm vibrationernas ***intensitet***.

Starkt märkbara	Tydligt märkbara	Knappt märkbara	Ej märkbara

2.2 Är golvet ***acceptabelt*** i ett nybyggt kontor?

Absolut oacceptabelt	Oacceptabelt	Acceptabelt	Absolut acceptabelt

2.3 På en skala mellan 1 och 10, bedöm hur du uppfattar golvets egenskaper med hänsyn till vibrationer.

1	2	3	4	5	6	7	8	9	10
Dåligt									Bra

Test 3: Utvärdering av hur vibrationer i skrivbordet påverkar arbetseffektiviteten

På en skala mellan 1 och 10, bedöm hur vibrationer i skrivbordet kommer att påverka din arbetseffektivitet.

1	2	3	4	5	6	7	8	9	10
Kraftigt									Inte alls

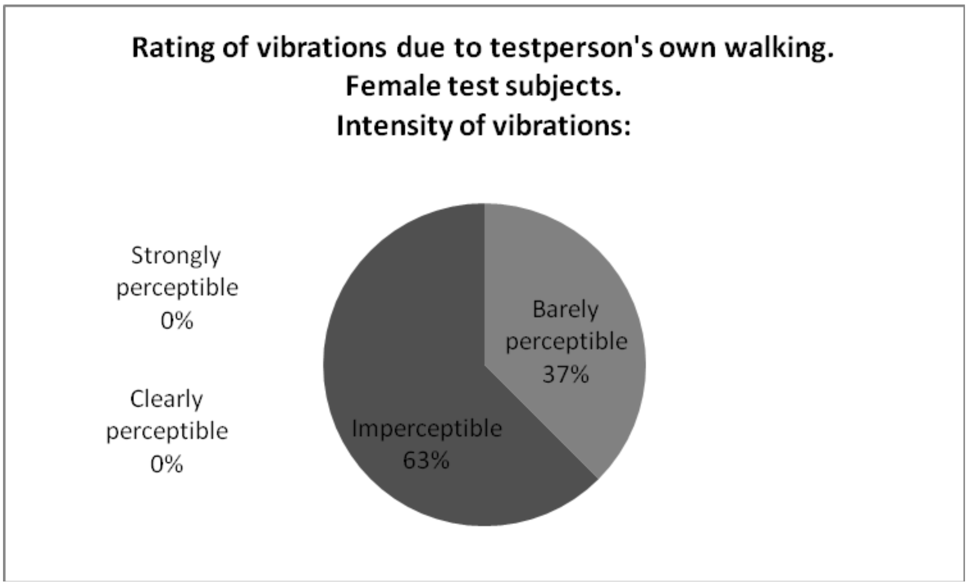
Tack för din medverkan!

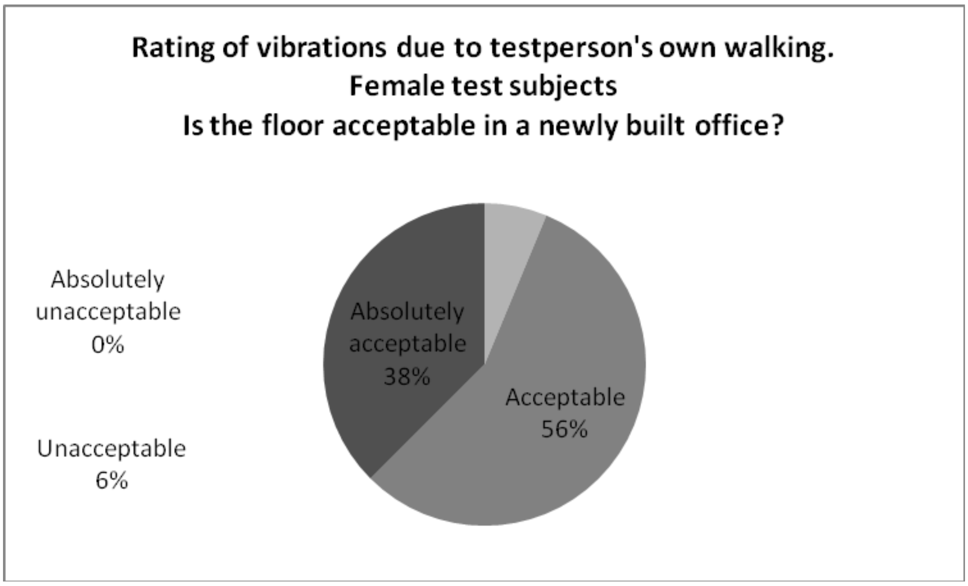
Om du har något att tillägga, skriv gärna kommentarer nedan:

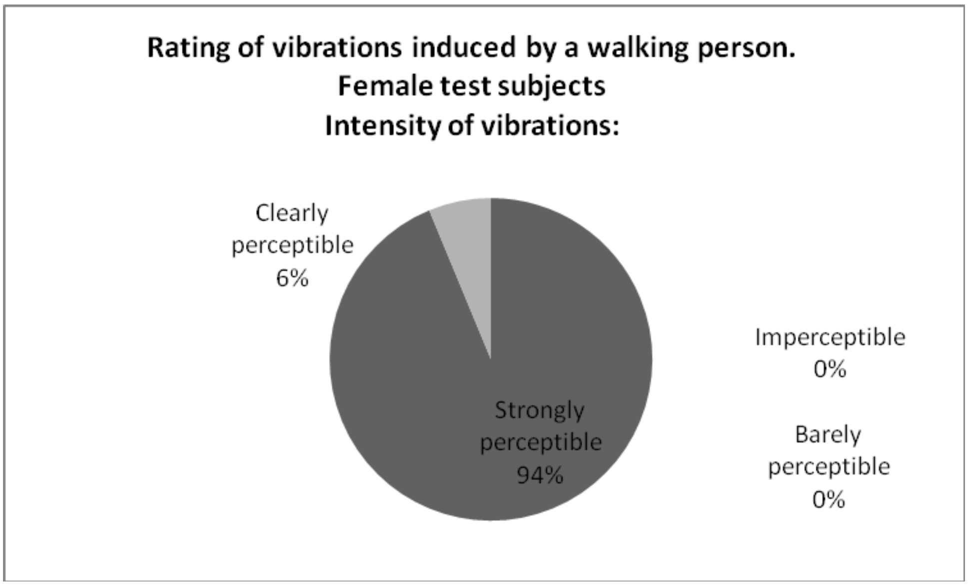
Appendix 2: Results from the subjective tests

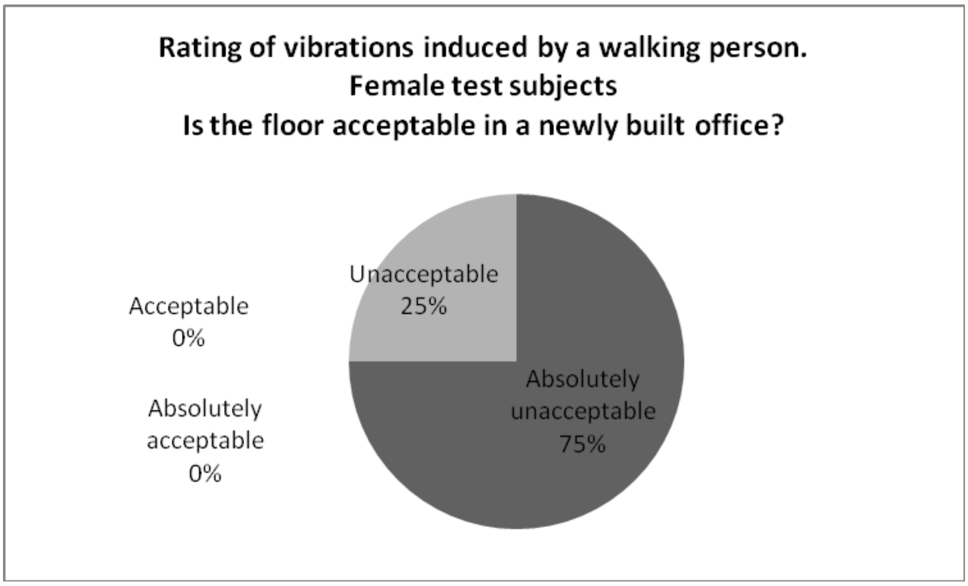
Before a concrete topping was cast

Female test persons





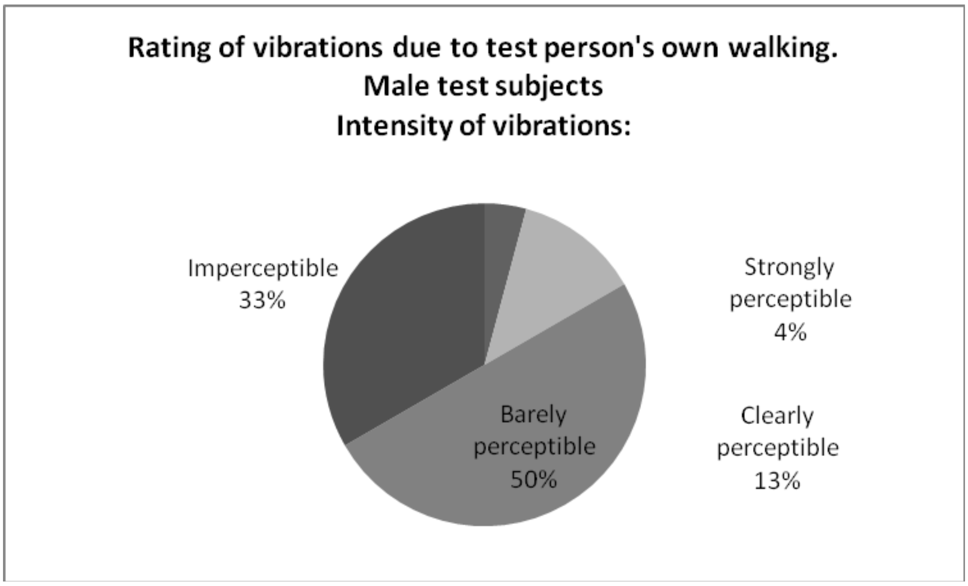


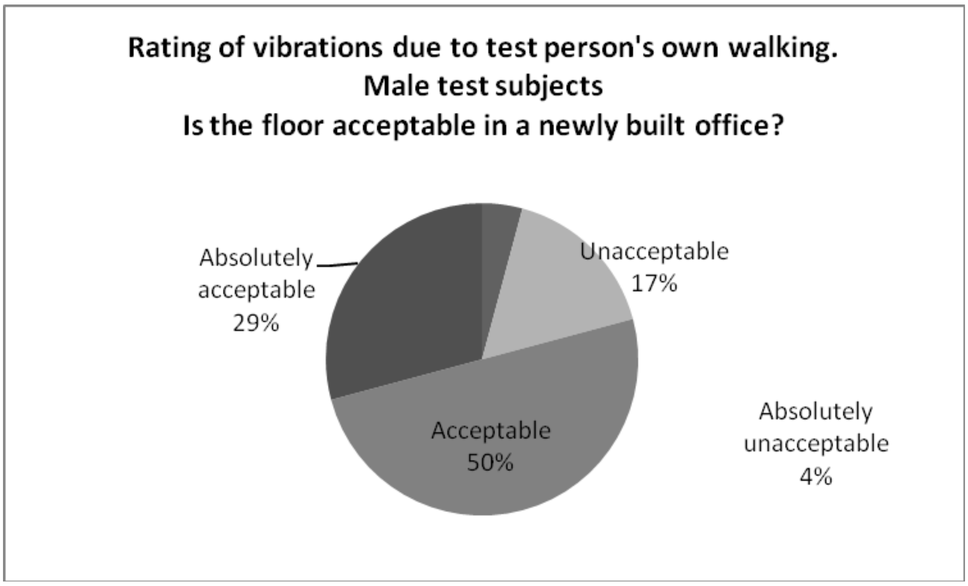


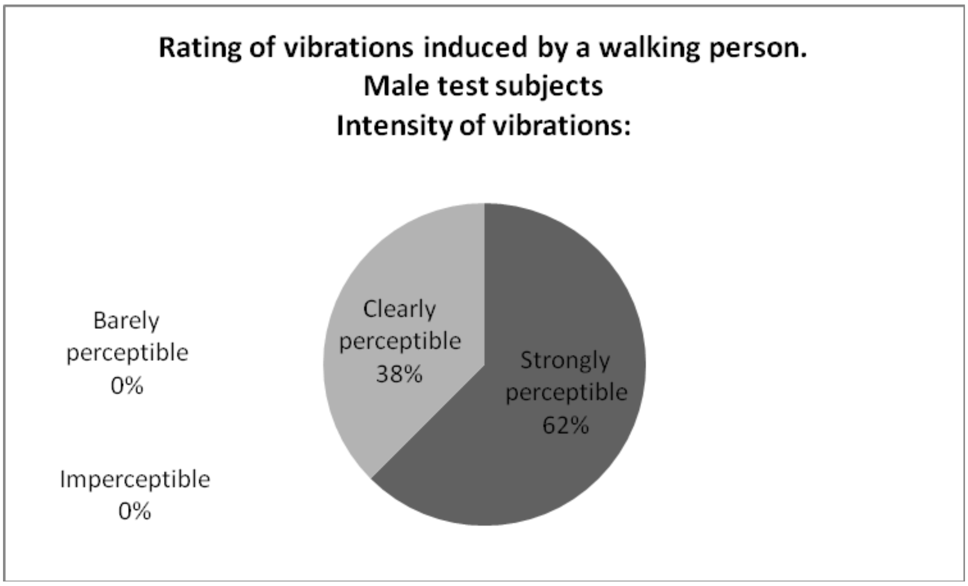
	Age [years]	Weight [kg]	Test 1	Test 2	Test 3
Mean value	23.8	63	7.4	1.4	1.9
Standard deviation	1.1	10.7	2.3	0.6	1.3

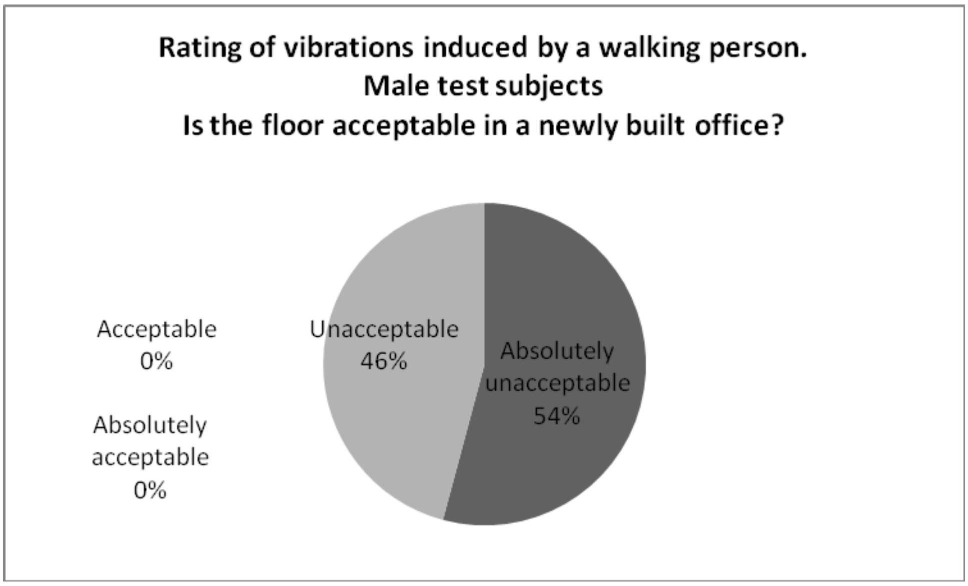
Table A2.1. Rating of the vibration performance of the floor.
Test 1: Vibrations due to test person's own walking. 1=very poor, 10=very good.
Test 2: Vibrations due to another person walking by. 1=very poor, 10=very good.
Test 3: Effect on working efficiency. 1=very much, 10=not at all.

Male test persons





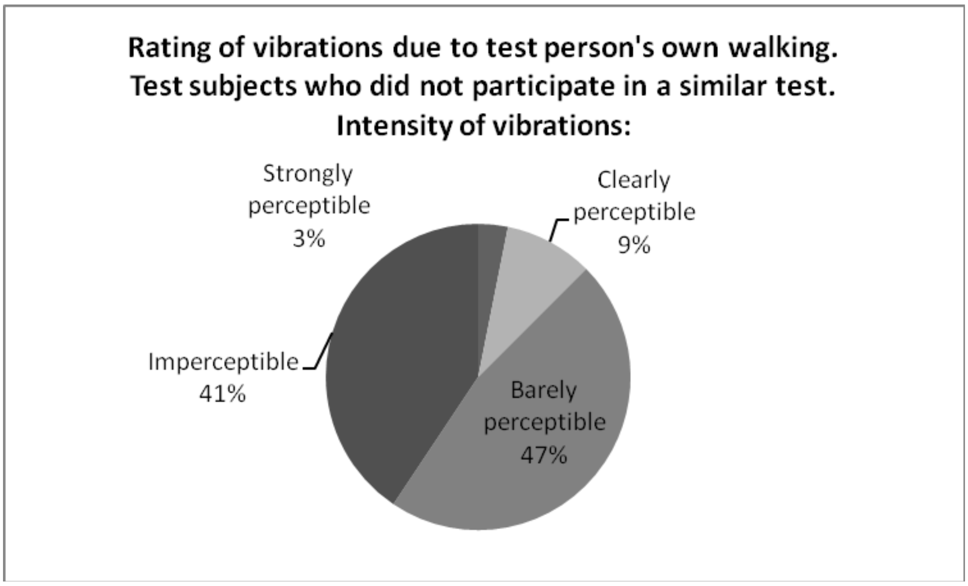


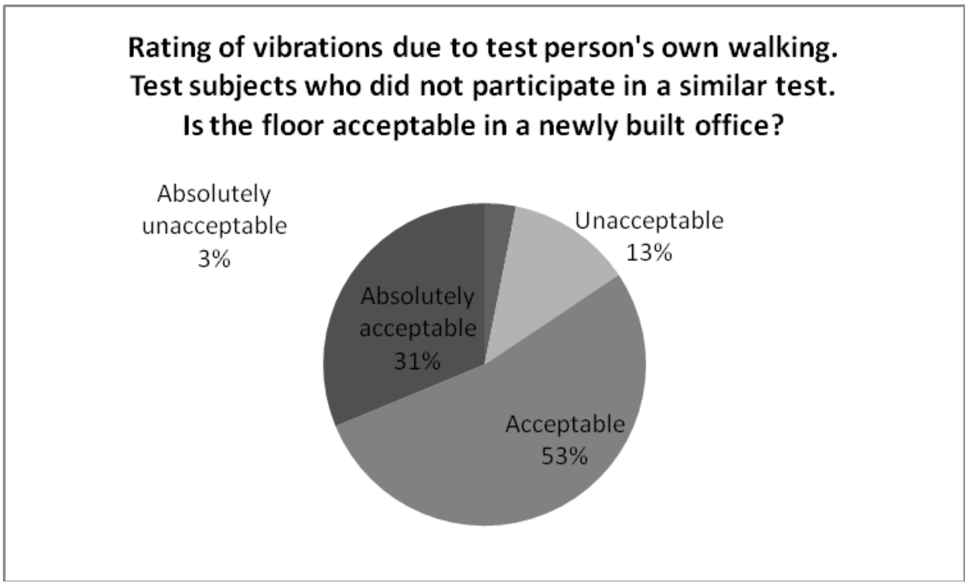


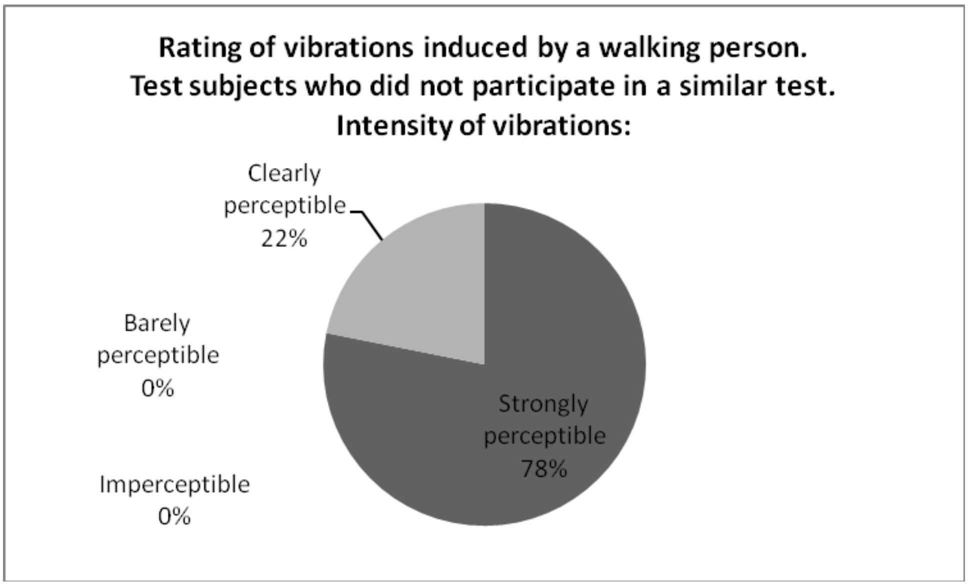
	Age [years]	Weight [kg]	Test 1	Test 2	Test 3
Mean value	28.3	79.8	7.0	2.2	2.8
Standard deviation	9.6	8.2	2.6	1.2	1.9

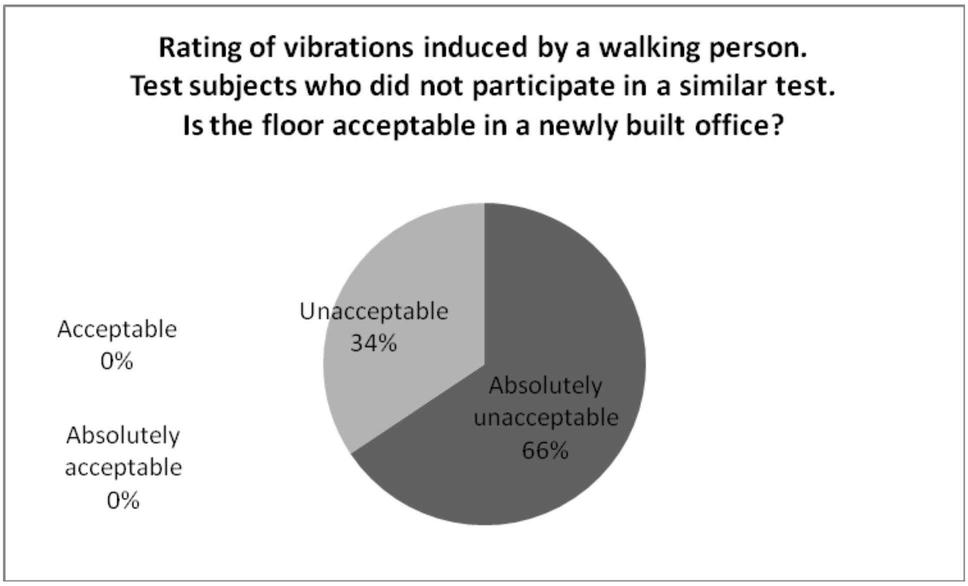
Table A2.2. Rating of the vibration performance of the floor.
Test 1: Vibrations due to test person's own walking. 1=very poor, 10=very good.
Test 2: Vibrations due to another person walking by. 1=very poor, 10=very good.
Test 3: Effect on working efficiency. 1=very much, 10=not at all.

Persons who had not participated in a similar test





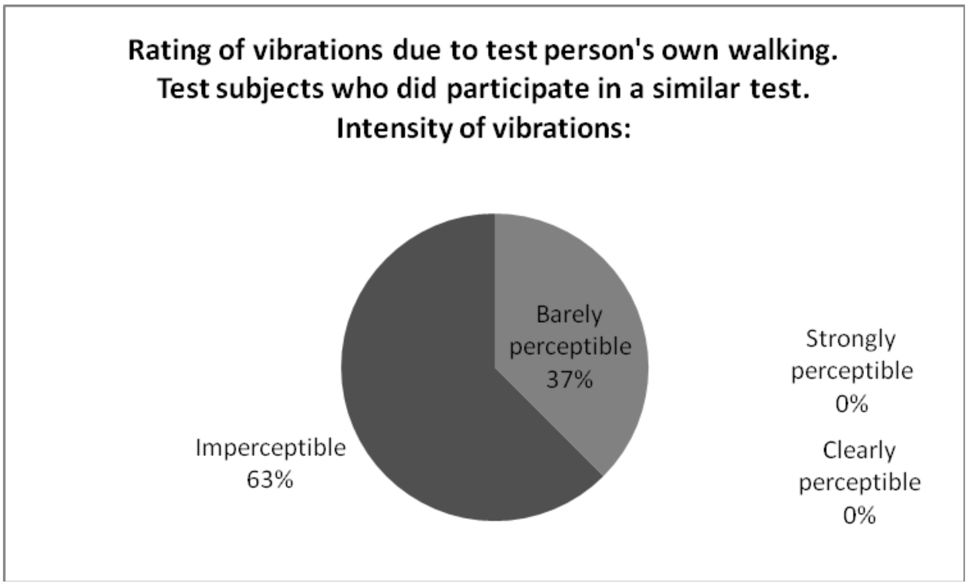


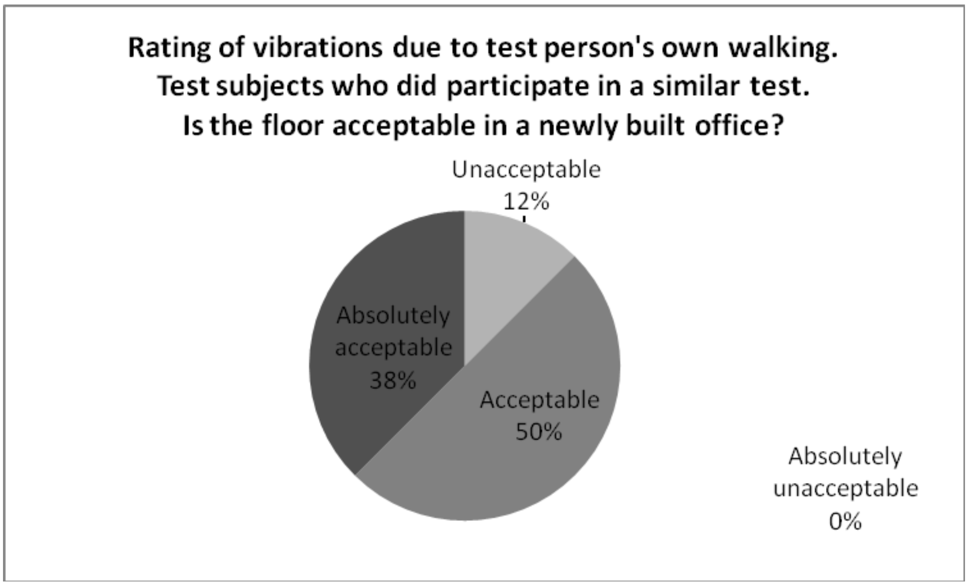


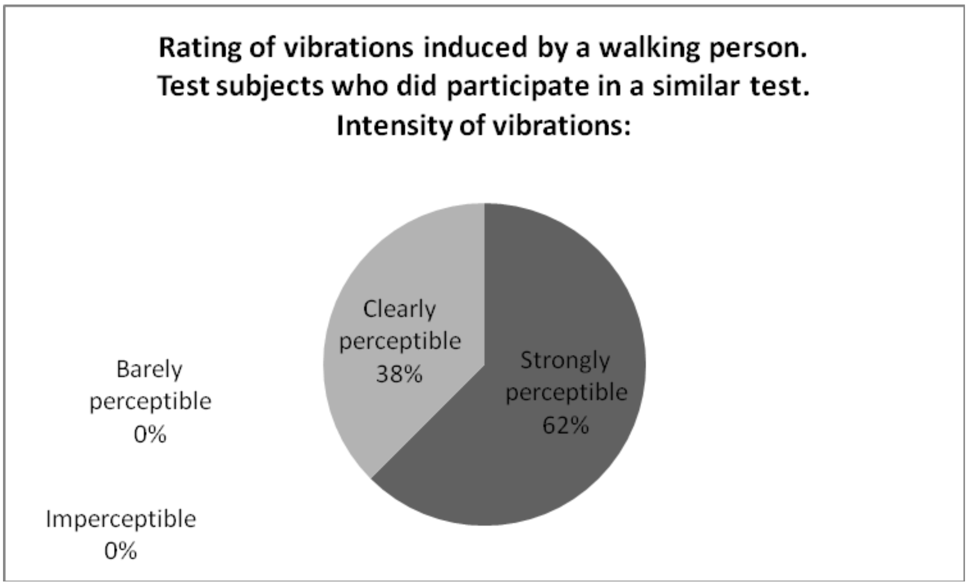
	Age [years]	Weight [kg]	Test 1	Test 2	Test 3
Mean value	25.8	74.0	7.0	1.9	2.4
Standard deviation	5.3	11.9	2.5	1.2	1.8

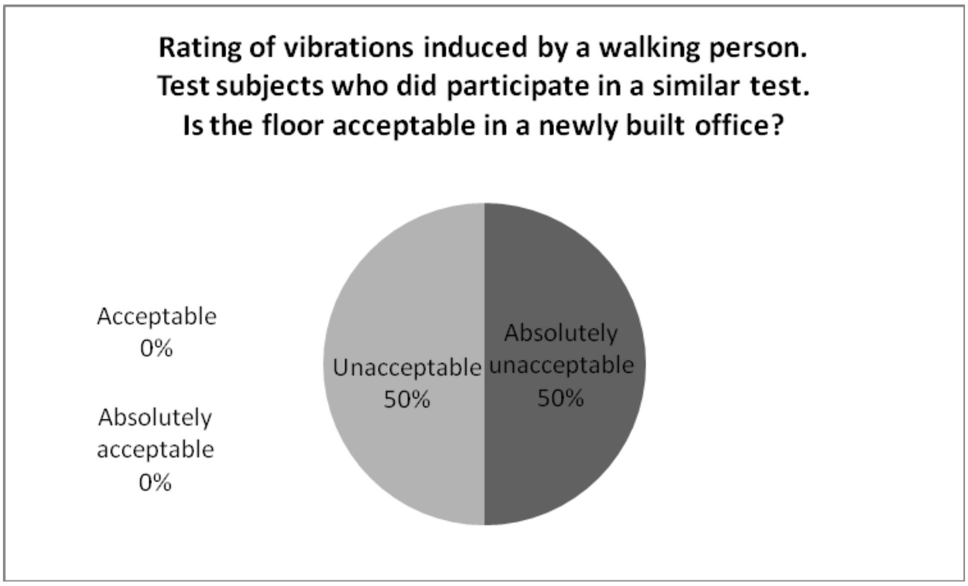
Table A2.3. Rating of the vibration performance of the floor.
Test 1: Vibrations due to test person's own walking. 1=very poor, 10=very good.
Test 2: Vibrations due to another person walking by. 1=very poor, 10=very good.
Test 3: Effect on working efficiency. 1=very much, 10=not at all.

Persons who had participated in a similar test







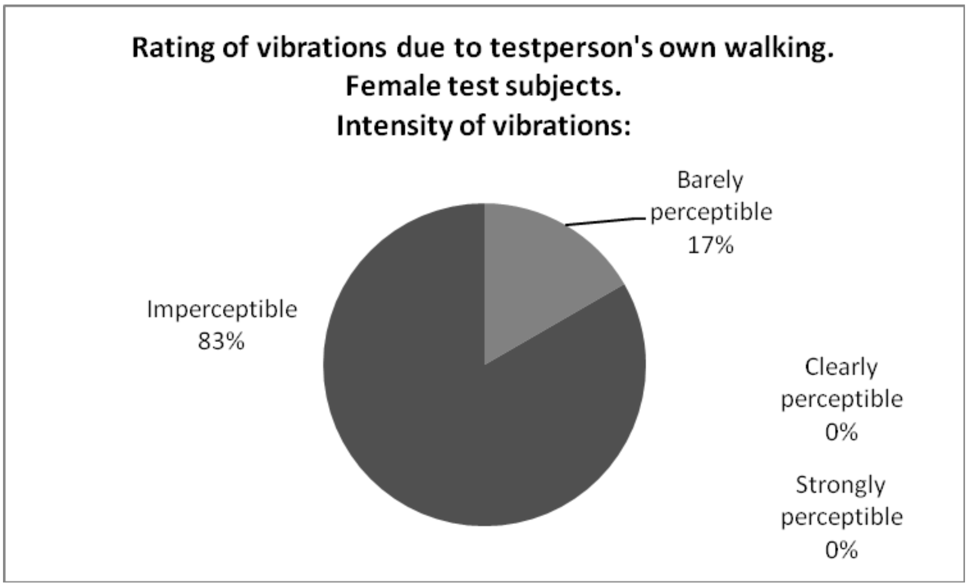


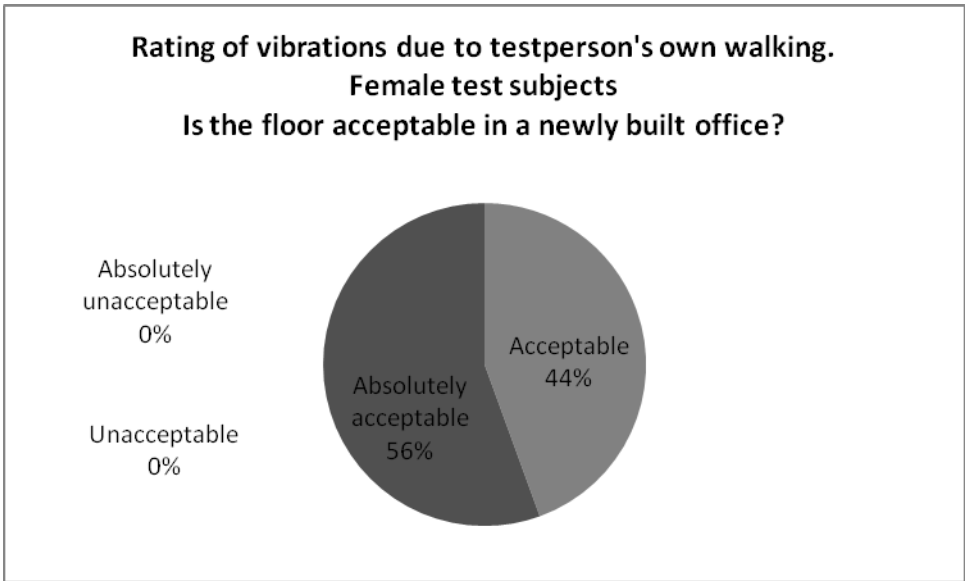
	Age [years]	Weight [kg]	Test 1	Test 2	Test 3
Mean value	29.4	69.5	8.1	1.9	2.5
Standard deviation	14.0	14.3	2.4	0.6	1.5

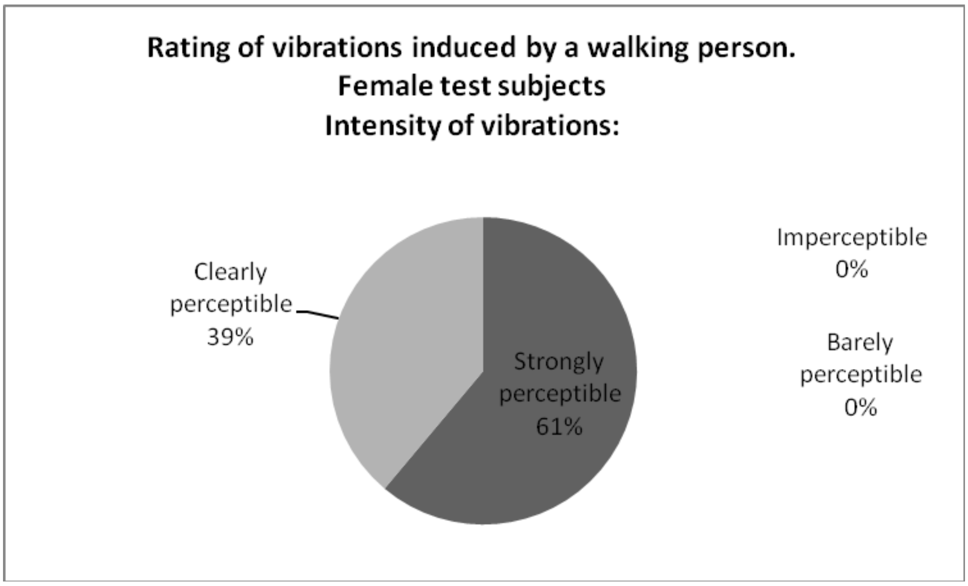
Table A2.4. Rating of the vibration performance of the floor.
Test 1: Vibrations due to test person’s own walking. 1=very poor, 10=very good.
Test 2: Vibrations due to another person walking by. 1=very poor, 10=very good.
Test 3: Effect on working efficiency. 1=very much, 10=not at all.

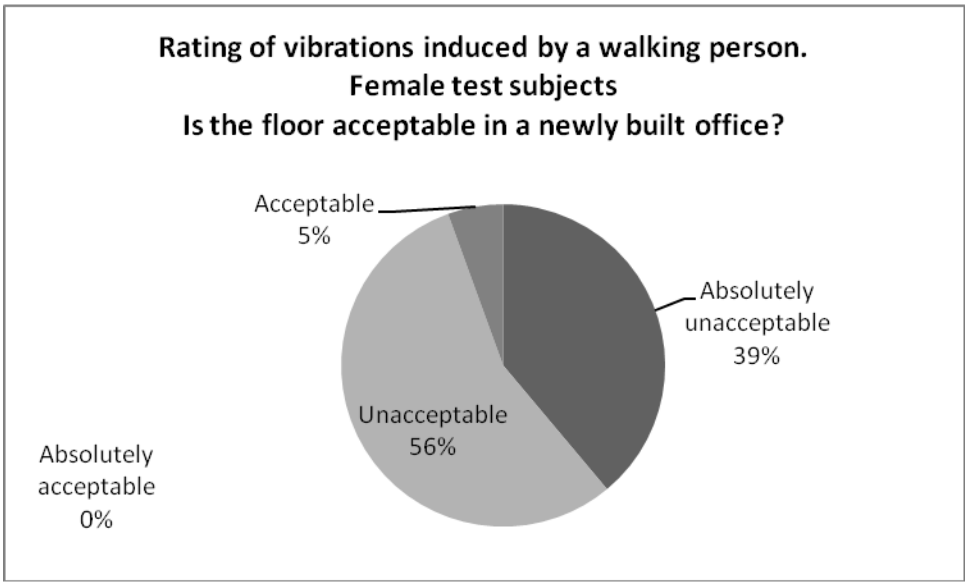
After a concrete topping was cast

Female test persons





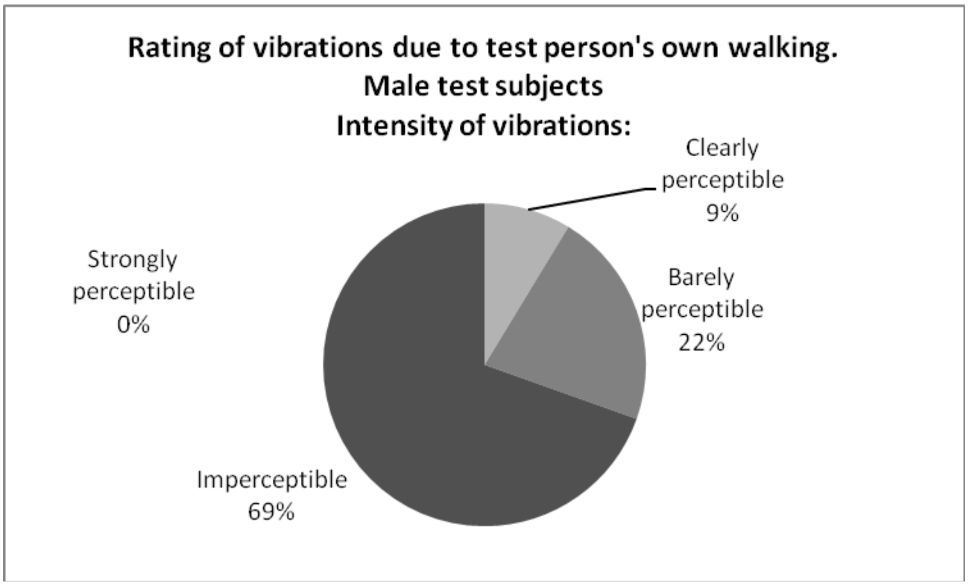


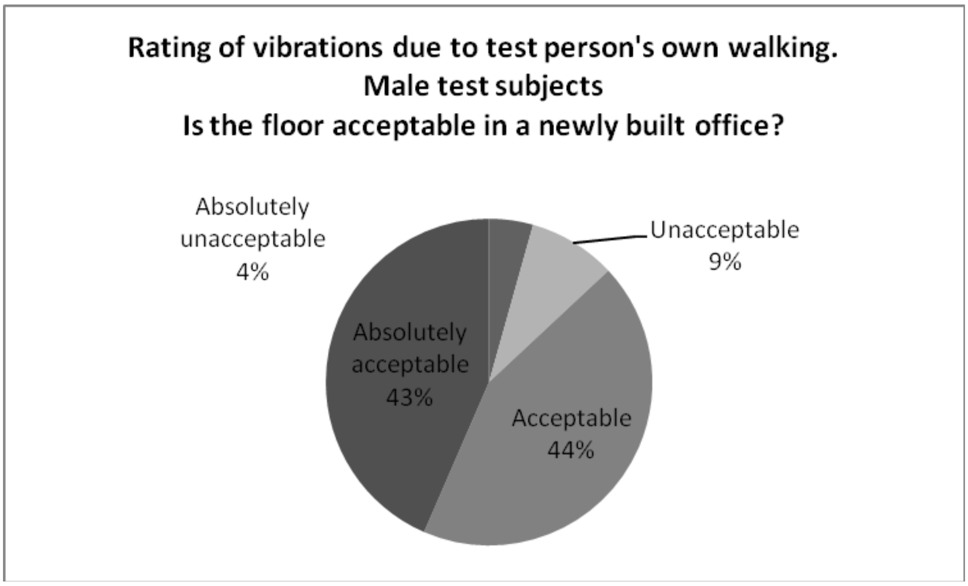


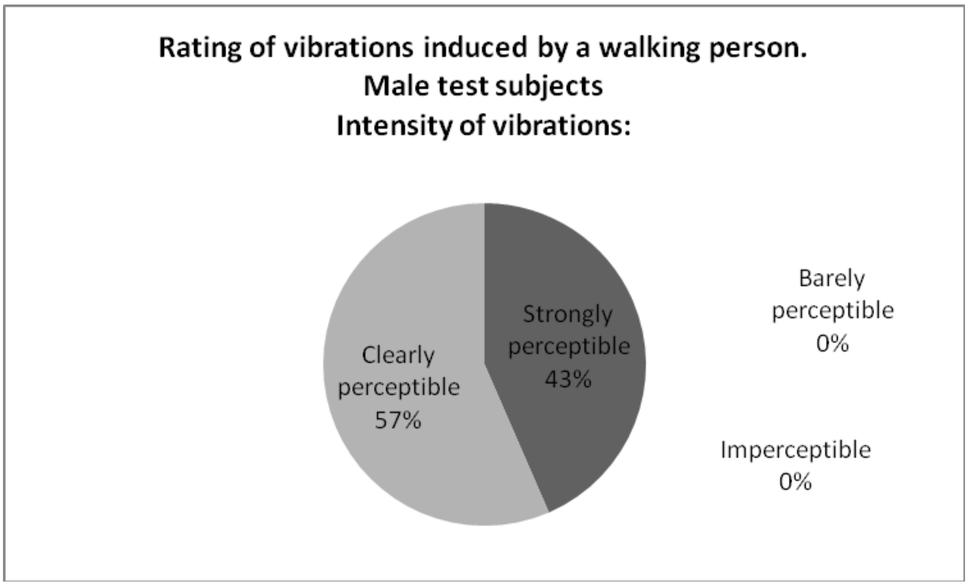
	Age [years]	Weight [kg]	Test 1	Test 2	Test 3
Mean value	29.7	62.6	8.9	2.3	2.8
Standard deviation	11.3	10.1	1.4	1.3	1.6

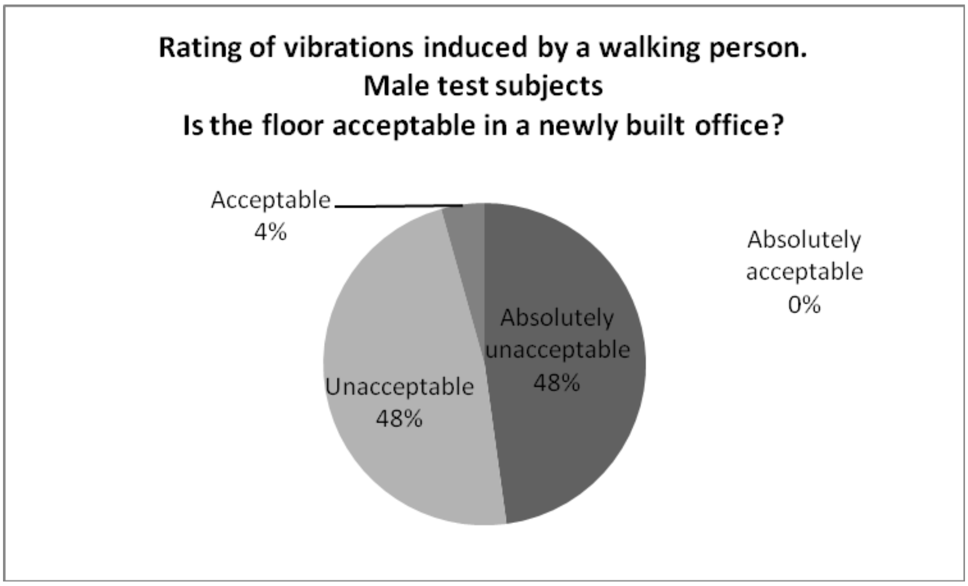
Table A2.5. Rating of the vibration performance of the floor.
Test 1: Vibrations due to test person's own walking. 1=very poor, 10=very good.
Test 2: Vibrations due to another person walking by. 1=very poor, 10=very good.
Test 3: Effect on working efficiency. 1=very much, 10=not at all.

Male test persons





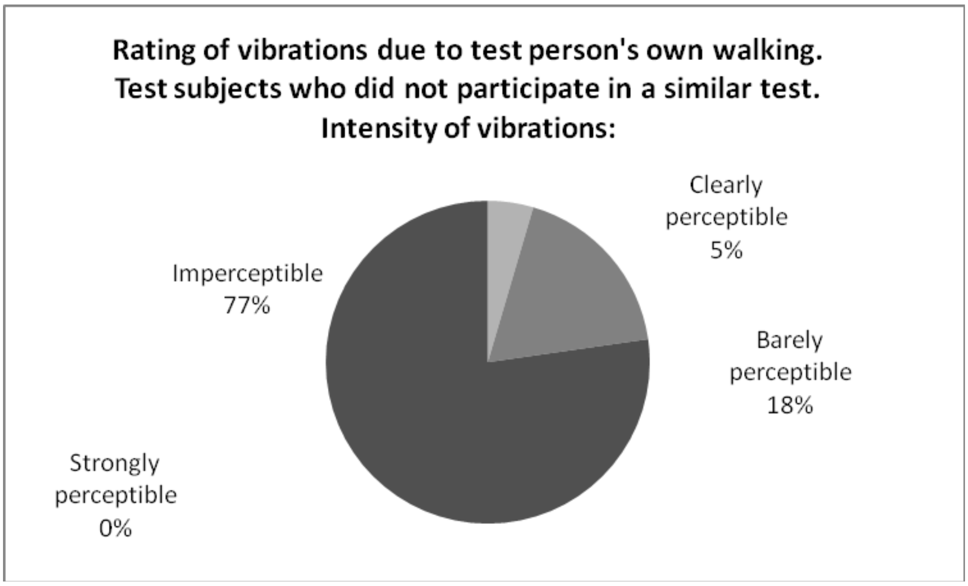


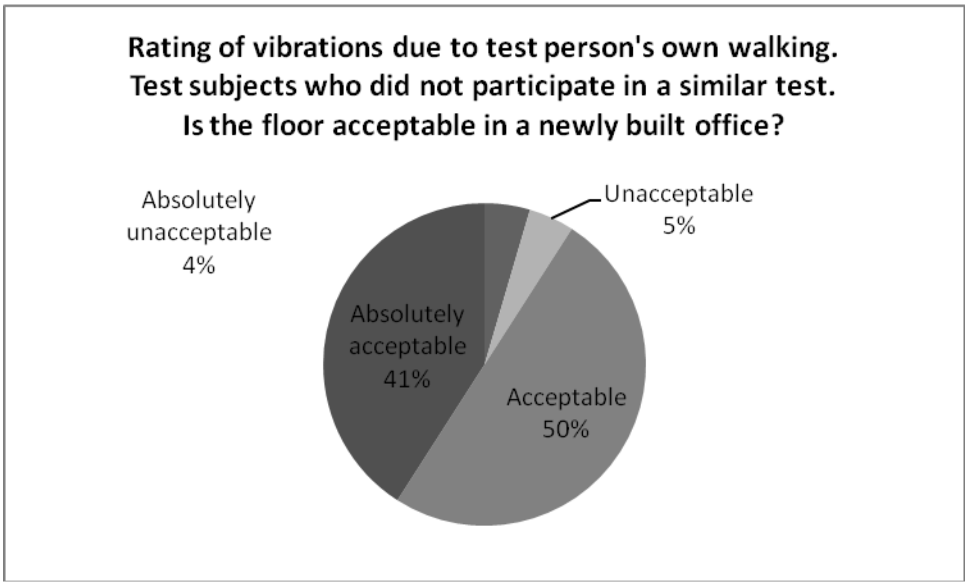


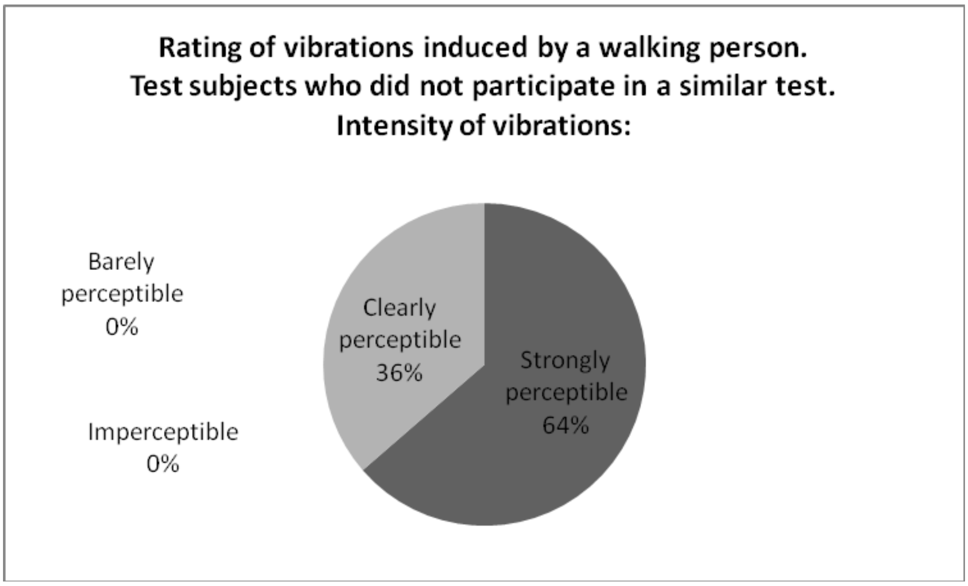
	Age [years]	Weight [kg]	Test 1	Test 2	Test 3
Mean value	33.3	83.6	8.1	2.7	2.7
Standard deviation	13.1	10.6	2.0	1.5	1.7

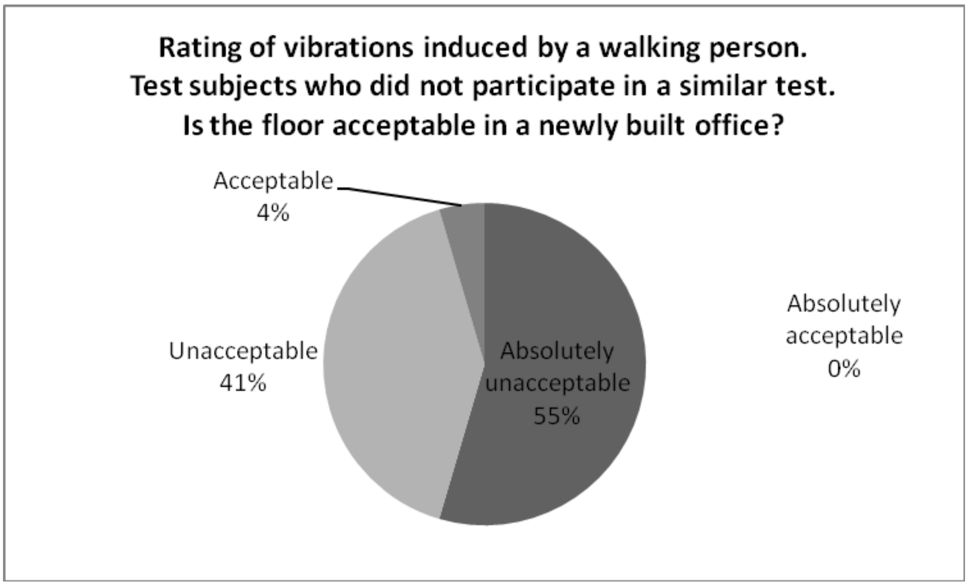
Table A2.6. Rating of the vibration performance of the floor.
Test 1: Vibrations due to test person's own walking. 1=very poor, 10=very good.
Test 2: Vibrations due to another person walking by. 1=very poor, 10=very good.
Test 3: Effect on working efficiency. 1=very much, 10=not at all.

Persons who had not participated in a similar test





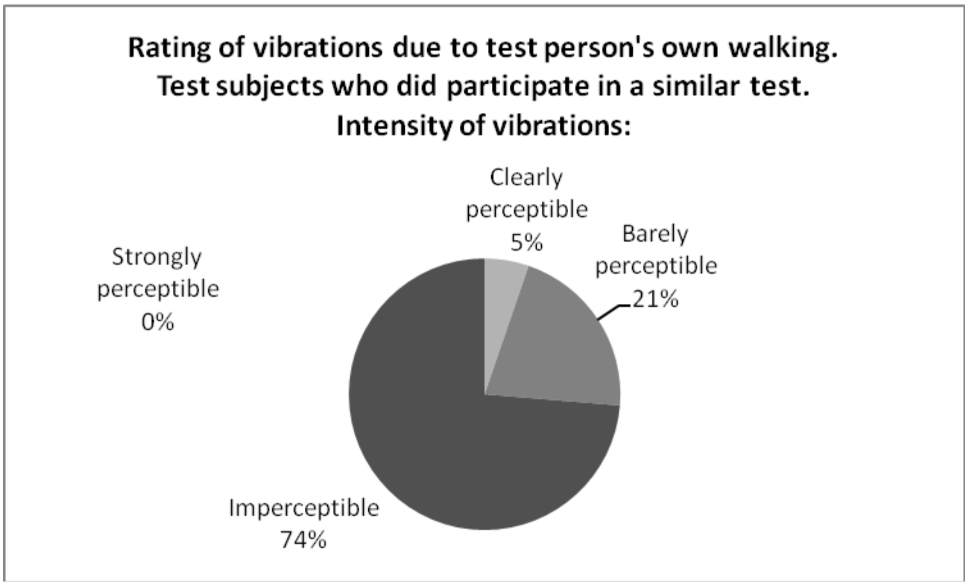


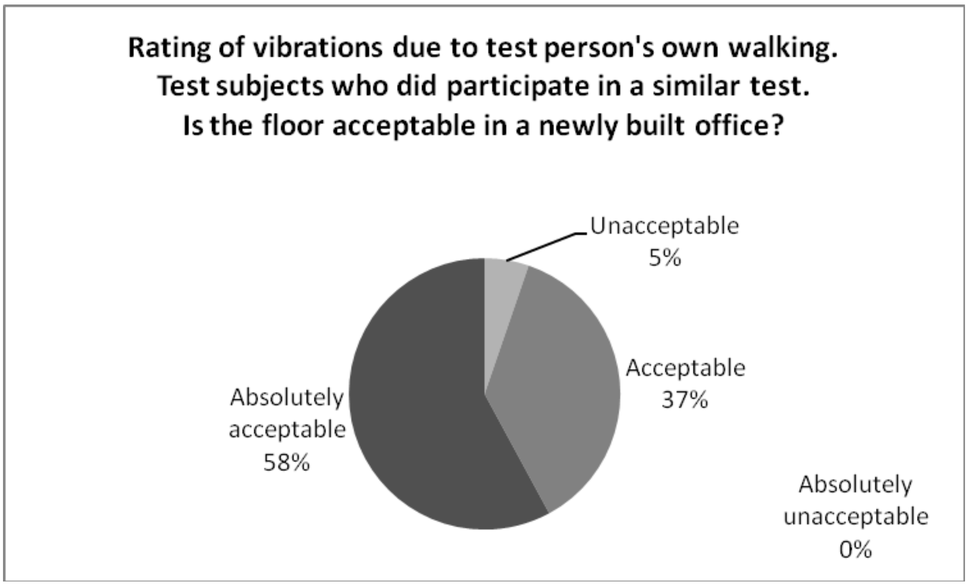


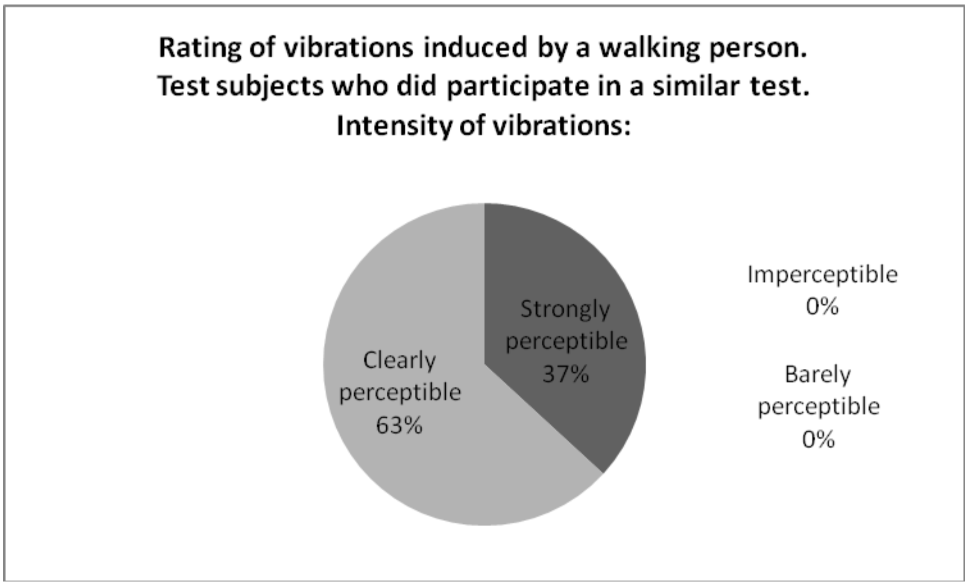
	Age [years]	Weight [kg]	Test 1	Test 2	Test 3
Mean value	32.6	71.7	8.0	2.3	2.5
Standard deviation	12.9	14.5	2.1	1.5	1.7

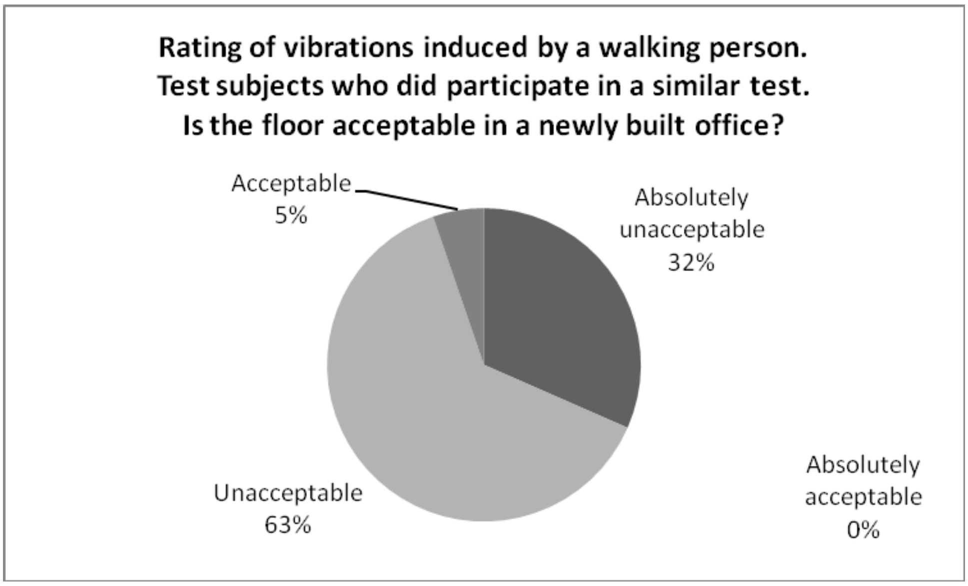
Table A2.7. Rating of the vibration performance of the floor.
Test 1: Vibrations due to test person's own walking. 1=very poor, 10=very good.
Test 2: Vibrations due to another person walking by. 1=very poor, 10=very good.
Test 3: Effect on working efficiency. 1=very much, 10=not at all.

Persons who had participated in a similar test









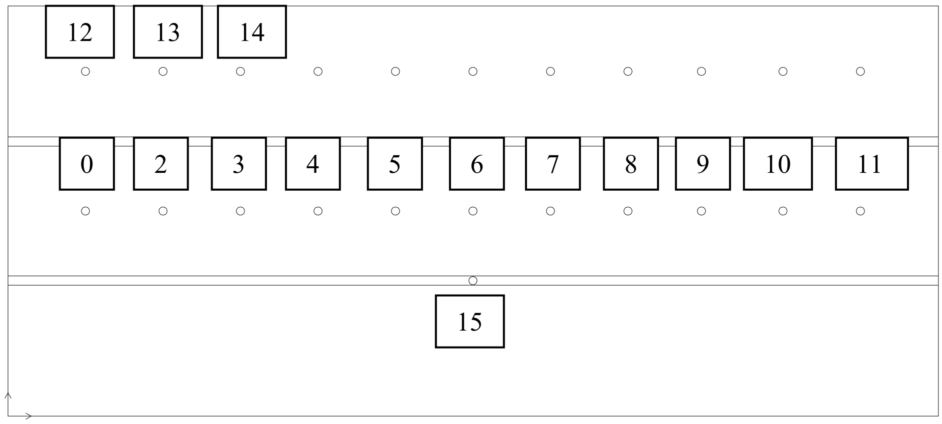
	Age [years]	Weight [kg]	Test 1	Test 2	Test 3
Mean value	30.7	77.4	8.9	2.7	3.0
Standard deviation	12.0	14.7	1.2	1.3	1.6

Table A2.8. Rating of the vibration performance of the floor.
Test 1: Vibrations due to test person's own walking. 1=very poor, 10=very good.
Test 2: Vibrations due to another person walking by. 1=very poor, 10=very good.
Test 3: Effect on working efficiency. 1=very much, 10=not at all.

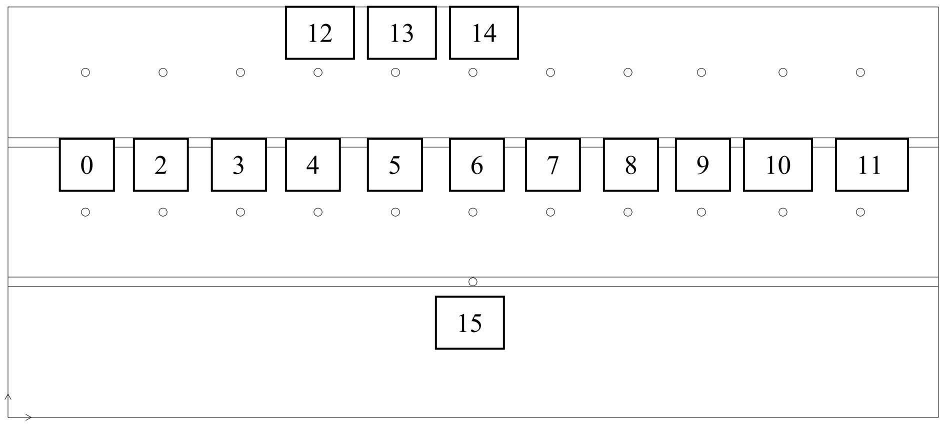
Appendix 3: Results from the measurements

Measurement set-ups

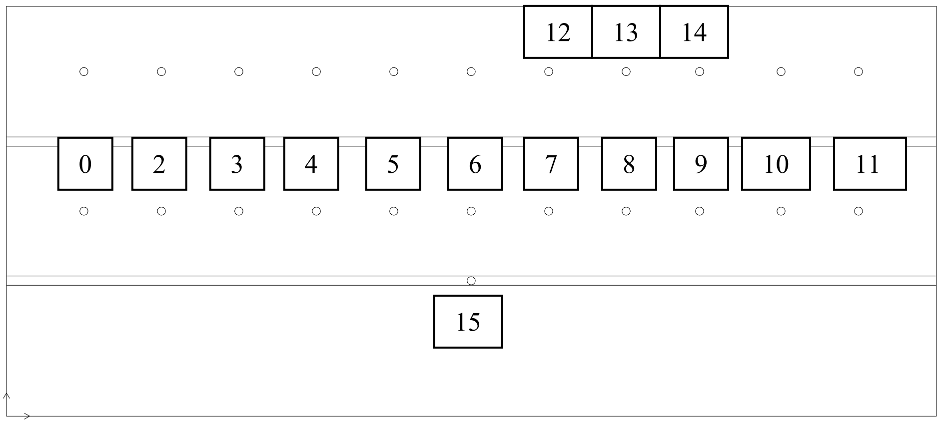
Set-up: a



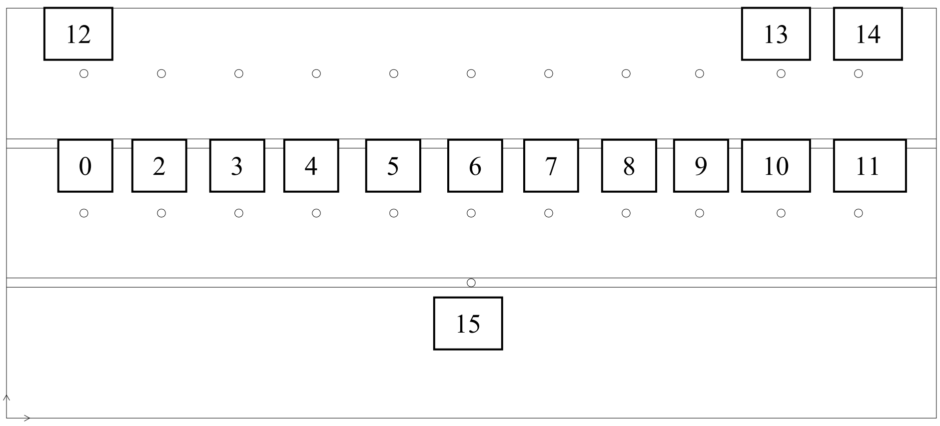
Set-up: b



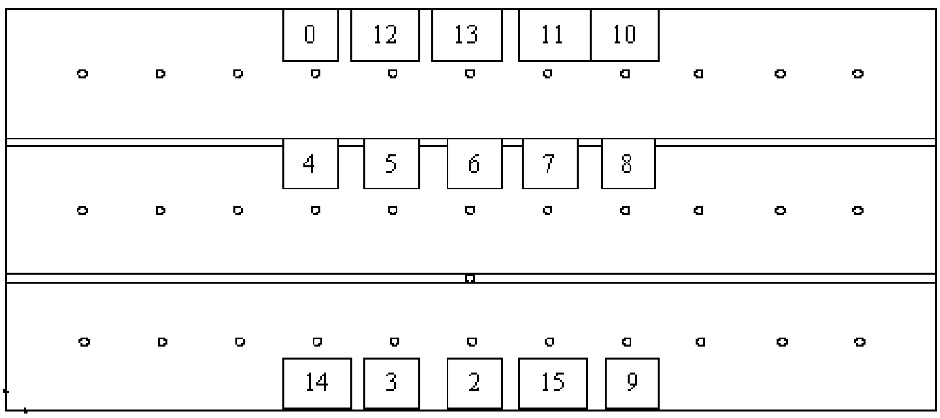
Set-up: c



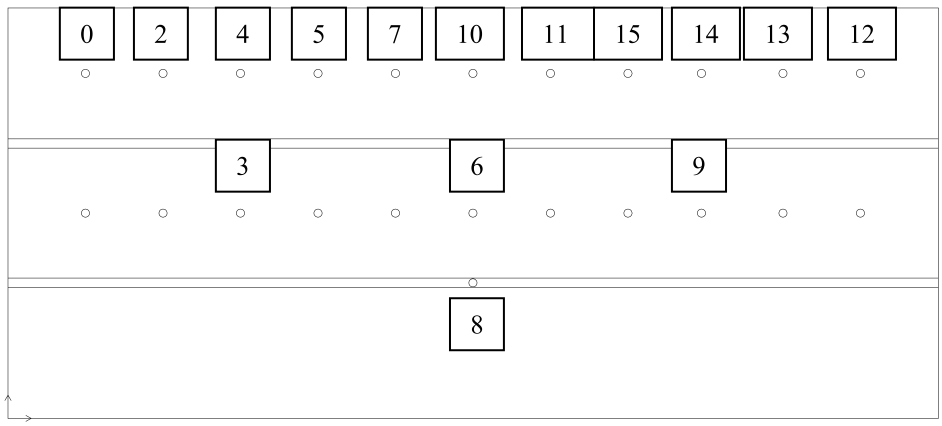
Set-up: d



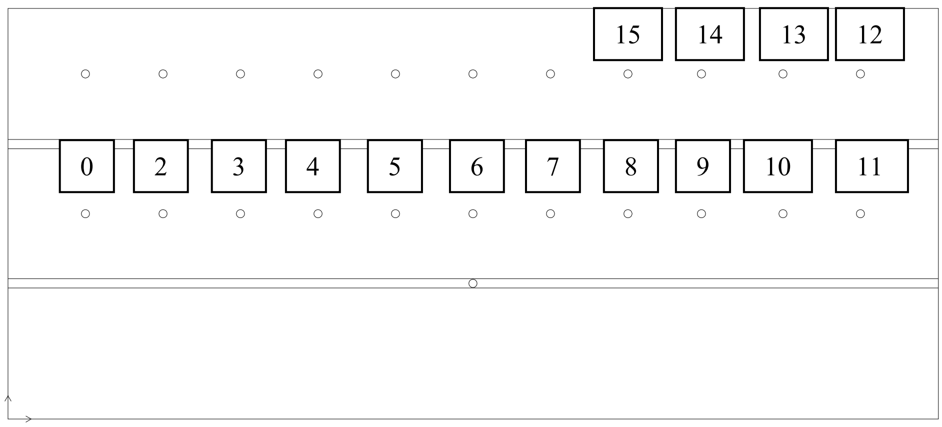
Set-up: e



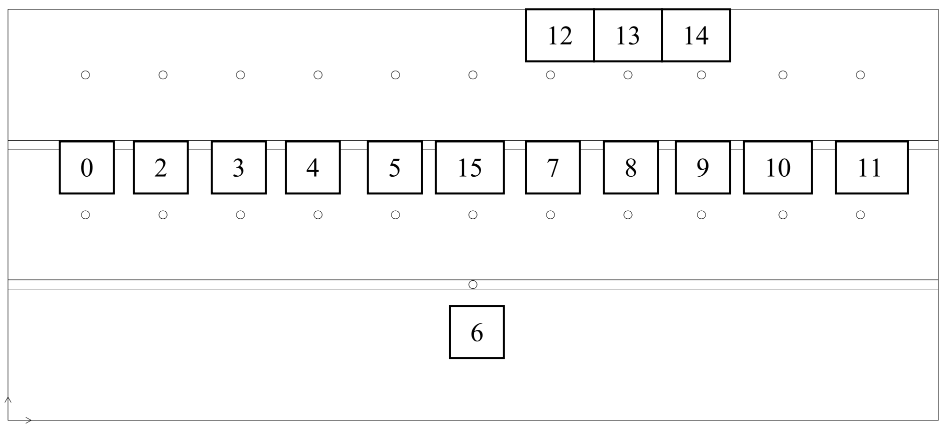
Set-up: f



Set-up: g



Set-up: h



Overall weighted acceleration [m/s^2], BEFORE a concrete topping was cast, averaging time: t=1s.

Acc. No:	**0**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Pia_Walk_1	0,0279	0,0156	0,0705	0,0829	0,063	0,0861	0,0566	0,0301
Pia_Walk_2	0,0186	0,0177	0,0584	0,04	0,0343	0,0607	0,0342	0,0337
Pia_Walk_3	0,0321	0,0137	0,0942	0,0397	0,059	0,0976	0,1021	0,0904
Pia_Walk_4	0,025	0,0187	0,0382	0,0249	0,0267	0,0937	0,1024	0,0665
Pia_Walk_5	0,0134	0,0159	0,07	0,0764	0,059	0,0859	0,0737	0,0505
Pia_Walk_6	0,1161	0,1446	0,1006	0,0479	0,1113	0,1593	0,1377	0,0933
Matteo_Walk	0,0074	0,0116	0,0331	0,0215	0,0137	0,0509	0,0157	0,0268
Vincent_Walk		0,0175	0,0789	0,0513	0,0566	0,1113	0,0693	0,0495

Acc. No:	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Pia_Walk_1	0,0424	0,0239	0,0225	0,0174	0,009	0,0716	0,0922
Pia_Walk_2	0,0357	0,0345	0,0155	0,0504	0,0639	0,0669	0,0363
Pia_Walk_3	0,0617	0,0188	0,0138	0,0992	0,097	0,0807	0,1045
Pia_Walk_4	0,0833	0,0299	0,0216	0,0122	0,018	0,0391	0,096
Pia_Walk_5	0,0699	0,0353	0,0173	0,0095	0,0454	0,0646	0,0935
Pia_Walk_6	0,1014	0,091	0,1005	0,1014	0,1175	0,1371	0,1656
Matteo_Walk	0,037	0,0146	0,0144	0,0111	0,0134	0,0121	0,048
Vincent_Walk	0,0646	0,0115	0,0283	0,0095	0,0164	0,0207	0,0885

	Averaging time (s)	**Set-up no.**	**Weight (kg)**	**Min**	**Max**	**Average**	**Under the chair**
Pia_Walk_1	1	a	60	0,009	0,0922	0,047447	0,0922
Pia_Walk_2	1	b	60	0,0155	0,0669	0,040053	0,0363
Pia_Walk_3	1	c	60	0,0137	0,1045	0,066967	0,1045
Pia_Walk_4	1	d	60	0,0122	0,1024	0,046413	0,096
Pia_Walk_5	1	a	60	0,0095	0,0935	0,05202	0,0935
Pia_Walk_6	1	e	60	0,0479	0,1656	0,11502	
Matteo_Walk	1	a	30	0,0074	0,0509	0,022087	0,048
Vincent_Walk	1	a	75	0,0095	0,1113	0,048136	0,0885

Overall weighted acceleration [m/s^2], BEFORE a concrete topping was cast, averaging time: t=10s.

Acc. No:	**0**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Pia_Walk_1	0,0019	0,0025	0,0041	0,0041	0,0034	0,0048	0,0045	0,004
Pia_Walk_4	0,0017	0,0022	0,0035	0,0034	0,0028	0,0039	0,0037	0,0034
Pia_Walk_5	0,0018	0,0029	0,0044	0,0043	0,0035	0,005	0,0047	0,0043
Vincent_Walk	0,0019	0,0026	0,004	0,0055	0,0032	0,0049	0,0042	0,0037

Acc. No:	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Pia_Walk_1	0,0035	0,0027	0,0023	0,0019	0,0027	0,0035	0,0048
Pia_Walk_4	0,003	0,0023	0,0019	0,0017	0,0024	0,0021	0,004
Pia_Walk_5	0,0037	0,0029	0,0022	0,0018	0,0029	0,0039	0,0048
Vincent_Walk	0,0034	0,0026	0,002	0,0016	0,0024	0,0034	0,0043

	Averaging time (s)	**Set-up no**	**Weight (kg)**	**Min**	**Max**	**Average**
Pia_Walk_1	10	a	60	0,0019	0,0048	0,00338
Pia_Walk_4	10	d	60	0,0017	0,004	0,0028
Pia_Walk_5	10	a	60	0,0018	0,005	0,00354
Vincent_Walk	10	a	75	0,0016	0,0055	0,003313

Overall weighted acceleration [m/s^2], AFTER a concrete topping was cast, averaging time: t=1s.

Acc. No:	**0**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
CT_Pia_1	0,0142	0,0114	0,0371	0,1223	0,0384	0,1945	0,0229	0,0418
CT_Jake_1a	0,0105	0,0133	0,01	0,0113	0,009	0,0104	0,0047	0,0107
CT_Jake_1b	0,0096	0,0161	0,0913	0,1515	0,1295	0,171	0,1559	0,1493
CT_Charlotte_1	0,0114	0,0117	0,0202	0,0916	0,0189	0,027	0,0886	0,0198
CT_Fredrik_2	0,0151	0,0355	0,0288	0,0317	0,0238	0,2697	0,074	0,046
CT_Charlotte_2	0,0086	0,0295	0,0302	0,0146	0,018	0,0486	0,0238	0,0266
CT_Jake_2a	0,0139	0,0234	0,0446	0,0461	0,0238	0,0784	0,0677	0,0405
CT_Jake_2b	0,0297	0,0297	0,0507	0,0676	0,0636	0,0835	0,1954	0,0593
CT_Pia_2	0,0087	0,0582	0,1099	0,0869	0,0846	0,0595	0,0767	0,1079
CT_Pia_3	0,0146	0,0101	0,0728	0,047	0,0671	0,0941	0,0895	0,0883
CT_Pia_4a	0,007	0,014	0,0332	0,0398	0,046	0,0583	0,0445	0,0501
CT_Pia_4b	0,016	0,0071	0,0297	0,0385	0,0506	0,0562	0,0378	0,0576
CT_Pia_5	0,0148	0,0302	0,0249	0,0317	0,0377	0,0689	0,0391	0,0263
CT_Pia_6	0,0161	0,0124	0,0284	0,0641	0,06	0,045	0,0214	0,0571

Acc. No:	**9**	**10**	**11**	**12**	**13**	**14**	**15**
CT_Pia_1	0,0296	0,0253	0,0179	0,0092	0,0133	0,0387	0,0502
CT_Jake_1a	0,0109	0,0081	0,0086	0,0086	0,0154	0,0105	0,0102
CT_Jake_1b	0,1229	0,0687	0,0497	0,0327	0,0796	0,1147	0,1446
CT_Charlotte_1	0,0274	0,0288	0,0179	0,0079	0,019	0,0216	0,0136
CT_Fredrik_2	0,2044	0,0729	0,0739	0,0066	0,0411	0,0403	0,021
CT_Charlotte_2	0,023	0,0312	0,1364	0,0054	0,0259	0,0336	0,0316
CT_Jake_2a	0,0565	0,0293	0,0498	0,0182	0,0193	0,0512	0,029
CT_Jake_2b	0,0655	0,3494	0,0645	0,0072	0,0285	0,0624	0,1035
CT_Pia_2	0,0555	0,1157	0,1241	0,0305	0,0653	0,0575	0,1112
CT_Pia_3	0,0751	0,0214	0,0163	0,0324	0,0399	0,0246	0,0908
CT_Pia_4a	0,0105	0,0184	0,0135	0,0298	0,0161	0,0339	0,0426
CT_Pia_4b	0,0309	0,0352	0,0378	0,0857	0,0633	0,0546	0,0554
CT_Pia_5	0,0478	0,0376	0,0161	0,0353	0,0316	0,0301	0,0515
CT_Pia_6	0,0448	0,0416	0,0297	0,0106	0,0577	0,041	0,0662

	Averaging time (s)	**Set-up no.**	**Weight (kg)**	**Min**	**Max**	**Average**	**Under the chair**
CT_Pia_1	1	g	60	0,0092	0,1945	0,044453	
CT_Jake_1a	1	g	80	0,0047	0,0154	0,010147	
CT_Jake_1b	1	g	80	0,0096	0,171	0,09914	
CT_Charlotte_1	1	g	50	0,0079	0,0916	0,02836	
CT_Fredrik_2	1	f	>90	0,0066	0,2697	0,065653	0,046
CT_Charlotte_2	1	f	50	0,0054	0,1364	0,032467	0,0266
CT_Jake_2a	1	f	80	0,0139	0,0784	0,039447	0,0405
CT_Jake_2b	1	f	80	0,0072	0,3494	0,084033	0,0593
CT_Pia_2	1	f	60	0,0087	0,1241	0,076813	0,1079
CT_Pia_3	1	a	60	0,0101	0,0941	0,052267	0,0908
CT_Pia_4a	1	b	60	0,007	0,0583	0,030513	0,0426
CT_Pia_4b	1	b	60	0,0071	0,0857	0,04376	0,0554
CT_Pia_5	1	c	60	0,0148	0,0689	0,034907	0,0515
CT_Pia_6	1	h	60	0,0106	0,0662	0,03974	0,045

Overall weighted acceleration [m/s^2], AFTER a concrete topping was cast, averaging time: t=10s.

Acc. no:	0	2	3	4	5	6	7	8
CT_Charlotte_1	0,0012	0,0014	0,0020	0,0066	0,0023	0,0023	0,0024	0,0020
CT_Charlotte_2	0,0015	0,0015	0,0020	0,0020	0,0023	0,0030	0,0025	0,0026
CT_Fredrik_2	0,0019	0,0024	0,0035	0,0032	0,0039	0,0045	0,0041	0,0042
CT_Jake_1_a	0,0019	0,0028	0,0036	0,0042	0,0046	0,0049	0,0047	0,0044
CT_Jake_1_b	0,0031	0,0046	0,0061	0,0075	0,0079	0,0088	0,0083	0,0075
CT_Jake_2_a	0,0021	0,0025	0,0036	0,0036	0,0041	0,0048	0,0045	0,0046
CT_Pia_1	0,0023	0,0030	0,0028	0,0039	0,0027	0,0032	0,0036	0,0030
CT_Pia_2	0,0016	0,0023	0,0032	0,0033	0,0036	0,0043	0,0041	0,0041

Acc. no:	9	10	11	12	13	14	15
CT_Charlotte_1	0,0018	0,0018	0,0015	0,0014	0,0015	0,0018	0,0024
CT_Charlotte_2	0,0020	0,0025	0,0024	0,0014	0,0019	0,0021	0,0022
CT_Fredrik_2	0,0034	0,0044	0,0043	0,0018	0,0026	0,0034	0,0042
CT_Jake_1_a	0,0038	0,0029	0,0021	0,0021	0,0031	0,0038	0,0045
CT_Jake_1_b	0,0063	0,0048	0,0033	0,0033	0,0050	0,0063	0,0078
CT_Jake_2_a	0,0036	0,0048	0,0047	0,0020	0,0029	0,0037	0,0044
CT_Pia_1	0,0027	0,0029	0,0027	0,0028	0,0029	0,0028	0,0033
CT_Pia_2	0,0032	0,0042	0,0042	0,0019	0,0027	0,0033	0,0038

Acc. no:	Averaging time (s)	Set-up	Weight (kg)	Min	Max	Average	Under the chair
CT_Charlotte_1	10	g	50	0,0012	0,0066	0,0022	
CT_Charlotte_2	10	f	50	0,0014	0,0030	0,0021	0,0026
CT_Fredrik_2	10	f	<90	0,0018	0,0045	0,0035	0,0042
CT_Jake_1_a	10	g	80	0,0019	0,0049	0,0036	
CT_Jake_1_b	10	g	80	0,0031	0,0088	0,0060	
CT_Jake_2_a	10	f	80	0,0020	0,0048	0,0037	0,0046
CT_Pia_1	10	g	60	0,0023	0,0039	0,0030	
CT_Pia_2	10	f	60	0,0016	0,0043	0,0033	0,0041

Comparison of overall weighted values before and after a concrete topping was cast

	Set-up	Acc. No:	0	2	3	4	5	6	7
Pia_Walk_1	a	Before	0,0279	0,0156	0,0705	0,0829	0,063	0,0861	0,0566
CT_Pia_3	a	After	0,0146	0,0101	0,0728	0,047	0,0671	0,0941	0,0895
Pia_Walk_2	b	Before	0,0186	0,0177	0,0584	0,04	0,0343	0,0607	0,0342
CT_Pia_4a	b	After	0,007	0,014	0,0332	0,0398	0,046	0,0583	0,0445
CT_Pia_4b	b	After	0,016	0,0071	0,0297	0,0385	0,0506	0,0562	0,0378
Pia_Walk_3	c	Before	0,0321	0,0137	0,0942	0,0397	0,059	0,0976	0,1021
CT_Pia_5	c	After	0,0148	0,0302	0,0249	0,0317	0,0377	0,0689	0,0391

	Set-up	8	9	10	11	12	13	14	15
Pia_Walk_1	a	0,0301	0,0424	0,0239	0,0225	0,0174	0,009	0,0716	0,0922
CT_Pia_3	a	0,0883	0,0751	0,0214	0,0163	0,0324	0,0399	0,0246	0,0908
Pia_Walk_2	b	0,0337	0,0357	0,0345	0,0155	0,0504	0,0639	0,0669	0,0363
CT_Pia_4a	b	0,0501	0,0105	0,0184	0,0135	0,0298	0,0161	0,0339	0,0426
CT_Pia_4b	b	0,0576	0,0309	0,0352	0,0378	0,0857	0,0633	0,0546	0,0554
Pia_Walk_3	c	0,0904	0,0617	0,0188	0,0138	0,0992	0,097	0,0807	0,1045
CT_Pia_5	c	0,0263	0,0478	0,0376	0,0161	0,0353	0,0316	0,0301	0,0515

	Set-up		Averaging Time (s)	Weight (kg)	Min	Max	Average	Under the chair
Pia_Walk_1	a	Before	1	60	0,009	0,0922	0,0474	0,0922
CT_Pia_3	a	After	1	60	0,0101	0,0941	0,0523	0,0908
Pia_Walk_2	b	Before	1	60	0,0155	0,0669	0,0401	0,0363
CT_Pia_4a	b	After	1	60	0,007	0,0583	0,0305	0,0426
CT_Pia_4b	b	After	1	60	0,0071	0,0857	0,0438	0,0554
Pia_Walk_3	c	Before	1	60	0,0137	0,1045	0,067	0,1045
CT_Pia_5	c	After	1	60	0,0148	0,0689	0,0349	0,0515

If an average is calculated from the maximum overall weighted values and the overall weighted values measured at the location of the chair, for all measurements of vibrations induced by the same walker as in the subjective tests, the following results are obtained:

Before a concrete topping was cast

Pia_Walk:	Average value
T=1s	
Max=	0,1042
Under the chair=	0,0845

After a concrete topping was cast

Pia_Walk:	Average value
T=1s	
Max=	0,0988
Under the chair=	0,0655

Appendix 4: Matlab code for frequency weighting according to ISO 2631-2:2003, and calculation of overall weighted values of acceleration

```
clc
fs=9500;

%Mechanical Vibration and Shock Evaluation of Human Exposure to
Whole-Body Vibration (ISO 2631-2)
fISO1=10^(-0.1);        wISO1=2*pi * fISO1;
fISO2=100;              wISO2=2*pi * fISO2;
fISO3=1/(0.028*2*pi);   wISO3=2*pi * fISO3;


%Chose one of the following frequency distributions
%Octave Band Distribution:
%FrequencyDistribution = [1 2 4 8 16 31.5 63 125 250 500 1000
2000 4000 8000];

%Third Octave Band Distribution (approximation):
%FrequencyDistribution = [1 1.25 1.6 2 2.5 3.15 4 5 6.3 8];

%Third Octave Band Distribution (exact definition):
FrequencyDistribution = [1 10^0.1 10^0.2 10^0.3 10^0.4 10^0.5
10^0.6 10^0.7 10^0.8 10^0.9];

SizeArray = size(FrequencyDistribution)
FrequencyCount  = SizeArray(2);
MagnitudeOrders = 2;

%ButtOrder=1; %1st order Butterworth filter
ButtOrder=2; %2nd order Butterworth filter

%Open the data file
[filename, pathname] = uigetfile('*.csv', 'Pick a CSV-file');
    if isequal(filename,0)|isequal(pathname,0)
       disp('File not found')
    else
       disp(['File ', pathname, filename, ' found'])
   end
   cd(pathname)

%Load the data file
FileData = csvread (filename, 1, 1);
%Use the 2nd column (index=1) into "Acc"
Acc = FileData (:,1);

[m,n] = size(Acc);
nfft = pow2(nextpow2(m)-1);
dF = fs/nfft;
```

```
dt = 1/fs;

%AccMean=Mean(M)
%Speed = dt*cumtrapz(M-AccMean);

Speed = dt*cumtrapz(Acc);
SpeedMean = mean(Speed);
Speed=Speed-SpeedMean;

%figure
%plot(Speed)

% Power Spectrum Density calculation
[PsAcc,F] = pwelch(Acc,nfft,nfft/2,nfft,fs,'onesided');
UAcc = sqrt(PsAcc);

[PsSpeed,F] = pwelch(Acc,nfft,nfft/2,nfft,fs,'onesided');
USpeed = sqrt(PsSpeed);

%FreqSpeed = cumtrapz (F,Ps);
%figure
%plot(FreqSpeed)

%break

%UAccLog   = 10*log10(abs(UAcc  /0.000002));
%USpeedLog = 10*log10(abs(USpeed/(5*10^-8)));

%UAccLog   = 10*log10(abs(UAcc));
%USpeedLog = 10*log10(abs(USpeed));

UAccLog   = (abs(UAcc));
USpeedLog = (abs(USpeed));

%figure
%semilogx(F,10*log10(abs(UAcc/0.000002)+eps));
%xlabel('Frequency(Hz)')
%ylabel('Lp (dB)')

%        xxx = [-10 0 10]
%        yyy = heaviside(xxx+15)
%        zzz = (xxx+15).* xxx

%Test = [1 2 3 4 5]
%Test2 = Test * Test'

%break

% mult is initialized to 1 and multiplied by 10 at each loop
step
mult=1;
for j=(0:MagnitudeOrders-1)
```

```
    for i=1:FrequencyCount
        %Normalized frequency:
        WnCenter=FrequencyDistribution(i)*mult
        Wn1=0.707*WnCenter;
        Wn2=1.414*WnCenter;
        Wn = [Wn1 Wn2];

        [Hh, Hl, Ht] = Butterworth2(WnCenter, fISO1, fISO2,
fISO3);
        Weight = Hh*Hl*Ht


%         Step = heaviside((F-1000)) %.* heaviside(-(F-Wn2))
        Step = heaviside((F-Wn1)) .* heaviside(-(F-Wn2));
        yy = UAcc .* Step;

        StepCount = Step' * Step;                  %


        if StepCount==0              % If StepCount=0, we set
it to 1, in order to avoid a division by 0
            RSSAcc   (j*10 + i) = NaN;
            RSSSpeed (j*10 + i) = NaN;
        else
            Delta = dF/StepCount;

    %        SumPSD    = Step' * U     * dF/StepCount;  %
%            SumPSD    = Step' * UAccLog     * Delta +
10*log10(Weight);  %
            SumPSD    = Step' * UAcc     * Delta * (Weight);  %
            RSSAcc   (j*10 + i) = SumPSD;

%            SumPSD    = Step' * USpeedLog   * Delta +
10*log10(Weight);  %
            SumPSD    = Step' * USpeed   * Delta * (Weight);  %
            RSSSpeed (j*10 + i) = SumPSD;
        end;
        FThirdOctave (j*10 + i) = WnCenter;

        if StepCount==0              % If StepCount=0, we set
it to 1, in order to avoid a division by 0
            Delta = 0;
        else
            Delta = dF/StepCount;
        end;


    end

    % jump to the next decade
    mult=mult*10;
end
```

```
%          figure
%          [xb, yb] = stairs (FThirdOctave,RSSAcc);
%          semilogx (xb, yb)
%          xlabel('Frequency (Hz)');
%          ylabel('Acceleration (m.s^{-2})');

%         figure
%         [xb, yb] = stairs (FThirdOctave,RSSSpeed);
%         semilogx (xb, yb)
%         xlabel('Frequency (Hz)');
%         ylabel('Speed (m.s^{-1})');

%ResultData = xb
%ResultData (:,2) = yb

%ResultData = FThirdOctave
%ResultData (:,2) = RSS

ResultData = [FThirdOctave' RSSAcc' RSSSpeed'];

Resultfilename = strrep (filename, '.csv', '_results.csv');
csvwrite (Resultfilename, ResultData);

% Overall weighted acceleration

RSSAcc2=RSSAcc.^2
RSSAccSum=0;

SizeOfRSSAcc2 = size(RSSAcc2);
CountOfRSSAcc2 = SizeOfRSSAcc2(2);
for j=(1:CountOfRSSAcc2)
    if (isnan (RSSAcc2(j))==0)
        RSSAccSum   = RSSAccSum+RSSAcc2(j)
    end
end

RSSAccSum
aw=sqrt(RSSAccSum)
%aw=sqrt(sum(RSSAcc2))

function [Hh, Hl, Ht] = Butterworth2 (f, f1, f2, f3)

%Defining 2nd order Butterworth filters

F2  = f ^2;
F4  = f ^4;
F14 = f1^4;
F24 = f2^4;
F32 = f3^2;
Hh = sqrt (F4 /(F4 + F14));
Hl = sqrt (F24/(F4 + F24));
Ht = sqrt (F32/(F2 + F32));
```

Appendix 5: Evaluation of the measurements according to the base curve of ISO 2631-2:1989

The base curve for building vibration in the foot-to-head direction can be seen in figure A5.1. The base curve represents magnitudes of approximately the same human response with the respect to annoyance and/or complaints about interference with activities. The satisfactory magnitudes in different situations are specified in multiples of the base curve. For instance, for offices the base curve should be multiplied with 4, which is represented by the thinner line in figure A5.1. For magnitudes below the values in the base curves generally no adverse comments or complaints have been reported.

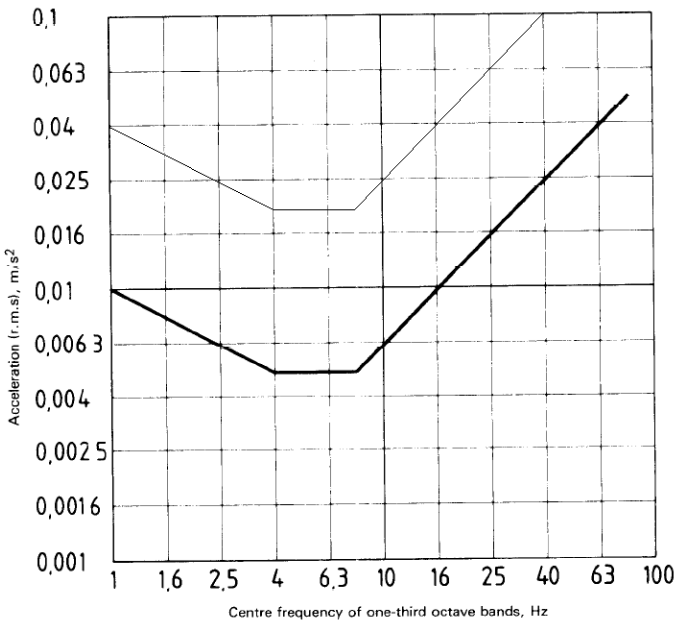


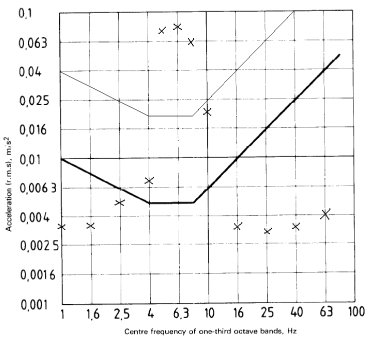
Figure A5.1. Building vibration z-axis base curve for acceleration. The thinner line is valid for offices.

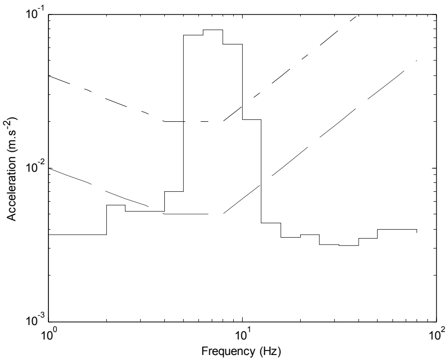
Measurements before a concrete topping was cast.

Averaging time: T=1s

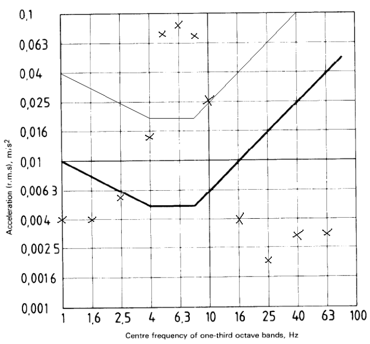
Pia_Walk_1

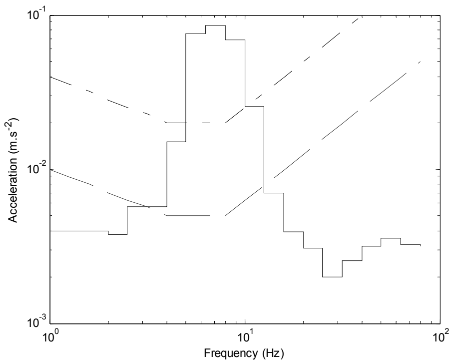
Accelerometer no.6, placed at the midpoint of the floor:



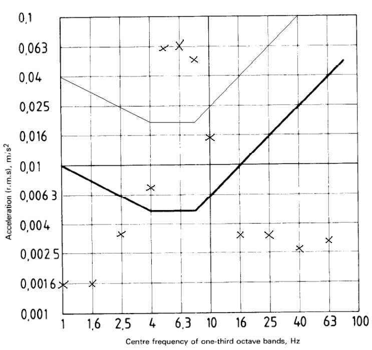


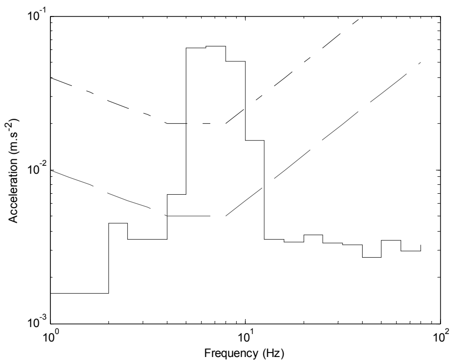
Accelerometer no. 15, placed under the chair that was used in the subjective tests. This was the maximum overall weighted acceleration that was recorded for this walk:



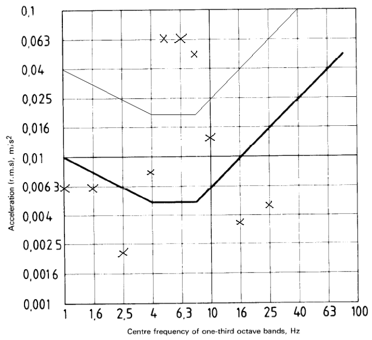


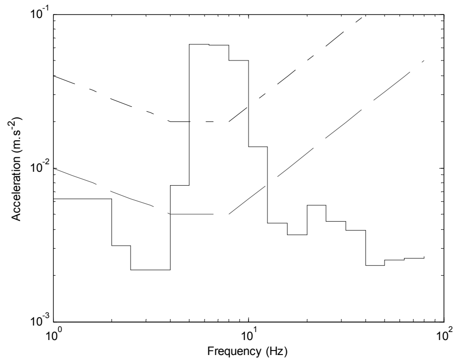
Accelerometer no. 3, placed at one quarter of the span, on the centre element:



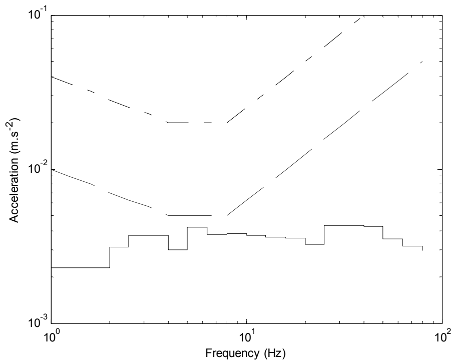


Accelerometer no. 14, placed at one quarter of the span, on one of the side elements:



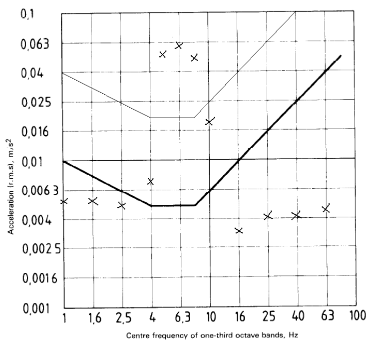


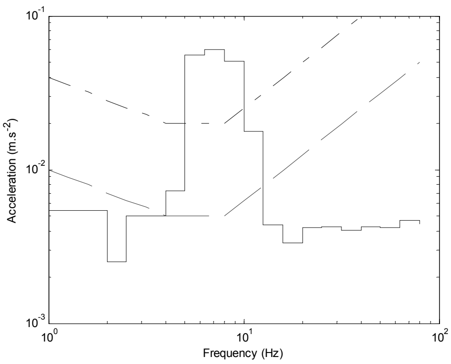
Accelerometer no. 13, placed 1.3 m from the edge on a side element. The smallest value of overall weighted acceleration was recorded here:



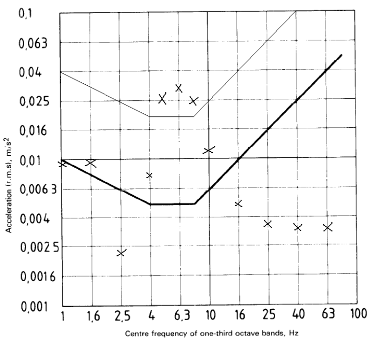
Pia_Walk_2

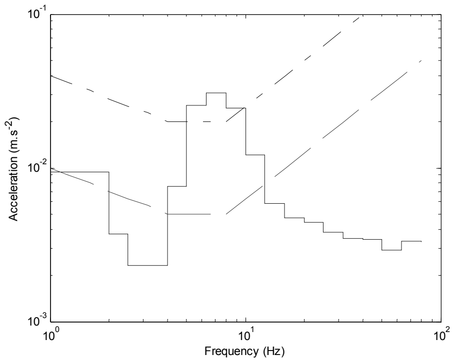
The largest overall weighted value of acceleration was measured by accelerometer no.14 in this case. This accelerometer was placed in the middle of the span, on one of the side elements.



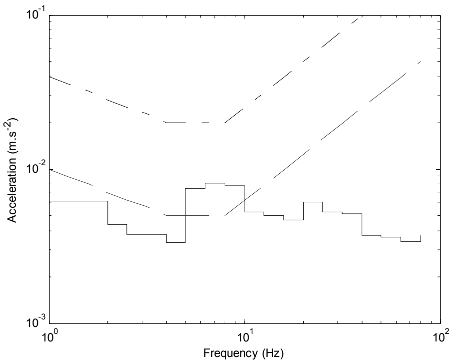


Accelerometer no. 15, placed under the chair that was used in the subjective tests:



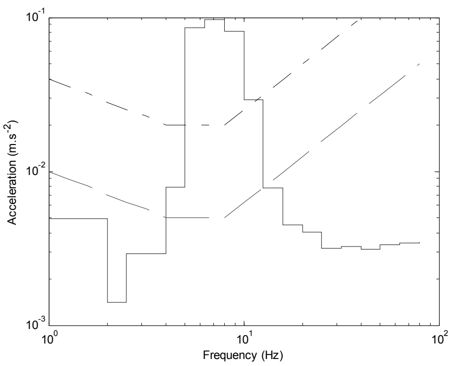


Accelerometer no.11, placed 0.9 m from the edge on the centre element. The smallest overall weighted value was recorded here:

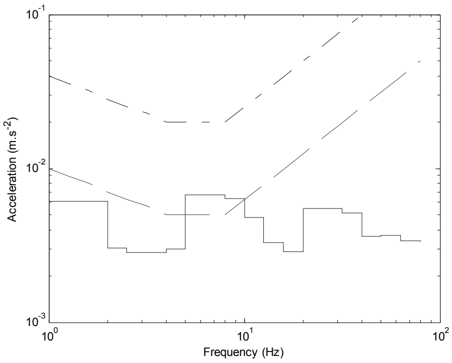


Pia_Walk_3

Accelerometer no.15, placed under the chair that was used in the subjective test. This location also showed the highest overall weighted acceleration for this walk:

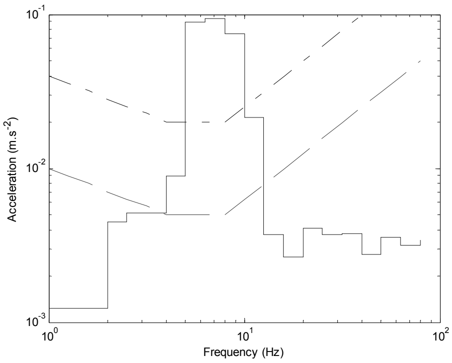


Accelerometer no. 2, placed 1.3 m from the edge on the centre element. The smallest overall weighted value was recorded here:

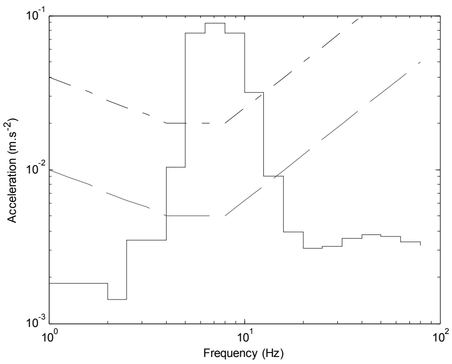


Pia_Walk_4

In this case, the highest overall weighted value of acceleration was obtained at the location of accelerometer no. 7, which was placed 3.4 m from the edge of the slab on the centre element, i.e. 600 mm from the midpoint of the floor.

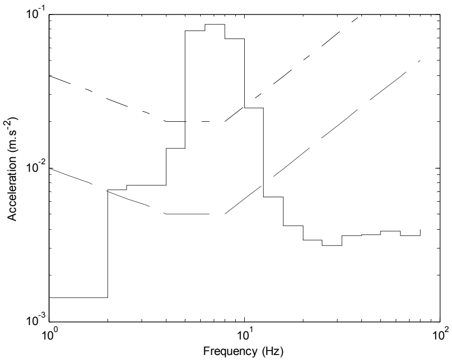


Accelerometer no 15,placed at the location of the chair that was used in the subjective tests:



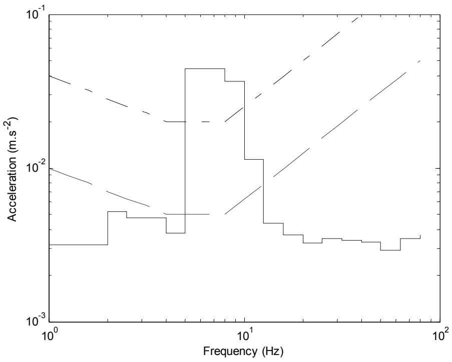
Pia_Walk_5

The highest overall weighted acceleration was measured at the location of the chair that was used in the subjective tests:



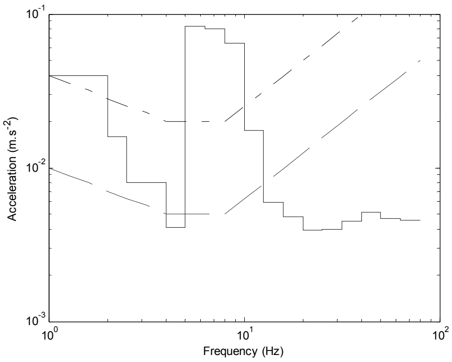
Matteo_Walk

The highest value of overall weighted acceleration was obtained at the midpoint of the floor, accelerometer no. 6:



Vincent_Walk

The highest value of overall weighted acceleration was obtained at the midpoint of the floor, acc no 6:

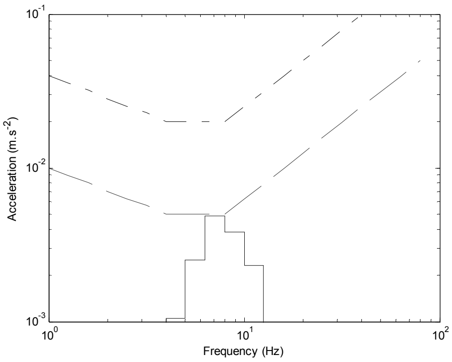


Measurements before a concrete topping was cast.

Averaging time: T=10s

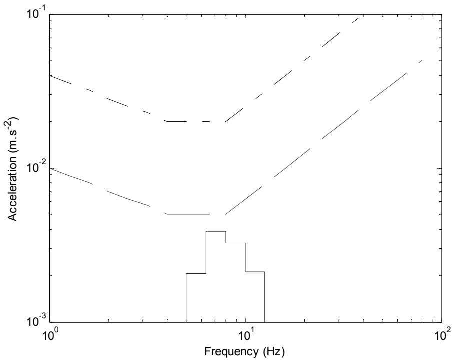
Pia_Walk_1

The highest value of overall weighted acceleration was measured under the chair and at the midpoint of the floor. Accelerometer no. 15, under the chair:



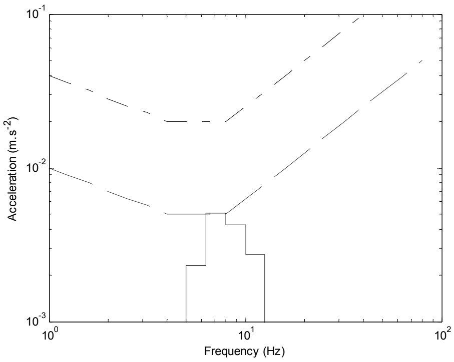
Pia_Walk_4

The highest value of overall weighted acceleration was measured under the chair:



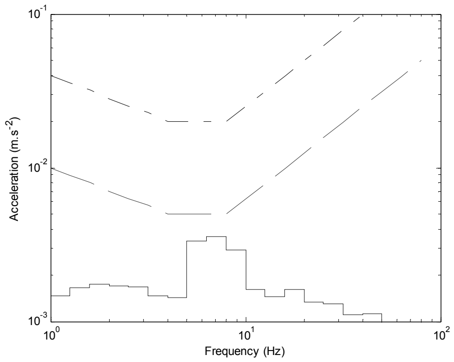
Pia_Walk_5

The highest overall weighted value was obtained at the midpoint of the floor:



Vincent_Walk

The highest overall weighted value was obtained 700 mm from the midpoint of the floor on the centre element, accelerometer no.4:

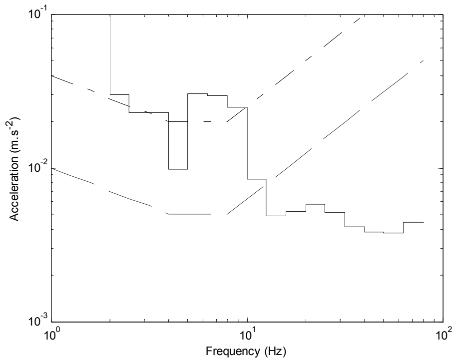


Measurements after a concrete topping was cast.

Averaging time: T=1s

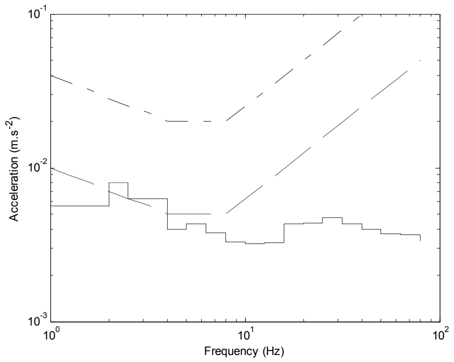
CT_Pia _1

The highest value of overall weighted acceleration was obtained at the midpoint of the floor, accelerometer no 6:



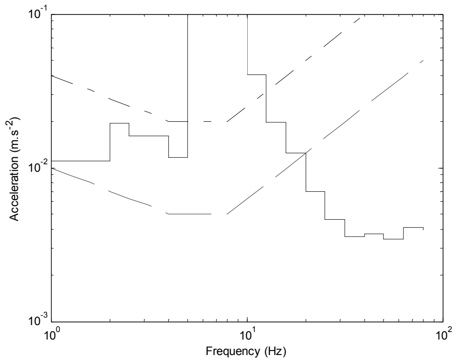
CT_Jake _1a

The highest value of overall weighted acceleration was obtained on one of the side elements, 1.5 m from the edge, accelerometer no 13:



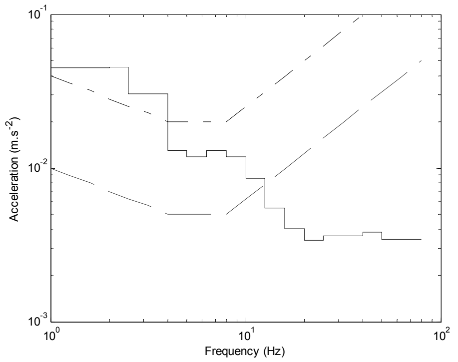
CT_Jake _1b

The highest value of overall weighted acceleration was obtained at the midpoint of the floor, accelerometer no 6:



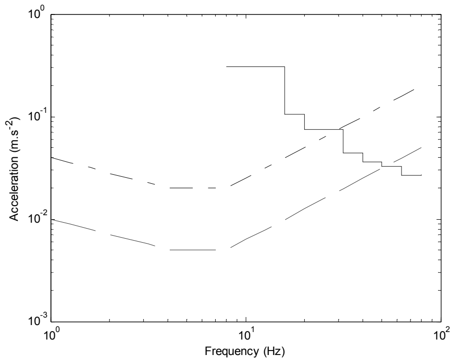
CT_Charlotte _1

The highest value of overall weighted acceleration was obtained on the centre element, 2.6 m from the edge, accelerometer no. 4:



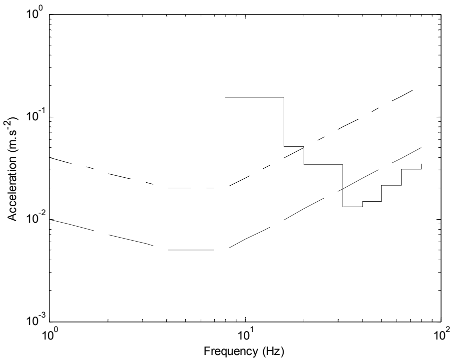
CT_Fredrik _2

The highest value of overall weighted acceleration was obtained at the midpoint of the floor, accelerometer no.6:



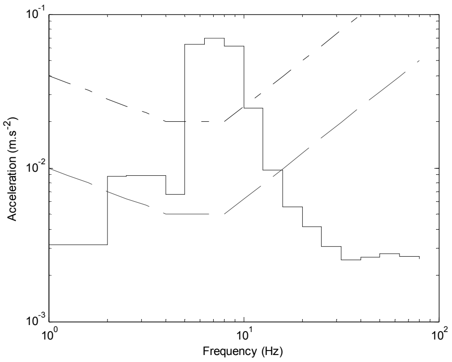
CT_Charlotte _2

The highest value of overall weighted acceleration was obtained on one of the side elements, 600 mm from the midpoint, accelerometer no. 11:



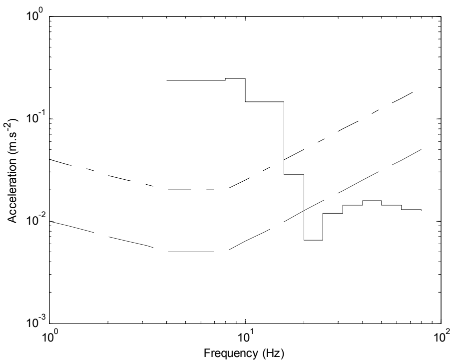
CT_Jake _2a

The highest value of overall weighted acceleration was obtained at the midpoint of the floor, accelerometer no. 6:



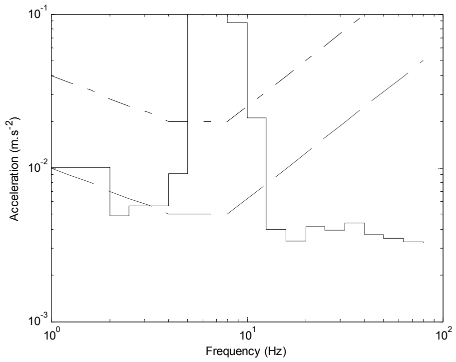
CT_Jake _2b

The highest value of overall weighted acceleration was obtained at the midpoint of one of the side elements, accelerometer no. 10:

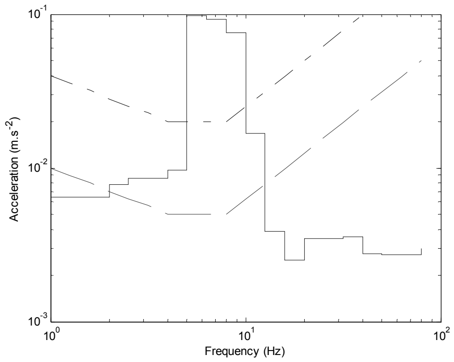


CT_Pia _2

The highest value of overall weighted acceleration was obtained on one of the side elements, 600 mm from the midpoint, accelerometer no. 11:

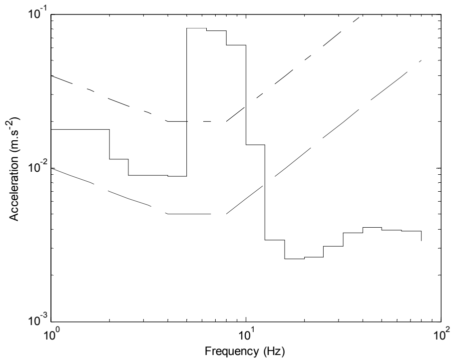


Accelerometer no. 8, under the chair that was used in the subjective tests:

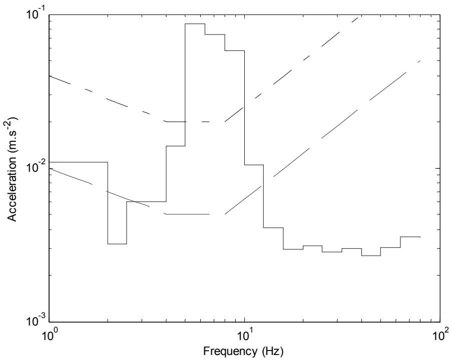


CT_Pia _3

The highest value of overall weighted acceleration was obtained at the midpoint of the floor, accelerometer no. 6:

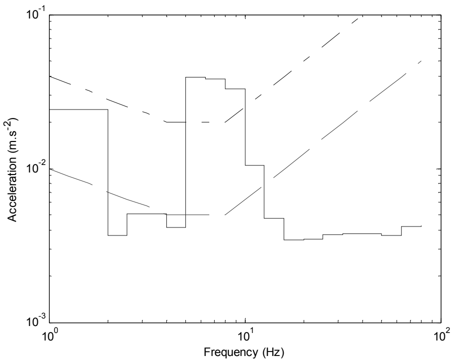


Accelerometer no. 15, under the chair that was used in the subjective tests:

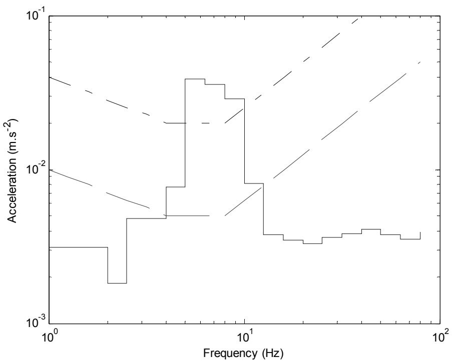


CT_Pia _4a

The highest value of overall weighted acceleration was obtained at the midpoint of the floor, accelerometer no. 6:

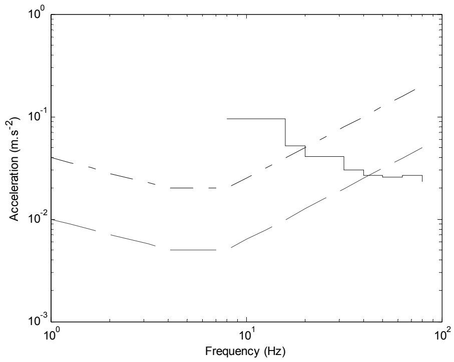


Accelerometer no. 15, under the chair that was used in the subjective tests:

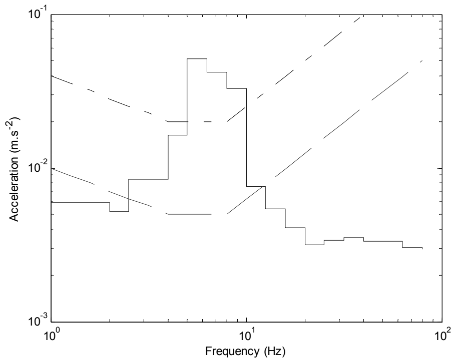


CT_Pia _4b

The highest value of overall weighted acceleration was obtained on one of the side elements, 2.6 m from the edge, accelerometer no. 12:

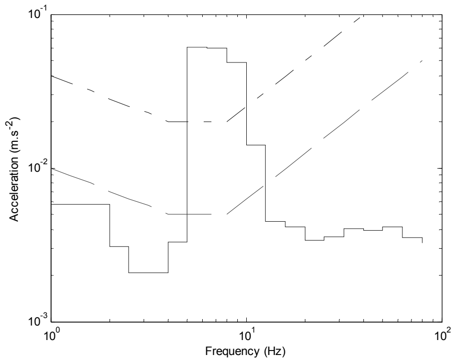


Accelerometer no. 15, under the chair that was used in the subjective tests:



CT_Pia _5

The highest value of overall weighted acceleration was obtained at the midpoint of the floor, accelerometer no. 6:



Accelerometer no. 15, under the chair that was used in the subjective tests: