Human induced vibrations in Light steel floors

- A study based on vibration measurements on an apartment-separating floor

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Preface

This publication describes the results of vibration measurements of one apartment separating light gauge steel floor during five phases in the construction process. The measurements as well as the analyse and reporting have been made by the Swedish Institute of Steel Construction in co-operation with the division of Sound and Vibration at Human Work Science, Luleå University of Technology.

The purpose with this project was to increase the knowledge about the vibration properties of light steel floors and the influence of interior walls and floating floors on the vibration performance. The measurements included hammer impact tests, heel drop tests and a subjective evaluation of the floor.

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Summary

Since the use of lightweight building systems is a relatively new concept for apartment separating structure there is a great need for increasing the knowledge in various technical areas. One of those concerns floor vibration. The vibration properties of lightweight floors are totally different compared to heavy floors. In order to increase the knowledge about lightweight floors and the vibration behavior due to human induced vibrations, a measurement program was made on a lightweight steel floor.

This report presents today's knowledge about acceptance criteria for vibrations in lightweight floors and summarizes the result of a test program performed in five different phases during the construction of a floor. The objective was to find out the vibration properties of as many aspects as possible within a limited number of measurements. Four test methods were therefore used:

1) Impact hammer measurements to find the resonance frequencies of the floor and their damping values.
2) Walking induced vibration to evaluate acceleration at realistic situations.
3) Heel drop induced vibrations to evaluate "worst case" vibrations.
4) Subjective evaluations to evaluate individual's perception of walking induced vibration in the floor.

The results of the measurements confirm that adding walls to the bare floor slight changes the dynamic properties of the structure. Adding partition walls to the floor structure will reduce the vibration at high frequency because the partition walls will create a nodal line where the wall is erected or by generally increasing the stiffness. Adding parquet to the finished floor will cause a decreased sound insulation at higher frequencies, which can be solved by adding sound absorbents to the ceiling. The damping ratio changed from 0.09 for bare floor to 0.12 for the finished floor, but at building phase 3 and 4, new modes appeared which may cause discomfort to human.

Sammanfattning

Lätta byggsystem för lägenhetsskiljande konstruktioner är en relativt ny företeelse. Det finns idag fungerande byggsystem samtidigt som t ex bjälklag med längre spännvidder efterfrågas. För att komma närmare lösningen med längre spännvidder på lätta bjälklag behöver kunskapen om lätta bjälklags vibrationsegenskaper ökas. Lätta och tunga bjälklag har helt olika egenskaper vad gäller vibrationer.

För att öka kunskapen om vibrationer i lätta bjälklag orsakade av människor i rörelse har en mätserie utförts och denna rapport sammanfattar resultatet av mätningarna. Vibrationsmätningarna utfördes på ett lätt stålbjälklag i fem olika skeden under bjälklagets uppbyggnad.

Fyra testmetoder användes:

1) Hammarexcitering för att finna bjälklagets resonansfrekvenser och deras respektive dämpning.
2) Gångspektrum för att utvärdera bjälklagets acceleration vid verklig belastning.
3) Excitering genom “Heel drop” för att bestämma värsta fallet.
4) Subjektiv utvärdering för att få människors uppfattning om bjälklagets vibrationsegenskaper. Störande vibrationer eller inte störande.

Mätresultaten bekräftar att det endast blir en liten förändring av vibrationsegenskaperna när väggar på bjälklagets långsidor monteras. Däremot sker en reduktion av högfrekventa vibrationer när innerväggar monteras på bjälklaget. Innerväggarna bildar en nodlinje och ökar bjälklagets styvhet. Parkettgolvet påverkar ljudisoleringen vid höga frekvenser negativt, detta kan man dock åtgärda genom att montera ljudabsorbenter i undertaket. Dämpningen förändrades från 0.09 för fritt upplagt golv till 0.12 för färdigt golv.

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1 Introduction

Light Gauge Steel Framing for Housing is a collective name for construction systems that contains primarily light gauge steel profiles, gypsum and mineral wool. Steel studs have been used in interior walls and curtain walls for more than 30 and 10 years respectively, and light gauge steel floor structures that separates apartments have during the last years become more competitive and are still under development. Around the world there are lot of knowledge about vibrations properties for heavy apartment separating floors made of concrete and steel in combination. Vibration properties of lightweight floors are not as known at the moment and the properties of lightweight floors differ a lot to heavy floors. This report is the result of a research project managed by the SBI in order to increase the knowledge about the vibration behavior of light steel floors. The report includes design recommendations and the criteria described are developed by a research group at VTT in Finland (Talja et al, 2002). Today, this is the most relevant criterion developed to be used for light steel floors. The VTT criteria are based on the Canadian criteria developed by Donald M Onysko (Canadian Wood Council, 1997).

Figure 2: Light steel framed floors have C- or Z-profiles for load bearing.

Objectives

The objective of this project was to study experimentally the lightweight steel floor structure dynamic properties during different construction phases and the human response to walking induced floor vibrations. The project consisted of hammer impact test on floor structure, measurement of vibration induced by walking, measurement of vibration generated by heel drop and subjective evaluation of vibration that induced by walking on the floor structure.

This report should be used as a recommendation based on today's knowledge and it should be born in mind that ongoing and future research will improve the design criteria and increase the knowledge about which parameters in light weight floors that affect the floor vibration properties.

2 Light steel floor properties

During the last decade several new more lightweight building systems have been developed. The weight of an apartment with light gauge steel is about 150 kg per square meter and out of that the weight of the floor structure is 60-100 kg per square meter. The weight is about 20-30 percent of the weight of an apartment block made of concrete. The need for lower cost apartments has driven the development towards lightweight building systems in steel. The benefits are the dry and sustainable material with high tolerances, which are prerequisites for an industrialised and thus more productive and efficient building process. These advantages and needs have put light steel framing as a good choice when developing new lightweight building systems.

Light gauge steel studs have successfully been used in interior and exterior walls for several years. The newest part in the building system, that is called Light Steel Framing, is the floor. There are lightweight floors on the market for apartment houses and they have been used in Sweden for more than five years. When designing a lightweight floor the design limit is the dynamic behaviour of the floor due to people in motion. The reason is that the low weight of the floor implies that people can, by walking; jumping or running, induce annoying vibrations if the floor is not designed correctly.

Figure 3: A light-gauge steel frame for modular housing units.

Since lightweight apartments separating floors quite recently have been developed and used, the experiences are limited and there is lots of ongoing research in this field in order to understand which parameters that affect people's perception of vibrations. The question is why some vibrations are acceptable and some vibrations are not.

2.1 Definition of low frequency- and high frequency floors

Heavy floors and lightweight floors have different vibration properties and must be designed in different ways. Talja, et al, 2002, have divided floors into three different categories:

Low frequency floors are usually quite heavy floors and another person standing still on the floor can feel the resonance vibration due to a person walking. The resonance vibration is the parameter that designs low frequency floors. Floors with a fundamental frequency below 10 Hz are defined as low frequency floors. This report only considers vibration design of high frequency floors. The design of low frequency floors is described in (Burstrand and Talja, 2001).

High frequency floors are usually quite lightweight floors and a person standing still on the floor may feel the impacts due to separate steps. Trembling is governing the floors with high fundamental frequency. High frequency floors are defined as floors with a fundamental frequency higher than 10 Hz.

The third category of floors is the *floating floors and raised floors*. These types of superstructures are increasingly used due to the improvement of sound insulation and the flexibility that raised floors implies as they gives space for service installations. There are not much experiences of vibration behaviour for these kinds of floors.

In practise, the vibration types of the three main groups appear more or less mixed.

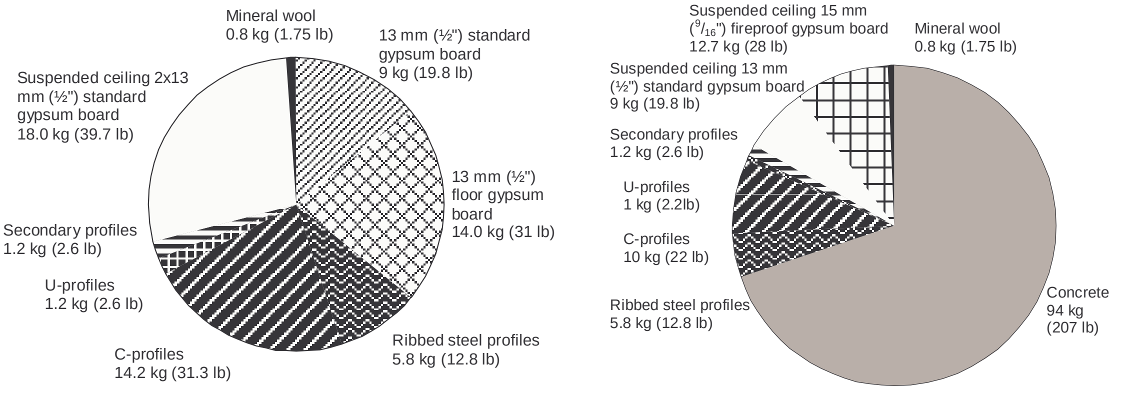

Figure 4: Left: A lightweight steel framed floor with gypsum floorboards weight about 65 kg/square meter. Right: A light framed floor with anhydrite topping weight about 135 kg/square meter.

3 Acceptance criteria

Although human annoyance criteria for floor vibration have been known for many years, it has only recently become practical to apply such criteria to the design of floor structures. The reason for this is that the problem is complex - the loading is complex and the response complicated, involving a large number of modes of vibration. Experience and research have shown, however, that the problem can be simplified sufficiently to provide practical design criteria. Griffin (Griffin, 1990) argues that while perception is best predicted by making measurements on seats or in beds, it is common to assess the acceptability of building vibration by measuring on the floor.

3.1 Parameters that influence people's perception of vibrations

The human body is very sensitive to vibrations. Even very small vibrations can be annoying. The floor vibrations transmitted to furniture, glassware and pot plants may cause annoying noise and leaf movements. Ordinary walking consists of both cyclic and impact components. The lowest cyclic component is a step frequency 1,6-2,2 Hz, but multiple frequencies 3,2-8,8 Hz are also present. Annoying vibrations may result, as the cyclic components may be magnified due to resonance, i.e. when the load frequency is equal to the lowest natural vibration frequency of the floor. The impact components may also excite higher frequency for large trembling amplitudes. Usually the walking person himself may not perceive the vibrations, even though other persons may experience the vibrations as annoying.

Continuous vibrations are felt more annoying than short-term, infrequent vibrations. If the vibrations are transferred from the neighbouring apartment, the disturbance is more irritating than if the vibrations have been caused in the same apartment. Also the type of room may have effect on the disturbance.

The response of the floor when loaded by human walking depends mostly on the *mass* and *fundamental frequency* of the floor. When the mass is high and the fundamental frequency is low, the natural vibration is dominating, but when the mass is low and the fundamental frequency is high the deflections due to steps are dominating. The limit frequency between high- and low frequency floor was earlier defined as 8 Hz. New results (Talja et al, 2002) suggest 10 Hz as a better limit frequency. Generally saying a deflection criterion is applicable for high frequency floor while acceleration criterion is applicable for low frequency floor.

Modal analysis is widely used for dynamic floor vibration test, and Fahy (Fahy and Westcott, 1978) has concluded that the damping ratios and peak mobilities of low frequency resonance's of buildings are very much affected by the degree of completion and occupation. Completed, occupied buildings exhibited damping ratios in the range 6-14% compared with the range 1-3% for unoccupied, incomplete buildings. Low frequency peak mobility values, which partially determine the form of vibration insulator on which it is necessary to mount machinery, lie generally in the range 10^{-5} to 10^{-6} (m/s)/N.

Although several investigations have been conducted on the human evaluation of steady-state vibration, the most frequently cited reference is the study by Reiher and Meister, 1931. Wiss and Parmelee, 1974 developed a prediction model to evaluate the human response to vertical transient vibrations based on vibration frequency, vibration displacement and damping ratio. The International Organization for Standardization's standard ISO 2631-2:1989 is written to cover many building vibration environments. The standard presents acceleration limits for mechanical vibrations as a function of exposure time and frequency, for both longitudinal and transverse directions of persons in standing, sitting, and lying position.

4 Design criteria

Human induced floor vibrations can either be in the form of sudden impacts from jumping, heel drop, dropping objects etc, or repeated impacts from walking. The sudden impacts will excite the natural modes of the floor. Ordinary walking consists of both cyclic and impact components. The reason is that a repeated force like walking can be represented by a combination of sinusoidal forces whose frequencies, *f*, are multiples or harmonics of the basic frequency of the force repetition. In theory, if any frequency associated with the sinusoidal forces matches the natural frequency of a vibration mode resonance will occur causing severe vibration amplification. Annoying vibration may result, as the cyclic components may be magnified due to this resonance. The impact components may also excite higher frequencies for large trembling amplitudes.

4.1 Summary of design criteria

Different nationals have their own requirements/standard considering the serviceability of floor vibrations, see Table 1 below.

Table 1: Summary of different nation’s requirements/standards regarding serviceability of lightweight steel floor vibrations (Burstrand, Talja 2001).

Country	**Requirements/standard**		
	Fundamental frequency	**Deflection**	**Remarks**
Finland	> 8* Hz	<0.6 mm (under 1 kN point load)	The deflection is span depending, 1.5 mm for long span and 0.6 for short one.
Sweden	-	1.5 mm (under 1 kN point load)	Recommended that the fundamental frequency should be > 8 Hz
Canada	-	Span/360	The deflection of a single joist are based on an unfactored imposed load limit of span/360
Australia	-	2.0 mm (under 1 kN point load)	Alternatively by calculating the max impact velocity of an ideal 1.0 Ns unit impulse load
United Kingdom	-	Span/360	
USA	$a_p / g \leq 0.5\% \times g$		a_p / g is the estimated peak acceleration (in unit of g)

* The Finnish criteria have been rewritten and the lowest fundamental frequency should be > 10 Hz.

4.2 The ISO guidance

ISO offers guidance on the human response to human induced vibrations in floors. Weighting curves of frequency response of how humans perceive vibrations are also included in the standard (ISO 2631-2:1989). As for European standard, Section 4 of

Eurocode 3 Part 1.1 deals with the serviceability limit state and recommend a table of limiting values for vertical deflections. EC3 Part 1.1 applies to steel structures in general and therefore the same limits apply to all applications. For floors and roofs supporting plaster of other brittle finishes the limits are span/250 for net deflection due to dead and imposed load, and span/350 for deflection due to imposed loads. The net deflection limit allows any pre-camber effects to be taken into account. *However, in practice, the limit of span/250 can be relaxed if a raised floor or suspended ceiling is used.*

There are many different design criteria that have been proposed for floors in residential buildings. For lightweight floors they are usually based on the deflection due to a 1 kN point load. Some of the deflection limits are span dependent and some of them are frequency dependent. (Talja et al, 2002) propose that the deflection limit of high frequency floors is independent of the span, but depends on the size of the room. The design recommendations given by Talja, et al 2002 are based on about 100 full size tests including 14 different floor types from a wide span range. The measurements of design quantities and the subjective rating of intensity and acceptability were made using the standardised VTT-testing procedure (Burstrand, Talja 2001). In rating by sense perceptions the observations were made based on body feeling and on vibrations of different objects. The observations were:

- body perception from a sitting position,
- clinking of a coffee cup with a spoon in the cup and on a saucer,
- leaf movements of a 30-40 cm high plant
- ripping of water in a glass bowl and
- clinking of a glass pane.

The design criteria proposed by Talja et al are described below.

4.3 Design criteria by Talja et al

Design criteria for lightweight floors are under development in several countries. The recommendation today is to follow the described criteria below by the notification that it will be revised and improved when more research in this field have been carried out.

4.3.1 Vibration classes

Talja et al have in their criteria proposed a five-class classification of floors in residential and office buildings. The classes are taking vibration within an apartment into account as well as vibrations from adjacent apartments. The proposed limits between the classes will, if necessary, be adjusted when more experiences exist. This classification is material independent and it presumes that walking induced vibrations are accepted as the basis of the design.

Table 2: The vibration classification of floors is based on the intensity of the vibration. The class I composed of a capital letter and a number. The letter represents the sense perception of a sitting person and the number represents the sense perception from vibrations of objects.

	Body perception		Vibration indicators
A	The vibrations are usually imperceptible.	1	The clinking of glassware and the leaf movements of a pot plant are usually imperceptible.
B	The vibrations are barely perceptible	2	The clinking of glassware is usually imperceptible and the leaf movements are barely perceptible.
C	The vibrations are perceptible.	3	The clinking of glassware is barely perceptible. The leaf movements perceptible.
D	The vibrations are clearly perceptible.	4	The clinking of glassware and the leaf movements are clearly perceptible.
E	The vibrations are strongly perceptible.	5	The clinking of glassware and the leaf movements of a plant are strongly perceptible.

Table 3: The table gives a proposal for the lowest permissible vibration classes. Because there is little experience about the disturbance effects of vibrating articles, it is suggested to choose one class better vibration class in the design than given in the table. If the performance is not experimentally verified, it is good practice to use class C2 instead of C3 and class B1 instead of B2.

A1	Normal class for vibrations transferred from another apartment. Special class for vibrations inside one apartment.
B2	Low class for vibration transferred from another apartment. High class for vibrations inside one apartment.
C3	Normal class for vibrations inside one apartment.
D4	Low class for vibrations inside one apartment. For example attics and vacation cottages.
E5	Class without restrictions.

4.3.2 Acceptance limits

The acceptance limiting values for vibrations are given in Table 3. The limiting values are given for the following design quantities:

- The fundamental frequency f_0 . The frequency f_0 = 10Hz divides the floors into low frequency and high frequency floors.
- The amplitude of the acceleration a [m/s^2] is used for low-frequency floors in resonance vibration.
- The local displacement δ [mm] due to 1 kN point load is used for high-frequency floors. The distance from the force to the reference point, from where the displacement is measured, is not less than 600 mm. The distance and the local displacement are measured from the top surface of the floor.

- The slope ϕ due to 1 kN point load is used for both low and high frequency floors with and without a floating or raised floor. The distance from the force to the reference point gives the maximum slope, but the distance shall not be less than 450 mm. The distance and the slope is measured from the top surface of the floor.
- In addition, the normal deflection limits given in other design codes shall be fulfilled.

If walking induced vibrations are measured, the limit values for the following quantities are proposed:

- The peak vertical displacement $|u_{max}|$ for high frequency floors.
- ISO factor for low frequency floors (ISO 2631-2, 1989). The value is determined by filtering the measured sample to 1/3 octave bands, weighting the RMS-accelerations by curve Wk (ISO 2631-1, 1997) and dividing the maximum RMS-acceleration by the value 0.005 m/s^2.
- The peak horizontal displacement $|w_{max}|$ at a height of 1,2 m from the floor surface. The vibrations are measured from the top of a firm tripod support.

If the largest side of the room is less than L=6 m and the vibrations take place inside one apartment, the limit values of a, ISO-factor, δ and $|u_{max}|$ may be multiplied by a factor

$$k_L = \frac{1}{0{,}318+0{,}114\,L}$$

This factor takes into account the fact that the walking excitation is lower in small rooms than in large rooms.

Table 4: Acceptance limits for vibration classes.

Low Frequency floors			High Frequency floors. floating floors and raised floors			All floors		
Class	a [1) $[m/s^2]$	ISO factor	Class	δ [1) [mm]	$\lvert u_{max}\rvert$ [2) [mm]	Class	ϕ [1) [mm]	$\lvert w_{max}\rvert$ [2) [mm]
A	≤0,03	≤4	A	≤0,12	≤0,05	1	≤1/6000	≤0,1
B	≤0,05	≤7	B	≤0,25	≤0,1	2	≤1/3000	≤0,2
C	≤0,075	≤11	C	≤0,5	≤0,2	3	≤1/1500	≤0,4
D	≤0,12	≤17	D	≤1,0	≤0,4	4	≤1/750	≤0,8
E	>0,12	>17	E	>1,0	>0,4	5	>1/750	>0,8

1) Static design criteria (load: 1kN for u and w)

2) Dynamic test criteria (load: walking person)

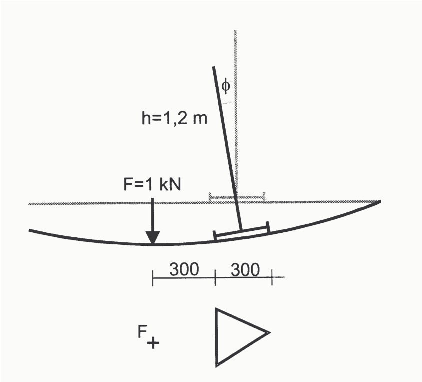

Figure 5: Determination of the slope of the top surface of the floor due to 1 kN point load.

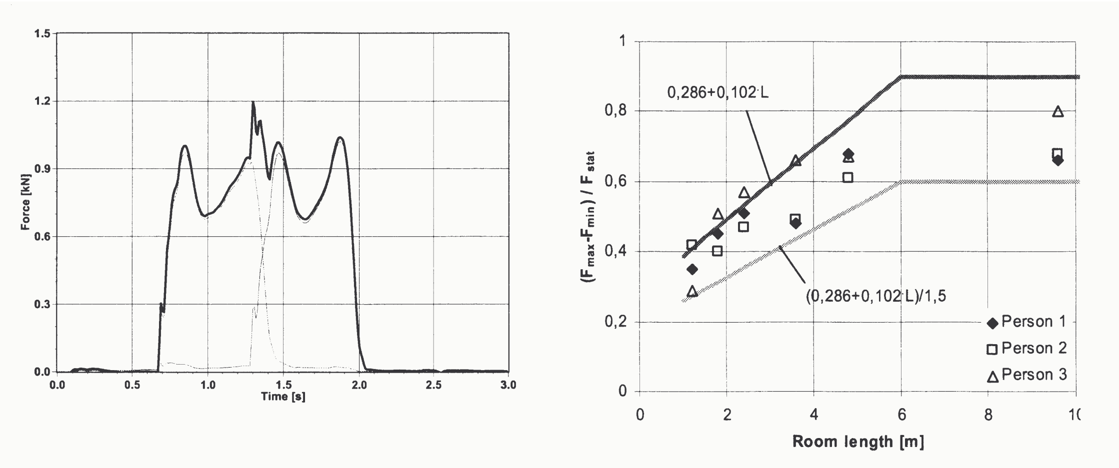

Figure 6: Left: Measured excitation force load induced by left and right footstep. Right: Force range of the continuous walking load measured from three different persons normal walking. Both forces are given proportional to the weight of the walker.

4.3.3 Experimental verification of the acceptance limits

The developed acceptance criteria have been verified by series of experimental tests on different floor structures. The test series include steel-and wood framed floors with building boards or concrete slab top-flooring, hollow-core concrete slab floors, laminated veneer lumber (LVL) floors, floating floors and raised floors. More than 50% of the tests have been performed in laboratory circumstances and the rest in buildings under construction. Figure 7 shows span and fundamental frequency of the tested floors.

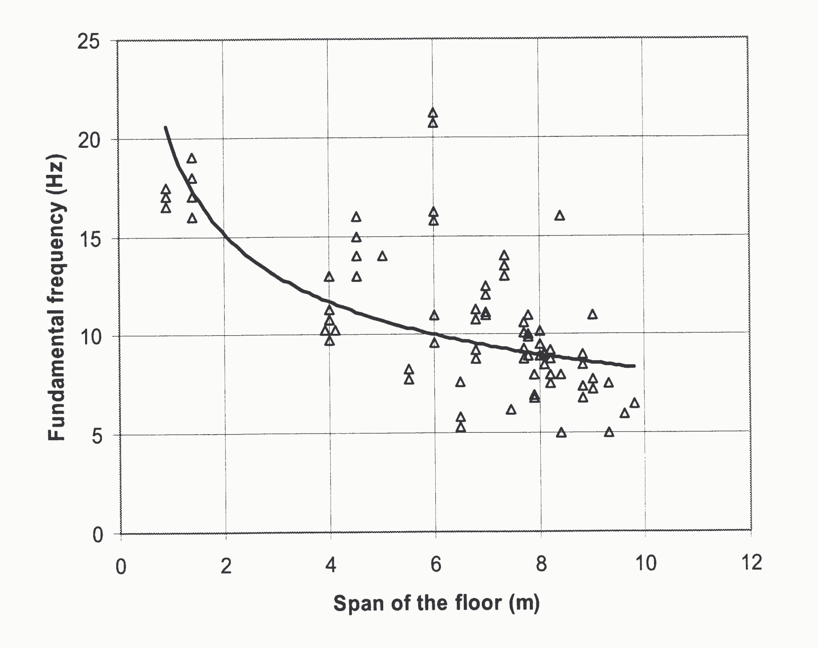

Figure 7: Fundamental frequency versus span of the tested floors.

5 The test program

5.1 The tested floor construction

The tested floor was a 6m span lightweight steel floor, with the area $6 \times 18m^2$, see Figure 8 for the layout of the floor. All the tests and measurements mentioned below went through the following construction phases:

1. Without any wall (bare floor);
2. With wall around;
3. With wall around and room partition walls ;
4. With wall around, room partition walls and floating floor;
5. With wall around, room partition walls, floating floor and furniture inside.

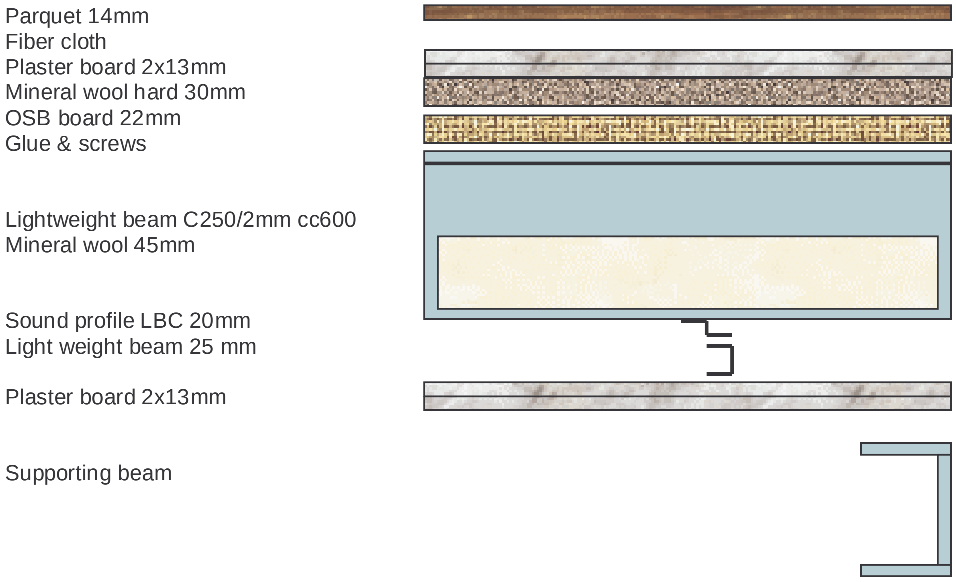

Figure 8: The composition of the lightweight steel floor that was tested. The total floor height is 415 mm.

5.2 Principal vibration behavior of the floor during the five building phases

The aim of this chapter is to give an easy to understand description of the vibration behavior of the type of built up floor that is evaluated in the report. It is of great interest to understand how the floor vibrates at different frequencies in order to understand how damping and stiffness can be utilized to improve the vibration properties of the floor. A built up floor is very difficult to describe exactly through models like FEM models or wave models. It is also very time consuming to exactly measure how the floor behaves. In order to do so, a very large number of measurement points have to be distributed both over the floor and over the ceiling. And this has to be repeated at each phase of the building steps. Even though this is possible to do so if there is a enough time, the complexity of the floor would anyhow make it difficult to get a clear picture of the basic vibration principles of the floor at the different building phases.

Therefore, in order to give the reader a picture of what principally can be expected to happen with the vibration behavior of the floor at each building phase, this chapter gives a simplified description with explanations and drawings of how the floor principally behaves at its first natural frequencies. In a real floor the behavior is not as simple and unambiguous as these pictures show.

Natural frequency

First of all a definition is given of an natural frequency and its damping. If a floor structure is hit, e.g. by a heel drop, the floor will start to vibrate at its own natural modes, the 1st, the 2nd, the 3rd, the 4th etc. The frequencies of the natural modes are determined by the mass and stiffness of the floor, by the way the floor is suspended to its support and surroundings, by how much mass the floor is loaded with and by how much additional stiffness is added through e.g. interior walls. The mode shape can also be seen as a representation of the wavelength of the vibration. The relationship between frequency and wavelength is the well-known relationship $\lambda=c/f$, where λ is the wavelength, f is the frequency and c is the wave speed of the bending wave in the floor. Note; the natural frequencies of bending modes are *not* integer numbers of the first natural frequency.

Damping

The time a floor will vibrate after it is being hit by an impact will be decided by the damping. The damping of the natural modes is caused by relative motions combined with friction between the different floor layers, mounting points in the floor and through friction at the surround against the support and against walls that are connected to the floor. There is also a damping effect by the vibration propagation to the connected structures.

5.2.1 The first building phase: Bare floor

At the first building phase the principal mode shape of the first natural frequency will look like in Figure 10. There are two alternatives shown in the picture, the continuous curve shows the shape as if the floor is simply supported to the beams. The dotted curve shows the shape as if the floor was clamped at the support. A clamped support would require a strong coupling to the beam and a totally rigid beam. With a strong coupling the floor beam will start to bend down at some distance from the support. Thereby the mode shape will be a bit shorter, and thus the frequency will be a bit higher. In the investigated floor, the floor beam is resting on the supporting beams and is bolted to the beams through mounting plates. Therefore the floor can be expected to behave like something in between the two alternatives.

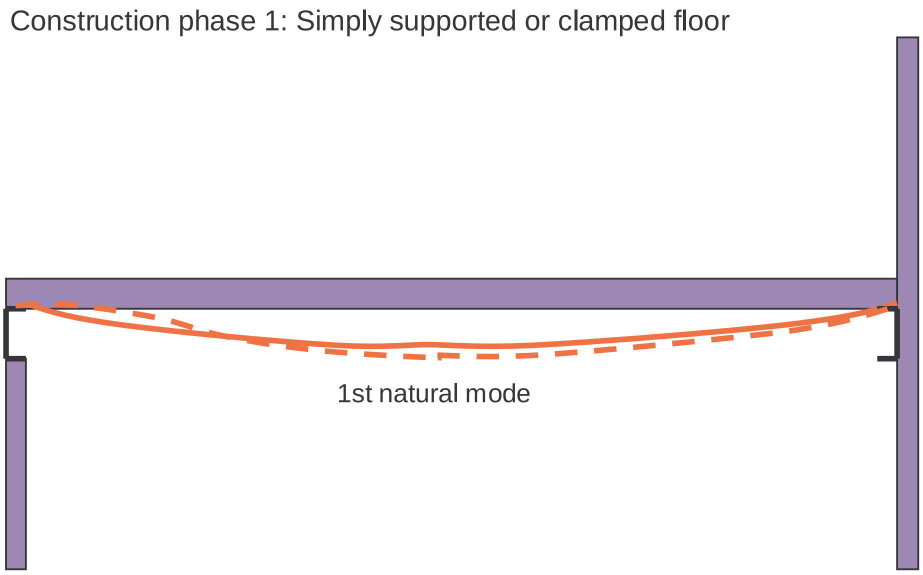

Figure 10: Simplified drawing showing the expected mode shape of the floor at the 1st building phase. There are two alternative mode shapes, depending on how rigid the connection is to the supporting beam and the flexibility is depending on the torsional stiffness. (The amplitude is exaggerated.)

The damping of the mode is mainly caused by internal damping of the floor and by damping in the contact with the supports. If the floor beams are allowed to slide against the supporting girders, friction will give damping. If the floor is strongly coupled to the girder and the girder is very rigid, less friction may occur and therefore the damping may be reduced. But, if the girder has limited stiffness and if there is a strong coupling, vibration energy will propagate to the girder and therefore there will be less vibration energy in the floor and thus damping may increase. On the other hand, if the girder is weak, girder natural modes will interfere with the floor modes. The combination of vibration damping, girder natural modes, energy propagation in a coupling is very complex, so simple conclusions are not easily drawn. If there is too strong propagation of vibration to the supporting structure, the disadvantage of a strong flanking transmission will also arise.

To consider

In the choice of a construction principle there should be a combination between friction to occur in the coupling and added stiffness from the coupling.

5.2.2 The second building phase: Wall placed on top of the floor

At the second building phase the principal mode shape of the first natural frequency will look like in Figure 12. An exterior wall is erected on one end of the floor. At the other end, close to the buildings exterior wall, the wall covering is erected to the exterior wall and not on the floor. The main change here will be added mass of the wall standing on the end of the floor. This can, depending on how the erection is done, increase the stiffness and the damping. If there is relative motion and a high friction between the wall and the floor the damping will be increased. If the coupling, on the other hand, of the wall to the floor is so strong that there is no relative motion, the damping will be reduced and the natural frequencies will be higher.

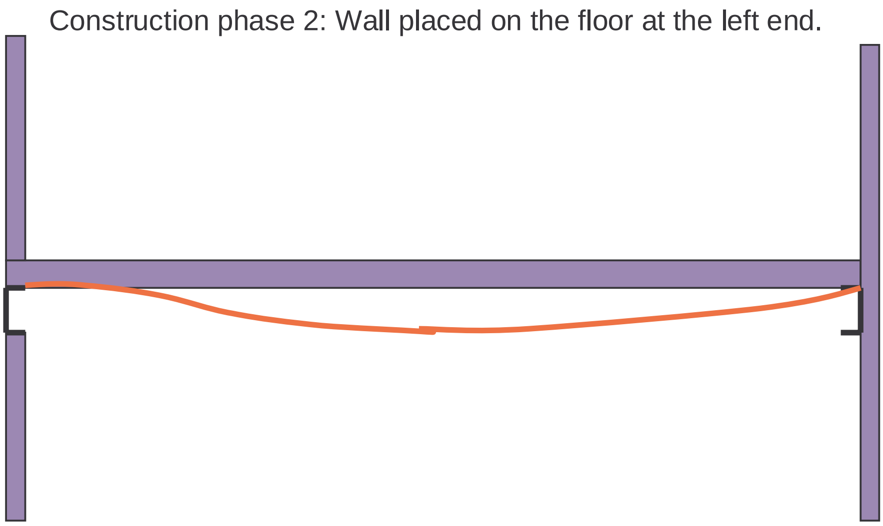

Figure 12: Simplified drawing showing the expected mode shape of the floor at the 2nd building phase.

To consider

A strong friction combined with relative motion between the floor and the wall will increase the damping.

5.2.3 The third building phase: Interior walls placed on the floor

Figure 13: Interior wall.

At the third building phase the principal mode shape of the first natural mode will look like in Figure 14. An exterior wall is placed at one end of the floor and interior walls are mounted as can be seen in Figure 13 and Figure 14. The mass of the interior walls will try to lower the natural frequencies, especially the first natural mode, while the added stiffness will try to increase the natural frequency. In Figure 14, it can be seen that the walls can, if the additional stiffness is strong enough, provoke new natural modes (the continuous curve) to occur where the mode shape will be according to half wavelengths for the length of the room or the width of the corridor. The additional stiffness is also dependant on how the interior walls are mounted to ceiling and on how stiff the walls are. The walls may also have a strong reduction effect of the amplitude of the fundamental frequency as the added stiffness and friction is added near the maximum of the mode. Damping will also be increased from friction at the coupling.

Construction phase 3: Interior walls erected on the floor.

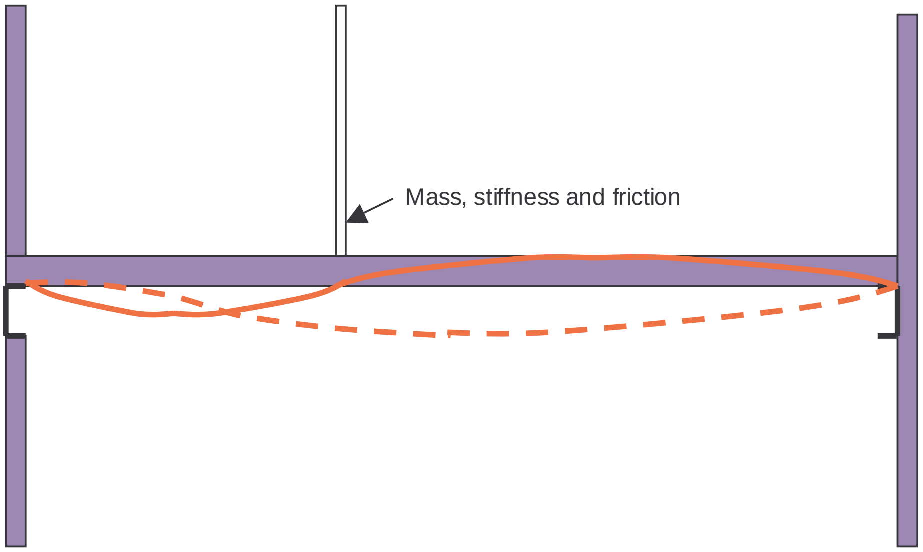

Figure 14: Simplified drawing showing some expected mode shapes of the floor at the 3rd building phase. 1st natural mode, dotted line. Provoked natural modes caused by the additional stiffness of the interior wall, continuous line.

To consider

If there are problems with the first natural mode efficient reductions can be introduced through the interior walls. Additional damping at other frequencies can also be introduced over a larger frequency range through the coupling of the interior walls to the floor.

5.2.4 The fourth building phase: Floating floor placed on the floor

At the fourth building phase the principal mode shape of the first natural mode and the provoked natural modes by the interior walls will look like in previous cases. A mineral wool layer and double plasterboards are freely laid on the floor. The main effect of the floating floor on the low frequency behavior of the floor will be where the relative motion of the floating floor relative to the core structure of the floor is highest, where there will be an increase of the damping due to friction. The floating floor will also add some additional mass, which may be seen as slightly lowered natural frequencies. The resilient floating floor will also act as a vibration filter and reduce some of the energy from foot steps and heel drops, the reductions will be increasing at higher frequencies.

Construction phase 4: Influence of floating floor.

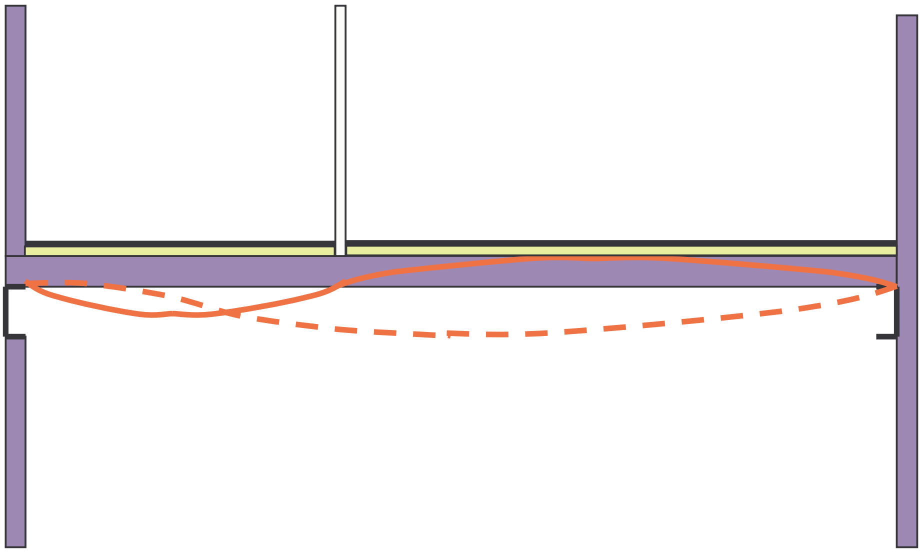

Figure 15: Simplified drawing showing some expected mode shapes of the floor at the 4th construction phase.

To consider

A floating floor is an efficient structure to increase the damping of a lightweight floor. The resilient layer must not be too soft in order to avoid compression caused by heavy furniture or unpleasant perception when walking on the floor. In the structure a mineral wool layer of approximately 130 kg/m^3 is chosen.

5.2.5 The fifth building phase: Parquet floor and furniture added

At the fifth building phase a parquet floor is put on a felt cloth on the plaster boards and some furniture, i.e. drawer and book shelf with books in a couple of offices, book shelf and a copy machine in the wide part of the corridor. The furniture will add mass which may be seen for heavy furniture as lowered natural frequencies. Heavy furniture may also increase damping as an added pressure on the floating floor. The parquet may increase the vibrations at higher frequencies of the floor, due to vibrations at the natural frequencies of the freely lying parquet floor and due to a faster impact force from shoes. These effects may also cause a stronger high frequency content of the impact force that reaches the floor. The parquet may also cause problems as a decreased sound insulation at higher frequencies.

Construction phase 5: Exterior wall +interior walls+ floating floor + parquet + furniture

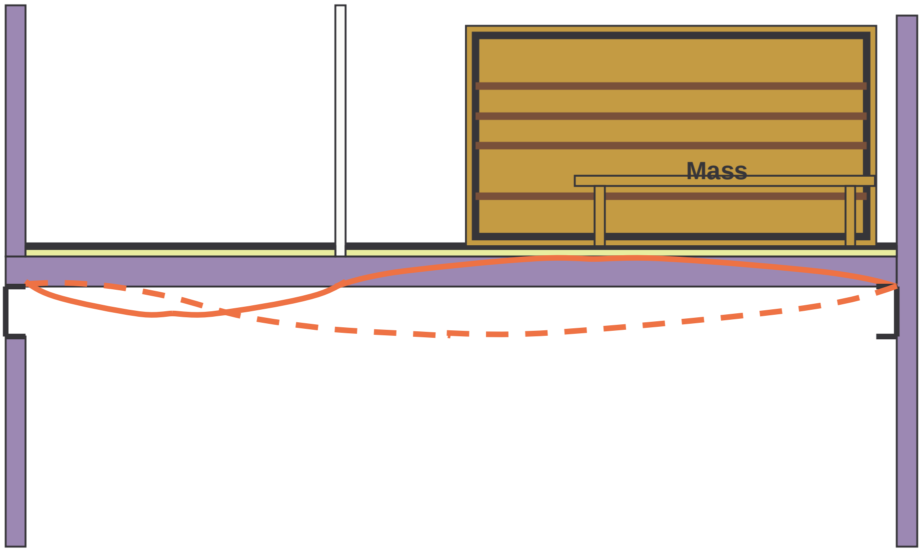

Figure 16: Simplified drawing showing the expected mode shape of the floor at the 5th building phase.

To consider
If there are problems with vibrations or sound insulation at high frequencies a parquet floor with added damping should be used. Experimentation could also be done with the elastic layer underneath the parquet. There are alternatives like various cloth or cork particles.

6 Measurements

The objective with the test program was to find out the vibration properties of as many aspects as possible within a limited number of measurements. Four methods were therefore used to measure the vibration properties:

1. Excitation with an impact hammer to find the resonance frequencies of the floor and their damping values.
2. Walking induced vibration to evaluate acceleration at realistic situations.
3. Heel drop induced vibrations to evaluate "worst case" vibrations and
4. Subjective evaluations to evaluate individual's perception of walking induced vibration in the floor.

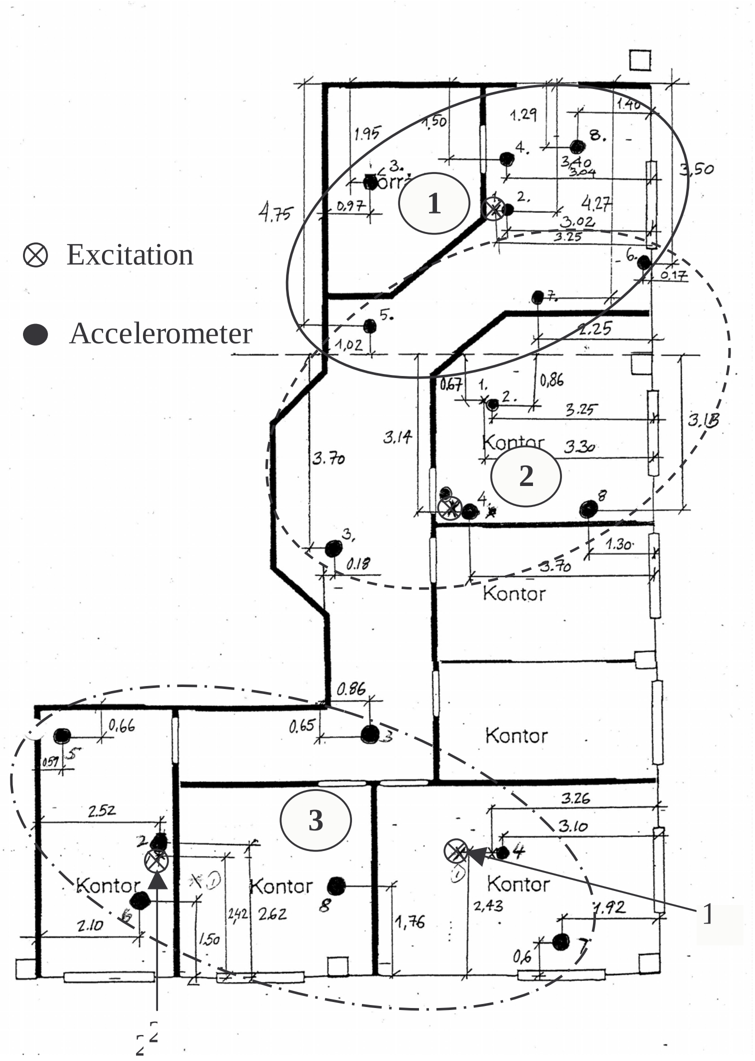

Figure 17: Impact test: Three parts of the tested floor and the distribution of measurement and excitation points.

6.1 Impact hammer excitation test

This method is considered to be an accurate measurement technique for measurements of resonance frequencies and damping. The method has the advantage that the force exerted on the floor is measured through a force transducer on the hammer. In order to obtain the most accurate data possible, it is often necessary to repeat these tests a number of times at a particular point on the floor, so that a mean reading may be obtained. The disadvantage of using this type of test is that when it is conducted in a 'noisy' atmosphere or when the floor is behaving non-linear, errors may develop (SCI, 2000) The tested floor was geometrically divided into three parts for these measurements, see Figure 17.

Figure 18: Hammer excitation of the floor.

A sledgehammer was used to excite the floor and a Bofors force transducer model LS-1 was utilized to measure the force signal. B&K accelerometers (model 4332, 4339, 4366, 4368,4371 and 8001) were used for the response signals; see Figure 17 for the distribution of measurement/excitation points. Note that there are 2 excitation points for part 3. Both force and response signal were recorded by using an 8-channel SONY data recorder, frequency response functions (FRF´s) were analyzed later on by using B & K Front-end 2827 together with a B&K PULSE system. (SCI, 2000)

6.2 Walking induced vibrations

The tests were used to determine the likely vibration levels generated on a floor when in normal use. Typically, the form these tests took was that an accelerometer was positioned at the point on the floor where the maximum displacement was measured in the forced vibration tests, and a person was asked to walk to a beat generated by a portable computer: so that the pace frequency of the walker could be controlled. In order to generate the worst loading case, the beat frequency generated by the portable computer was set at an integer fraction (harmonic) of one of the measured natural frequencies of the floor, i.e. a step frequency of about 2Hz. Thus, in these tests, it was attempted to cause resonant excitation of the floor to find the

maximum in situ acceleration response.
The test persons wore well-specified shoes and were walking on the floor along the walking path showed in Figure 20. Five accelerometers were placed beside the walking path, and another two were put at the place where the sitting person in measurement 4) made the subjective evaluation of the vibration behavior of the floor.

6.3 Heel drop tests

Literature shows that heel drop test is also an important way of testing floor vibration. (SCI, 2000) The main advantage of conducting this type of test is that it is reasonably simple to set up. Even though the actual force from the heel drop is unknown, for comparison purposes, it is useful to undertake this sort of test, as the simple loading function proved by a heel drop has, in the past, been used within some design guides to assess the acceptability of a floor. The heel drop test was performed from phase 3 to phase 5. An experimenter of 80 kg raised himself on the balls of his feet, and suddenly dropped onto the heels, thus providing a strong impact to the floor.

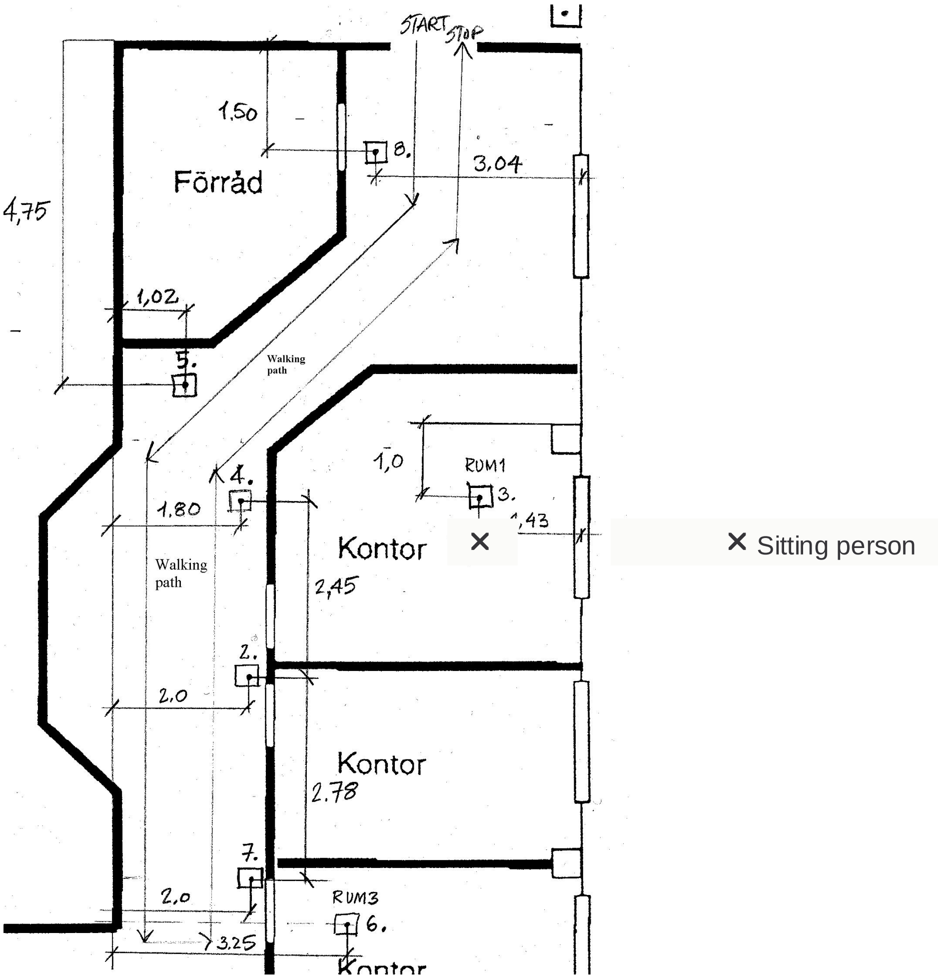

Figure 20: Walking paths and the location of the accelerometers during the subjective evaluation.

6.4 Subjective evaluation of walking induced floor vibration

The test subjects were first asked to walk on the floor and then rate the vibration on a 5-point scale (5-perfect, 4-acceptable, 3-barely acceptable, 2-not acceptable, 1-really unpleasant[1]); secondly, they were asked to sit on a chair positioned at the points shown in Figure 20 and evaluate the vibration again by using a 5-point scale. (5-not noticeable, 4-noticeable, 3-little disturbing, 2-clearly disturbing, 1-annoying[2]) while another person was walking around. Lastly, they were asked whether or not they accept this kind of floor vibration in their home. 10 people have joined the test. Friedman's two-way analysis of variance of ranks, Mann-Whitney U-test and Chi-square test for association were applied for the data analyses.

6.5 General difficulties during measuring and evaluation

It is of great interests to analyze mode shapes, natural frequencies and damping of a floor structure, as these are predominantly determining the vibration behavior of the floor. Measurements of these dynamic properties in completed buildings meet a number of complications that have to be taken into account when planning the measurements and evaluating the results. The main reasons for these complications are:

- The damping is relatively high in completed buildings
- Averaging over large surfaces smears out natural frequencies and damping since the floor sections are not identical over the whole surface
- There are difficulties to distribute excitation energy over large surfaces and through floating floors
- There are large variations in the force that is caused by walking persons and in persons that are making heel drops. It is most difficult to control the repeatability from one measurement occasion to another.
- Subjective evaluations with a long time between assessments are difficult to use as direct comparisons, as the sensation memory is very short.

In order to meet these complications, the following preparations for measurements were done. Presented in the same order as above:

- A large impact sledgehammer was used to excite the floor. A relatively narrow frequency band was used in the analyses.
- Natural frequencies and damping were evaluated over smaller areas and averaged afterwards.
- Accelerometers with high sensitivity were used for distant measurement points and a sledgehammer was used for the excitation impact.
- The same walking persons were used and they were given precise instructions of how to walk. The shoes were also well specified.
- The subjective evaluations were made for each building phase with a time period between. The test persons were given well defined instructions and questions, therefore the evaluations must be seen as

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[1] In Swedish, 5-perfekt, 4-acceptabelt, 3-knappt acceptabelt, 2-oacceptabelt, 1-klart otrevligt

[2] In Swedish, 5-ej märkbar, 4-märkbar, 3-lätt störande, 2-klart störande, 1-obehagligt

7 Measurement results

7.1 Results of deflection measurement

The deflection measurements were made with the objective to evaluate the stiffness and the classification of the floor. Measurements were made on building phase 4.

Loading 72 kg 0.035 mm
Loading 80 kg 0.055 mm

7.2 Results of hammer impact test measurement

In the hammer impact measurements the acceleration divided by the impact force is measured. This achieves a normalized response of the floor. The results can be seen both in the time domain, as in Figure 21 and 22 and in frequency domain, as in Figure 23, 25, 26. In time domain the longest duration of the vibration frequency is seen. In the frequency domain the natural frequencies can be identified and the damping can be obtained from the sharpness of the response peaks.

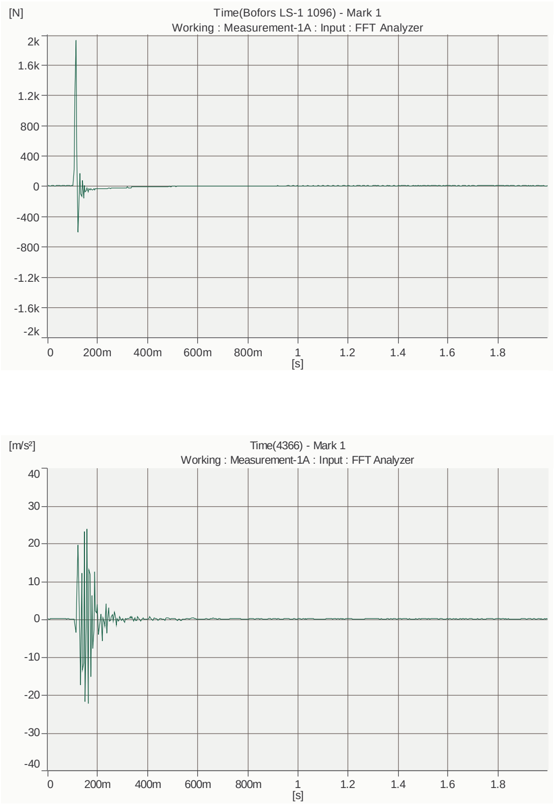


Figure 21: The charts show the typical impact force signal induced by hitting the floor with the sledgehammer (upper chart) and response signal, i.e. the floor response to the induced force. (lower chart).

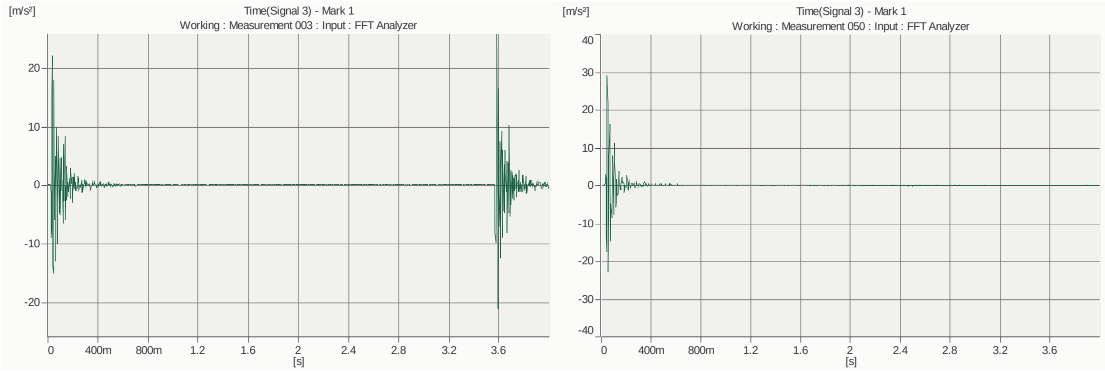


Figure 22: The charts show the response signal of the impact hammer test for construction phase 1 (Left chart) and phase 5 (Right chart)

The decaying characteristic of the response signals shown above may be used as a means to evaluate the damping ratio associated with a given system (Maia, Silva, etc, 1997). Therefore, since the signals measured for phase 1 died out slower than that of phase 5, it indicates qualitatively that the damping ratio of phase 1 is smaller than that of phase 5. The following measurement results in the frequency domain will show the actual damping ratios. Usually vibration is measured in terms of motion and therefore the corresponding FRF may be presented in terms of displacement, velocity or acceleration. Table 5 below gives details of all six of the FRF parameters and of the names variously used for them (Ewins, 2000).

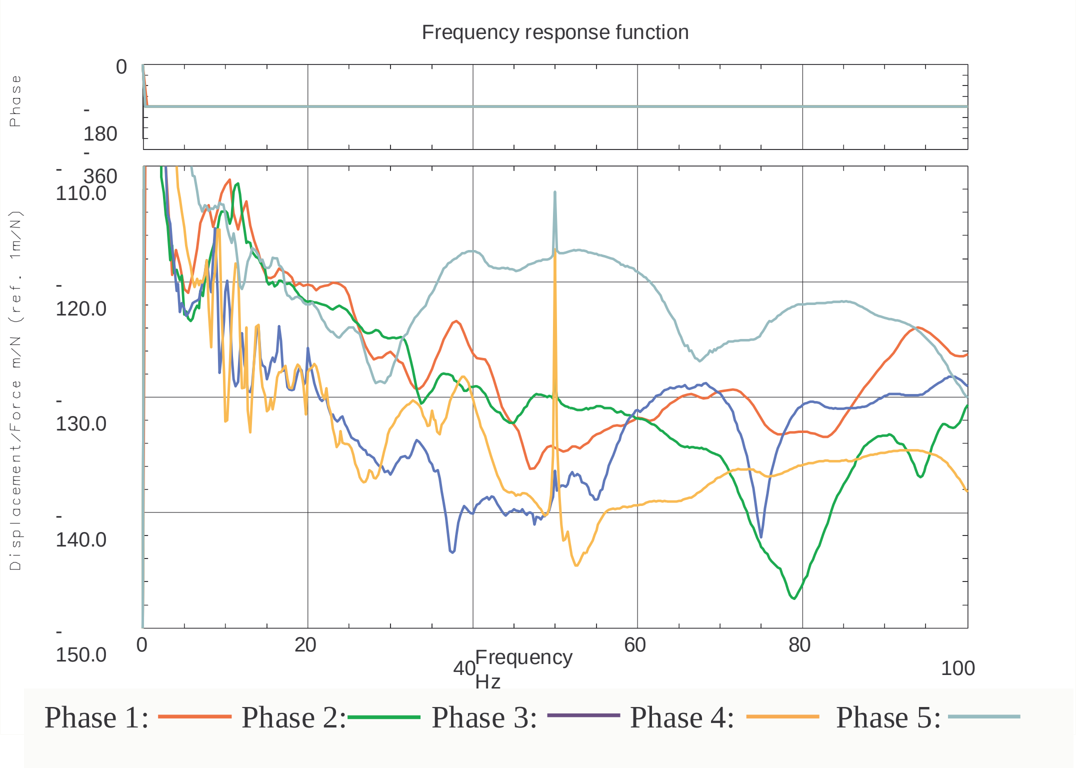
Table 5: Definitions of Frequency Response Functions

Response Parameter R	**Standard FRF: R/F**	**Expression**	**Inverse FRF: F/R**
Displacement	Receptance Admittance Dynamic compliance Dynamic flexibility	$\alpha(\omega)$	Dynamic stiffness
Velocity	Mobility	$Y(\omega)$	Mechanical impedance
Acceleration	Accelerance Inertance	$A(\omega)$	Apparent mass

Since we are more interested in the displacement when dealing with floor vibration, therefore, receptance plots are studied for the impact hammer test.

7.2.1 Construction Phase 1

The receptance peaks in Figure 23 indicate the response at the natural frequencies. Even though the limited number 7) of accelerometers make the analysis of the response a bit uncertain, still, three peaks were found at 8 Hz, 10.5 Hz and 12.5 Hz respectively for building phase 1, which indicate the fundamental frequency of the bare floor (building phase 1) is about 8 Hz, and it is categorized as low frequency floor (Burstrand, Talja, 2001). The calculated damping ratio is about 0.09 for bare floor.



Note: For all plots, the peaks at 50 Hz are due to the disturbance from the electrical circuit, which can be ignored here.

Figure 23: Receptance plots of 5 different building phases for lightweight steel floor part 1

7.2.2 Construction Phase 2

Two peaks were found at 10 Hz and 12 Hz for building phase 2, the fundamental frequency goes upward from 8 Hz of building phase 1 to 12 Hz of building phase 2, it verifies some of the effects that were discussed in Section 5.2. And generally say: there are small changes comparing building phase 1 to phase 2, in other word, adding exterior walls to the lightweight steel floor slightly change the dynamic properties of the floor. Figure 24 gives a further comparison between building phase 1 and 2. The calculated damping ratio is about 0.10 for this building phase.

7.2.3 Construction Phase 3

As mentioned in Section 5.2, the mass of the interior walls will try to lower the natural frequencies, especially the first natural mode, while the added stiffness will try to increase the natural frequency, and if the additional stiffness is strong enough, the walls can provoke new natural modes to occur where the mode shape will be according to half wavelengths for the length of the room or the width of the corridor. The walls may also have a strong reduction effect of the amplitude of the first eigenfrequency as the added stiffness and friction is added near the maximum of the mode. The receptance plot of building phase 3 shows there are peaks at 8 Hz, 9 Hz, 10.5 Hz, 12 Hz, 14 Hz and 16.5 Hz respectively, which means the interior walls provoke some new natural modes. Also the amplitude is lowered compared with building phase 2 and 1.

7.2.4 Construction Phase 4

For building phase 4, at low frequencies, say <20 Hz, the receptance plots look like those in the previous phase. Adding the mass of the floating floor did not lower the natural frequency, which may due to relatively big floor area. The resilient floating floors act as a vibration filter, the reduction effect is clearly shown for higher frequencies.

For both building phase 3 and 4, peaks are found rather sharp and clear, which indicate low damping at those resonant frequencies, which can cause strong discomfort to human being.

7.2.5 Construction Phase 5

At building phase 5, the parquet caused problems as a decreased sound insulation at higher frequencies, thus effective sound insulation materials are strongly recommended; they can be put on the ceiling, for example. The damping ratio is calculated as 0.12 for the finished lightweight steel floor.

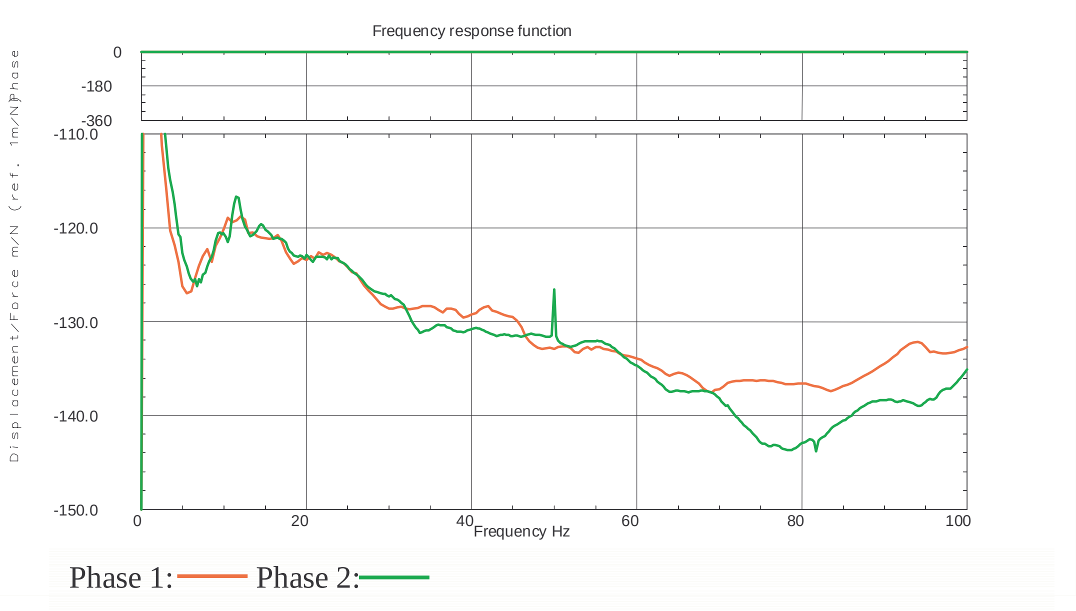


Figure 24: Averaged receptance plots for phase 1 and 2 over the whole steel floor

The comparison between building phase 1 and 2 is shown above, a peak is found at 8 Hz for building phase 1 while a peak is found at 10 Hz for building phase 2, which indicates what is mentioned in Section 5.2 happened. For building phase 2, there is about 6 dB reduction for the frequency range above 70 Hz compared with phase 1. Since two plots have similar shape, a conclusion is made that adding exterior wall to the lightweight steel floor only slightly affect the dynamic properties of the floor. Figure 25 below shows the comparison between inside/outside office measurements for finished lightweight steel floor part 2. There is a peak at 13.5 Hz for outside office measurement while inside office measurement showed the peak at 13.5 Hz was damped and a new peak was found at 17.5 Hz. Lower level is found for outside measurements at the frequency range < 35 Hz, the explanation is that the partition walls block the wave from propagation, particularly for high frequency range.

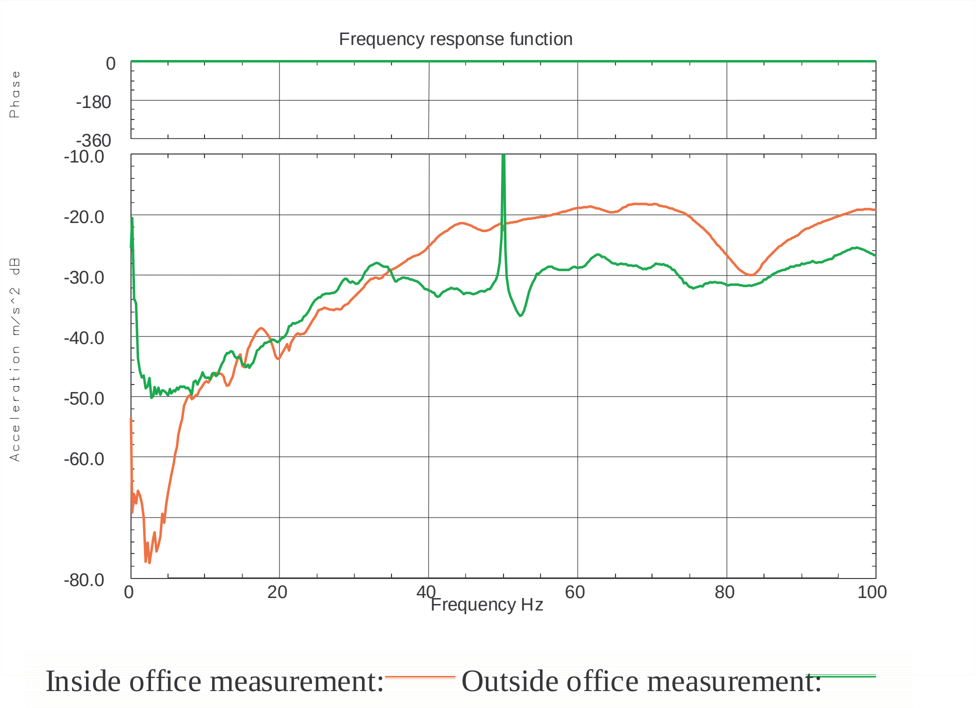


Figure 25: Comparison between inside/outside measurements for finished lightweight steel floor part 2.

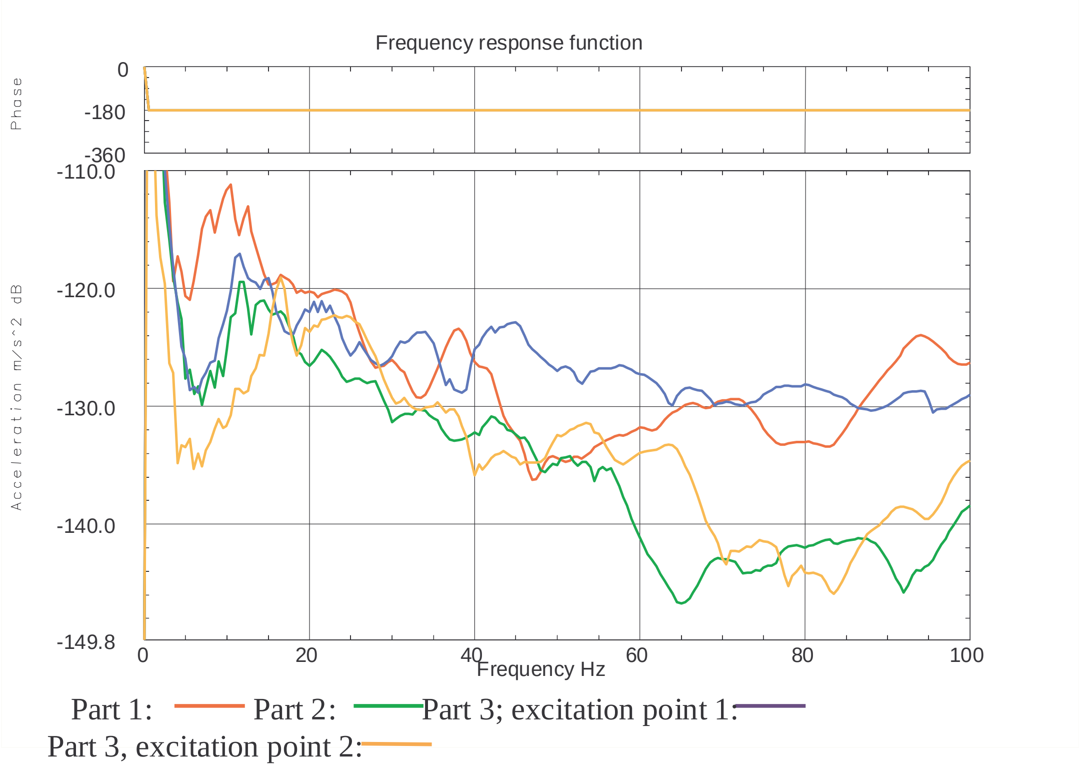


Figure 26: Recpetance plots of building phase 1 for different lightweight steel floor parts

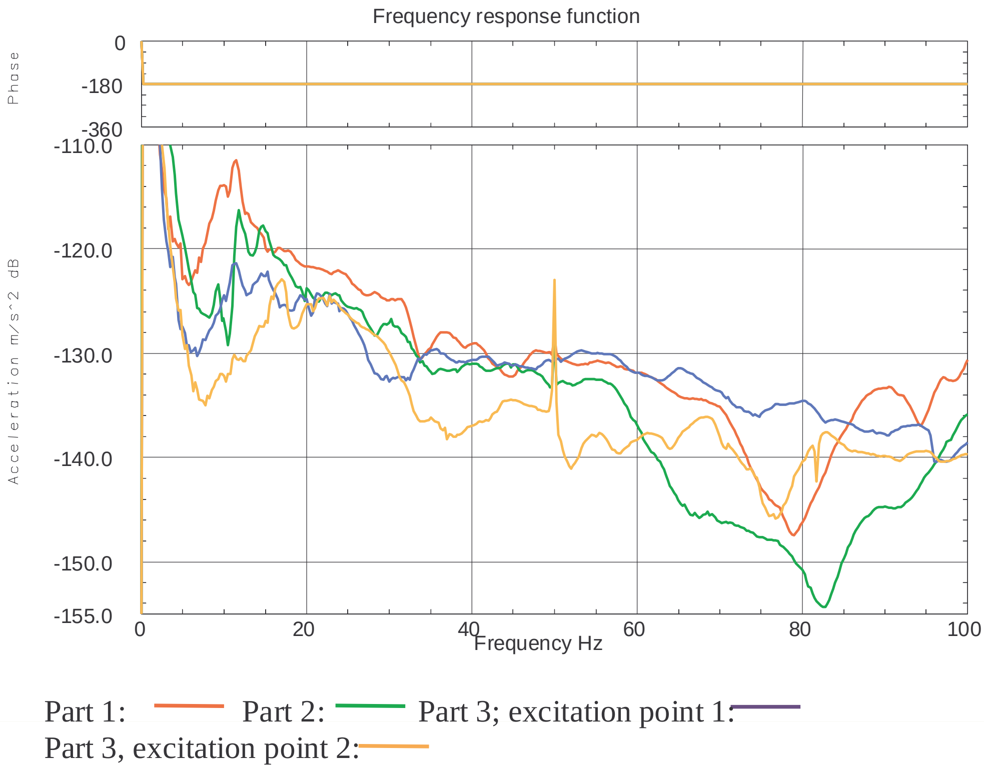


Figure 27: Receptance plots of building phase 2 for different lightweight steel floor

Receptance plots of building phase 1 and 2 for different parts are shown above. For brown curves, corresponding to the measurement of floor part 3, excitation point No.2, peaks are found at relatively higher frequency, which can due to the excitation point is far away to the corner and the supporting beams damped the lower modes.

7.2.6 Conclusion from the measurements

From the measurement results, the following conclusions are made:

1. Adding exterior walls to the bare floor slight changes the dynamic properties of the structure.
2. Adding partition walls to the floor structure will reduce the vibration at high frequency because the partition walls will create a nodal line where the wall is mounted or by generally increasing the stiffness.
3. Adding parquet to the finished floor will cause a decreased sound insulation at higher frequencies, which can be solved by adding sound absorbents to the ceiling.
4. The damping ratio changed from 0.09 for bare floor to 0.12 for the finished floor, but at building phase 3 and 4, new modes appeared which may cause discomfort to human.

Damping ratio was calculated from the impact hammer test by using the equation

$$\zeta = \frac{B_{3dB}}{2 f_{\max}}$$

Where ζ represents the damping ratio, $f_{\max}$ is the frequency where the peak is identified, and B_{3dB} means the 3 dB bandwidth of $f_{\max}$.

The results are shown in 28. For construction phase 3 and 4, damping is decrease as new modes appeared and they are very close to each other, in the figure this is shown as an unspecified rise of damping, see the dashed line. In the figure it can be seen that the damping is steadily increasing the more complex the building becomes.

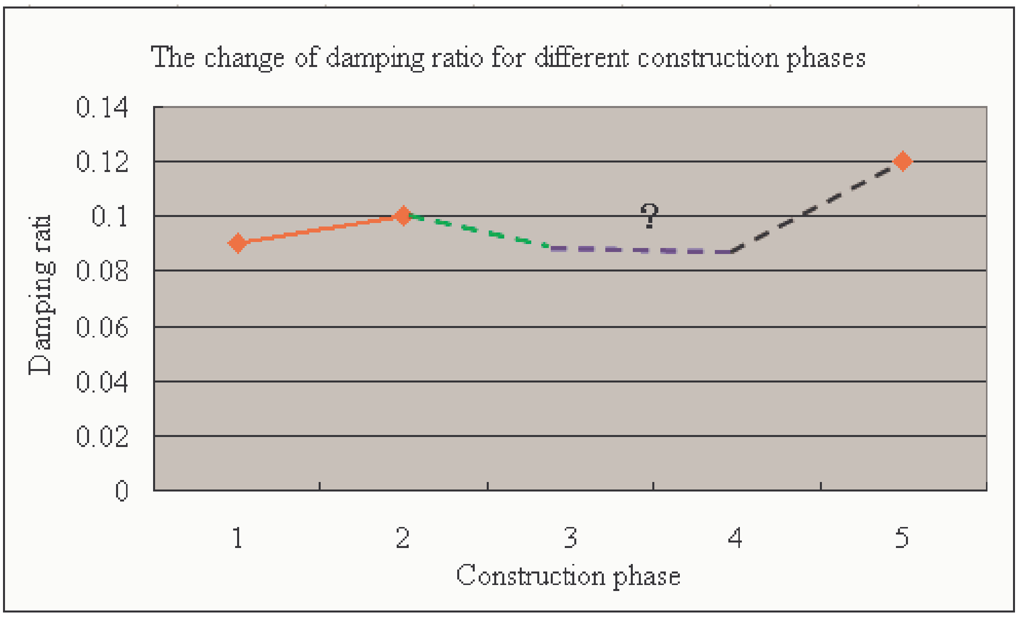


Figure 28: Calculated damping ratio for different construction phases.

7.3 Results of walking induced vibration measurement

In general, a repeated force can be represented by a combination of sinusoidal forces whose frequencies, f, are multiples or harmonics of the basic frequency of the repeating force, e.g. step frequency, f_{step}, for human activities.

The time-dependent repeated force can be represented by the Fourier series (AISC/CISC,1997):

$$F = P\left[1 + \sum \alpha_i \cos(2\pi i f_{step} t + \phi_i)\right]$$

where P = person’s weight
α_i = dynamic coefficient for the harmonic force
f_{step} = step frequency of the activity
t = time
ϕ_i = phase angle for the harmonic

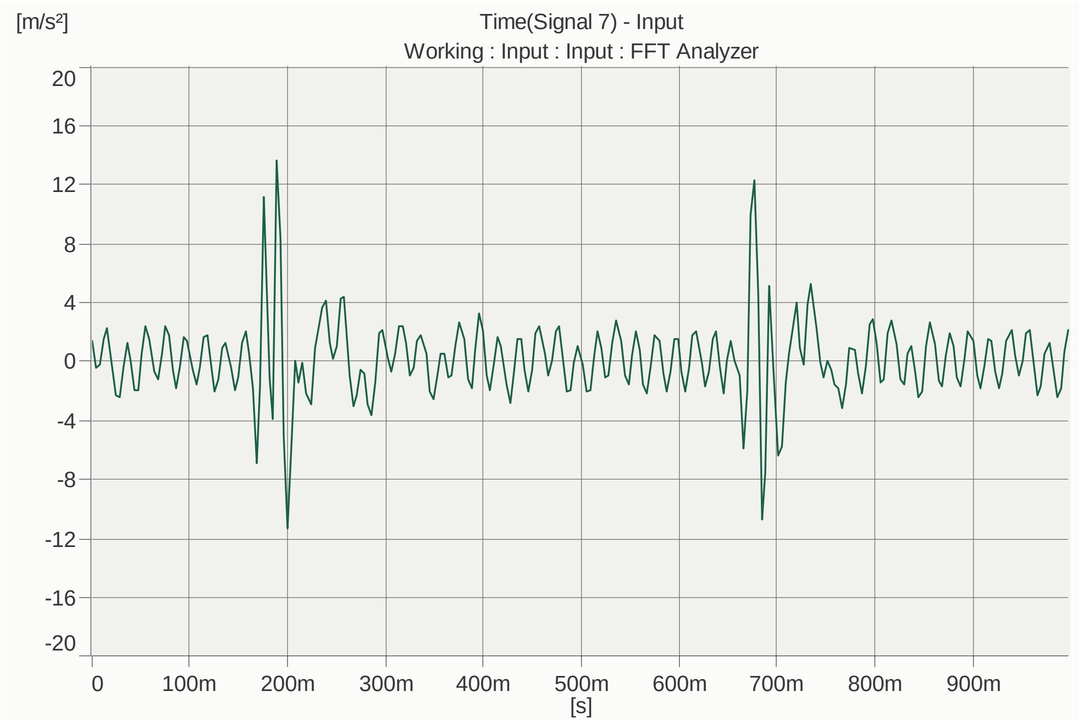


Figure 29: Typical walking induced vibration signal. The step frequency is 2 Hz as it is required for walking test.(Talja et al 2002)

The picture above shows the measurement of the walk force with a step frequency of 2 Hz. It is clear that the walk force is a combination of sinusoidal forces.

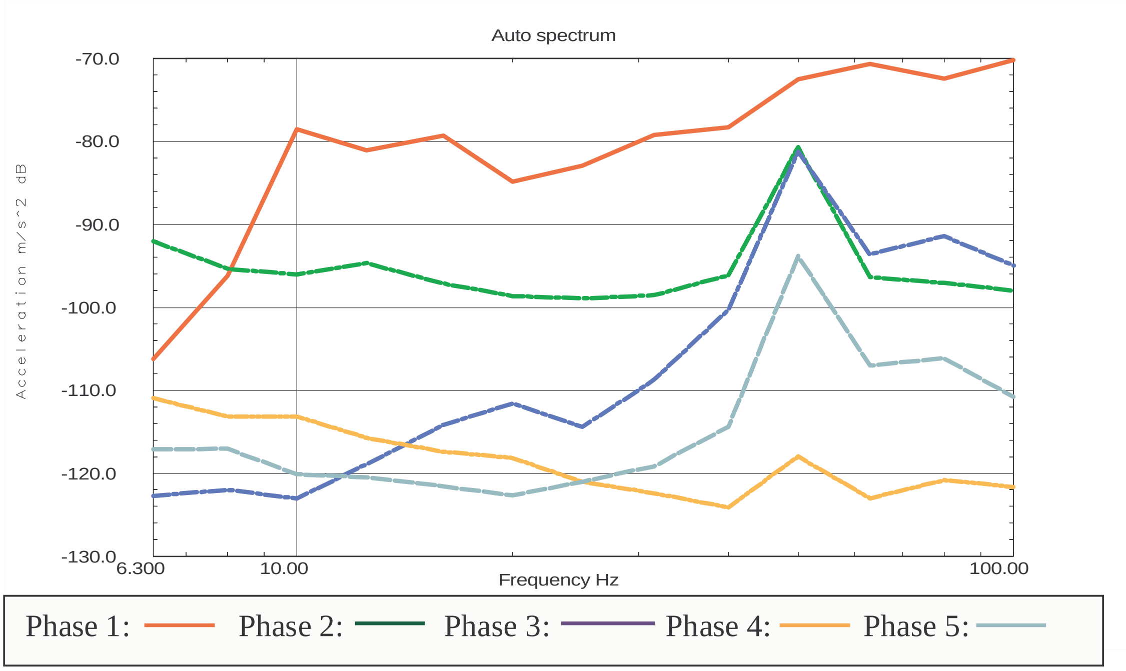


Figure 30: The picture shows the measurement result of walking induced vibration in one-third octave band (6.3 Hz ~ 100 Hz). (Note: The peaks at 50 Hz are due to electrical disturbance of the measurement devices).

By using the Fourier Transform of the walking force signal from time domain to frequency domain, all frequency components were displayed. The resulting acceleration levels in one-third octave band from 6.3 Hz ~ 100 Hz are shown in Figure 29. The results show the sum of all the frequencies that are included in a frequency band, in contradiction to the narrow band results in Figure 23 and Figure 27. Therefore, individual frequencies cannot be seen in the figure. Instead, one-third octave band levels should be interpreted as the sum of e.g. one or two natural frequencies and one component of the walking spectrum. Natural frequencies can thus be identified as individual peaks or as areas of high levels.

For phase 1, tendency to resonant behavior can be identified around 10 Hz as higher levels in this frequency. It can be seen from the flatness of the curves of phase 2-5 that the natural frequencies are strongly damped when exterior walls, interior walls floating floors and furniture are added to the floor.

It can also be seen that the overall strongest vibration levels are in phase 1, and that adding an exterior wall to the bare floor decreased the overall vibration level by as much as about 15 dB. (This is higher than expected and can partially be due to the inconsistent walking.)

Adding exterior walls to the floor damped the resonant frequency at 10 Hz compared with the bare floor, but a tendency to natural frequency response is found at about 12.5 Hz.
Adding partition walls on the floor construction strong reduced the resonant behavior up to 12.5 Hz, but a tendency of a resonant frequency is found at around 20 Hz.
Floating floor is a very good vibration damper, both for floor resonances and for the impacts of the foot steps. That is why the construction in phase 4 has the lowest vibration level from 25 Hz till 100 Hz. The increased levels above 25 Hz in phase 5 is probably due to resonances in the parquet floor and from the harder impact of walking as explained in the earlier section.

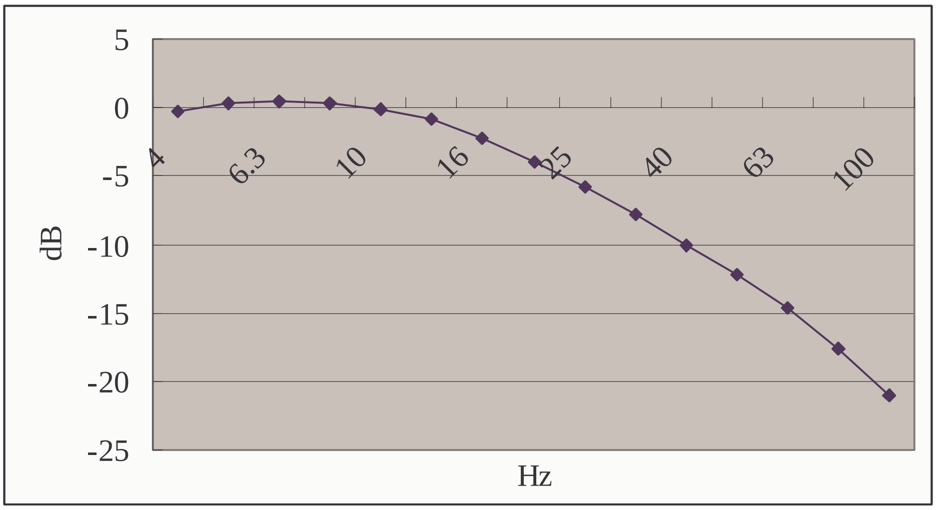


Figure 31: Plot of W_k weighting factor according to ISO 2631-1:1997 in the frequency range 4~100 Hz.

W_k is a frequency weighting factor defined for the z-axis or vertical axis (ISO 2631-1,1997). Considering whole-body vibration, a person is most sensitive for vibrations in the range 5~8 Hz, therefore W_k emphasizes the vibration in these one-third octave bands, see Figure 31 above.
In order to correlate the walking induced vibration with subjective vibration perception, according to Talja, 2002., the measured walking induced vibration was filtered by curve W_k (ISO 2631-1,1997), and then dividing the maximum acceleration by value 0.005 m/s^2, the result is shown below

Table 6: Classification of the floors according to Talja et al 2002

Construction phase	ISO factor	Class	Body perception description
1	229.6	E	The vibrations are strongly perceptible
2	51.8	E	
3	5.9	B	The vibrations are barely perceptible
4	5.8	B	
5	0.3	A	The vibrations are usually imperceptible

7.4 Results of heel drop induced vibration measurement

Due to the fact that heel drop induced vibrations are very much dependant on the body weight of the experimenter, i.e. how much force he exerted on the floor, etc, the results of the heel drop tests are not unambiguous. Therefore explanation and analysis of the results are at this moment omitted.

7.5 Results of subjective evaluation of walking induced vibration

The acceptance ratio is 10%, 14.3% and 75% respectively from building phase 1 to 3, see Figure 32 below. Friedman test was performed to see if there are differences among those tested conditions (refer to three different construction phases). Later on, Mann-Whitney U-test for association showed that subjects only felt annoying of floor vibration when somebody was walking around, and they did not feel uncomfortable when they walked on the floor structures. Chi-square test results revealed that there are no differences of people’s perception of floor vibration for construction phase 1 and 2, but there are significant differences between phase 1 and 3 or phase 2 and 3, which means bare floor and adding out walls to the bare floor were not accepted in terms of floor vibration, but adding partition wall was graded acceptable. This result is consistent with acceptance ratio, see Figure 32 below.

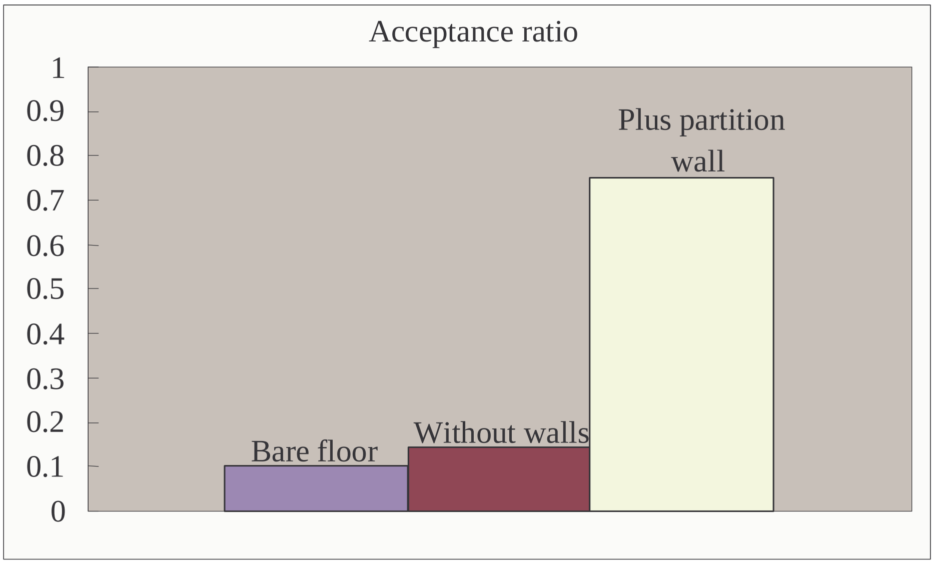


Figure 32: Acceptance ratio as result of the subjective evaluation.

The results from subjective evaluation of floor vibration are consistent pretty well with the classification of floor based on the results of the walking test.

8 Discussion

8.1 Design due to flanking construction

A lightweight steel floor is strongly influenced by how the construction is designed at the boundaries of the floor and the connection to walls and to the supporting structure, *the flanking construction*. The damping, stiffness and natural frequencies of the floor, will be influenced by the design of connections.

The boundaries will add damping to the floor, which is caused by how much energy that is absorbed when the vibration waves reaches and are being reflected at the boundaries. If the boundaries include high friction and allow a relative motion between structures, damping will increase. If the boundaries are weak and the coupling is strong, the damping of the floor may also increase, as vibration energy will propagate into the walls and supporting structure. The disadvantage then is that that energy will not be lost into heat, but instead propagate as flanking noise and vibration to the building structure.

The walls can add stiffness to the floor, depending on how much pressure the wall sets to the floor. If the pressure or bolted contact becomes strong enough the fundamental frequency of the floor will be increased. In that case the damping may also be reduced, as the relative motion between structures will also decrease.

If the stiffness and rigidity of the supporting girder and walls are low, these can give interfering vibrations to the floor.

General advice regarding flanking constructions:

- If more stiffness is needed, use stiff girders, strong couplings and the added pressure that can be obtained from the exterior walls.
- If more damping is needed, design for as much friction and relative motion between structures as possible.
- If there are problems with flanking transmission of sound, use as flexible coupling as possible and avoid momentum transfer.

8.2 The influence by interior walls on floor vibrations

Interior walls can give both added mass, added stiffness, contributions of nodal lines for the natural modes and add damping through friction.

- The added weight of the interior walls will lower the fundamental frequency. In our example, the fundamental frequency will be reduced by approximately 2 Hz.
- The added stiffness will increase the fundamental frequency. In the experiments the interior walls gave two natural frequencies that were identifiable in the low frequency range, both one with lower and one with higher frequency.
- The interior walls add damping through friction to the floor. The interior walls also reduce the vibration levels by the added pressure, tension and mass that the walls give on the floor.

- The position of the walls and the rigidity of the coupling between the walls and the floor can provoke new modes or enhance e.g. the second mode if the wall is mounted close to a nodal line, e.g. in the middle of the floor.

Recommendations regarding interior wall constructions:
Interior walls will increase damping and reduce the vibration levels of lightweight floors. If a strong effect is wanted there should be a strong coupling of the wall to the floor. The position of the wall can be used to influence the damping of the fundamental mode, i.e. build the wall where the amplitude is high, but not exactly in the middle of the floor.

8.3 The influence by floating floors on floor vibrations

Floating floors are very efficient to increase damping through friction and to decrease the impact force from walking.

Recommendations regarding floating floors:
The floating floors should have an elastic layer that is relatively stiff in order to act as an efficient vibration damper and in order to avoid compression problems from furniture. In the example a mineral wool layer of approximately 130 kg/m^3 was chosen. The top boards should be stiff and heavy in order to efficiently utilize the friction damping by the elastic layer. A recommended construction is to use double floor plasterboards.

8.4 The influence by parquet floor and furniture on floor vibrations

Parquet floors will increase vibrations at higher frequencies, in the experiments above 25 Hz. They will also increase the sound from walking with hard soles. For vibration comfort there was no influence. There was found a damping influence by the combination of furniture and parquet floor.

Recommendations regarding parquet floors:
If there are problems with vibrations or sound insulation at high frequencies a parquet floor *with added damping* should be used. Experimentation could also be done with the elastic layer underneath the parquet. There are alternatives like various cloth or cork particles.

8.5 Comparison of measured results to acceptance criteria

In this report, vibrations from lightweight steel floors induced by impact hammer, and walking were analyzed. The vibration classification of floors based on measurements of walking induced vibrations correlated well with subjective evaluations of floor vibrations for different construction phases. The results illustrate the usefulness of the method for applications. For the impact hammer test, the damping ratios were found at 0.09, 0.10, and 0.12 respectively for construction phase 1, 2 and 5. Damping ratio has the tendency to decrease for phase 3 and 4 since new modes appeared and difficult to distinguish from each other.

Clear fundamental modes were found at approximately 10 Hz for phase 1 and 2. The FRF measurements prove that adding exterior walls slight change the dynamic properties of the floor since FRF curves are quite similar from measurements of building phase 1 and 2. There are new modes appeared in phase 3 and 4 and are quite close to each other, generally, the levels are lower than the previous 2 phases which means effective vibration reduction. Parquet floors caused some high frequency components to be signified.
For the walking test, the vibration classification of floors is associated with the peak RMS-accelerations. The results confirm further that adding exterior walls to the floor structure wouldn’t change the dynamic properties of it. Floating floor is very good damper for higher frequency range vibrations, but on the other hand, adding parquet to the floor may cause high frequency vibrations. Adding interior walls strongly suppressed the resonant vibrations at quite long frequency range (<12.5 Hz). According to Talja’s method the vibrations are strongly perceptible in construction phase 1 and 2, for construction phase 3 and 4, the vibrations are barely perceptible; the vibrations are usually imperceptible for phases 5.

Subjective assessment of the vibrations implies subjects perceived the vibration level on phase 1 as not acceptable, the acceptance ratio is increased a little for phase 2, as for phase 3, the vibrations are satisfactory.

9 Future work

Investigate the influence of the flanking connections, with the objective to increase the understanding, develop new prediction models and to develop new engineering solutions.

The flanking connection influences the floor properties in several ways:

1. The connection of the floor to exterior walls will add damping to the floor.
2. The connections may also add stiffness to the floor.
3. It is also well known that flank transmission of sound is a common problem in lightweight building structures.
4. The stiffness and rigidity of the supporting girder and walls give interfering vibrations to the floor.

There is a strong need to improve the knowledge about how these factors exactly influence the floor vibrations and the impact sound behavior of the floor

Improvement of the understanding of subjective responses and of subjective evaluation methods.

1. It is not known what properties of the floor that people are annoyed by, e.g. natural modes, direct response, beat modulation caused by double resonances etc. In order to optimize floor design for good vibration comfort the knowledge about these properties should be improved. It can be done through motion simulators and subjective evaluation.
2. Since the vibration classification of floors based on the intensity of floor vibrations is clearly stated, a subjective evaluation questionnaire using the same definition of the classification can be a good association of subjective assessment and objective measurement.

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