Andres Bäckblom

Vibration of Long-Span Floors in Sport Facilities

Master’s thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Technology.

Espoo, September 4, 2017
Supervisor: Professor Risto Kiviluoma
Advisors: Veikko Leino, M.Sc. (Tech.) and Hannu Nissinen, M.Sc. (Tech.)
Recently, significant floor vibration problems have arisen due to rhythmic activities in sport facilities. The main reasons for these problems are increased human activities, increased floor spans, as well as low damping and mass in structures. The principal factor behind most mechanical vibration problems in buildings is resonance. Resonance occurs when a structure is subjected to a dynamic force with a frequency close to the natural frequency, which causes an excessive amplification of vibration. Increased floor vibration may also result in other disturbances, such as structure-borne sound. However, the principal factor behind most acoustic problems is impact forces.

Therefore, the aim of this thesis is to introduce approaches to estimate floor vibrations and clarify what considerations to make when designing long-span floor structures in sport facilities for both vibration serviceability and acoustic performance. Floor vibrations of three different floor structures; a concrete structure, a concrete element structure and a steel-concrete composite structure; are estimated using design guides and finite element analysis (FEA) software. The acoustic performance of these floor structures is analysed in FEA software.

The results show that floor structures subjected to rhythmic excitation require a high natural frequency to avoid resonant behavior. When the natural frequency is higher than approximately 9 Hz, there is no significant floor acceleration. Furthermore, heavyweight floor structures are less sensitive to vibrations. The natural frequencies are lower in the design guide calculations, compared to the results in the FEA software. All analyzed floor structures meet the recommended acceleration limits for occupants in a sport facility. However, neither of the floor structures, with no added vibration isolation, satisfies the criteria for impact sound insulation in sport facilities.
Viime aikoina on syntynyt merkittäviä väärähtelyongelmia liikuntatilojen välipohjissa rytmisen toiminnan vuoksi. Ongelmien tärkeimmät syyt ovat lisääntynyt ihmistoiminta, pidemmät jännevälit sekä vaiemnukksen että massan vähennyset rakenteessa. Resonanssi on tärkein tekijä rakennuksen mekaanisten väärähtelyongelmien takana. Resonanssi tapahtuu kun rakenteeseen kohdistuu dynaaminen voima, jonka kohteen on ominaistaaajan lähellä, aiheuttaen liialliset väärähtelyt. Lisääntynyt välipohjaväärähtely voi myös aiheuttaa muita häiriöitä, kuten runkoääniä. Törmäysvoimat on kuitenkin tärkein tekijä akustisten ongelmien takana.

Opinnäytetyön tavoite on esittää lähestymistapojen välipohjaväärähtelyjen arvioimiseksi ja selvittää mitkä asiat pitkästään ottaa huomioon välipohjien suunnittelussa liikuntatiloissa pitkillä jännevälille, väärähtelyyn ja akustiikan kannalta. Välipohjaväärähtely on arvioitu kolmella eri välipohjarakenteella; betonirakenteeseen, betonielementtirakenteeseen ja liittorakenteeseen. Arvioinnissa on käytetty sekä suunnitteluvapaata että FEA-ohjelmistoa. Välipohjen akustiset ominaisuudet on analysoitu FEA-ohjelmistossa.


**Avainsanat** välipohja, väärähtely, rytminen toiminta, ominaistajuus, askelääneneristyks
Författare: Andres Bäckblom

Titel: Vibrationer i golv med långa spann i idrottslokaler

Utbildningsprogram: Konstruktions- och byggnadsproduktion

Huvudämne: Konstruktionsteknik

Övervakare: Professor Risto Kiviluoma

Handledare: DI Veikko Leino och DI Hannu Nissinen

Datum: 04.09.2017

Sidantal: 58-61

Språk: Engelska


Syftet med denna avhandling är att presentera tillvägagångssätt för att uppskatta golvvibrationer och klargöra vad som bör tas i beaktande när man planerar golvkonstruktioner med långa spann i idrottslokaler, med hänsyn till både vibrationer och akustik. Golvvibrationer i tre olika golvkonstruktioner; en betongkonstruktion, en betongelementskonstruktion och en samverkanskonstruktion; uppskattas med användning av designguider och FEA-mjukvara. Golvkonstruktionernas akustiska egenskaper analyseras i FEA-mjukvara.


Nyckelord: golv, vibration, rytmisk aktivitet, egenfrekvens, stegljudsisolering
Acknowledgements

This master’s thesis has been written for Sweco Rakenneteknikka Oy. I would like to express my deepest gratitude to Veikko Leino and Hannu Nissinen at Sweco Rakennetekniikka Oy for their support and guidance throughout the process of researching and writing this thesis.

I would also like to thank Professor Risto Kiviluoma at Aalto University for valuable advice and comments on the thesis.

A special thanks to Patrick Grahn and other staff at COMSOL for their technical assistance.

Finally I wish to thank my family and friends for their support and encouragement throughout this process.

Espoo, September 4, 2017

Andres Bäckblom
# Contents

## Abbreviations and Acronyms

## Symbols

<table>
<thead>
<tr>
<th>1 Introduction</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1 Background Information</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Aim and Objectives</td>
<td>2</td>
</tr>
<tr>
<td>1.3 Methodology</td>
<td>2</td>
</tr>
<tr>
<td>1.4 Scope and Limitations</td>
<td>3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2 Introduction to Floor Vibration</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1 Dynamics of Structures</td>
<td>4</td>
</tr>
<tr>
<td>2.1.1 Single-Degree-of-Freedom System</td>
<td>4</td>
</tr>
<tr>
<td>2.1.2 Multi-Degree-of-Freedom System</td>
<td>6</td>
</tr>
<tr>
<td>2.2 Types of Vibration</td>
<td>6</td>
</tr>
<tr>
<td>2.2.1 Walking</td>
<td>6</td>
</tr>
<tr>
<td>2.2.2 Rhythmic Activity</td>
<td>7</td>
</tr>
<tr>
<td>2.2.3 Mechanical Equipment</td>
<td>7</td>
</tr>
<tr>
<td>2.3 Natural Frequency of Vibration and Modal Mass</td>
<td>7</td>
</tr>
<tr>
<td>2.3.1 Determination of Dynamic Properties of Floor Structures</td>
<td>8</td>
</tr>
<tr>
<td>2.3.2 Natural Frequency and Modal Mass from Mode Shape</td>
<td>8</td>
</tr>
<tr>
<td>2.3.2.1 Isotropic Plates and Beams</td>
<td>8</td>
</tr>
<tr>
<td>2.3.2.2 Orthotropic Floor Systems</td>
<td>9</td>
</tr>
<tr>
<td>2.3.3 Natural Frequency from the Self-Weight Approach</td>
<td>10</td>
</tr>
<tr>
<td>2.3.4 Natural Frequency from the Dunkerley Approach</td>
<td>11</td>
</tr>
<tr>
<td>2.4 Damping</td>
<td>11</td>
</tr>
<tr>
<td>2.5 Resonance</td>
<td>14</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3 Introduction to Structure-Borne Sound</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1 Classification and Sources of Sound</td>
<td>17</td>
</tr>
<tr>
<td>3.1.1 Airborne Sound</td>
<td>17</td>
</tr>
</tbody>
</table>
3.1.2 Structure-Borne Sound .................................. 17
3.2 Basic Concepts of Acoustics ............................... 18
  3.2.1 Sound Pressure and Sound Pressure Level ............ 18
  3.2.2 Frequency Bands .................................. 19
  3.2.3 Frequency Weighting ................................ 20
  3.2.4 Equivalent Sound Absorption Area and Reverberation
        Time .................................................. 21
3.3 Impact Sound Insulation .................................. 22
  3.3.1 Weighted Reduction of Impact Sound Pressure Level . 23

4 Noise and Vibration Control ................................. 25
  4.1 Vibration Isolation and Absorption ...................... 25
    4.1.1 Resilient Floor Covering ......................... 25
    4.1.2 Floating Floor .................................. 26
    4.1.3 Spring and Elastomeric Vibration Isolators ........ 26
    4.1.4 Tuned Mass Damper ................................ 28
  4.2 Sound-Absorbing Materials ............................... 28
    4.2.1 Porous Material .................................. 28
    4.2.2 Perforated Board ................................ 29
  4.3 Criteria and Limit Values ............................... 29
    4.3.1 Criteria for Floor Vibrations Due to Rhythmic Activities 29
    4.3.2 Acoustic Criteria ................................ 32
    4.3.2.1 Criteria for Impact Sound Insulation in Sport
              Facilities ..................................... 32
    4.3.2.2 Criteria for A-Weighted Sound Level ........... 33

5 Case Study of Long-Span Floors .......................... 34
  5.1 Concrete Structures .................................. 34
  5.2 Concrete Element Structures .......................... 35
  5.3 Steel-Concrete Composite Structures .................. 35

6 Calculation and Evaluation ................................ 37
  6.1 Analysis of Mechanical Vibration ...................... 37
    6.1.1 Concrete Structures ............................. 37
    6.1.2 Concrete Element Structures ..................... 38
    6.1.3 Steel-Concrete Composite Structures ............. 38
  6.2 Analysis of Acoustics ................................ 39
    6.2.1 Concrete Structures ............................. 43
    6.2.2 Concrete Element Structures ..................... 43
    6.2.3 Steel-Concrete Composite Structures ............. 45
  6.3 Special Cases .......................................... 47
6.3.1 Steel-Concrete Composite Structures in a Multi-Story Building ........................................ 47
6.3.2 Steel-Concrete Composite Structures with a Resilient Floor Covering ................................. 48
6.3.3 Steel-Concrete Composite Structures with a Floating Floor .............................................. 49
6.4 Comparison and Conclusion ............................................. 49
6.4.1 Mechanical Vibration .................................................. 49
6.4.2 Acoustics ................................................................. 50

7 Conclusions ............................................................... 52

Bibliography ............................................................... 55

A Tables

B PTC Mathcad Calculations
   B.1 Concrete Structures ..............................................
   B.2 Concrete Element Structures .................................
   B.3 Steel-Concrete Composite Structures ......................
   B.4 Steel-Concrete Composite Structures in a Multi-Story Building

C Acoustic Calculations
   C.1 Concrete Structures ..............................................
   C.2 Concrete Element Structures .................................
   C.3 Steel-Concrete Composite Structures ......................
   C.4 Steel-Concrete Composite Structures with a Resilient Floor Covering ...........................
   C.5 Steel-Concrete Composite Structures with a Floating Floor
## Abbreviations and Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DOF</td>
<td>Degree of freedom</td>
</tr>
<tr>
<td>FEA</td>
<td>Finite element analysis</td>
</tr>
<tr>
<td>MDOF</td>
<td>Multi-degree-of-freedom system</td>
</tr>
<tr>
<td>SDOF</td>
<td>Single-degree-of-freedom system</td>
</tr>
<tr>
<td>SPL</td>
<td>Sound pressure level</td>
</tr>
<tr>
<td>TMD</td>
<td>Tuned mass damper</td>
</tr>
</tbody>
</table>
Symbols

Latin upper case letters

\( A \)  
Equivalent sound absorption area

\( A_0 \)  
Reference equivalent sound absorption area

\( BW \)  
Bandwidth

\( C \)  
Damping matrix in a dynamic system

\( E \)  
Modulus of elasticity

\( F \)  
Force

\( I \)  
Moment of inertia

\( K \)  
Stiffness matrix in a dynamic system

\( L_A \)  
A-weighted sound level

\( L_{A,i} \)  
A-weighted sound pressure level in frequency bands

\( L_{A,eq,T} \)  
A-weighted equivalent sound level

\( L_i \)  
Impact sound pressure level in frequency bands

\( L_r \)  
Normalized impact sound pressure level

\( L_{n,w} \)  
Weighted normalized impact sound pressure level

\( L_p \)  
Sound pressure level

\( L_{p,tot} \)  
Total sound pressure level

\( \Delta L_w \)  
Weighted reduction of impact sound pressure level

\( M \)  
Total mass

\( M \)  
Mass matrix in a dynamic system

\( M_{mod} \)  
Modal mass

\( S \)  
Surface area

\( T \)  
Observation period

\( T_{60} \)  
Reverberation time

\( |T_f| \)  
Force transmissibility

\( U_{max} \)  
Initial energy of a system

\( \Delta U \)  
Energy dissipated per cycle

\( V \)  
Room volume

\( W \)  
Weight of a jumper
Latin lower case letters

\( a_0 \) Acceleration limit
\( a_m \) Effective maximum acceleration
\( a_p \) Peak acceleration
\( c \) Viscous damping coefficient
\( c_{cr} \) Critical damping coefficient
\( d \) Drop distance of the hammer
\( f \) Forcing frequency
\( f_o \) Resonance frequency
\( f_c \) Center frequency
\( f_D \) Damping force in a dynamic system
\( f_L \) Lower frequency band limit
\( f_n \) Natural frequency
\( f_r \) Repetition frequency of a standard tapping machine
\( f_s \) Resisting force in a dynamic system
\( f_{step} \) Step frequency
\( f_U \) Upper frequency band limit
\( g \) Gravity
\( k \) Stiffness
\( m \) Mass
\( m' \) Mass per unit area of a floating structure
\( p \) Sound pressure
\( p_0 \) Reference sound pressure
\( p(t) \) External force in a dynamic system
\( \mathbf{p}(t) \) External force vector in a dynamic system
\( s' \) Dynamic stiffness of a resilient layer
\( u \) Displacement in a dynamic system
\( \mathbf{u} \) Displacement vector in a dynamic system
\( \dot{u} \) Velocity in a dynamic system
\( \mathbf{u} \) Velocity vector in a dynamic system
\( \ddot{u} \) Acceleration in a dynamic system
\( \ddot{u} \) Acceleration vector in a dynamic system
\( v_0 \) Velocity of hammer at impact
\( w_o \) Effective weight of participants
\( w_l \) Effective total weight of floor structure and participants
Greek lower case letters

$\alpha$  Dynamic coefficient
$\alpha_s$  Sound absorption coefficient
$\delta$  Deflection
$\delta_{\text{max}}$  Maximum deflection
$\zeta$  Damping ratio
$\eta$  Loss factor
$\phi$  Phase lag
$\omega$  Angular frequency
$\omega_n$  Natural angular frequency
Chapter 1

Introduction

1.1 Background Information

Stiffness and structural dynamics are nowadays principal issues for floor serviceability in the design of floor structures. While stiffness criteria have existed for almost 200 years, structural dynamics was ignored until about 50 years ago when problems arose with vibrations caused by walking on floors that satisfied general stiffness criteria [19].

More recently, significant floor vibration problems have arisen due to rhythmic activities [19]. Floor vibrations in buildings are disturbing to the occupants and, in some cases, unacceptable for human safety. The main reasons for these problems are increased human activities, such as aerobics and dancing; decreased natural frequency as a result of increased floor spans; and decreased damping and mass in structures [2].

Resonance is the principal factor behind most mechanical vibration problems in buildings. Resonance occurs when a structure is subjected to a dynamic force with a frequency close to the natural frequency. This causes an excessive amplification of vibration, which is controlled only by the damping of the structure [2].

The trend towards long-span floors has resulted in more common use of lightweight floor structures, such as steel framed floor structures [25]. Therefore, most existing design guides for floor vibrations are concentrated on steel framed floor structures. Regular concrete floor structures have performed well, much due to their heavy weight, with regard to vibration serviceability. Still, the use of pre-stressing and stronger concrete has resulted in floor structures with longer spans and slenderer cross-sections. This means that pre-stressed floor structures are more sensitive to vibrations due to their somewhat light weight [14].
CHAPTER 1. INTRODUCTION

The human perception of vibration is very subjective. Various occupants react differently to the same vibration, and the reaction also depends highly on what the occupants are doing. Therefore, acceleration limits for each occupancy are used to determine whether the floor structure meets serviceability requirements [19].

Increased floor vibration may also result in additional disturbances, such as structure-borne sound. Structure-borne sound occurs when the floor structure is set into vibration. The vibrations are then transmitted to other building elements throughout the building structure. Therefore, one source of structure-borne sound could cause annoyance to many different occupants. Due to numerous sources and transmission paths, structure-borne sound in buildings can be difficult to predict [4].

1.2 Aim and Objectives

The aim of this thesis is to introduce approaches to estimate floor vibrations and clarify what considerations to make when designing long-span floor structures in sport facilities for both vibration serviceability and acoustic performance.

The primary objective of the thesis is to outline the fundamental principles of floor vibration and analyze three different types of floor structures. The secondary objective is to analyze the acoustic performance of the floor structures with regard to impacts and present how to reduce structure-borne sound in the space below.

1.3 Methodology

The thesis begins with a literature review, where the basic principles of floor vibration and acoustics are investigated. The principles of acoustics are mainly focused on structure-borne sound. Criteria and limit values for sound and vibration are also provided through literature review.

Mechanical vibration analyses of the floor structures are carried out in a math software using design guides. All floor structures are designed to have approximately the same natural frequency.

A model of each floor structure is built in a finite element analysis (FEA) software. Mechanical vibration analyses of the floor structures are carried out in the FEA software and the results are then compared with those of the design guide calculations. All acoustic analyses are mainly carried out in the FEA-software.
1.4 Scope and Limitations

This thesis has limited its scope to the vibration and acoustic analysis of long-span floors subjected to rhythmic activities. Vibrations due to walking and mechanical equipment are ignored since the floors are located in sport facilities. In the acoustic analysis, no additional structure-borne or airborne sound sources are taken into consideration.
Chapter 2

Introduction to Floor Vibration

2.1 Dynamics of Structures

2.1.1 Single-Degree-of-Freedom System

A dynamic system consists of one or multiple masses. For dynamic analysis, the number of displacements required to determine the displacements of all the masses is called the number of degrees of freedom (DOFs) [7].

A simple model of a floor structure can be considered as a single-degree-of-freedom system (SDOF). The floor structure has only one DOF, one displacement, for dynamic analysis if the mass is concentrated at one location [7].

A SDOF model can be used to determine the displacement, velocity and acceleration of a structure caused by a dynamic force. An idealized SDOF system consists of three separate components: a mass component, a stiffness component and a damping component. All the forces acting on the mass \( m \) at some instant of time are shown in Figure 2.1. The external force \( p(t) \) is acting in one direction while the resisting force \( f_S \) and the damping resisting force \( f_D \) are acting in the opposite direction [7].

At small deflections, as in the case of vibrations in a floor structure, the force-displacement relation is linear. For a linear system, the resisting force is [7]

\[
f_S = ku
\]  

(2.1)

where

\( k \) is the stiffness of the system (N/m),
\( u \) is the displacement (m).
Damping is the process which makes the free vibration of a structure steadily diminish in amplitude. The reason for this is that the energy of the vibrating structure is dissipated by various mechanisms. The damping in a SDOF structure can be considered a linear viscous damper. This means that the damping force is equivalent to the velocity across the damper [7]:

\[ f_D = c \dot{u} \]  \hspace{1cm} (2.2)

where

- \( c \) is the viscous damping coefficient (Ns/m),
- \( \dot{u} \) is the velocity (m/s).

Using the forces acting on the mass and Newton's second law of motion on the SDOF system in Figure 2.1 gives [7]

\[ p(t) - f_S - f_D = m \ddot{u} \]  \hspace{1cm} (2.3)

where

- \( m \) is the mass (Ns²/m),
- \( \ddot{u} \) is the acceleration (m/s²).

After substituting the terms with Equations 2.1 and 2.2, it can be written as
\[ m \ddot{u} + c \dot{u} + ku = p(t), \] (2.4)

which is the equation of motion [7].

2.1.2 Multi-Degree-of-Freedom System

A system with a finite number of DOFs is called a multi-degree-of-freedom system (MDOF). The system consists of multiple masses with different displacements, e.g., a floor structure divided into smaller parts. Since the system consists of multiple parts, the terms in the equation of motion for a MDOF system contain matrices and vectors and can be written as [7]

\[ M \ddot{u} + C \dot{u} + Ku = p(t) \] (2.5)

where

- \( M \) is the mass matrix,
- \( \ddot{u} \) is the acceleration vector,
- \( C \) is the damping matrix,
- \( \dot{u} \) is the velocity vector,
- \( K \) is the stiffness matrix,
- \( u \) is the displacement vector,
- \( p(t) \) is the external force vector.

2.2 Types of Vibration

2.2.1 Walking

A walking person’s foot striking the floor causes a vibration in the floor structure. The vibration could be disturbing to other occupants in the same building, such as an office building, a residential building or a hospital. Even though several people could be walking in the same area at the same time, the footsteps are not normally synchronized and therefore the analysis is based on a single person walking [10].
2.2.2 Rhythmic Activity

There are situations where several people could participate in a coordinated activity. Dancing, audience participation in arenas and concert halls and gym activities, such as aerobics and weightlifting, can result in crucial levels of floor vibration. Both participators in the rhythmic activity and occupants in the nearby areas, such as offices and business spaces, could be disturbed by the vibration. The people participating in the rhythmic activity have, however, a greater level of tolerance than those in the nearby areas [10, 20].

For rhythmic activities, resonant or near resonant behavior causes a crucial dynamic enlargement and consequently discomfort. Therefore the natural frequency of the floor structure must be significantly higher than the frequencies excited by the activities as to prevent resonance [10, 20].

2.2.3 Mechanical Equipment

Mechanical equipment with a constant frequency could create a continuing impulse, causing the floor structure to vibrate. To prevent crucial vibration problems, equipment such as heating, ventilation and air-conditioning systems as well as washing machines must be properly isolated [10, 20].

2.3 Natural Frequency of Vibration and Modal Mass

The natural frequency is the most important parameter for the vibration serviceability design and evaluation of floor structures [19]. It is important in determining how floor structures will respond to forces causing vibrations as well as how occupants will perceive the vibrations [10].

Each structure has as many natural frequencies and mode shapes as DOFs and they are sorted by the amount of energy that is activated by the vibration. The first natural frequency, also called the fundamental frequency, is associated with the lowest energy level and is thus the most likely to be activated. The equation for the natural frequency of a SDOF system is [12]

$$f_n = \frac{1}{2\pi} \sqrt{\frac{k}{m}} \quad (2.6)$$

where
$f_n$ is the natural frequency (Hz),
k is the stiffness,
m is the mass.

Floors are generally divided into low-frequency floors and high-frequency floors. Low-frequency floors are usually heavy structures with long spans, while high frequency floors are lighter structures with shorter spans. General floors are considered to be low-frequency floors when the natural frequency is below 10 Hz and high-frequency floors when the natural frequency is above 10 Hz. The low- to high-frequency cut-off varies depending on the activity, e.g., floors subjected to rhythmic activities have a higher cut-off of 24 Hz [25, 28].

The modal mass is defined as the fraction of the total mass of a floor that is activated when the floor vibrates in a specific mode shape. Each mode shape is associated with a specific modal mass [12].

### 2.3.1 Determination of Dynamic Properties of Floor Structures

In case of hand calculations, the dynamic response of a floor structure can be represented by a SDOF system based on the natural frequency. The natural frequency calculation uses a load corresponding to the self-weight and 10% of the imposed load, which represents the permanent loading on the floor [12].

The elastic modulus for vibration analysis is larger than the static values [1]. The dynamic modulus of elasticity for concrete should be considered 10% higher than the static modulus $E_{cm}$ [12].

### 2.3.2 Natural Frequency and Modal Mass from Mode Shape

#### 2.3.2.1 Isotropic Plates and Beams

Formulas for the determination of the natural frequency and the modal mass of isotropic plates are given in Table A.2 for different support conditions. For the application of the given formulas, it is assumed that no deflection at any edges of the plate occurs [12].

Formulas for the determination of the natural frequency and the modal mass of beams are given in Table A.1 for different support conditions [12].
2.3.2.2 Orthotropic Floor Systems

Orthotropic floor systems have different stiffnesses in length and width \((EI_y > EI_x)\). Figure 2.2 shows a composite floor with steel beams in the longitudinal direction and a concrete plate in the transverse direction [12].

![Figure 2.2: Dimensions and axis of an orthotropic floor [12].](image)

The natural frequency of orthotropic floor systems being simply supported at all edges can be determined from [12]

\[
f_n = \frac{\pi}{2} \sqrt{\frac{EI_y}{ml^4}} \left[ 1 + \left( \frac{b}{l} \right)^2 \right] \left( \frac{EI_x}{EI_y} \right) \tag{2.7}
\]

where

- \(f_n\) is the natural frequency (Hz),
- \(m\) is the mass distribution (permanent loads) (kg/m²),
- \(l\) is the length of the floor (in x-direction) (m),
- \(b\) is the width of the floor (in y-direction) (m),
- \(E\) is the modulus of elasticity (N/m²),
- \(I_x\) is the moment of inertia for bending about the x-axis (m⁴),
- \(I_y\) is the moment of inertia for bending about the y-axis (m⁴).

If the mode shape of a floor is approximated by a normalized function \(\delta(x, y)\) with \(|\delta(x, y)|_{max} = 1.0\), the modal mass of the floor can be obtained from [12]

\[
M_{mod} = m \int_F \delta^2(x, y) dF \tag{2.8}
\]

where
\( m \) is the mass distribution,
\( \delta(x, y) \) is the vertical deflection at location \( x, y \).

The mass distribution in this approximation may be considered as

\[
m = \frac{M}{l_x l_y}.
\]  

(2.9)

For orthotropic floor systems, where a plate is spanning in one direction between beams that are simply supported, the approximation of mode shape is \([12]\)

\[
\delta(x, y) = \frac{\delta_x}{\delta} \sin \left( \frac{\pi x}{l_x} \right) + \frac{\delta_y}{\delta} \sin \left( \frac{\pi y}{l_y} \right); \quad |\delta(x, y)|_{\text{max}} = 1.0
\]  

(2.10)

where

\( \delta_x \) is the deflection of the beam,
\( \delta_y \) is the deflection of the slab assuming that \( \delta_x = 0 \),
\( \delta \) is \( \delta_x + \delta_y \).

Thus the modal mass for orthotropic floor systems is

\[
M_{\text{mod}} = m \int_F \delta^2(x, y) dF = \frac{M}{l_x l_y} \int_0^{l_x} \int_0^{l_y} \frac{\delta_x}{\delta} \sin \left( \frac{\pi x}{l_x} \right) + \frac{\delta_y}{\delta} \sin \left( \frac{\pi y}{l_y} \right) \right]^2 dx dy 
\]  

(2.11)

\[
= M \left[ \frac{\delta_x^2 + \delta_y^2}{2\delta^2} + \frac{8}{\pi^2} \frac{\delta_x \delta_y}{\delta^2} \right].
\]

\subsection*{2.3.3 Natural Frequency from the Self-Weight Approach}

The self-weight approach is a practical approximation when the deflection \( \delta_{\text{max}} \) is determined. This approach has its origin in the general frequency equation presented in Equation 2.6 \([12]\).

The stiffness \( k \) can be approximated by the assumption \([12]\)

\[
k = \frac{mg}{\frac{3}{4} \delta_{\text{max}}}
\]  

(2.12)

where
**m** is the total mass of the vibrating system,

\( g = 9.81 \) is the gravity (m/s²),

\( \frac{3}{4} \delta_{max} \) is the average deflection.

The approximated natural frequency from the self-weight approach is [10]

\[
f_n = \frac{1}{2\pi} \sqrt{\frac{k}{m}} = \frac{1}{2\pi} \sqrt{\frac{4g}{3\delta_{max}}} = 0.18 \sqrt{\frac{g}{\delta_{max}}}
\]  \hfill (2.13)

where

\( \delta_{max} \) is the maximum deflection due to permanent loads (m).

### 2.3.4 Natural Frequency from the Dunkerley Approach

The Dunkerley approach is an approximation for cases where the mode shape is complex but can be divided into different simple modes for which the natural frequency can be determined [12]. The mode shape of a floor structure can be divided into the simple mode shapes of the slab, the secondary beam and the primary beam. Columns in tall buildings supporting floor structures with rhythmic activities can create resonance problems, thus the column effect may be included [19].

The natural frequency \( f_n \) of a total system can be approximated using the Dunkerley relationship [12]

\[
\frac{1}{f_n^2} = \frac{1}{f_1^2} + \frac{1}{f_2^2} + \frac{1}{f_3^2} + \ldots
\]  \hfill (2.14)

The Dunkerley relationship shows that equation 2.13 will give the natural frequency of a floor system when \( \delta_{max} \) is taken as the sum of the deflections of each and every structural component [25].

### 2.4 Damping

As mentioned in Chapter 2.1.1, damping makes the free vibration of a structure steadily diminish in amplitude due to energy dissipation by different mechanisms [7].

In vibrating buildings the most important type of damping is structural damping [10]. These include friction at connections as well as friction between
the structure itself and non-structural elements such as partition walls and furniture. The internal damping of materials also contributes to the energy dissipation such as internal friction in the material, the thermal effect of repeated elastic straining of the structure as well as opening and closing of microcracks in concrete [7].

Due to lack of knowledge with reference to damping mechanisms, it is impossible to identify or describe the energy dissipating mechanisms mathematically in buildings. The damping for a structure can be measured or estimated using measured data from comparable structures. The combined effects of the different energy dissipating mechanisms are measured in the measurements. Therefore it is practical to idealize the damping in a SDOF system by a linear viscous damper in order to combine the effects of the different mechanisms [7].

The damping constant $c$ is a measure of the energy dissipated in a cycle of free vibration. Instead of using the damping constant, the damping ratio $\zeta$ is commonly used to describe damping. The damping ratio is a dimensionless measure which also depends on the mass and stiffness of a system. It describes the ratio of the damping constant to the critical damping constant $c_{cr}$, where the critical damping constant is the smallest value of $c$ that results in a system returning to its equilibrium position without oscillating [7]:

$$\zeta = \frac{c}{c_{cr}} = \frac{c}{2\sqrt{km}} \quad (2.15)$$

where

$\zeta$ is the damping ratio,
$c$ is the viscous damping coefficient,
$c_{cr}$ is the critical damping coefficient,
$k$ is the stiffness of the system,
$m$ is the mass of the system.

Structures can be divided into three different categories depending on the damping ratio: underdamped systems ($c < c_{cr}$ or $\zeta < 1$), critically damped systems ($c = c_{cr}$ or $\zeta = 1$) and overdamped systems ($c > c_{cr}$ or $\zeta > 1$). Figure 2.3 shows the free vibration of these systems. Buildings, bridges and other similar structures are typically underdamped structures, with damping ratios less than 0.10 [7]. The damping ratio can be determined using values for various components, such as structural material, furniture and types of finishes, given in Table 2.1.
Figure 2.3: Free vibration of underdamped, critically damped and overdamped systems [7].

Table 2.1: Determination of Damping [12]

<table>
<thead>
<tr>
<th>Type</th>
<th>Damping (% of critical damping)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural Damping $\xi_1$</td>
<td></td>
</tr>
<tr>
<td>- Wood</td>
<td>6%</td>
</tr>
<tr>
<td>- Concrete</td>
<td>2%</td>
</tr>
<tr>
<td>- Steel</td>
<td>1%</td>
</tr>
<tr>
<td>- Steel-concrete composite</td>
<td>1%</td>
</tr>
<tr>
<td>Damping Due to Furniture $\xi_2$</td>
<td></td>
</tr>
<tr>
<td>- Traditional office for 1-3 persons with separation walls</td>
<td>2%</td>
</tr>
<tr>
<td>- Paperless office</td>
<td>0%</td>
</tr>
<tr>
<td>- Open plan office</td>
<td>1%</td>
</tr>
<tr>
<td>- Library</td>
<td>1%</td>
</tr>
<tr>
<td>- Houses</td>
<td>1%</td>
</tr>
<tr>
<td>- Schools</td>
<td>0%</td>
</tr>
<tr>
<td>- Gymnastic</td>
<td>0%</td>
</tr>
<tr>
<td>Damping Due to Finishes $\xi_3$</td>
<td></td>
</tr>
<tr>
<td>- Ceiling under the floor</td>
<td>1%</td>
</tr>
<tr>
<td>- Free floating floor</td>
<td>0%</td>
</tr>
<tr>
<td>- Swimming screed</td>
<td>1%</td>
</tr>
<tr>
<td>Total Damping $\xi = \xi_1 + \xi_2 + \xi_3$</td>
<td></td>
</tr>
</tbody>
</table>

Since damping is difficult to predict, the loss factor $\eta$ is the most appropriate index when damping is defined as a specific property of a material [6]. The loss factor is the ratio of the energy dissipated per radian to the initial energy of the system:
\[ \eta = \frac{\Delta U}{2\pi U_{\text{max}}} \]  

(2.16)

where \( \Delta U \) is the energy dissipated per cycle

\[ \Delta U = 2\pi x_0^2 \omega_n \omega \zeta \]  

(2.17)

and \( U_{\text{max}} \) is the initial energy of the system

\[ U_{\text{max}} = \frac{1}{2} \omega_n^2 x_0^2. \]  

(2.18)

Therefore, from Equation 2.16, the loss factor for a viscously damped system is

\[ \eta = \frac{2\pi x_0^2 \omega_n \omega \zeta}{2\pi \frac{1}{2} \omega_n^2 x_0^2} = \frac{2\omega \zeta}{\omega_n}. \]  

(2.19)

In case of low damping, an approximation \( \omega \cong \omega_n \) may be implemented. This approximation is also what must be considered for forced oscillation with regard to energy dissipation. In both cases, the loss factor is approximately

\[ \eta = 2\zeta. \]  

(2.20)

The loss factors of some useful materials are given in Table 2.2 [10].

<table>
<thead>
<tr>
<th>Material</th>
<th>Loss Factor ( \eta \cong 2\xi )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>0.00002 to 0.002</td>
</tr>
<tr>
<td>Concrete</td>
<td>0.02 to 0.06</td>
</tr>
<tr>
<td>Glass</td>
<td>0.001 to 0.002</td>
</tr>
<tr>
<td>Rubber</td>
<td>0.1 to 1</td>
</tr>
<tr>
<td>Steel</td>
<td>0.002 to 0.01</td>
</tr>
<tr>
<td>Wood</td>
<td>0.005 to 0.01</td>
</tr>
</tbody>
</table>

2.5 Resonance

Resonance occurs when a structure is subjected to a dynamic force with a frequency close to the natural frequency. This causes an excessive amplifica-
tion of vibration. As mentioned in Chapter 2.2.2, the natural frequency of a structure must be significantly higher than the frequency of the dynamic force to avoid resonance [10].

If resonance occurs in an undamped structure, the deformation amplitude will tend to infinity. In reality, the deformation will not grow that big due to existing damping. Figure 2.4 shows the impacts of different damping ratios on the resonant response. The deformation response factor $R_d$ is the ratio of the dynamic deformation to the static deformation [7].

![Figure 2.4: Deformation response factor for a damped system excited by harmonic force [7].](image)
Chapter 3

Introduction to Structure-Borne Sound

Sound is the result of vibrating bodies. It is caused by vibrating particles of elastic media that may be either solid or fluid. When a vibratory force or impulse disturbs or displaces the particles, they collide with the adjacent particles, which then transfer motion to other particles. Thus the disturbance may be spread rapidly over great distances and in many directions in the medium and adjacent media [4].

A great part of the sound exciting the air is generated from or transmitted through vibrating solid structures. This is called structure-borne sound. As shown in Figure 3.1, the structural acoustic process can be described by four stages. The first stage, generation, comprises the source of or mechanism behind vibration. The second stage, transmission, represents the transfer of vibrational energy from the generation mechanism to a structure. The third stage, propagation, covers the energy distribution throughout the structural system. The fourth stage, radiation, is recognized when vibrational energy is emitted into a fluid environment, such as air, as audible sound [8].

![Figure 3.1: Structural acoustic process [8].](image)
CHAPTER 3. INTRODUCTION TO STRUCTURE-BORNE SOUND

3.1 Classification and Sources of Sound

Sound in buildings can be classified according to its source, as either airborne, structure-borne or a combination of both. Airborne sound can cause structure-borne sound which then can be re-emitted again as airborne sound. Both types of sound produce pressure variations in the surrounding air which are perceived by a person as sound [4].

3.1.1 Airborne Sound

Airborne sound is the sound generated by a source which radiates straight into the air. Airborne waves are transmitted as pressure variations in the air. If a wall or any other barrier is in the way of the airborne sound wave, the varying sound pressure against the wall makes it vibrating. Thus the sound is transferred to the opposite side of the wall from where it is re-emitted as airborne sound waves. Some of the vibrational energy of the wall is transferred to other elements of the building where it eventually appears as airborne sound. Even though structure-borne sound transmission occurs, the sound is classified as airborne because the original sound was airborne. Airborne sound usually disturbs only areas near the source because airborne sound generally is of much lower intensity and more easily reduced than structure-borne sound [4].

The sources of airborne sound can be divided into two categories: outdoor sound sources and indoor sound sources. The most essential sources of outdoor sound are aircraft, vehicular traffic, rail transportation systems, industrial plant operations, heavy equipment and power garden equipment such as lawn mowers and chain saws [4].

Among the indoor sources of sound, the most disturbing sources are consumer electronic devices such as televisions and stereos. Other main sources of indoor sound are musical instruments, home appliances such as washing machines and vacuum cleaners and people singing or shouting [4].

3.1.2 Structure-Borne Sound

When building elements such as walls and floors are set into vibration by direct contact with vibrating sources, structure-borne sound occurs. The vibrational energy is transferred to other wall and floor elements throughout the building structure. The vibrational energy of the vibrating elements is then re-emitted as airborne sound into adjacent areas. As mentioned in Chapter 3.1.1, the intensity of structure-borne sound is usually much higher than that
generated by airborne sound. Therefore, the vibrations are transferred over long ranges throughout the building structures with little reduction [4].

One of the most observable sources of structure-borne sound is impacts. When an object strikes against or slides on walls or floors, impact sound occurs. In buildings, impact sound is typically produced by walking, jumping, falling objects or moving furniture [4].

Further major sources that cause annoyance to building occupants are plumbing systems and heating and air-conditioning systems. In many cases, other mechanical equipment and appliances in buildings, such as elevator hoist equipment, ventilation and exhaust systems and laundry appliances, also generate disturbing sound [4].

External sources, such as vehicular, rail road and subway traffic as well as industrial operations, may generate structure-borne sound in buildings close to the source [4]. Structure-borne sound caused by vibrations transmitted through the ground is often described as ground-borne sound [31].

3.2 Basic Concepts of Acoustics

3.2.1 Sound Pressure and Sound Pressure Level

Any vibration in the audible frequency range caused by a variation in air pressure can be perceived by a person as sound. A variation in pressure above or below atmospheric pressure is described as sound pressure [3].

Sound pressure is a difficult quantity to use, because of the wide amplitude of sound pressure to which the ear responds. Therefore, sound pressures are expressed in terms of the logarithm of the ratio of the sound pressure to an applicable reference quantity. The reference quantity is taken as 20 μPa, because it is the sound pressure at the threshold of hearing [3]. Now the magnitude of the sound pressure can be described as the sound pressure level (SPL) $L_p$ in units of decibels (dB) [16]:

$$L_p = 10 \log \frac{p^2}{p_0^2} = 20 \log \frac{p}{p_0}$$

(3.1)

where

$p$ is the instantaneous sound pressure (Pa),

$p_0 = 2 \cdot 10^{-5}$ is the reference sound pressure (Pa).

The total SPL $L_{p,tot}$ from several sound sources can be calculated as [16]
\[ L_{p,tot} = 10 \log \sum_{i=1}^{n} 10^{L_{p,i}/10} \]  

(3.2)

### 3.2.2 Frequency Bands

Sound is distributed over a wide frequency range and the SPL is different for individual frequencies. The sound spectrum is therefore divided into smaller parts called frequency bands. Common bandwidths are octave bands and one-third octave bands [16].

In octave bands, the center frequency \( f_C \) is approximately twice the previous one. The lower band limit \( f_L \) and upper band limit \( f_U \) for octave bands are

\[ f_L = \frac{f_C}{\sqrt{2}} \quad \text{and} \quad f_U = \sqrt{2} f_C. \]  

(3.3)

Thus the center of the frequency bands can be defined as

\[ f_C = \sqrt{f_L f_U} \]  

(3.4)

and the bandwidth is [30]

\[ BW = f_U - f_L = \frac{f_C}{\sqrt{2}}. \]  

(3.5)

If every octave band is divided into three parts, one-third octave bands are formed. The ratio of the one-third octave band center frequency to the previous one is approximately \( \sqrt{2} \). The following equations for lower and upper band limits as well as center frequencies are

\[ f_L = \frac{f_C}{\sqrt{2}}, \quad f_U = \sqrt{2} f_C \]  

(3.6)

and

\[ f_C = \sqrt{f_L f_U}. \]  

(3.7)

Using these relationships, the bandwidth of one-third octave bands is [30]
\[ BW = f_U - f_L = f_C \left( \sqrt{2} - \frac{1}{\sqrt{2}} \right). \] (3.8)

The octave bands have been standardized for acoustic measurements [30]. Standardized octave bands and one-third octave bands are shown in Table A.3. The acoustics in buildings are measured as one-third octave bands with center frequencies from 100 Hz to 3150 Hz or 50 Hz to 5000 Hz [16].

3.2.3 Frequency Weighting

SPL describes the physical strength of sound pressure. The general range of human hearing is 20 Hz to 20,000 Hz, however, the sensitivity of human hearing is frequency dependent over the entire audio range. The normal ear is most sensitive at frequencies between 2,000 Hz and 5,000 Hz [16].

Frequency weighting takes the human sensitivity to sound into account at different frequencies. The A-weighted sound level corresponds to the human response to soft sounds and is obtained by modifying the SPL in every frequency band. There are also other frequency weightings. The most common of these is C-weighting, which corresponds to the human response to loud sounds. The modifications for A-weighting and C-weighting in each frequency band are shown in Table A.4 [30].

The total A-weighted sound level \( L_A \) is obtained by the logarithmic sum of A-weighted SPL in each frequency band \( L_{A,i} \) with units dB(A) [16]:

\[ L_A = 10 \log \sum 10^{L_{A,i}/10}. \] (3.9)

The equivalent sound level \( L_{A,eq,T} \) is the continuous sound level over a defined period of time. The equivalent sound level depends on the duration of the sound produced by the sound sources and the duration of the entire observation period. An accurate determination of the equivalent sound level requires continuous measurements with an integrating sound level meter over the observed period. Long-term measurements are not always possible, therefore, an average noise level must be estimated based on short-term measurements, so that the entire observation period \( T \) is covered. The equivalent sound level can be calculated from the instantaneous sound levels \( L_{A,i} \) and the corresponding durations \( T_i \) [16]:
\begin{equation}
L_{A, eq,T} = 10 \log \left( \frac{1}{T} \sum T_i \cdot 10^{L_{A,i}/10} \right).
\end{equation}

The day-night equivalent sound level is used in the observation of environmental noise: \( L_{A, eq,07-22} \) for daytime (7 AM to 10 PM) and \( L_{A, eq,22-07} \) for night time (10 PM to 7 AM). The maximum sound level \( L_{A, max} \) is the highest appearing sound level during the observed period [23].

### 3.2.4 Equivalent Sound Absorption Area and Reverberation Time

The sound absorption coefficient \( \alpha_a \) characterizes the ability of a material to absorb sound. This value can range between 0 and 1, where 0 is total reflection and 1 is total absorption. The equivalent sound absorption area \( A \) is the amount of material with a sound absorption coefficient of 1 [16].

The equivalent sound absorption area of a room is calculated from the sound absorption coefficients \( \alpha_{a,i} \) and areas \( S_i \) of the surface materials [16]:

\begin{equation}
A = \alpha_{a,1}S_1 + \alpha_{a,2}S_2 + \ldots + \alpha_{a,n}S_n = \sum_{i=1}^{n} \alpha_{a,i}S_i.
\end{equation}

Reverberation time \( T_{60} \) describes the time taken for a sound to decay by 60 dB once the sound source has been stopped. It is measured in seconds and may be obtained by using Sabine's formula [16]:

\begin{equation}
T_{60} = 0.16 \frac{V}{A}
\end{equation}

where

\( V \) is the volume of the room (m³),

\( A \) is the total sound absorption area of surfaces (m²).

The equivalent sound absorption area of a room may also be obtained by inverting equation 3.12 if a valid reverberation time in the room is known [15].
3.3 Impact Sound Insulation

Impact sound insulation between different spaces is described by the normalized impact SPL $L'_{n}$, which denotes the quantity of sound transmitted by structures from one space to another [23]. The sound is transmitted to each structural element in the receiving room due to impact on a structural element in the source room [24]. A standard tapping machine is used to evaluate the impact sound insulation of floors. Impact sound insulation can be measured in either a laboratory or a building, as shown in Figure 3.2. Measurements in a laboratory give the impact sound insulation for a single structural element. In a building, flanking structural elements also affect the impact sound insulation [16].

![Figure 3.2: Impact SPL measurement in a laboratory and a building [13].](image)

A standard tapping machine consists of five hammers. Each hammer has a mass of 0.5 kg and falls from a height of 40 mm twice a second making the overall frequency of the machine equal to 10 Hz. The impact SPLs $L'_{j}$ are measured at different locations in the receiving room as one-third octave bands with center frequencies from 100 Hz to 3150 Hz. The average of the impact SPLs measured in the receiving room is defined as [16]
\[ L'_i = 10 \log \left( \frac{1}{n} \sum_{j=1}^{n} 10^{L'_j/10} \right) \]  \hspace{1cm} (3.13)

The impact SPL also depends on the absorption area of the receiving room. This results in the normalized impact SPL, expressed at center frequencies as [16]

\[ L'_n = L'_i + 10 \log \frac{A}{A_0} \] \hspace{1cm} (3.14)

where

- \( L'_n \) is the normalized impact SPL (dB),
- \( L'_i \) is the impact SPL measured in the receiving room (dB),
- \( A \) is the equivalent sound absorption area of the receiving room (m²),
- \( A_0 = 10 \) is the reference equivalent sound absorption area (m²).

The criteria of the impact sound insulation of a floor are presented as the weighted normalized impact SPL \( L'_{n,w} \). This quantity is obtained by comparing measured normalized impact SPLs with a reference curve. The reference curve is moved towards the measured normalized impact SPL values in steps of 1 dB until the allowable sum of unfavourable deviations, 32.0 dB, is reached, as shown in Figure 3.3. When the reference curve is placed at the lowest possible position, the weighted normalized impact SPL is read as the value of the reference curve at centre frequency 500 Hz [16].

### 3.3.1 Weighted Reduction of Impact Sound Pressure Level

The weighted reduction of impact SPL \( \Delta L_w \) describes the improvement of impact sound insulation achieved by floor covering. The reduction is acquired through normalized impact SPL measurements of a standardized massive concrete floor slab with, and without, floor covering. The difference of the measured values is then received in each one-third octave band [16].

The weighted normalized impact SPL is calculated for the standardized floor slab with floor covering \( L_{n,w} \) and without floor covering \( L_{n,eq,0,w} \). The
Figure 3.3: Reference curve and example of measured normalized impact SPLs. Weighted normalized impact SPL $L'_{n,w}$ is 52 dB [15].

Weighted reduction of impact SPL, which denotes the impact of the floor covering, is then

$$\Delta L_w = L_{n,eq,0,w} - L_{n,w}.$$  \hspace{1cm} (3.15)

$\Delta L_w$ values are only applicable to heavyweight masonry floor structures, such as hollow core slabs and cast-in-situ concrete slabs [16].
Chapter 4

Noise and Vibration Control

4.1 Vibration Isolation and Absorption

Vibration isolation and absorption are general approaches to suppress undesirable floor vibrations. Although these two approaches seem similar, their way of reducing vibrations are quite different. In vibration isolation, the floor system is isolated from vibration excitations. The isolator is placed in the transmission path between the source of vibration and the floor system. In vibration absorption, a secondary system, also known as an absorber, is attached to the floor system to protect it from vibration. The absorber is placed at the floor system’s highest acceleration point where it absorbs the vibrational energy [9, 10, 21].

4.1.1 Resilient Floor Covering

The impact sound insulation of hollow core slabs and cast-in-situ concrete slabs is based on large mass. Improvement of impact sound insulation by increasing the mass is only reasonable up to a certain point due to load bearing issues and costs. The most effective way to improve impact sound insulation is to use resilient floor coverings [16].

General resilient floor coverings in residential buildings are soft plastic carpets and parquet with resilient underlay. $\Delta L_{w}$ values of these resilient floor coverings are usually 17-20 dB for soft plastic carpets and 17-18 dB for parquet with resilient underlay. Resilient floor coverings in staircases usually have a $\Delta L_{w}$ value of 2-14 dB [16]. $\Delta L_{w}$ values of resilient floor coverings commonly used in sport facilities are shown in Table 4.1 [5, 27]. In the design of floor structure solutions with resilient floor coverings, only floor coverings with known $\Delta L_{w}$ values should be used [16].
Table 4.1: $\Delta L_w$ Values of Resilient Floor Coverings Commonly Used in Sport Facilities [5, 27]

<table>
<thead>
<tr>
<th>Floor Covering</th>
<th>$\Delta L_w$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rubber</td>
<td></td>
</tr>
<tr>
<td>- everroll® compact (4 mm)</td>
<td>18 dB</td>
</tr>
<tr>
<td>- everroll® impact (8 mm)</td>
<td>21 dB</td>
</tr>
<tr>
<td>Vinyl</td>
<td></td>
</tr>
<tr>
<td>- Sportex 4.5 (4.5 mm)</td>
<td>19 dB</td>
</tr>
<tr>
<td>- Sportex 8 (8 mm)</td>
<td>21 dB</td>
</tr>
</tbody>
</table>

4.1.2 Floating Floor

A floating floor consists of a resilient layer with a floating structure, such as a building board or a cast-in-situ concrete slab, built on top of it. Mineral wool, expanded polystyrene or anti vibration mounts may be used as the resilient layer. The resonance frequency of the floating floor $f_0$ (Hz) is acoustically the most important factor of floating floors. It depends on the mass per unit area of the floating structure $m'$ (kg/m²) and the dynamic stiffness of the resilient layer $s'$ (MN/m³). The resonance frequency of a floating floor is

$$f_0 = 160 \sqrt{\frac{s'}{m'}}.$$  \hspace{1cm} (4.1)

The acoustical performance of a floating floor is better, the lower its resonance frequency is. The resonance frequency may be reduced by increasing the dynamic coefficient of the resilient layer or by increasing the mass of the floating structure [16].

Floating floors without resilient floor covering, built on top of massive supporting structures, usually have a weighted reduction of impact SPL $\Delta L_w$ greater than 25 dB [16]. $\Delta L_w$ values of concrete floating floors may be obtained from Figure 4.1 [24]. $\Delta L_w$ values of resilient floor coverings are not applicable to floating floors [16].

4.1.3 Spring and Elastomeric Vibration Isolators

Spring and elastomeric vibration isolators are used for the isolation of a system from the source of vibration. They are placed in the transmission path between the system and the source in order to minimize transfer of energy. For efficient isolation, the natural frequency of the isolator has to
be considerably lower than the main excitation frequency of the vibration source [29].

![Graph showing the weighted reduction of impact SPL for concrete floating floors.](image)

*Figure 4.1: Weighted reduction of impact SPL for concrete floating floors. A is the weighted impact sound reduction index $\Delta L_w$ in dB, B is the mass per unit area $m'$ of the floating structure in kg/m$^2$ and C is the dynamic stiffness per unit area $s'$ of the resilient layer in MN/m$^3$ [24].*

Spring isolators are widely used as the base isolation of heavy duty machinery, while elastomeric isolators are more commonly used as base isolation of lighter machinery, such as machine tools and home appliances. Spring and elastomeric isolators can also be used to isolate buildings from external vibrations. Rooms with sensitive equipment are generally isolated using elastomeric isolators [29].
4.1.4 Tuned Mass Damper

A tuned mass damper (TMD) is attached to a vibrating system in order to absorb vibrational energy from it. This may reduce the vibration amplitude of the system significantly. TMDs are designed to efficiently absorb vibrational energy from the vibrating system at its natural frequency [29].

The mass damper can be tuned in different ways, depending on the specific application [29]. Typical applications are the vibration control of high-rise buildings and bridges due to strong winds, but TMDs may also be used to control floor vibrations [11].

4.2 Sound-Absorbing Materials

Sound-absorbing materials are generally used to prevent the unpleasant consequences of sound reflection by hard and rigid surfaces and therefore reduce the reverberant sound levels in buildings. Sound absorbers reduce the energy of a sound wave by converting the mechanical motion of the air particles into heat within the material, resulting in an amplitude reduction of the reflected waves [22]. The sound-absorbing materials can be divided into different groups depending on their physical properties.

4.2.1 Porous Material

The sound absorption capability of porous materials is based on the heat losses in tight fibrous structures caused by friction. The particle velocity of the sound wave reflected by the structure is at the lowest at the surface of the structure and at the highest at the quarter wavelength, $\lambda/4$. Porous materials absorb frequencies with a wavelength smaller than four times the thickness of the material more effective. In addition to thickness, the absorption of porous materials also depends on the surface treatment and the flow response. The density of the materials should be large enough so that absorption may occur. Common porous materials are mineral wool and thick textiles [16].

Low sound wavelengths are long, while the material layers generally are not that thick. Therefore, porous materials absorb mostly mid-range frequency and high sounds. At low frequencies, the absorption is better the thicker the materials are. The absorption of low frequencies may be improved by leaving an air gap between the porous material and the structure, in order that the material layer coincides with the quarter wavelength. For example, many ceiling structures function this way [16].
4.2.2 Perforated Board

The sound absorption capability of perforated boards is based on that the air in the holes functions as a mass and the air in the air gap between the board and the structure functions as a spring, forming a mass-spring system. The sound absorption becomes a maximum at the mass-spring system's natural frequency, i.e., at resonant frequency. The natural frequency and absorption depend on the air gap thickness, the hole size, the hole shape, the number of holes and the board thickness. Any regular board used in construction can be applied for this, such as drywall or plywood [16].

The absorption of the perforated board is lower for sounds at other frequencies than the natural frequency. The absorption may be increased by filling the air gap with porous material, making the absorption somewhat high over the whole frequency range [16].

4.3 Criteria and Limit Values

4.3.1 Criteria for Floor Vibrations Due to Rhythmic Activities

The human sensitivity to vibrations depends mostly on human activities. People in residences or offices do not approve noticeable vibrations, while people participating in rhythmic activities tolerate vibrations about 10 times better. People in a shopping mall or in a gym lifting weights accept something in between. As shown in Figure 4.2, people are most sensitive to vibration frequencies in the range of 4 to 8 Hz. Beyond this range, the acceleration limits for vibrations are higher [19].

The criteria for the design of floor structures for rhythmic excitation are based on the structural systems' dynamic response to rhythmic excitation forces distributed over the floor. The peak acceleration of a floor structure due to a rhythmic force may be approximated from

\[
\frac{a_p}{g} = \frac{1.3\alpha_i w_p/w_t}{\sqrt{\left[\left(\frac{f_n}{f}\right)^2 - 1\right]^2 + \left[\frac{2\kappa f_n}{f}\right]^2}}
\]

(4.2)

where
\( \alpha_P \) is the ratio of peak acceleration to gravity,
\( \alpha_i \) is the dynamic coefficient,
\( w_p \) is the effective weight of participants (kN/m²),
\( w_t \) is the effective total weight of floor structure and participants (kN/m²),
\( f_n \) is the natural frequency (Hz),
\( f \) is the forcing frequency \( i f_{step} \) (Hz),
\( i \) is the number of harmonic,
\( f_{step} \) is the step frequency (Hz),
\( \zeta \) is the damping ratio.

This approximation is obtained from the classical steady-state acceleration response assuming that there is only one mode of vibration [19]. For practical problems where resonance is involved, this assumption is generally close enough [2].

At resonance \((f_n = f)\), Equation 4.2 may be simplified as

\[
\frac{\alpha_P}{g} = \frac{1.3 \alpha_i w_p}{2 \zeta w_t} \tag{4.3}
\]

and above resonance \((f_n > 1.2f)\) as [19]

\[
\frac{\alpha_P}{g} = \frac{1.3}{(f_n/f)^2 - 1} \frac{\alpha_i w_p}{w_t} \tag{4.4}
\]

The effective maximum acceleration, taking peak accelerations from all harmonics into account, can be calculated as

\[
a_m = \left( \sum a_{P,i}^{1.5} \right)^{1/1.5} \tag{4.5}
\]

where

\( a_{P,i} \) is the peak acceleration for the \( i \)th harmonic

and can then be compared with the acceleration limits in Figure 4.2 [19].

The dynamic forces are usually large for rhythmic activities. To avoid resonant vibration, a design criterion for minimum natural frequency for a floor structure can be provided by inverting Equation 4.4:

\[
f_n \geq f \sqrt{1 + \frac{k}{a_0/g}} \frac{\alpha_i w_p}{w_t} \tag{4.6}
\]
Figure 4.2: Recommended permissible peak acceleration levels acceptable for human comfort for vibrations due to human activities [10].

where

\[ k \quad \text{is a constant (1.3 for dancing, 1.7 for a lively concert or sports event, 2.0 for aerobics),} \]

\[ a_0/g \quad \text{is the acceleration limit} \]

and the remaining parameters are defined in Equation 4.2. Recommended acceleration limits due to rhythmic activities are presented in Table 4.2. Estimated values of forcing frequencies \( f \), dynamic coefficients \( \alpha_i \) and distributed weight of participants \( w_p \) are given in Table 4.3. The damping ratio \( \zeta \) is taken into consideration only if resonance occurs. Since participants contribute to the damping, a value of 0.06 may be used [19].
Table 4.2: Recommended Acceleration Limits for Vibrations Due to Rhythmic Activities [19]

<table>
<thead>
<tr>
<th>Occupancies Affected by the Vibration</th>
<th>Acceleration Limit, % gravity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Office and residential</td>
<td>0.4-0.7</td>
</tr>
<tr>
<td>Dining and weightlifting</td>
<td>1.5-2.5</td>
</tr>
<tr>
<td>Rhythmic activity only</td>
<td>4.0-7.0</td>
</tr>
</tbody>
</table>

Table 4.3: Estimated Loading During Rhythmic Events [19]

<table>
<thead>
<tr>
<th>Activity</th>
<th>Forcing Frequency f (Hz)</th>
<th>Weight of Participants ( w_p ) (kN/m²)</th>
<th>Dynamic Coefficient ( \alpha )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dancing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- 1\textsuperscript{st} Harmonic</td>
<td>1.5-3.0</td>
<td>0.6</td>
<td>0.5</td>
</tr>
<tr>
<td>Lively concert or sports event</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- 1\textsuperscript{st} Harmonic</td>
<td>1.5-3.0</td>
<td>1.5</td>
<td>0.25</td>
</tr>
<tr>
<td>- 2\textsuperscript{nd} Harmonic</td>
<td>3.0-5.0</td>
<td>1.5</td>
<td>0.05</td>
</tr>
<tr>
<td>Jumping exercises</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- 1\textsuperscript{st} Harmonic</td>
<td>2.0-2.75</td>
<td>0.2</td>
<td>1.5</td>
</tr>
<tr>
<td>- 2\textsuperscript{nd} Harmonic</td>
<td>4.0-5.5</td>
<td>0.2</td>
<td>0.6</td>
</tr>
<tr>
<td>- 3\textsuperscript{rd} Harmonic</td>
<td>6.0-8.25</td>
<td>0.2</td>
<td>0.1</td>
</tr>
</tbody>
</table>

4.3.2 Acoustic Criteria

4.3.2.1 Criteria for Impact Sound Insulation in Sport Facilities

Several considerations must be taken into account in the design of floor structures in sport facilities. Larger facilities, such as gymnasium halls, are often intended for different types of ball games, while smaller facilities, such as health clubs, are intended for aerobics and weightlifting. Unsynchronized running and jumping have a different impact than rhythmic activities on floor structures. The floor design is also affected by the location of the sport facility.

Floor structures in health clubs are designed with a floating floor onto the supporting structure to prevent the transmission of structure-borne sound to other supporting structures. The floating structure is usually a concrete slab with a thickness of at least 80 mm. The dynamic stiffness of the resilient layer should not exceed 20 MN/m³. Furthermore, a suspended ceiling with flexible acoustic barriers should be installed underneath the supporting structure. The maximum weighted normalized impact SPL for floor structures in health clubs is 49 dB. If the health club is located in an office building or residential building, this value may be much lower [17].

A gymnasium hall or its floor structure is completely separated from the
surrounding building structures by expansion joints to prevent the transmission of structure-borne sound. If the floor is a supporting structure, a floating floor is required onto the supporting floor structure. The maximum weighted normalized impact SPL for floor structures in gymnasium halls is 49 dB [17].

### 4.3.2.2 Criteria for A-Weighted Sound Level

As mentioned in Chapter 3.2.3, the day-night equivalent sound level is used in the observation of environmental noise. Guideline values for day-night equivalent sound levels in sport facilities are not available. Guideline values for other types of spaces are given in Table 4.4 [26]. These guideline values should also be taken into account when a floor structure is designed [17].
Chapter 5

Case Study of Long-Span Floors

In the present study, three different types of floor structures are analyzed: a concrete structure, a concrete element structure and a steel-concrete composite structure. The floors are located in a sport facility combining aerobics and weightlifting. The sport facility is located in a commercial building and the floor structures are supported by columns. A parking lot is located in the basement of the building, therefore, the spacings between the columns are chosen to be 8.1 m and 16.2 m. The story height in the building is 5.2 m. The spacings between the columns and the story height are chosen according to an existing construction project. The floor structures are designed to have approximately the same natural frequency at about 9.5 Hz.

5.1 Concrete Structures

The concrete floor structure consists of primary and secondary cast-in-situ reinforced concrete beams with slabs spanning between them.

The primary beams are supported on concrete columns and have a length of 8.1 m. They have a rectangular cross-section with a width and height of 680 mm and 980 mm. The bay width of the primary beams is 16.2 m. The secondary beams are supported by the primary beams and have a length of 16.2 m. They have a rectangular cross-section with a width and height of 480 mm and 980 mm. The bay width of the secondary beams is 1.62 m. The slab is cast onto the beams with a thickness of 250 mm. The beams and the slab are cast with concrete of strength class C40/50 and all joints are considered to be clamped. A cross section of the concrete floor structure is shown in Figure 5.1.
5.2 Concrete Element Structures

The concrete element floor structure consists of prestressed and precast concrete beams with hollow core slabs spanning between them and a cast-in-situ topping layer onto the surface.

The beams are supported by concrete columns and have a length of 15.5 m. They are inverted T-beams with a web width and height of 480 mm and 500 mm and a flange width and height of 880 mm and 1380 mm. The bay width of the beams is 8.1 m. The hollow core slabs are supported by the inverted T-beams. They have a cross-sectional width and height of 1200 mm and 500 mm. The beams and hollow core slabs are precast with concrete of strength classes C40/50 and C50/60 respectively. The concrete topping is cast-in-situ onto the top surface of the hollow core slabs with concrete of strength class C30/37 and a thickness of 100 mm. All joints are considered to be simply supported. A cross section of the concrete element floor structure is shown in Figure 5.2.

5.3 Steel-Concrete Composite Structures

The steel-concrete composite floor structure consists of primary and secondary I-profiled beams. A concrete slab is cast-in-situ onto a profiled steel sheeting with ribs perpendicular to the secondary beams. Shear studs are placed on both the primary and secondary beams.

The primary beams are supported by steel-concrete composite columns and have a length of 7.4 m. They have a symmetrical cross-section with a web thickness and height of 30 mm and 1280 mm and a flange width and thickness of 420 mm and 60 mm. The bay width of the primary beams is 8.1
m. The secondary beams are supported by the primary beams and have a length of 16.2 m. They have a symmetrical cross-section with a web thickness and height of 24 mm and 920 mm and a flange width and thickness of 360 mm and 40 mm. The bay width of the secondary beams is 1.62 m. The steel grade of the beams is S355. The concrete slab is cast-in-situ onto the profiled steel sheeting with concrete of strength class C30/37 and a thickness of 250 mm. All joints are considered to be simply supported. A cross section of the steel-concrete composite floor structure is shown in Figure 5.3.
Chapter 6

Calculation and Evaluation

6.1 Analysis of Mechanical Vibration

Mechanical vibration analyses of the floor structures are first carried out in the math software PTC Mathcad using design guides. The floors are subjected to rhythmic excitation with a forcing frequency of $i \cdot 2.5$ Hz for the $i$'th harmonic. All floor structures are designed to have approximately the same natural frequency, at about 9.5 Hz, to avoid resonance at the third harmonic. The natural frequencies are approximated using the self-weight approach combined with the Dunkerley approach. The effective maximum acceleration is calculated for each floor structure.

Mechanical vibration analyses are then carried out in the FEA software COMSOL Multiphysics. A FEA model of each floor structure is built with a floor length and width of 16.2 m and 8.1 m. All loads considered as permanent loads are added to the models. The deflection and first natural frequency of each floor structure are computed. A dynamic boundary load of 0.2 kN/m² is then added to the models with the forcing frequency of each harmonic. The dynamic coefficient of each harmonic is also taken into account. The peak acceleration of each harmonic is computed and, lastly, the effective maximum acceleration is computed for each floor structure using Equation 4.5.

6.1.1 Concrete Structures

The floor structure properties and mechanical vibration calculations of the concrete floor carried out in the math software using design guides are presented in Appendix B.1. By using the self-weight approach combined with the Dunkerley approach, the concrete floor structure gets a static deflection of 3.48 mm and a natural frequency of 9.55 Hz. The effective maximum acceleration of the floor structure due to rhythmic excitation is 0.67% gravity,
which corresponds to an acceleration of 0.07 m/s².

The computation of the FEA model, shown in Figure 6.1, results in a static deflection of 1.88 mm and a first natural frequency of 13.78 Hz. The calculated effective maximum acceleration is 0.27% gravity, which corresponds to an acceleration of 0.03 m/s².

![Figure 6.1: FEA model of the concrete floor structure showing the mode shape of the first natural frequency.](image)

### 6.1.2 Concrete Element Structures

The floor structure properties and mechanical vibration calculations of the concrete element floor carried out in the math software using design guides are presented in Appendix B.2. By using the self-weight approach combined with the Dunkerley approach, the concrete element floor structure gets a static deflection of 3.48 mm and a natural frequency of 9.56 Hz. The effective maximum acceleration of the floor structure due to rhythmic excitation is 1.02% gravity, which corresponds to an acceleration of 0.10 m/s².

The computation of the FEA model, shown in Figure 6.2, results in a static deflection of 0.99 mm and a first natural frequency of 19.33 Hz. The calculated effective maximum acceleration is 0.12% gravity, which corresponds to an acceleration of 0.01 m/s².

### 6.1.3 Steel-Concrete Composite Structures

The floor structure properties and mechanical vibration calculations of the steel-concrete composite floor carried out in the math software using design
guides are presented in Appendix B.3. By using the self-weight approach combined with the Dunkerley approach, the steel-concrete composite floor structure gets a static deflection of 3.55 mm and a natural frequency of 9.47 Hz. The effective maximum acceleration of the floor structure due to rhythmic excitation is 1.08% gravity, which corresponds to an acceleration of 0.11 m/s².

The computation of the FEA model, shown in Figure 6.3, results in a static deflection of 1.97 mm and a first natural frequency of 12.98 Hz. The calculated effective maximum acceleration is 0.44% gravity, which corresponds to an acceleration of 0.04 m/s². The profiled steel sheeting and shear studs are missing from the FEA model for simplicity’s sake.

6.2 Analysis of Acoustics

The acoustic analyses are carried out in the FEA software. An air domain is added to the FEA models, which represents the space below the sport facility. Because of an increase of mesh elements, symmetries of the floor structures are utilized using a quarter of the geometry, as shown in Figure 6.4. Each frequency wavelength needs to be resolved with at least five mesh elements, resulting in extremely fine mesh elements at higher frequency vibrations. This is an impossible approach for these models due to lack of computer storage. Therefore, coarser mesh elements are used at higher fre-
Figure 6.3: FEA model of the steel-concrete composite floor structure showing the mode shape of the first natural frequency.

frequency vibrations as well.

The computed SPLs are evaluated at eight different positions, at a height of 1.5 m, in the air domain, as shown in Figure 6.5. The air domain does not have any sound absorbing surfaces.

In the analyses of the impact sound insulation of the floor structures, the impact SPLs are measured as one-third octave bands with center frequencies from 100 Hz to 3150 Hz. The force amplitude $F_n$ of a standard tapping machine is calculated as [18]

$$F_n \cong 2f_r m v_0 = 2f_r m \sqrt{2gd}$$  \hspace{1cm} (6.1)

where

- $f_r$ is the repetition frequency (Hz),
- $m$ is the mass of the hammer (kg),
- $v_0$ is the velocity of the hammer at impact (m/s),
- $d$ is the drop distance of the hammer (m),
- $g = 9.81$ is the gravity (m/s$^2$).

This amplitude is considered to be constant at all frequencies and is placed at the corner of the models, at the floor structures’ symmetry axes, as a dynamic point load. In other words, the tapping machine is considered being
at the center of each entire floor structure.

A-weighted sound levels are calculated in the air domain when the floor structures are subjected to rhythmic excitation. The A-weighting is performed on SPLs measured as one-third octave bands with center frequencies from 16 Hz to 20,000 Hz. The force amplitude of the jumping persons is determined using the load function expressed as a Fourier series [25]:

\[
F(t) = W \left[ 1.0 + \sum_{h=1}^{H} \alpha_h \sin \left( 2h\pi f_{step} t + \phi_h \right) \right]
\]  
(6.2)

where

- \( W \) is the weight of a jumper (N),
- \( H \) is the number of Fourier terms,
- \( \alpha_h \) is the Fourier coefficient (or dynamic load factor) of the \( h^{th} \) term,
- \( f_{step} \) is the step frequency of the jumping load (Hz),
- \( \phi_h \) is the phase lag of the \( h^{th} \) term.

The weight of each jumper is taken as 800 N and the phase lags for the first three harmonics are considered to be \( \phi_1 = \pi/6 \), \( \phi_2 = -\pi/6 \) and \( \phi_3 = -\pi/2 \). The first three Fourier coefficients are [25]
Figure 6.5: Point positions in the air domain, at which SPLs are evaluated at a height of 1.5 m.

\[ \alpha_1 = 1.61n_p^{-0.082}, \quad \alpha_2 = 0.94n_p^{-0.24} \quad \text{and} \quad \alpha_3 = 0.44n_p^{-0.31} \quad (6.3) \]

where

\( n_p \) is the number of participants in the rhythmic activity \((2 \leq n_p \leq 64)\).

The obtained force amplitude is placed at eight different positions in the model as dynamic point loads. The spacings between the point loads are 2 m and each point load represents a jumping person. This means that there is considered to be a total of 32 jumping persons on the whole floor structure. There is considered to be a reduction of the force magnitude due to damping of the human leg. The force transmissibility magnitude at each center frequency is obtained from [9]

\[ |T_f| = \sqrt{\frac{1 + \left(2\zeta \frac{f_C}{f_n}\right)^2}{\left[1 - \left(\frac{f_C}{f_n}\right)^2\right]^2 + \left(2\zeta \frac{f_C}{f_n}\right)^2}} \quad (6.4) \]

where

\( \zeta \) is the damping ratio of the human leg,

\( f_C \) is the center frequency (Hz),

\( f_n \) is the natural frequency of the human leg (Hz).
The damping ratio and the natural frequency of a human leg with a sport shoe is assumed to be $\zeta=0.35$ and $f_n=5$ Hz.

### 6.2.1 Concrete Structures

The measured normalized impact SPLs in the air domain at each center frequency, when the tapping machine is running, are shown in Figure 6.6. The measurements lead to a weighted normalized impact SPL $L'_{n,w}$ of 60 dB for the concrete floor structure.

<table>
<thead>
<tr>
<th>Concrete Floor Structure</th>
<th>Frequency (Hz)</th>
<th>Measurement (dB)</th>
<th>Reference curve (dB)</th>
<th>Unfavorable deviation (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100</td>
<td>17.4</td>
<td>62</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>125</td>
<td>29</td>
<td>62</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>160</td>
<td>59.3</td>
<td>62</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>30.4</td>
<td>62</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>250</td>
<td>38.9</td>
<td>62</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>315</td>
<td>48</td>
<td>62</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>51.4</td>
<td>61</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>41.3</td>
<td>60</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>630</td>
<td>52.6</td>
<td>59</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>800</td>
<td>40.5</td>
<td>58</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>1,000</td>
<td>68.3</td>
<td>57</td>
<td>11.3</td>
</tr>
<tr>
<td></td>
<td>1,250</td>
<td>73.5</td>
<td>54</td>
<td>19.5</td>
</tr>
<tr>
<td></td>
<td>1,600</td>
<td>27.1</td>
<td>51</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>2,000</td>
<td>0</td>
<td>48</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>2,500</td>
<td>0</td>
<td>45</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>3,150</td>
<td>0</td>
<td>42</td>
<td>0</td>
</tr>
</tbody>
</table>

![Figure 6.6](image)

**Figure 6.6:** Reference curve and measured normalized impact SPLs. The weighted normalized impact SPL $L'_{n,w}$ for the concrete floor structure is 60 dB. Normalized impact SPLs below 0 dB are not presented.

The A-weighted sound level is calculated when the concrete floor structure is subjected to rhythmic excitation. A-weighting is performed on the SPL at each center frequency, as shown in Figure 6.7. The total A-weighted sound level $L_A$ in the air domain is 105.8 dB(A).

### 6.2.2 Concrete Element Structures

The measured normalized impact SPLs in the air domain at each center frequency, when the tapping machine is running, are shown in Figure 6.8. The measurements lead to a weighted normalized impact SPL $L'_{n,w}$ of 70 dB for the concrete element floor structure.
CHAPTER 6.  CALCULATION AND EVALUATION

Figure 6.7: Measured and A-weighted SPLs in the air domain when the concrete floor structure is subjected to rhythmic excitation. The total A-weighted sound level \( L_A \) is 105.8 dB(A).

<table>
<thead>
<tr>
<th>Concrete Element Floor Structure</th>
<th></th>
<th>Measurement</th>
<th>Reference curve</th>
<th>Unfavourable deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (Hz)</td>
<td>100</td>
<td>31.7</td>
<td>72</td>
<td>0</td>
</tr>
<tr>
<td>125</td>
<td>28.9</td>
<td>72</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>160</td>
<td>42.6</td>
<td>72</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>200</td>
<td>91.2</td>
<td>72</td>
<td>19.2</td>
<td>0</td>
</tr>
<tr>
<td>250</td>
<td>48.7</td>
<td>72</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>315</td>
<td>38.8</td>
<td>72</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>400</td>
<td>47.8</td>
<td>71</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>500</td>
<td>52.7</td>
<td>70</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>630</td>
<td>43.5</td>
<td>69</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>800</td>
<td>51</td>
<td>68</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1,000</td>
<td>63</td>
<td>67</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1,250</td>
<td>73.2</td>
<td>64</td>
<td>9.2</td>
<td>0</td>
</tr>
<tr>
<td>1,600</td>
<td>61.9</td>
<td>61</td>
<td>0.9</td>
<td>0</td>
</tr>
<tr>
<td>2,000</td>
<td>16.4</td>
<td>58</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2,500</td>
<td>0</td>
<td>55</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3,150</td>
<td>5.4</td>
<td>52</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 6.8: Reference curve and measured normalized impact SPLs. The weighted normalized impact SPL \( L'_{n, w} \) for the concrete element floor structure in question is 70 dB. Normalized impact SPLs below 0 dB are not presented.

The A-weighted sound level is calculated when the concrete element floor structure is subjected to rhythmic excitation. A-weighting is performed on the SPL at each center frequency, as shown in Figure 6.9. The total A-weighted sound level \( L_A \) in the air domain is 101.4 dB(A).
Figure 6.9: Measured and A-weighted SPLs in the air domain when the concrete element floor structure is subjected to rhythmic excitation. The total A-weighted sound level $L_A$ is 101.4 dB(A).

6.2.3 Steel-Concrete Composite Structures

The measured normalized impact SPLs in the air domain at each center frequency, when the tapping machine is running, are shown in Figure 6.10. The measurements lead to a weighted normalized impact SPL $L_{n,w}'$ of 69 dB for the steel-concrete composite floor structure.

The A-weighted sound level is calculated when the steel-concrete composite floor structure is subjected to rhythmic excitation. A-weighting is performed on the SPL at each center frequency, as shown in Figure 6.11. The total A-weighted sound level $L_A$ in the air domain is 114.6 dB(A).
Figure 6.10: Reference curve and measured normalized impact SPLs. The weighted normalized impact SPL $I'_n,w$ for the steel-concrete composite floor structure in question is 69 dB. Normalized impact SPLs below 0 dB are not presented.

Figure 6.11: Measured and A-weighted SPLs in the air domain when the steel-concrete composite floor structure is subjected to rhythmic excitation. The total A-weighted sound level $L_A$ is 114.6 dB(A).
6.3 Special Cases

6.3.1 Steel-Concrete Composite Structures in a Multi-Story Building

The mechanical vibration calculations of the steel-concrete composite floor in a multi-story building carried out in the math software using design guides are presented in Appendix B.4. The floor is located on the sixth floor supported by steel-concrete composite columns. The height of each story is 5.2 m. By using the self-weight approach combined with the Dunkerley approach, the steel-concrete composite floor structure gets a static deflection of 9.98 mm and a natural frequency of 5.64 Hz. The effective maximum acceleration of the floor structure due to rhythmic excitation is 15.00% gravity, which corresponds to an acceleration of 1.47 m/s².

The computation of the FEA model, shown in Figure 6.12, results in a static deflection of 3.50 mm and a first natural frequency of 11.74 Hz. The calculated effective maximum acceleration is 0.51% gravity, which corresponds to an acceleration of 0.05 m/s².

![Figure 6.12: FEA model of the steel-concrete composite floor structure in a multi-story building showing the mode shape of the first natural frequency.](image)
6.3.2 Steel-Concrete Composite Structures with a Resilient Floor Covering

The A-weighted sound level is calculated when the steel-concrete composite floor structure with a resilient floor covering is subjected to rhythmic excitation. This analysis is carried out by calculating the force transmissibility at each center frequency. The force transmissibility magnitude proves to be equivalent to the change of response amplitude of the floor structure using the equation of motion. The force transmissibility magnitude is therefore used to change the sound pressures in the air domain. The resilient floor covering, with a thickness of 10 mm, has a dynamic stiffness of 30 MN/m³. The impact of the resilient floor covering is analyzed with four different loss factors. The change in A-weighted SPL at each center frequency, with the loss factors 0.1, 0.2, 0.5 and 1; is shown in Figure 6.13. The change in the total A-weighted sound level in the air domain is -50.7 dB(A) for loss factor 0.1, -46.0 dB(A) for loss factor 0.2, -38.3 dB(A) for loss factor 0.5 and -32.3 dB(A) for loss factor 1.

![Figure 6.13: The change in A-weighted SPLs in the air domain when the steel-concrete composite floor structure has a resilient floor covering with loss factors 0.1, 0.2, 0.5 and 1.](image)
6.3.3 Steel-Concrete Composite Structures with a Floating Floor

The A-weighted sound level is calculated when the steel-concrete composite floor structure with a floating floor is subjected to rhythmic excitation. The floating floor consists of a resilient layer, with a thickness of 30 mm, and a floating concrete slab, with a thickness of 80 mm. The resilient layer have a dynamic modulus of elasticity equivalent to a dynamic stiffness of 10 MN/m³. The loss factor of the resilient layer is 0.1. The impact of the floating floor is analyzed. The change in A-weighted SPL at each center frequency is shown in Figure 6.14. The change in the total A-weighted sound level in the air domain is -45.3 dB(A).

![Sound pressure level (dB)](image)

*Figure 6.14: The change in A-weighted SPLs in the air domain when the steel-concrete composite floor structure has a floating floor.*

6.4 Comparison and Conclusion

6.4.1 Mechanical Vibration

The results of mechanical vibration analysis are presented in Table 6.1. Since the floor structures are designed to have approximately the same static deflection and natural frequency using design guides, an easy conclusion is that lightweight floor structures are more sensitive to vibrations. The concrete floor structure has a much lower effective maximum acceleration than the other floor structures. However, all floor structures still meet the recommended acceleration limits, presented in Table 4.2, for people dining or in a
Table 6.1: Results of Mechanical Vibration Analysis

<table>
<thead>
<tr>
<th>Type of Long-Span Floor Structure</th>
<th>Deflection (mm)</th>
<th>Natural Frequency (Hz)</th>
<th>Acceleration (% gravity)</th>
<th>Acceleration (m/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Design guides</td>
<td>3.48</td>
<td>9.55</td>
<td>0.67</td>
<td>0.07</td>
</tr>
<tr>
<td>- FEA software</td>
<td>1.88</td>
<td>13.78</td>
<td>0.27</td>
<td>0.03</td>
</tr>
<tr>
<td>Concrete element</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Design guides</td>
<td>3.48</td>
<td>9.56</td>
<td>1.02</td>
<td>0.10</td>
</tr>
<tr>
<td>- FEA software</td>
<td>0.99</td>
<td>19.33</td>
<td>0.12</td>
<td>0.01</td>
</tr>
<tr>
<td>Steel-concrete composite</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Design guides</td>
<td>3.55</td>
<td>9.47</td>
<td>1.08</td>
<td>0.11</td>
</tr>
<tr>
<td>- FEA software</td>
<td>1.97</td>
<td>12.98</td>
<td>0.44</td>
<td>0.04</td>
</tr>
<tr>
<td>Steel-concrete composite + multi-story building</td>
<td>9.98</td>
<td>5.64</td>
<td>15.00</td>
<td>1.47</td>
</tr>
<tr>
<td>- Design guides</td>
<td>3.50</td>
<td>11.74</td>
<td>0.51</td>
<td>0.05</td>
</tr>
<tr>
<td>- FEA software</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The results obtained from the FEA software show a significantly higher natural frequency for all the floor structures due to a decreased static deflection, especially for the concrete element floor structure. The reason for this may be that the FEA software computes the whole floor structure at once instead of each structural element separately. The impact of the joints between the structural elements may also be considered differently in the FEA software than in the design guide calculations. However, the relationships between the static deflections and the natural frequencies are still about the same. According to the results in the FEA software, all floor structures meet the recommended acceleration limits for people in offices and residences.

When the steel-concrete composite floor structure is located on the sixth floor in a multi-story building, its natural frequency decreases considerably in the design guide calculations. The following effective maximum acceleration is unacceptable. When the floor structure is computed in the FEA software, it has a much higher natural frequency and meets the recommended acceleration limits for people in offices and residences.

6.4.2 Acoustics

The results of the acoustic analysis are presented in Table 6.2. The concrete floor structure has better impact sound insulation than the other floor structures, probably due to its heavy weight. However, neither of the floor structures satisfies the criteria for impact sound insulation in sport facilities.

The A-weighted sound levels are extremely high and therefore also unacceptable. The lowest A-weighted sound level is achieved for the concrete
element floor structure. The reason for this is that the concrete element floor structure produces the highest SPLs at center frequencies where the human hearing is less sensitive. The other floor structures produce the highest SPLs at center frequencies where the A-weighting is close to zero.

The steel-concrete composite floor structure with a resilient floor covering reduces the A-weighted sound level significantly. The loss factor of the resilient floor covering has a big impact on the A-weighted sound level. Higher loss factors work better near the resonance frequency of the resilient floor covering, while lower loss factors provide better damping at higher frequencies. The lowest A-weighted sound level is therefore reached for loss factor 0.1 since the crucial SPL is at center frequency 1000 Hz. However, neither of the A-weighted sound levels meets any of the guideline values presented in Table 4.4.

When the steel-concrete composite floor is built with a floating floor, the A-weighted sound level is considerably reduced as well. The A-weighted sound level does still not meet any of the guideline values presented in Table 4.4.

---

**Table 6.2: Results of Acoustic Analysis**

<table>
<thead>
<tr>
<th>Type of Long-Span Floor Structure</th>
<th>$L_{A,w}$ (dB)</th>
<th>$L_A$ (dB(A))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>60</td>
<td>105.8</td>
</tr>
<tr>
<td>Concrete element</td>
<td>70</td>
<td>101.4</td>
</tr>
<tr>
<td>Steel-concrete composite</td>
<td>69</td>
<td>114.6</td>
</tr>
<tr>
<td>Steel-concrete composite +</td>
<td></td>
<td></td>
</tr>
<tr>
<td>resilient floor covering</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Loss factor 0.1</td>
<td></td>
<td>63.9</td>
</tr>
<tr>
<td>- Loss factor 0.2</td>
<td></td>
<td>68.6</td>
</tr>
<tr>
<td>- Loss factor 0.5</td>
<td></td>
<td>76.3</td>
</tr>
<tr>
<td>- Loss factor 1</td>
<td></td>
<td>82.3</td>
</tr>
<tr>
<td>Steel-concrete composite +</td>
<td></td>
<td></td>
</tr>
<tr>
<td>floating floor</td>
<td></td>
<td>69.3</td>
</tr>
</tbody>
</table>
Chapter 7

Conclusions

Three different types of long-span floor structures; a concrete structure, a concrete element structure and a steel-concrete composite structure; have been analyzed for vibration serviceability due to rhythmic activities. The acoustic performance of the floor structures has also been analyzed with regard to impacts.

The mechanical vibration analyses were carried out in a math software using design guides. All floor structures were designed to have approximately the same natural frequency, at about 9.5 Hz, using the self-weight approach combined with the Dunkerley approach.

A model of each floor structure was built in a FEA software. Mechanical vibration analyses were carried out and compared with those of the design guide calculations. All acoustic analyses were mainly carried out in the FEA software.

Different special cases of the steel-concrete composite structure were also analyzed with regard to either vibration serviceability or acoustic performance.

According to the design guides, the floor structures meet the recommended acceleration limits for people participating in rhythmic activities, but also for occupants that are more sensitive to vibrations such as people lifting weights. If the floor is intended for rhythmic activities only, the dimensions of the floor structures may be reduced.

The results obtained from the FEA software show a very low static deflection for all floor structures, resulting in high natural frequencies as well as low accelerations. According to the results in the FEA software, all floor structures meet the recommended acceleration limits for people in offices and residences. This means that the dimensions of the analyzed floor structures are highly overestimated if the floor is intended for rhythmic activities only.

When the steel-concrete composite floor structure is located in a multi-
story building, the effective maximum acceleration of the floor increases well above all recommended limits according to the design guides. In the FEA software, however, the effective maximum acceleration of the floor is slightly increased and the recommended limits of the floor are still met for people in offices and residences.

The results of the acoustic analysis show that neither of the floor structures satisfies the criteria for impact sound insulation in sport facilities. The A-weighted sound levels in the space below, when the floor structures are subjected to rhythmic excitation, are very high and therefore also unacceptable.

When the steel-concrete composite floor structure is analyzed with a resilient floor covering, the A-weighted sound level is significantly reduced. The loss factor of the resilient floor covering has a big impact on the A-weighted sound level as well. When the resilient floor covering is replaced with a floating floor, the reduction of the A-weighted sound level is about the same.

The results of the acoustic analysis, however, can be considered as very rough approximations since the mesh elements of the air domain are too large to resolve vibrations properly. The FEA software used in this thesis is therefore not appropriate for acoustic analysis of large structures involving high frequencies.

Floor vibrations are estimated using design guides and FEA software. When comparing the results, the natural frequencies are lower in the design guide calculations. However, in both estimations, the relationships between the static deflections and the natural frequencies are still about the same, meaning that natural frequencies of floor structures could be approximated using the self-weight approach and static deflections obtained from various FEA software.

Floor structures subjected to rhythmic excitation require a high natural frequency to avoid resonant behavior followed by high accelerations. Since the natural frequency is related to the static deflection through mass and stiffness, long-span floor structures need to be designed with very high resistance to deflection. When the natural frequency of a floor structure is higher than approximately 9 Hz, there is no significant floor acceleration, meaning the floor structure is suitable for rhythmic activities in sport facilities. Even though regular concrete floor structures are less sensitive to vibrations, it is still more practical to use lightweight floor structures for longer spans.

When a floor structure is designed for vibration serviceability, the activity of the occupants has to be taken into account. People participating in rhythmic activities tolerate vibrations better than others. If the floor is intended for rhythmic activities combined with other activities, the floor structure needs to meet recommended acceleration limits for the most sensi-
tive occupants. Another consideration is that a floor structure located in a multi-story building is more sensitive to vibrations.

According to literature, floor structures in sport facilities should be designed with a floating floor to prevent the transmission of structure-borne sound to other supporting structures. Furthermore, a suspended ceiling with flexible acoustic barriers should be installed underneath the floor structure. If it is not possible to use a floating floor in the sport facility, different types of resilient floor coverings may be used instead to improve the impact sound insulation.

If the A-weighted sound level in the space below the sport facility does not meet the desirable sound level, the space requires other acoustic solutions such as absorbing surfaces.

Alternative solutions for floors that do not meet required vibration criteria are not presented in this thesis. Further studies should therefore be made for situations where it is not possible to design floor structures to have high natural frequencies.
Bibliography


### Appendix A

#### Tables

*Table A.1: First Natural Frequency and Modal Mass for Beams [12]*

<table>
<thead>
<tr>
<th>Supporting conditions</th>
<th>Values of $\alpha$ and $\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\triangle \quad \triangle$</td>
<td>$\alpha = \pi$ \hspace{1cm} $\beta = 0.50$</td>
</tr>
<tr>
<td>$\triangle \quad L \quad \triangle$</td>
<td>$\alpha = 3.927$ \hspace{1cm} $\beta = 0.45$</td>
</tr>
<tr>
<td>$\triangle \quad L \quad \triangle$</td>
<td>$\alpha = 4.730$ \hspace{1cm} $\beta = 0.41$</td>
</tr>
<tr>
<td>$\triangle \quad L \quad \triangle$</td>
<td>$\alpha = 1.875$ \hspace{1cm} $\beta = 0.64$</td>
</tr>
</tbody>
</table>

$$f_n = \frac{\alpha^2}{2\pi L^2} \sqrt{\frac{EI}{m}} \hspace{2cm} M_{mod} = \beta mL$$
Table A.2: First Natural Frequency and Modal Mass for Isotropic Plates [12]

<table>
<thead>
<tr>
<th>Supporting conditions</th>
<th>Values of $\alpha$ and $\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Supporting conditions" /></td>
<td>$\alpha = 1.57(1 + \lambda^2)$</td>
</tr>
<tr>
<td><img src="image" alt="Supporting conditions" /></td>
<td>$\beta \approx 0.25$ for all $\lambda$</td>
</tr>
<tr>
<td><img src="image" alt="Supporting conditions" /></td>
<td>$\alpha = 1.57 \sqrt{1 + 2.5\lambda^2 + 5.14\lambda^4}$</td>
</tr>
<tr>
<td><img src="image" alt="Supporting conditions" /></td>
<td>$\beta \approx 0.20$ for all $\lambda$</td>
</tr>
<tr>
<td><img src="image" alt="Supporting conditions" /></td>
<td>$\alpha = 1.57 \sqrt{5.14 + 2.92\lambda^2 + 2.44\lambda^4}$</td>
</tr>
<tr>
<td><img src="image" alt="Supporting conditions" /></td>
<td>$\beta \approx 0.18$ for all $\lambda$</td>
</tr>
<tr>
<td><img src="image" alt="Supporting conditions" /></td>
<td>$\alpha = 1.57 \sqrt{1 + 2.33\lambda^2 + 2.44\lambda^4}$</td>
</tr>
<tr>
<td><img src="image" alt="Supporting conditions" /></td>
<td>$\beta \approx 0.22$ for all $\lambda$</td>
</tr>
<tr>
<td><img src="image" alt="Supporting conditions" /></td>
<td>$\alpha = 1.57 \sqrt{2.44 + 2.72\lambda^2 + 2.44\lambda^4}$</td>
</tr>
<tr>
<td><img src="image" alt="Supporting conditions" /></td>
<td>$\beta \approx 0.21$ for all $\lambda$</td>
</tr>
<tr>
<td><img src="image" alt="Supporting conditions" /></td>
<td>$\alpha = 1.57 \sqrt{5.14 + 3.13\lambda^2 + 5.14\lambda^4}$</td>
</tr>
<tr>
<td><img src="image" alt="Supporting conditions" /></td>
<td>$\beta \approx 0.17$ for all $\lambda$</td>
</tr>
</tbody>
</table>
Table A.3: Center and Approximate Cutoff Frequencies (Hz) for Standard Set of Octave Bands and One-Third Octave Bands [3]

<table>
<thead>
<tr>
<th>Octave</th>
<th>Lower Band Limit</th>
<th>Center</th>
<th>Upper Band Limit</th>
<th>One-Third Octave</th>
<th>Lower Band Limit</th>
<th>Center</th>
<th>Upper Band Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>11</td>
<td>16</td>
<td>22</td>
<td>14.1</td>
<td>16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td></td>
<td></td>
<td></td>
<td>17.8</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td></td>
<td></td>
<td></td>
<td>22.4</td>
<td>25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>22</td>
<td>31.5</td>
<td>44</td>
<td>28.2</td>
<td>31.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td></td>
<td></td>
<td></td>
<td>35.5</td>
<td>40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td></td>
<td></td>
<td></td>
<td>44.7</td>
<td>50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>44</td>
<td>63</td>
<td>88</td>
<td>56.2</td>
<td>63</td>
<td></td>
<td></td>
</tr>
<tr>
<td>19</td>
<td></td>
<td></td>
<td></td>
<td>70.8</td>
<td>80</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td></td>
<td></td>
<td></td>
<td>89.1</td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>88</td>
<td>125</td>
<td>177</td>
<td>112</td>
<td>125</td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td></td>
<td></td>
<td></td>
<td>141</td>
<td>160</td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td></td>
<td></td>
<td></td>
<td>178</td>
<td>200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>177</td>
<td>250</td>
<td>355</td>
<td>224</td>
<td>250</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td></td>
<td></td>
<td></td>
<td>282</td>
<td>315</td>
<td></td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>355</td>
<td>500</td>
<td>710</td>
<td>447</td>
<td>500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>27</td>
<td></td>
<td></td>
<td></td>
<td>562</td>
<td>630</td>
<td></td>
<td></td>
</tr>
<tr>
<td>28</td>
<td></td>
<td></td>
<td></td>
<td>708</td>
<td>800</td>
<td></td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>710</td>
<td>1,000</td>
<td>1,420</td>
<td>891</td>
<td>1,000</td>
<td>1,122</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td></td>
<td></td>
<td></td>
<td>1,122</td>
<td>1,250</td>
<td>1,413</td>
<td></td>
</tr>
<tr>
<td>31</td>
<td></td>
<td></td>
<td></td>
<td>1,413</td>
<td>1,600</td>
<td>1,778</td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>1,420</td>
<td>2,000</td>
<td>2,840</td>
<td>1,778</td>
<td>2,000</td>
<td>2,239</td>
<td></td>
</tr>
<tr>
<td>33</td>
<td></td>
<td></td>
<td></td>
<td>2,239</td>
<td>2,500</td>
<td>2,818</td>
<td></td>
</tr>
<tr>
<td>34</td>
<td></td>
<td></td>
<td></td>
<td>2,818</td>
<td>3,150</td>
<td>3,548</td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>2,840</td>
<td>4,000</td>
<td>5,680</td>
<td>3,548</td>
<td>4,000</td>
<td>4,467</td>
<td></td>
</tr>
<tr>
<td>36</td>
<td></td>
<td></td>
<td></td>
<td>4,467</td>
<td>5,000</td>
<td>5,623</td>
<td></td>
</tr>
<tr>
<td>37</td>
<td>4,467</td>
<td>5,000</td>
<td>5,623</td>
<td>5,623</td>
<td>6,300</td>
<td>7,079</td>
<td></td>
</tr>
<tr>
<td>38</td>
<td></td>
<td></td>
<td></td>
<td>7,079</td>
<td>8,000</td>
<td>8,913</td>
<td></td>
</tr>
<tr>
<td>39</td>
<td>5,680</td>
<td>8,000</td>
<td>11,360</td>
<td>7,079</td>
<td>8,000</td>
<td>8,913</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td></td>
<td></td>
<td></td>
<td>8,913</td>
<td>10,000</td>
<td>11,220</td>
<td></td>
</tr>
<tr>
<td>41</td>
<td></td>
<td></td>
<td></td>
<td>11,220</td>
<td>12,500</td>
<td>14,130</td>
<td></td>
</tr>
<tr>
<td>42</td>
<td>11,360</td>
<td>16,000</td>
<td>22,720</td>
<td>14,130</td>
<td>16,000</td>
<td>17,780</td>
<td></td>
</tr>
<tr>
<td>43</td>
<td></td>
<td></td>
<td></td>
<td>17,780</td>
<td>20,000</td>
<td>22,390</td>
<td></td>
</tr>
<tr>
<td>Frequency, (Hz)</td>
<td>A-weighting Relative Response, (dB)</td>
<td>C-weighting Relative Response, (dB)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>----------------</td>
<td>------------------------------------</td>
<td>------------------------------------</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>-56.7</td>
<td>-8.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>-50.5</td>
<td>-6.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>-44.7</td>
<td>-4.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>31.5</td>
<td>-39.4</td>
<td>-3.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>-34.6</td>
<td>-2.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>-30.2</td>
<td>-1.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>63</td>
<td>-26.2</td>
<td>-0.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>-22.5</td>
<td>-0.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>-19.1</td>
<td>-0.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>125</td>
<td>-16.1</td>
<td>-0.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>160</td>
<td>-13.4</td>
<td>-0.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>-10.9</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>250</td>
<td>-8.6</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>315</td>
<td>-6.6</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>-4.8</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>-3.2</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>630</td>
<td>-1.9</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>800</td>
<td>-0.8</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1,000</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1,250</td>
<td>0.6</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1,600</td>
<td>1.0</td>
<td>-0.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2,000</td>
<td>1.2</td>
<td>-0.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2,500</td>
<td>1.3</td>
<td>-0.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3,150</td>
<td>1.2</td>
<td>-0.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4,000</td>
<td>1.0</td>
<td>-0.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5,000</td>
<td>0.5</td>
<td>-1.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6,300</td>
<td>-0.1</td>
<td>-2.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8,000</td>
<td>-1.1</td>
<td>-3.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10,000</td>
<td>-2.5</td>
<td>-4.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12,500</td>
<td>-4.3</td>
<td>-6.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16,000</td>
<td>-6.6</td>
<td>-8.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20,000</td>
<td>-9.3</td>
<td>-11.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table A.5: Force Transmissibility Magnitude at Each Center Frequency when the Damping Ratio and the Natural Frequency of the Human Leg with a Sport Shoe is 0.35 and 5 Hz

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Transmissibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>0.2580</td>
</tr>
<tr>
<td>20</td>
<td>0.1950</td>
</tr>
<tr>
<td>25</td>
<td>0.1500</td>
</tr>
<tr>
<td>31.5</td>
<td>0.1160</td>
</tr>
<tr>
<td>40</td>
<td>0.0900</td>
</tr>
<tr>
<td>50</td>
<td>0.0710</td>
</tr>
<tr>
<td>63</td>
<td>0.0560</td>
</tr>
<tr>
<td>80</td>
<td>0.0440</td>
</tr>
<tr>
<td>100</td>
<td>0.0350</td>
</tr>
<tr>
<td>125</td>
<td>0.0280</td>
</tr>
<tr>
<td>160</td>
<td>0.0220</td>
</tr>
<tr>
<td>200</td>
<td>0.0180</td>
</tr>
<tr>
<td>250</td>
<td>0.0140</td>
</tr>
<tr>
<td>315</td>
<td>0.0110</td>
</tr>
<tr>
<td>400</td>
<td>0.0088</td>
</tr>
<tr>
<td>500</td>
<td>0.0070</td>
</tr>
<tr>
<td>630</td>
<td>0.0056</td>
</tr>
<tr>
<td>800</td>
<td>0.0044</td>
</tr>
<tr>
<td>1,000</td>
<td>0.0035</td>
</tr>
<tr>
<td>1,250</td>
<td>0.0028</td>
</tr>
<tr>
<td>1,600</td>
<td>0.0022</td>
</tr>
<tr>
<td>2,000</td>
<td>0.0018</td>
</tr>
<tr>
<td>2,500</td>
<td>0.0014</td>
</tr>
<tr>
<td>3,150</td>
<td>0.0011</td>
</tr>
<tr>
<td>4,000</td>
<td>0.0009</td>
</tr>
<tr>
<td>5,000</td>
<td>0.0007</td>
</tr>
<tr>
<td>6,300</td>
<td>0.0006</td>
</tr>
<tr>
<td>8,000</td>
<td>0.0004</td>
</tr>
<tr>
<td>10,000</td>
<td>0.0004</td>
</tr>
<tr>
<td>12,500</td>
<td>0.0003</td>
</tr>
<tr>
<td>16,000</td>
<td>0.0002</td>
</tr>
<tr>
<td>20,000</td>
<td>0.0002</td>
</tr>
</tbody>
</table>
Appendix B

PTC Mathcad Calculations

B.1 Concrete Structures
Concrete Floor Structure

Introduction

The concrete floor structure is located in a low-rise building supported by concrete columns. The spacing between the columns are 8.1 m and 16.2 m. The diameter of the columns is assumed to be 0.7 m. The floor is subjected to rhythmic excitation.

The floor consists of primary and secondary cast-in-situ reinforced concrete beams, considered to be clamped, with slabs spanning between them. The columns are made of reinforced concrete.

The floor structure is designed to satisfy the design criteria according to the Eurocodes. In the floor vibration analysis, the slabs' deflections may be neglected due to the short span. The column effect may be neglected as well when the floor is located in a low-rise building.

Material Properties

Concrete C40/50

Density \( \rho_c : \frac{2400 \text{ kg}}{\text{m}^3} \)

Modulus of elasticity \( E_{cm} : 35000 \text{ MPa} \)

Dynamic modulus of elasticity \( E_{c,dyn} : 1.1E_{cm} \times 3.85 \times 10^4 \text{ MPa} \)

Reinforcement A500HW

Density \( \rho_s : \frac{7850 \text{ kg}}{\text{m}^3} \)

Modulus of elasticity \( E_s : 21000 \text{ MPa} \)

Dimensions

Distance between columns \( L_1 : 8.1 \text{ m} \)
\( L_2 : 16.2 \text{ m} \)

Diameter of column \( d_{col} : 0.7 \text{ m} \)

Length of primary beam \( L_p : L_1 = 8.1 \text{ m} \)

Length of secondary beam \( L_s : L_2 = 16.2 \text{ m} \)

Equivalent span of beams:
Primary beam \( L_{c,p} : 0.7L_p = 5.67 \text{ m} \)
Secondary beam

\[ L_{e,s} : \quad 0.7L_s \quad 11.34 \text{ m} \]

Bay width of primary beam

\[ B_p : \quad L_2 \quad 16.2 \text{ m} \]

Bay width of secondary beam

\[ B_s : \quad 1.62 \text{ m} \]

**Concrete Slab**

**Concrete Slab**

Slab depth

\[ h_c : \quad 250 \text{ mm} \]

Effective width of concrete flange:

**Primary beam**

Width of web

\[ b_{w,p} : \quad 680 \text{ mm} \]

\[ b_{eff,p} : \quad 2 \min \left( 0.2 \frac{B_p - b_{w,p}}{2} + 0.1L_{e,p} \frac{B_p - b_{w,p}}{2} \right) + b_{w,p} \quad 2.948 \text{ m} \]

**Secondary beam**

Width of web

\[ b_{w,s} : \quad 480 \text{ mm} \]

\[ b_{eff,s} : \quad 2 \min \left( 0.2 \frac{B_s - b_{w,s}}{2} + 0.1L_{e,s} \frac{B_s - b_{w,s}}{2} \right) + b_{w,s} \quad 1.62 \text{ m} \]

**Primary Beam**

**Dimensions of the Beam**

Height of web

\[ h_{w,p} : \quad 980 \text{ mm} \]

Width of web

\[ b_{w,p} \quad 680 \text{ mm} \]

Total height of beam

\[ h_p : \quad h_{w,p} + h_c \quad 1.23 \times 10^3 \text{ mm} \]

**Reinforcement**

Thickness of bars

\[ \phi_p : \quad 32 \text{ mm} \]

The reinforcement bars are placed in 2 layers with 8 bars per layer:

Number of bars per layer

\[ n_p : \quad 8 \]
Number of layers \( l_p: 2 \)

Eccentricity \( e_p: 110 \text{mm} \)

Distance from top of beam \( d_p: h_p - e_p \quad 1.12 \times 10^3 \text{mm} \)

**Section Properties of the Beam**

Cross-sectional areas:

Reinforcement \( A_{s,p} : \left(n_p \frac{d_p}{2}\right)^2 \quad 1.287 \times 10^4 \text{mm}^2 \)

Web \( A_{w,p} : b_{w,p} b_{w,p} - A_{s,p} \quad 6.535 \times 10^5 \text{mm}^2 \)

Flange \( A_{f,p} : h_c b_{eff,p} \quad 7.37 \times 10^5 \text{mm}^2 \)

**Moment of Inertia for Transformed Section**

New effective area for reinforcement:

\( n_i : \frac{E_s}{E_{c,dyn}} \quad 5.455 \)

\( A_{s,t,p} : n_i A_{s,p} \quad 7.019 \times 10^4 \text{mm}^2 \)

Distance from the top of the section to the Neutral Axis (cracked):

\( \frac{b_{eff,s} x_s^2}{2} - A_{s,t,s} (d_s - x_s) \quad 0 \)

\( x_p: 208.353 \text{ mm} \quad \text{Neutral axis is in the slab} \)

Moment of inertia:

Reinforcement \( d_{s,p} : d_p - x_p \quad 911.647 \text{mm} \)

Flange \( I_{f,p} : \frac{b_{eff,p} x_p^3}{12} \quad 2.222 \times 10^9 \text{mm}^4 \)

\( A_{f,t,p} : b_{eff,p} x_p \quad 6.142 \times 10^5 \text{mm}^2 \)

\( d_{f,p} : \frac{x_p}{2} \quad 104.177 \text{mm} \)
Total moment of inertia for transformed cracked section

\[ I_p = I_{p,p} + A_{f,t,p}d_{f,p}^2 + I_{w,p} + A_{s,t,p}d_{s,p}^2 = 6.722 \times 10^{10}\text{ mm}^4 \]

**Secondary Beam**

**Dimensions of the Beam**

Height of web \( h_{w,s} = 980\text{ mm} \)

Width of web \( b_{w,s} = 480\text{ mm} \)

Total height of beam \( h_s = h_{w,s} + h_c = 1.23 \times 10^3\text{ mm} \)

**Reinforcement**

Thickness of bars \( \phi_s = 32\text{ mm} \)

The reinforcement bars are placed in 2 layers with 5 bars per layer:

Number of bars per layer \( n_s = 5 \)

Number of layers \( l_s = 2 \)

Eccentricity \( e_s = 110\text{ mm} \)

Distance from top of beam \( d_s = h_s - e_s = 1.12 \times 10^3\text{ mm} \)

**Section Properties**

Cross-sectional areas:

Reinforcement

\[ A_{s,s} = (n_s l_s) \pi \left( \frac{\phi_s}{2} \right)^2 = 8.042 \times 10^3\text{ mm}^2 \]

Web

\[ A_{w,s} = h_{w,s} b_{w,s} - A_{s,s} = 4.624 \times 10^5\text{ mm}^2 \]

Flange

\[ A_{f,s} = h_c b_{eff,s} = 4.05 \times 10^5\text{ mm}^2 \]

**Moment of Inertia for Transformed Section**

New effective area for reinforcement:

\[ A_{s,t,s} = n_t A_{s,s} = 4.387 \times 10^4\text{ mm}^2 \]

Distance from the top of the section to the Neutral Axis (cracked):
\[
\frac{b_{eff.s}x_s^2}{2} - A_{s.t.s}(d_s - x_s) = 0
\]

\(x_s = 220.692\ mm\) \quad \text{Neutral axis is in the slab}

**Moment of inertia:**

**Reinforcement**
\(d_{s.s} = d_s - x_s = 899.308\ mm\)

**Flange**
\(I_{f.s} = \frac{b_{eff.s}x_s^3}{12} = 1.451 \times 10^9\ mm^4\)
\(A_{f.t.s} = b_{eff.s}x_s\)
\(d_{f.s} = \frac{x_s}{2} = 110.346\ mm\)

**Total moment of inertia for transformed cracked section**
\(I_s = I_{f.s} + A_{f.t.s}d_{f.s}^2 + A_{s.t.s}d_{s.s}^2 = 4.128 \times 10^{10}\ mm^4\)

**Loads**

**Partial factors**

**Dead load** \(\gamma_G = 1.15\)

**Live load** \(\gamma_Q = 1.5\)

**Dead Loads**

**Primary beam:**
\(g_{p,k} = g\left[A_{w,p}\,\rho_c + A_{s,p}\,\rho_s + \frac{5B_p}{L_p}\left(A_{w.s}\,\rho_c + A_{s,s}\,\rho_s + h_c B_s\,\rho_c\right)\right] = 226.704\ kNm\)

**Secondary beam:**
\(g_{s,k} = g\left(A_{w.s}\,\rho_c + A_{s,s}\,\rho_s + h_c B_s\,\rho_c\right) = 21.033\ kNm\)

**Live Loads**

For areas with possible physical activities:
\(q_k = 5.0\ \frac{kN}{m^2}\)
Q_k : 7.0kN

Primary beam:

\[ q_{p,k} : \frac{5(B_p B_s q_k)}{L_p} \text{ kN/m} \]

Secondary beam:

\[ q_{s,k} : B_s q_k \text{ kN/m} \]

**Floor Vibration**

**Natural Frequency of the Concrete Floor Structure**

Percentage of imposed load, representing permanent loading on the floor:

\[ \gamma_{v,Q} : 10\% \]

Deflection of secondary beam:

\[ \delta_s : \frac{(g_{s,k} + \gamma_{v,Q} q_{s,k}) L_s^4}{384 E_{c,dyn} I_s} \text{ 2.465-mm} \]

Deflection of primary beam:

\[ \delta_p : \frac{(g_{p,k} + \gamma_{v,Q} q_{p,k}) L_p^4}{384 E_{c,dyn} I_p} \text{ 1.017-mm} \]

Total deflection of floor structure:

\[ \delta_{max} : \delta_s + \delta_p \text{ 3.482-mm} \]

Natural frequency:

\[ f_n : 0.18 \sqrt{\frac{g}{\delta_{max}}} \text{ 9.552-Hz} \]

**Minimum Natural Frequency of the Floor Structure**

Forcing frequency:

First harmonic \( f_1 : 2.5\text{Hz} \)
Second harmonic $f_2 : 2 \cdot f_1 \quad 5\text{-Hz}$

Third harmonic $f_3 : 3 \cdot f_1 \quad 7.5\text{-Hz}$

Acceleration limit:
$$a_0 : 5\% \cdot g = 0.49 \frac{m}{s^2}$$
$$k : 2.0$$

Dynamic coefficient:
First harmonic $\alpha_1 : 1.5$
Second harmonic $\alpha_2 : 0.6$
Third harmonic $\alpha_3 : 0.1$

Effective weight:
Participants $w_p : 0.2 \text{kN/m}^2$
Floor structure + participants $w_l : \frac{B_s \cdot k + \gamma \cdot Q \cdot q_s \cdot k}{B_s} + w_p$ $13.683 \text{kN/m}^2$

First harmonic $f_{n,\text{min.1}} : f_1 \sqrt{1 + \frac{k \cdot \alpha_1 \cdot w_p}{a_0 \cdot w_l} \frac{m}{s^2}}$ $3.425\text{-Hz}$

Second harmonic $f_{n,\text{min.2}} : f_2 \sqrt{1 + \frac{k \cdot \alpha_2 \cdot w_p}{a_0 \cdot w_l} \frac{m}{s^2}}$ $5.811\text{-Hz}$

Third harmonic $f_{n,\text{min.3}} : f_3 \sqrt{1 + \frac{k \cdot \alpha_3 \cdot w_p}{a_0 \cdot w_l} \frac{m}{s^2}}$ $7.716\text{-Hz}$

The normal frequency is not close to the forcing frequency for the third harmonic.
$f_n > 1.2 \cdot f_3$ $1$
\[ a_{p3} : \frac{1.3}{\left(\frac{f_n}{f_3}\right)^2 - 1} \cdot \frac{\alpha_3 \cdot w_p}{w_t} \quad 0.305\% \]

\[ a_{p2} : \frac{1.3}{\left(\frac{f_n}{f_2}\right)^2 - 1} \cdot \frac{\alpha_2 \cdot w_p}{w_t} \quad 0.43\% \]

\[ a_{p1} : \frac{1.3}{\left(\frac{f_n}{f_1}\right)^2 - 1} \cdot \frac{\alpha_1 \cdot w_p}{w_t} \quad 0.21\% \]

Effective maximum acceleration

\[ a_m : \left( a_{p1}^{1.5} + a_{p2}^{1.5} + a_{p3}^{1.5} \right)^{\frac{1}{1.5}} \quad 0.669\% \]
B.2 Concrete Element Structures
Concrete Element Floor Structure

Introduction

The concrete element floor structure is located in a low-rise building supported by concrete columns. The spacing between the columns are 8.1 m and 16.2 m. The diameter of the columns is assumed to be 0.7 m. The floor is subjected to rhythmic excitation.

The floor consists of prestressed and precast inverted T-beams, considered to be simply supported, with hollow core slabs spanning between them and a cast-in-situ topping layer onto the surface. The columns are made of reinforced concrete.

The floor structure is designed to satisfy the design criteria according to the Eurocodes. In the floor vibration analysis, the column effect may be neglected when the floor is located in a low-rise building.

Material Properties

Concrete

Density
\[ \rho_c : \frac{2400 \text{ kg}}{\text{m}^3} \]

C30/37 (topping):

Modulus of elasticity
\[ E_{cm30} : \ 33000 \text{ MPa} \]

Dynamic modulus of elasticity
\[ E_{cm, dyn30} : \ 1.1 \cdot E_{cm30} \ 3.63 \times 10^4 \text{ MPa} \]

C40/50 (beam):

Modulus of elasticity
\[ E_{cm40} : \ 35000 \text{ MPa} \]

Dynamic modulus of elasticity
\[ E_{cm, dyn40} : \ 1.1 \cdot E_{cm40} \ 3.85 \times 10^4 \text{ MPa} \]

C50/60 (hollow core slab):

Modulus of elasticity
\[ E_{cm50} : \ 37000 \text{ MPa} \]

Dynamic modulus of elasticity
\[ E_{cm, dyn50} : \ 1.1 \cdot E_{cm50} \ 4.07 \times 10^4 \text{ MPa} \]

Prestressed Strands

Density
\[ \rho_p : \frac{7850 \text{ kg}}{\text{m}^3} \]

Modulus of elasticity
\[ E_p : \ 195000 \text{ MPa} \]
**Dimensions**

Distance between columns

\[ L_1 := 8.1 \text{m} \]
\[ L_2 := 16.2 \text{m} \]

Diameter of column

\[ d_{\text{col}} := 0.7 \text{m} \]

Length of beam

\[ L_b := L_2 - d_{\text{col}} = 15.5 \text{m} \]

Equivalent span of elements:

Primary beam

\[ L_{\text{c}, b} := L_1 \cdot L_b = 15.5 \text{m} \]

Bay width of beam

\[ B_b := L_1 = 8.1 \text{m} \]

**Topping**

Depth

\[ h_t := 100 \text{mm} \]

Moment of inertia

\[ I_t := \frac{h_t^3}{12} = 8.333 \times 10^7 \frac{\text{mm}^4}{\text{m}} \]

Effective width of topping for composite action of the beam:

\[ b_{\text{eff}, b} := \min \left( \frac{L_{\text{c}, b}}{8}, \frac{B_b}{2} \right) = 3.875 \text{m} \]

**Beam**

**Dimensions of the Beam**

Height of web

\[ h_{w, b} := 500 \text{mm} \]

Width of web

\[ b_{w, b} := 480 \text{mm} \]

Height of flange

\[ h_{f, b} := 1380 \text{mm} \]

Width of flange

\[ b_{f, b} := 880 \text{mm} \]

Total height of beam

\[ h_b := h_{w, b} + h_{f, b} = 1.88 \times 10^3 \text{mm} \]

**Prestressed Strands**

Thickness of strands

\[ \phi_b := 12.5 \text{mm} \]

Area of strands

\[ A_{p, b1} := 93 \text{mm}^2 \]

The prestressed strands are placed in 5 layers with 15 strands per layer:
Number of strands per layer \( n_b : 15 \)

Number of layers \( l_b : 5 \)

Eccentricity \( e_b : 170\text{mm} \)

Distance from top of beam \( d_b : h_b - e_b = 1.71 \times 10^3\text{mm} \)

**Section Properties of the Beam**

Cross-sectional areas:

Prestressed strands 
\[ A_{p.b} = n_b l_b A_{p.b1} = 6.975 \times 10^3\text{mm}^2 \]

Web 
\[ A_{w.b} = h_{w,b} b_{w,b} = 2.4 \times 10^5\text{mm}^2 \]

Flange 
\[ A_{f.b} = h_{f,b} b_{f,b} - A_{p.b} = 1.207 \times 10^6\text{mm}^2 \]

**Moment of Inertia for Transformed Section**

New effective area for prestressed strands:
\[ n_{t,b} : \frac{E_p}{E_{c,dyn40}} = 5.065 \]

\[ A_{p,t,b} : n_{t,b} A_{p,b} = 3.533 \times 10^4\text{mm}^2 \]

Distance from the top of the section to the Neutral Axis (uncracked):
\[ x_b : \frac{A_{w,b} \frac{h_{w,b}}{2} + A_{f,b} \left( h_{w,b} + \frac{h_{f,b}}{2} \right) + A_{p,t,b} d_b}{A_{w,b} + A_{f,b} + A_{p,t,b}} = 1.05 \times 10^3\text{mm} \]

Moment of inertia:

Prestressed strands 
\[ d_{p,b} : d_b - x_b = 659.76\text{mm} \]

Web 
\[ I_{w,b} : \frac{b_{w,b} \left( h_{w,b} \right)^3}{12} = 5 \times 10^9\text{mm}^4 \]

\[ d_{w,b} : x_b - \frac{h_{w,b}}{2} = 800.24\text{mm} \]

Flange 
\[ I_{f,b} : \frac{b_{f,b} h_{f,b}^3}{12} = 1.927 \times 10^{11}\text{mm}^4 \]
\[
d_{f,b} = h_b - \frac{h_{f,b}}{2} - x_b \quad 139.76\text{-mm}
\]

Total moment of inertia for transformed uncracked section

\[
l_b = l_{f,b} + \left(A_{f,b} + A_{p,b}\right)d_{f,b}^2 + l_{w,b} + A_{w,b}d_{w,b}^2 + \left(n_{t,b} - 1\right)A_{p,b}d_{p,b}^2 = 3.875 \times 10^{11}\text{-mm}^4
\]

**Moment of Inertia for Transformed Composite Section**

New effective width for topping:

\[
n_{t,\text{comp.b}} = \frac{E_{c,\text{dyn30}}}{E_{c,\text{dyn40}}} = 0.943
\]

\[
b_{\text{eff.comp.b}} = n_{t,\text{comp.b}}b_{\text{eff.b}} = 3.654 \text{ m}
\]

Area of transformed sections:

**Topping**

\[
A_{t,b} = b_{\text{eff.comp.b}}h_t = 3.654 \times 10^5\text{-mm}^2
\]

**Beam**

\[
A_b = A_{w,b} + A_{f,b} + A_{p,t,b} = 1.483 \times 10^6\text{-mm}^2
\]

Total area

\[
A_{\text{comp.b}} = A_{t,b} + A_b = 1.848 \times 10^6\text{-mm}^2
\]

Distance from the top of the section to the Neutral Axis (uncracked):

\[
x_{\text{comp.b}} = \frac{A_b \left(h_t + x_b\right) + A_{t,b} \frac{h_t}{2}}{A_{\text{comp.b}}} = 932.731\text{-mm}
\]

Moment of inertia:

**Beam**

\[
d_{\text{comp.b}} = x_b + h_t - x_{\text{comp.b}} = 217.509\text{-mm}
\]

**Topping**

\[
l_{\text{comp.t.b}} = \frac{b_{\text{eff.comp.b}} \left(h_t\right)^3}{12} = 3.045 \times 10^8\text{-mm}^4
\]

\[
d_{\text{comp.t.b}} = x_{\text{comp.b}} - \frac{h_t}{2} = 882.731\text{-mm}
\]

Total moment of inertia for transformed uncracked composite section

\[
l_{\text{comp.b}} = l_b + A_b'd_{\text{comp.b}}^2 + l_{\text{comp.t.b}} + A_{t,b}d_{\text{comp.t.b}}^2 = 7.426 \times 10^{11}\text{-mm}^4
\]
Hollow Core Slab O50

Depth \( h_{hcs} := 500 \text{mm} \)

Width \( b_{hcs} := 1200 \text{mm} \)

Length \( L_{hcs} := L_1 - b_{w,b} = 7.62 \text{m} \)

Moment of inertia of section without strands is assumed to be \( I_{hcs0} := 8400000000 \text{mm}^4 \)

Area of section is assumed to be \( A_{hcs0} := 280000 \text{mm}^2 \)

Weight \( \rho_{hcs0} := 600 \text{kg/m}^3 \)

Prestressed Strands

Thickness of strands \( \phi_{hcs} := 12.5 \text{mm} \)

Area of strands \( A_{p.hcs1} := 93 \text{mm}^2 \)

The prestressed strands are placed in one 1 layer with 13 strands:

Number of strands per layer \( n_{hcs} := 13 \)

Eccentricity \( e_{hcs} := 40 \text{mm} \)

Distance from top of HCS \( d_{hcs} := h_{hcs} - e_{hcs} = 460 \text{mm} \)
Section Properties of the Hollow Core Slab

Cross-sectional areas:

Prestressed strands
\[ A_{p, hcs} : \quad n_{hcs} A_{p, hcs1} = 1.209 \times 10^3 \text{ mm}^2 \]

HCS section
\[ A_{hcs0} = 2.8 \times 10^5 \text{ mm}^2 \]

Moment of Inertia for Transformed Section

New effective area for prestressed strands:
\[ n_{t, hcs} = \frac{E_p}{E_{c, dyn 50}} = 4.791 \]
\[ A_{p, t, hcs} = n_{t, hcs} A_{p, hcs} = 5.793 \times 10^3 \text{ mm}^2 \]

Distance from the top of the section to the Neutral Axis (uncracked):
\[ x_{hcs} = \frac{A_{hcs0} \frac{h_{hcs}}{2} + (n_{t, hcs} - 1) A_{p, hcs} d_{hcs}}{A_{hcs0} + (n_{t, hcs} - 1) A_{p, hcs}} = 253.382 \text{ mm} \]

Moment of inertia:

Prestressed strands
\[ d_{p, hcs} = d_{hcs} - x_{hcs} = 206.618 \text{ mm} \]

HCS section
\[ I_{hcs0} = 8.4 \times 10^9 \text{ mm}^4 \]
\[ d_{hcs0} = x_{hcs} = \frac{h_{hcs}}{2} = 3.382 \text{ mm} \]

Total moment of inertia for transformed uncracked section
\[ I_{hcs} = I_{hcs0} + A_{hcs0} d_{hcs0}^2 + (n_{t, hcs} - 1) A_{p, hcs} d_{p, hcs}^2 = 8.599 \times 10^9 \text{ mm}^4 \]

Moment of Inertia for Transformed Composite Section

New effective width for topping:
\[ n_{t, comp, hcs} = \frac{E_{c, dyn 30}}{E_{c, dyn 50}} = 0.892 \]
$b_{\text{eff.comp.hcs}}: \quad n_{t,\text{comp,b}} \cdot b_{\text{hcs}} \quad 1.131 \, \text{m}$

**Area of transformed sections:**

**Topping**  
$A_{t,\text{hcs}}: \quad b_{\text{eff.comp.hcs}} \cdot h_t \quad 1.131 \times 10^5 \cdot \text{mm}^2$

**Hollow core slab**  
$A_{\text{hcs}}: \quad \frac{A_{\text{hcs0}} + (n_{t,\text{hcs}} - 1) \cdot A_{p,\text{hcs}}}{A_{\text{hcs}}} \quad 2.846 \times 10^5 \cdot \text{mm}^2$

**Total area**  
$A_{\text{comp.hcs}}: \quad A_{t,\text{hcs}} + A_{\text{hcs}} \quad 3.977 \times 10^5 \cdot \text{mm}^2$

**Distance from the top of the section to the Neutral Axis (uncracked):**

$$x_{\text{comp.hcs}}: \quad \frac{A_{\text{hcs}}(h_t + x_{\text{hcs}}) + A_{t,\text{hcs}} \cdot \frac{h_t}{2}}{A_{\text{comp.hcs}}} \quad 267.078 \, \text{mm}$$

**Moment of inertia:**

**Hollow core slab**  
$d_{\text{comp.hcs}}: \quad x_{\text{hcs}} + h_t - x_{\text{comp.hcs}} \quad 86.304 \, \text{mm}$

**Topping**  
$I_{\text{comp.t.hcs}}: \quad \frac{b_{\text{eff.comp.hcs}}(h_t)^3}{12} \quad 9.429 \times 10^7 \cdot \text{mm}^4$

$$d_{\text{comp.t.hcs}}: \quad x_{\text{comp.hcs}} - \frac{h_t}{2} \quad 217.078 \, \text{mm}$$

**Total moment of inertia for transformed uncracked composite section**

$$I_{\text{comp.hcs}}: \quad I_{\text{hcs}} + A_{\text{hcs}} \cdot d_{\text{comp.hcs}}^2 + I_{\text{comp.t.hcs}} + A_{t,\text{hcs}} \cdot d_{\text{comp.t.hcs}}^2 \quad 1.614 \times 10^{10} \cdot \text{mm}^4$$

**Loads**

**Partial factors**

**Dead load**  
$\gamma_G: \quad 1.15$

**Live load**  
$\gamma_Q: \quad 1.5$

**Dead Loads**

**Beam:**

$$g_{b,k}: \quad g\left[\left(\frac{L}{L_b}\right)^2 + \frac{A_{w,b} + A_{f,b}}{A_{p,b} \cdot \rho_p} + \frac{l_{\text{hcs}} \cdot g_{\text{hcs0}} + B_b \cdot h_t \cdot \rho_c}{L_b}\right] \quad 101.389 \, \text{kN/m}$$

**Hollow core slab:**
$g_{hcs,k} : \frac{\gamma}{\gamma_{hcs0} + \gamma_{c}' \rho_{c}} \cdot b_{hcs} \quad 9.885 \, \text{kN/m}$

**Live Loads**

For areas with possible physical activities:

$q_k : \frac{5.0}{m^2}$

$Q_k : \quad 7.0 \, \text{kN}$

**Beam:**

$q_{b,k} : \frac{B_b \cdot L_2 \cdot q_k}{L_b} \quad 42.329 \, \text{kN/m}$

**Hollow core slab:**

$q_{hcs,k} : b_{hcs} \cdot q_k \quad 6 \, \text{kN/m}$

**Floor Vibration**

**Natural Frequency of the Concrete Element Floor Structure**

Percentage of imposed load, representing permanent loading on the floor:

$\gamma_{v,Q} : \quad 10\%$

Deflection of hollow core slab:

$\delta_{\text{hcs}} : \frac{5 \left( g_{hcs,k} + \gamma_{v,Q} q_{hcs,k} \right) L_{\text{hcs}}^4}{384 \cdot E_{c, \text{dyn50}} \cdot l_{\text{comp, hcs}}} \quad 0.701 \, \text{mm}$

Deflection of beam:

$\delta_{b} : \frac{5 \left( g_{b,k} + \gamma_{v,Q} q_{b,k} \right) L_{b}^4}{384 \cdot E_{c, \text{dyn40}} \cdot l_{\text{comp, b}}} \quad 2.776 \, \text{mm}$

Total deflection of floor structure:

$\delta_{\text{max}} : \delta_{\text{hcs}} + \delta_{b} \quad 3.477 \, \text{mm}$

Natural frequency:
\[ f_n = 0.18 \sqrt{\frac{g}{\delta_{\text{max}}}} \quad 9.559 \text{ Hz} \]

**Minimum Natural Frequency of the Floor Structure**

**Forcing frequency:**

First harmonic \( f_1 : 2.5 \text{ Hz} \)

Second harmonic \( f_2 : 2 \cdot f_1 \quad 5 \cdot \text{Hz} \)

Third harmonic \( f_3 : 3 \cdot f_1 \quad 7.5 \cdot \text{Hz} \)

**Acceleration limit:**

\[ a_0 : 5\% \cdot g \quad 0.49 \cdot \frac{m}{s^2} \]

\( k : 2.0 \)

**Dynamic coefficient:**

First harmonic \( \alpha_1 : 1.5 \)

Second harmonic \( \alpha_2 : 0.6 \)

Third harmonic \( \alpha_3 : 0.1 \)

**Effective weight:**

Participants \( w_p : 0.2 \cdot \frac{kN}{m^2} \)

Floor structure + participants \( w_1 : \frac{b_{\text{hcs},k} + \gamma_{\text{V.Q}} q_{\text{hcs},k}}{b_{\text{hcs}}} + w_p \quad 8.938 \cdot \frac{kN}{m^2} \)

First harmonic \( f_{\text{n.min.1}} : f_1 \cdot \sqrt{1 + \frac{k}{a_0 \cdot \frac{w_p}{g}}} \quad 3.826 \text{ Hz} \)

Second harmonic \( f_{\text{n.min.2}} : f_2 \cdot \sqrt{1 + \frac{k \cdot \alpha_2 \cdot w_p}{a_0 \cdot \frac{w_p}{g}}} \quad 6.199 \text{ Hz} \)
Third harmonic

\[ f_{n,\text{min.3}} : \quad f_3 \sqrt{1 + \frac{k}{a_0 \frac{\alpha_3^3 w_p}{w_t}}}, \quad 7.828\text{-Hz} \]

The normal frequency is not close to the forcing frequency for the third harmonic.

\[ f_n > 1.2 f_3 \quad 1 \]

\[ a_{p3} : \quad \frac{1.3}{\left(\frac{f_n}{f_3}\right)^2 - 1} \frac{\alpha_3^3 w_p}{w_t} \quad 0.466\% \]

\[ a_{p2} : \quad \frac{1.3}{\left(\frac{f_n}{f_2}\right)^2 - 1} \frac{\alpha_2^2 w_p}{w_t} \quad 0.657\% \]

\[ a_{p1} : \quad \frac{1.3}{\left(\frac{f_n}{f_1}\right)^2 - 1} \frac{\alpha_1^1 w_p}{w_t} \quad 0.32\% \]

Effective maximum acceleration

\[ a_m : \quad \left( a_{p1}^{1.5} + a_{p2}^{1.5} + a_{p3}^{1.5} \right)^{\frac{1}{1.5}} \quad 1.021\% \]
B.3 Steel-Concrete Composite Structures
Steel-Concrete Composite Floor Structure

Introduction

The steel-concrete composite floor structure is located in a low-rise building supported by composite columns. The spacing between the columns are 8.1 m and 16.2 m. The diameter of the columns is assumed to be 0.7 m. The floor is subjected to rhythmic excitation.

The floor consists of primary and secondary I-profiled beams, considered as simply supported. A concrete slab is cast-in-situ onto a profiled steel sheeting with ribs perpendicular to the secondary beams. Shear studs are placed on both the primary and secondary beams. The columns are concrete filled circular hollow sections with reinforcement.

The floor structure is designed to satisfy the design criteria according to the Eurocodes. In the floor vibration analysis, the slab's deflection may be neglected due to the short span. The column effect may be neglected as well when the floor is located in a low-rise building.

Material Properties

Structural Steel S355

Density \( \rho_a : \frac{7850 \text{ kg}}{\text{m}^3} \)

Modulus of elasticity \( E_a : 210000 \text{MPa} \)

Concrete C30/37 (slab)

Density \( \rho_c : \frac{2400 \text{ kg}}{\text{m}^3} \)

Modulus of elasticity \( E_{cm} : 33000 \text{MPa} \)

Dynamic modulus of elasticity \( E_{c,dyn} : 1.1 \cdot E_{cm} = 3.63 \times 10^4 \text{MPa} \)

Dimensions

Distance between columns \( L_1 : 8.1 \text{m} \)
\( L_2 : 16.2 \text{m} \)

 Diameter of column \( d_{col} : 0.7 \text{m} \)

Length of primary beam \( L_p : L_1 - d_{col} = 7.4 \text{m} \)

Length of secondary beam \( L_s : L_2 = 16.2 \text{m} \)

Equivalent span of beams:
Primary beam \( L_{e,p} := 1 \cdot L_p = 7.4 \text{ m} \)

Secondary beam \( L_{e,s} := 1 \cdot L_s = 16.2 \text{ m} \)

Bay width of primary beam \( B_p := L_2 = 16.2 \text{ m} \)

Bay width of secondary beam \( B_s := 1.62 \text{ m} \)

Concrete Slab with Profiled Steel Sheeting and Shear Studs

Concrete Slab

Slab depth \( h := 250 \text{ mm} \)

Effective width of concrete flange:

Primary beam \( b_{\text{eff},p} := 2 \cdot \min \left( \frac{L_{e,p}}{8}, \frac{B_p}{2} \right) = 1.85 \text{ m} \)

Secondary beam \( b_{\text{eff},s} := 2 \cdot \min \left( \frac{L_{e,s}}{8}, \frac{B_s}{2} \right) = 1.62 \text{ m} \)

Profiled Steel Sheeting SUPERHOLORIB SHR 51/600

Thickess \( t := 0.75 \text{ mm} \)

\( h_p := 51 \text{ mm} \)

\( h_c := h - h_p = 199 - \text{mm} \)

\( b_s := 150 \text{ mm} \)

\( b_{r,1} := 40 \text{ mm} \)

\( b_{r,2} := 15 \text{ mm} \)

\( b_0 := 110 \text{ mm} \)
Primary Beam

Dimensions of the I-Profile

Height
\[ h_{\text{a,p}} := 1400\text{mm} \]

Width
\[ b_{\text{a,p}} := 420\text{mm} \]

Thickness of top flange
\[ t_{\text{f,t,p}} := 60\text{mm} \]

Thickness of bottom flange
\[ t_{\text{f,b,p}} := 60\text{mm} \]

Thickness of web
\[ t_{\text{w,p}} := 30\text{mm} \]

Radius of welding depth
\[ r_{\text{p}} := 30\text{mm} \]

\[ h_{\text{w,p}} = h_{\text{a,p}} - t_{\text{f,t,p}} - t_{\text{f,b,p}} = 1.28 \times 10^3\text{mm} \]

Section Properties of the I-Profile

Cross-sectional areas:

Bottom flange
\[ A_{\text{f,b,p}} := b_{\text{a,p}} \cdot t_{\text{f,b,p}} = 2.52 \times 10^4\text{mm}^2 \]

Web
\[ A_{\text{w,p}} := t_{\text{w,p}} \cdot h_{\text{w,p}} = 3.84 \times 10^4\text{mm}^2 \]

Top flange
\[ A_{\text{f,t,p}} := b_{\text{a,p}} \cdot t_{\text{f,t,p}} = 2.52 \times 10^4\text{mm}^2 \]

Total area
\[ A_{\text{a,p}} := A_{\text{f,b,p}} + A_{\text{w,p}} + A_{\text{f,t,p}} = 8.88 \times 10^4\text{mm}^2 \]

Distance from the bottom of the section to the elastic Neutral Axis:
\[ y_{0,p} := \frac{A_{\text{f,b,p}} \cdot t_{\text{f,b,p}} / 2 + A_{\text{w,p}} \left(t_{\text{f,b,p}} + h_{\text{w,p}} / 2\right) + A_{\text{f,t,p}} \left(h_{\text{a,p}} - t_{\text{f,t,p}} / 2\right)}{A_{\text{a,p}}} = 700\text{mm} \]

Moment of inertia:

Bottom flange
\[ I_{y,f,b,p} := \frac{b_{\text{a,p}} \cdot t_{\text{f,b,p}}^3}{12} = 7.56 \times 10^6\text{mm}^4 \]
\[ d_{f,b,p} := y_{0,p} - t_{\text{f,b,p}} / 2 = 670\text{mm} \]

Web
\[ I_{y,w,p} := \frac{t_{\text{w,p}} \cdot h_{\text{w,p}}^3}{12} = 5.243 \times 10^9\text{mm}^4 \]
\[ d_{w,p} = \frac{t_{f,b,p} + \frac{h_{w,p}}{2}}{2} - y_{0,p} \quad 0\text{-mm} \]

**Top flange**

\[ I_{y,f.t,p} = \frac{b_{a,p} t_{f,t,p}^3}{12} \quad 7.56 \times 10^6 \text{mm}^4 \]

\[ d_{f.t,p} = \frac{t_{f,t,p}}{2} - y_{0,p} \quad 670\text{-mm} \]

**Total moment of inertia**

\[ I_{y,p} = I_{y,f.b,p} + A_{f,b,p} d_{f,b,p}^2 + I_{y,w,p} + A_{w,p} d_{w,p}^2 + I_{y,f.t,p} + A_{f,t,p} d_{f,t,p}^2 \quad 2.788 \times 10^{10} \text{mm}^4 \]

**Moment of Inertia for Transformed Section**

The ribs of the steel sheeting are parallel to the beam, therefore, the concrete in the metal deck ribs is considered.

**New effective widths of concrete sections:**

\[ n_{\text{comp}} = \frac{E_a}{E_{c,\text{dyn}}} \quad 5.785 \]

**Concrete slab**

\[ b_{c.1,p} = \frac{b_{\text{eff},p}}{n_{\text{comp}}} \quad 0.32\text{ m} \]

\[ b_{\text{eff},p} = b_{\text{eff},p} \left( \frac{b_{r.1} + b_{r.2}}{2 b_s} \right) \]

**Concrete in ribs**

\[ b_{c.2,p} = \frac{b_{\text{eff},p}}{n_{\text{comp}}} \quad 0.261\text{ m} \]

**Areas of transformed sections:**

**Concrete slab**

\[ A_{c.1,p} = b_{c.1,p} h_c \quad 0.064\text{ m}^2 \]

**Concrete in ribs**

\[ A_{c.2,p} = b_{c.2,p} h_p \quad 0.013\text{ m}^2 \]

**Total area**

\[ A_{\text{comp.p}} = A_{c.1,p} + A_{c.2,p} + A_{a,p} \quad 0.166\text{ m}^2 \]

**Distance from the bottom of the section to the elastic Neutral Axis:**

\[ y_{0,\text{comp.p}} = \frac{A_{a,p} y_{0,p} + A_{c.2,p} \left( h_{a,p} + \frac{h_p}{2} \right) + A_{c.1,p} \left( h_{a,p} + h_p + \frac{h_c}{2} \right)}{A_{\text{comp.p}}} \quad 1.085 \times 10^3\text{-mm} \]
Moment of inertia:

Concrete slab
\[ I_{c,1.p} := \frac{b_{c,1.p} h_{c}^3}{12} = 2.1 \times 10^8 \text{mm}^4 \]
\[ d_{c,1.p} := \frac{h_c}{2} + h_p + h_{a.p} - y_{0,comp.p} = 465.679 \text{mm} \]

Concrete in ribs
\[ I_{c,2.p} := \frac{b_{c,2.p} h_p^3}{12} = 2.887 \times 10^6 \text{mm}^4 \]
\[ d_{c,2.p} := \frac{h_p}{2} + h_{a.p} - y_{0,comp.p} = 340.679 \text{mm} \]

Steel section
\[ I_{y,p} = 2.788 \times 10^{10} \text{mm}^4 \]
\[ d_{a.p} := y_{0,comp.p} - y_{0,p} = 384.821 \text{mm} \]

Total moment of inertia for transformed section
\[ I_{y,comp.p} := I_{y,p} + A_{a.p} d_{a.p}^2 + I_{c,2,p} + A_{c,2.p} d_{c,2.p}^2 + I_{c,1.p} + A_{c,1.p} d_{c,1.p}^2 = 5.659 \times 10^{10} \text{mm}^4 \]

Secondary Beam

Dimensions of the I-Profile

Height \[ h_{a.s} := 1000 \text{mm} \]

Width \[ b_{a.s} := 360 \text{mm} \]

Thickness of top flange \[ t_{f,t,s} := 40 \text{mm} \]

Thickness of bottom flange \[ t_{f,b,s} := 40 \text{mm} \]

Thickness of web \[ t_{w,s} := 40 \text{mm} \]

Radius of welding depth \[ r_s := 24 \text{mm} \]

\[ h_{w,s} := h_{a.s} - t_{f,t,s} - t_{f,b,s} = 920 \text{mm} \]

Section Properties of the I-Profile

Cross-sectional areas:

Bottom flange \[ A_{t,b,s} := b_{a.s} t_{f,b,s} = 1.44 \times 10^4 \text{mm}^2 \]

Web \[ A_{w,s} := t_{w,s} h_{w,s} = 2.208 \times 10^4 \text{mm}^2 \]
Top flange

\( A_{f.t.s} : \ b_{a,s} \cdot t_{f.t.s} \quad 1.44 \times 10^{4}\text{ mm}^2 \)

Total area

\( A_{a,s} : \ A_{f.b.s} + A_{w,s} + A_{f.t.s} \quad 5.088 \times 10^{4}\text{ mm}^2 \)

Distance from the bottom of the section to the elastic Neutral Axis:

\[
y_{0.s} : \quad \frac{A_{f.b.s} \cdot \frac{t_{f.b.s}}{2} + A_{w.s} \left( \frac{t_{f.b.s}}{2} + \frac{h_{w.s}}{2} \right) + A_{f.t.s} \left( \frac{h_{a,s}}{2} - \frac{t_{f.t.s}}{2} \right)}{A_{a.s}} = 500\text{ mm}
\]

Moment of Inertia:

Bottom flange

\( I_{y.f.b.s} : \quad b_{a,s} \cdot t_{f.b.s}^3 \quad 1.92 \times 10^6\text{ mm}^4 \)

\( d_{f.b.s} : \quad y_{0.s} = \frac{t_{f.b.s}}{2} = 480\text{ mm} \)

Web

\( I_{y.w.s} : \quad \frac{t_{w.s} \cdot h_{w.s}^3}{12} = 1.557 \times 10^9\text{ mm}^4 \)

\( d_{w.s} : \quad \frac{t_{f.b.s}}{2} + \frac{h_{w.s}}{2} - y_{0.s} = -5.551 \times 10^{-14}\text{ mm} \)

Top flange

\( I_{y.f.t.s} : \quad b_{a,s} \cdot t_{f.t.s}^3 \quad 1.92 \times 10^6\text{ mm}^4 \)

\( d_{f.t.s} : \quad \frac{h_{a,s}}{2} - \frac{t_{f.t.s}}{2} - y_{0.s} = 480\text{ mm} \)

Total moment of inertia

\[
I_{y.s} : \quad I_{y.f.b.s} + A_{f.b.s} \cdot d_{f.b.s}^2 + I_{y.w.s} + A_{w.s} \cdot d_{w.s}^2 + I_{y.f.t.s} + A_{f.t.s} \cdot d_{f.t.s}^2 = 8.197 \times 10^9\text{ mm}^4
\]

**Moment of Inertia for Transformed Section**

The ribs of the steel sheeting are perpendicular to the beam, therefore, the concrete in the metal deck ribs is ignored.

New effective width of concrete section:

Concrete slab

\( b_{c,s} : \quad \frac{b_{\text{eff.s}}}{n_{\text{comp}}} = 0.28\text{ m} \)

Area of transformed section:

Concrete slab

\( A_{c,s} : \quad b_{c,s} \cdot h_{c} = 0.056\text{ m}^2 \)
Total area

\[
A_{\text{comp.s}}: \quad A_{c.s} + A_{a.s} \quad 0.107 \, \text{m}^2
\]

Distance from the bottom of the section to the elastic Neutral Axis:

\[
y_{0,\text{comp.s}} = \frac{A_{a.s}y_{0.s} + A_{c.s} \left(h_{a.s} + h_p + \frac{h_c}{2}\right)}{A_{\text{comp.s}}} \quad 840.034 \, \text{mm}
\]

Moment of inertia:

Concrete slab

\[
l_{c.s} = \frac{b_{c.s}h_{c}^3}{12} \quad 1.83 \times 10^8 \, \text{mm}^4
\]

\[
d_{c.s} = \frac{h_c}{2} + h_p + h_{a.s} - y_{0,\text{comp.s}} \quad 310.466 \, \text{mm}
\]

Steel section

\[
l_{y,s} = 8.197 \times 10^9 \, \text{mm}^4
\]

\[
d_{a.s} = y_{0,\text{comp.s}} - y_{0.s} \quad 0.34 \, \text{m}
\]

Total moment of inertia for transformed section

\[
l_{y,\text{comp.s}} = l_{y,s} + A_{a.s}d_{a.s}^2 + l_{c.s} + A_{c.s}d_{c.s}^2 \quad 1.963 \times 10^{10} \, \text{mm}^4
\]

**Loads**

**Partial factors**

Dead load \( \gamma_G : 1.15 \)

Live load \( \gamma_Q : 1.5 \)

**Dead Loads**

Primary beam:

\[
\sigma_{p,k} = \sqrt{A_{a.p} \rho_a + \frac{5}{L_p} \left[A_{a.s} B_p \rho_a + \left(h - h_p - \frac{b_{r.1} + b_{r.2}}{2 \cdot b_s}\right) B_s B_c \rho_c \right]} \quad 150.145 \, \text{kN/m}
\]

Secondary beam:

\[
\sigma_{s,k} = \sqrt{A_{a.s} \rho_a + \left(h - h_p - \frac{b_{r.1} + b_{r.2}}{2 \cdot b_s}\right) B_s B_c \rho_c } \quad 13.092 \, \text{kN/m}
\]
**Live Loads**

For areas with possible physical activities:

\[ q_k : \frac{5.0 \text{kN}}{\text{m}^2} \]

\[ Q_k : \text{7.0kN} \]

Primary beam:

\[ q_{p,k} : \frac{5(1 - B_p B_s q_k)}{L_p} = 88.662 \frac{\text{kN}}{\text{m}} \]

Secondary beam:

\[ q_{s,k} : B_s q_k = 8.1 \frac{\text{kN}}{\text{m}} \]

**Floor Vibration**

**Natural Frequency of the Steel-Concrete Composite Floor Structure**

Percentage of imposed load, representing permanent loading on the floor:

\[ \eta_{v,Q} : 10\% \]

Deflection of secondary beam:

\[ \delta_s : \frac{5}{384 E_a I_y, \text{comp.s}} \left( g_{s,k} + \frac{\eta_{v,Q} q_{s,k}}{384 E_a I_y, \text{comp.s}} \right) L_s^4 = 3.024 \text{mm} \]

Deflection of primary beam:

\[ \delta_p : \frac{5}{384 E_a I_y, \text{comp.p}} \left( g_{p,k} + \frac{\eta_{v,Q} q_{p,k}}{384 E_a I_y, \text{comp.p}} \right) L_p^4 = 0.522 \text{mm} \]

Total deflection of floor structure:

\[ \delta_{\text{max}} : \delta_s + \delta_p = 3.546 \text{mm} \]

Natural frequency:

\[ f_n : 0.18 \sqrt{\frac{g}{\delta_{\text{max}}}} = 9.466 \text{Hz} \]
Minimum Natural Frequency of the Floor Structure

Forcing frequency:

First harmonic \( f_1 : 2.5 \text{Hz} \)
Second harmonic \( f_2 : 2 \cdot f_1 = 5 \text{Hz} \)
Third harmonic \( f_3 : 3 \cdot f_1 = 7.5 \text{Hz} \)

Acceleration limit:
\( a_0 : 5\% g = 0.49 \frac{m}{s^2} \)
\( k : 2.0 \)

Dynamic coefficient:

First harmonic \( \alpha_1 : 1.5 \)
Second harmonic \( \alpha_2 : 0.6 \)
Third harmonic \( \alpha_3 : 0.1 \)

Effective weight:
Participants \( w_p : 0.2 \frac{kN}{m^2} \)
Floor structure + participants \( w_t : \frac{b_{s,k} + \gamma v Q s_{s,k}}{B_s} + w_p = 8.782 \frac{kN}{m^2} \)

First harmonic \( f_{n.min,1} : f_1 \sqrt{1 + \frac{k}{a_0} \frac{\alpha_1 w_p}{w_t}} = 3.846 \text{Hz} \)

Second harmonic \( f_{n.min,2} : f_2 \sqrt{1 + \frac{k}{a_0} \frac{\alpha_2 w_p}{w_t}} = 6.218 \text{Hz} \)

Third harmonic \( f_{n.min,3} : f_3 \sqrt{1 + \frac{k}{a_0} \frac{\alpha_3 w_p}{w_t}} = 7.834 \text{Hz} \)

Peak acceleration:
The normal frequency is not close to the forcing frequency for the third harmonic.

\( f_n > 1.2 \cdot f_3 \quad 1 \)

\[
a_{p3} : \frac{1.3}{\left( \frac{f_n}{f_3} \right)^2 - 1} \frac{\alpha_3 \cdot w_p}{w_t} \quad 0.499\% \\
a_{p2} : \frac{1.3}{\left( \frac{f_n}{f_2} \right)^2 - 1} \frac{\alpha_2 \cdot w_p}{w_t} \quad 0.687\% \\
a_{p1} : \frac{1.3}{\left( \frac{f_n}{f_1} \right)^2 - 1} \frac{\alpha_1 \cdot w_p}{w_t} \quad 0.333\% \\
\]

Effective maximum acceleration

\[
a_m : \left( a_{p1}^{1.5} + a_{p2}^{1.5} + a_{p3}^{1.5} \right)^{\frac{1}{1.5}} \quad 1.075\% 
\]
B.4 Steel-Concrete Composite Structures in a Multi-Story Building
Steel-Concrete Composite Floor Structure in a Multi-Story Building

Introduction

The steel-concrete composite floor structure is located on the sixth floor in a multi-story building supported by composite columns. The spacing between the columns are 8.1 m and 16.2 m and the height of each story is 5.2 m. The diameter of the columns is assumed to be 0.7 m. The floor is subjected to rhythmic excitation.

The floor consists of primary and secondary I-profiled beams, considered as simply supported. A concrete slab is cast on profiled steel sheeting with ribs perpendicular to the secondary beams. Shear studs are placed on both the primary and secondary beams. The columns are concrete filled circular hollow sections with reinforcement.

The floor structure is designed to satisfy the design criteria according to the Eurocodes. In the floor vibration analysis, the slab's deflection may be neglected due to the short span. The column effect is taken into account when the floor is located in a multi-story building.

Material Properties

Structural Steel S355

Density \( \rho_a : 7850 \frac{kg}{m^3} \)

Modulus of elasticity \( E_a : 210000 \text{MPa} \)

Concrete

Density \( \rho_c : 2400 \frac{kg}{m^3} \)

C30/37 (slab):

Modulus of elasticity \( E_{cm30} : 33000 \text{MPa} \)

Dynamic modulus of elasticity \( E_{c,dyn30} : 1.1 \cdot E_{cm30} \quad 3.63 \times 10^4 \text{MPa} \)

C40/50 (column):

Modulus of elasticity \( E_{cm40} : 35000 \text{MPa} \)

Dynamic modulus of elasticity \( E_{c,dyn40} : 1.1 \cdot E_{cm40} \quad 3.85 \times 10^4 \text{MPa} \)

Reinforcement A500HW

Density \( \rho_s : 7850 \frac{kg}{m^3} \)
Modulus of elasticity \( E_s := 210000\, \text{MPa} \)

**Dimensions**

Distance between columns
- \( L_1 := 8.1\, \text{m} \)
- \( L_2 := 16.2\, \text{m} \)

Diameter of column \( d_{\text{col}} := 0.7\, \text{m} \)

Length of primary beam \( L_p := L_1 - d_{\text{col}} = 7.4\, \text{m} \)

Length of secondary beam \( L_s := L_2 = 16.2\, \text{m} \)

Equivalent span of beams:

Primary beam \( L_{e,p} := 1L_p = 7.4\, \text{m} \)

Secondary beam \( L_{e,s} := 1L_s = 16.2\, \text{m} \)

Bay width of primary beam \( B_p := L_2 = 16.2\, \text{m} \)

Bay width of secondary beam \( B_s := 1.62\, \text{m} \)

**Concrete Slab with Profiled Steel Sheeting and Shear Studs**

**Concrete Slab**

Slab depth \( h := 250\, \text{mm} \)

Effective width of concrete flange:

Primary beam \( b_{\text{eff},p} := 2 \min \left( \frac{L_{e,p}}{8}, \frac{B_p}{2} \right) = 1.85\, \text{m} \)

Secondary beam \( b_{\text{eff},s} := 2 \min \left( \frac{L_{e,s}}{8}, \frac{B_s}{2} \right) = 1.62\, \text{m} \)

**Profiled Steel Sheeting SUPERHOLORIB SHR 51/600**

Thickness \( t := 0.75\, \text{mm} \)

\( h_p := 51\, \text{mm} \)
\[ h_c := h - h_p = 199 \text{-mm} \]
\[ b_s := 150 \text{mm} \]
\[ b_{r,1} := 40 \text{mm} \]
\[ b_{r,2} := 15 \text{mm} \]
\[ b_0 := 110 \text{mm} \]

**Primary Beam**

**Dimensions of the I-Profile**

- **Height**
  \[ h_{a,p} := 1400 \text{mm} \]
- **Width**
  \[ b_{a,p} := 420 \text{mm} \]
- **Thickness of top flange**
  \[ t_{f,t.p} := 60 \text{mm} \]
- **Thickness of bottom flange**
  \[ t_{f,b,p} := 60 \text{mm} \]
- **Thickness of web**
  \[ t_{w,p} := 30 \text{mm} \]
- **Radius of welding depth**
  \[ r_p := 30 \text{mm} \]

\[ h_{w,p} := h_{a,p} - t_{f,t.p} - t_{f,b,p} = 1.28 \times 10^3 \text{mm} \]

**Section Properties of the I-Profile**

**Cross-sectional areas:**

- **Bottom flange**
  \[ A_{f,b,p} := b_{a,p} \cdot t_{f,b,p} = 2.52 \times 10^4 \text{mm}^2 \]
- **Web**
  \[ A_{w,p} := t_{w,p} \cdot h_{w,p} = 3.84 \times 10^4 \text{mm}^2 \]
- **Top flange**
  \[ A_{f,t,p} := b_{a,p} \cdot t_{f,t,p} = 2.52 \times 10^4 \text{mm}^2 \]
- **Total area**
  \[ A_{a,p} := A_{f,b,p} + A_{w,p} + A_{f,t,p} = 8.88 \times 10^4 \text{mm}^2 \]

**Distance from the bottom of the section to the elastic Neutral Axis:**

\[ y_{0,p} := \frac{A_{f,b,p} \cdot t_{f,b,p} + A_{w,p} \left( t_{f,b,p} + \frac{h_{w,p}}{2} \right) + A_{f,t,p} \left( h_{a,p} - \frac{t_{f,t,p}}{2} \right)}{A_{a,p}} = 700 \text{mm} \]
Moment of inertia:

Bottom flange

\[ I_{y.f.b.p} = \frac{b_{a,p} \cdot t_{f.b.p}^3}{12} = 7.56 \times 10^6 \text{ mm}^4 \]

\[ d_{f.b.p} = y_{0.p} - \frac{t_{f.b.p}}{2} = 670 \text{ mm} \]

Web

\[ I_{y.w.p} = \frac{t_{w.p} \cdot h_{w.p}^3}{12} = 5.243 \times 10^9 \text{ mm}^4 \]

\[ d_{w.p} = t_{f.b.p} + \frac{h_{w.p}}{2} - y_{0.p} = 0 \text{ mm} \]

Top flange

\[ I_{y.f.t.p} = \frac{b_{a,p} \cdot t_{f.t.p}^3}{12} = 7.56 \times 10^6 \text{ mm}^4 \]

\[ d_{f.t.p} = h_{a,p} - \frac{t_{f.t.p}}{2} - y_{0.p} = 670 \text{ mm} \]

Total moment of inertia

\[ I_y = I_{y.f.b.p} + A_{f.b,p} \cdot d_{f.b,p}^2 + I_{y.w.p} + A_{w,p} \cdot d_{w,p}^2 + I_{y.f.t.p} + A_{f.t,p} \cdot d_{f.t.p}^2 = 2.788 \times 10^{10} \text{ mm}^4 \]

**Moment of Inertia for Transformed Section**

The ribs of the steel sheeting are parallel to the beam, therefore, the concrete in the metal deck ribs is considered.

New effective widths of concrete sections:

\[ n_{comp} = \frac{E_a}{E_{c,dyn30}} = 5.785 \]

Concrete slab

\[ b_{c,1.p} = \frac{b_{eff,p}}{n_{comp}} = 0.32 \text{ m} \]

\[ b_{eff,p} = \frac{b_{eff,p} (b_{r,1} + b_{r,2})}{2 \cdot b_s} \]

Concrete in ribs

\[ b_{c,2.p} = \frac{b_{eff,p}}{n_{comp}} = 0.261 \text{ m} \]

Areas of transformed sections:

Concrete slab

\[ A_{c,1.p} = b_{c,1.p} \cdot h_c = 0.064 \text{ m}^2 \]

Concrete in ribs

\[ A_{c,2.p} = b_{c,2.p} \cdot h_p = 0.013 \text{ m}^2 \]
Total area

\[ A_{\text{comp.p}} := A_{c.1.p} + A_{c.2.p} + A_{a.p} = 0.166 \text{ m}^2 \]

Distance from the bottom of the section to the elastic Neutral Axis:

\[ y_{0,\text{comp.p}} := \frac{A_{a.p} \cdot y_{0.p} + A_{c.2.p} \left( h_{a.p} + \frac{h_p}{2} \right) + A_{c.1.p} \left( h_{a.p} + h_p + \frac{h_c}{2} \right)}{A_{\text{comp.p}}} = 1.085 \times 10^3 \cdot \text{mm} \]

Moment of inertia:

Concrete slab

\[ I_{c.1.p} := \frac{h_{c.1.p} \cdot h_c^3}{12} = 2.1 \times 10^8 \cdot \text{mm}^4 \]

\[ d_{c.1.p} := \frac{h_c}{2} + h_p + h_{a.p} - y_{0,\text{comp.p}} = 465.679 \cdot \text{mm} \]

Concrete in ribs

\[ I_{c.2.p} := \frac{h_{c.2.p} \cdot h_p^3}{12} = 2.887 \times 10^6 \cdot \text{mm}^4 \]

\[ d_{c.2.p} := \frac{h_p}{2} + h_{a.p} - y_{0,\text{comp.p}} = 340.679 \cdot \text{mm} \]

Steel section

\[ I_{y.p} = 2.788 \times 10^{10} \cdot \text{mm}^4 \]

\[ d_{a.p} := y_{0,\text{comp.p}} - y_{0.p} = 384.821 \cdot \text{mm} \]

Total moment of inertia for transformed section

\[ I_{y,\text{comp.p}} := I_{y.p} + A_{a.p} \cdot d_{a.p}^2 + I_{c.2.p} + A_{c.2.p} \cdot d_{c.2.p}^2 + I_{c.1.p} + A_{c.1.p} \cdot d_{c.1.p}^2 = 5.659 \times 10^{10} \cdot \text{mm}^4 \]

**Secondary Beam**

**Dimensions of the I-Profile**

- **Height** \( h_{a.s} := 1000\text{mm} \)
- **Width** \( b_{a.s} := 360\text{mm} \)
- **Thickness of top flange** \( t_{f.t.s} := 40\text{mm} \)
- **Thickness of bottom flange** \( t_{f.b.s} := 40\text{mm} \)
- **Thickness of web** \( t_{w.s} := 24\text{mm} \)
- **Radius of welding depth** \( r_s := 24\text{mm} \)
- \( h_{w.s} := h_{a.s} - t_{f.t.s} - t_{f.b.s} = 920\cdot\text{mm} \)
**Section Properties of the I-Profile**

Cross-sectional areas:

**Bottom flange**

\[ A_{f,b,s} : \quad b_{a,s} t_{f,b,s} \quad 1.44 \times 10^4 \text{mm}^2 \]

**Web**

\[ A_{w,s} : \quad t_{w,s} h_{w,s} \quad 2.208 \times 10^4 \text{mm}^2 \]

**Top flange**

\[ A_{f,t,s} : \quad b_{a,s} t_{f,t,s} \quad 1.44 \times 10^4 \text{mm}^2 \]

**Total area**

\[ A_{a,s} : \quad A_{f,b,s} + A_{w,s} + A_{f,t,s} \quad 5.088 \times 10^4 \text{mm}^2 \]

Distance from the bottom of the section to the elastic Neutral Axis:

\[
\frac{A_{f,b,s} \frac{t_{f,b,s}}{2} + A_{w,s} \left( t_{f,b,s} + \frac{h_{w,s}}{2} \right) + A_{f,t,s} \left( b_{a,s} - \frac{t_{f,t,s}}{2} \right)}{A_{a,s}} \quad 500 \text{mm}
\]

Moment of inertia:

**Bottom flange**

\[ I_{y,f,b,s} : \quad \frac{b_{a,s} t_{f,b,s}^3}{12} \quad 1.92 \times 10^6 \text{mm}^4 \]

\[ d_{f,b,s} : \quad \gamma_{0,s} - \frac{t_{f,b,s}}{2} \quad 480 \text{mm} \]

**Web**

\[ I_{y,w,s} : \quad \frac{t_{w,s} h_{w,s}^3}{12} \quad 1.557 \times 10^9 \text{mm}^4 \]

\[ d_{w,s} : \quad t_{f,b,s} + \frac{h_{w,s}}{2} - \gamma_{0,s} \quad -5.551 \times 10^{-14} \text{mm} \]

**Top flange**

\[ I_{y,f,t,s} : \quad \frac{b_{a,s} t_{f,t,s}^3}{12} \quad 1.92 \times 10^6 \text{mm}^4 \]

\[ d_{f,t,s} : \quad b_{a,s} - \frac{t_{f,t,s}}{2} - \gamma_{0,s} \quad 480 \text{mm} \]

**Total moment of inertia**

\[ I_{y,s} : \quad I_{y,f,b,s} + A_{f,b,s} d_{f,b,s}^2 + I_{y,w,s} + A_{w,s} d_{w,s}^2 + I_{y,f,t,s} + A_{f,t,s} d_{f,t,s}^2 \quad 8.197 \times 10^9 \text{mm}^4 \]

**Moment of Inertia for Transformed Section**

The ribs of the steel sheeting are perpendicular to the beam, therefore, the concrete in the metal deck ribs is ignored.

New effective width of concrete section:
Concrete slab: \( b_{c,s} := \frac{b_{eff,s}}{n_{comp}} = 0.28 \text{ m} \)

Area of transformed section:

Concrete slab: \( A_{c,s} := b_{c,s} \cdot h_c = 0.056 \text{ m}^2 \)

Total area: \( A_{comp,s} := A_{c,s} + A_{a,s} = 0.107 \text{ m}^2 \)

Distance from the bottom of the section to the elastic Neutral Axis:

\[
\gamma_{0,comp,s} := \frac{A_{a,s} \gamma_{0,s} + A_{c,s} \left( h_{a,s} + h_p + \frac{h_c}{2} \right)}{A_{comp,s}} = 840.034 \text{ mm}
\]

Moment of inertia:

Concrete slab:

\[
I_{c,s} := \frac{b_{c,s} \cdot h_c^3}{12} = 1.839 \times 10^8 \text{ mm}^4
\]

\[
d_{c,s} := \frac{h_c}{2} + h_p + h_{a,s} - \gamma_{0,comp,s} = 310.466 \text{ mm}
\]

Steel section:

\[
I_{y,s} = 8.197 \times 10^9 \text{ mm}^4
\]

\[
d_{a,s} := \gamma_{0,comp,s} - \gamma_{0,s} = 0.34 \text{ m}
\]

Total moment of inertia for transformed section:

\[
I_{y,comp,s} := I_{y,s} + A_{a,s} \cdot d_{a,s}^2 + I_{c,s} + A_{c,s} \cdot d_{c,s}^2 = 1.963 \times 10^{10} \text{ mm}^4
\]

**Column**

Height of column: \( L_{col} := 5.2 \text{ m} \)

**Dimensions of the Circular Hollow Section**

Outer diameter: \( d_{col} = 0.7 \text{ m} \)

Wall thickness: \( t_{col} := 12 \text{ mm} \)

**Reinforcement**

Number of bars: \( n_{s,col} := 12 \)

Thickness of bars: \( \phi_{s,col} := 32 \text{ mm} \)
Areas of Column Components

Circular hollow section

\[ A_{a,\text{col}} : \pi \left( \frac{d_{\text{col}}}{2} \right)^2 - \pi \left( \frac{d_{\text{col}}}{2} - t_{\text{col}} \right)^2 = 0.026 \text{ m}^2 \]

Reinforcement

\[ A_{s,\text{col}} : n_{s,\text{col}} \pi \left( \frac{\phi_{s,\text{col}}}{2} \right)^2 = 9.651 \times 10^{-3} \text{ m}^2 \]

Concrete

\[ A_{c,\text{col}} : \pi \left( \frac{d_{\text{col}}}{2} - t_{\text{col}} \right)^2 - A_{s,\text{col}} = 0.349 \text{ m}^2 \]

Loads

Partial factors

Dead load \( \gamma_G : 1.15 \)
Live load \( \gamma_Q : 1.5 \)

Dead Loads

Primary beam:

\[ g_{p,k} : g \left[ A_{a,p} \rho_a + \frac{5}{L_p} \left( A_{a,s} B_p \phi_a + \left( h - h_p \frac{b_{r,1} + b_{r,2}}{2 \cdot b_s} \right) B_s \phi_c \right) \right] = 150.145 \text{ kN/m} \]

Secondary beam:

\[ g_{s,k} : g \left[ A_{s,p} \rho_a + \left( h - h_p \frac{b_{r,1} + b_{r,2}}{2 \cdot b_s} \right) B_s \phi_c \right] = 13.092 \text{ kN/m} \]

Remaining loads acting on the columns that are considered as permanent:

Floor weight and column weight of each story below 6th story acting on the columns are assumed to be

\[ G_{\text{below},k} : 1000 \text{kN} \]

Total floor weight, column weight and roof weight of remaining stories above 6th story acting on the columns is assumed to be

\[ G_{\text{above},k} : 2000 \text{kN} \]

Live Loads

For areas with possible physical activities:
\[ q_k := 5.0 \, \text{kN/m}^2 \]
\[ Q_k := 7.0 \, \text{kN} \]

Primary beam:
\[ q_{p,k} := \frac{5 (B_p B_s q_k)}{L_p} = 88.662 \, \text{kN/m} \]

Secondary beam:
\[ q_{s,k} := B_s q_k = 8.1 \, \text{kN/m} \]

**Floor Vibration**

**Natural Frequency of the Steel-Concrete Composite Floor Structure in a Multi-Story Building**

Percentage of imposed load, representing permanent loading on the floor:
\[ \gamma_{v,Q} := 10\% \]

Deflection of secondary beam:
\[ \delta_s := \frac{5 (g_{s,k} + \gamma_{v,Q} q_{s,k}) L_s^4}{384 E_a I_{y,comp.s}} = 3.024 \, \text{mm} \]

Deflection of primary beam:
\[ \delta_p := \frac{5 (g_{p,k} + \gamma_{v,Q} q_{p,k}) L_p^4}{384 E_a I_{y,comp.p}} = 0.522 \, \text{mm} \]

Axial shortening of column:

<table>
<thead>
<tr>
<th>1st story column:</th>
<th>( 4 \times G_{\text{below,k}} + G_{\text{above,k}} + (g_{p,k} + \gamma_{v,Q} q_{p,k}) L_p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2nd story column:</td>
<td>( 3 \times G_{\text{below,k}} + G_{\text{above,k}} + (g_{p,k} + \gamma_{v,Q} q_{p,k}) L_p )</td>
</tr>
<tr>
<td>3rd story column:</td>
<td>( 2 \times G_{\text{below,k}} + G_{\text{above,k}} + (g_{p,k} + \gamma_{v,Q} q_{p,k}) L_p )</td>
</tr>
<tr>
<td>4th story column:</td>
<td>( 1 \times G_{\text{below,k}} + G_{\text{above,k}} + (g_{p,k} + \gamma_{v,Q} q_{p,k}) L_p )</td>
</tr>
<tr>
<td>5th story column:</td>
<td>( G_{\text{above,k}} + (g_{p,k} + \gamma_{v,Q} q_{p,k}) L_p )</td>
</tr>
</tbody>
</table>
\[ \delta_{\text{col}}: \frac{10 \cdot G_{\text{below,k}} + 5 \cdot G_{\text{above,k}} + 5 \cdot (\hat{g} \cdot k + \gamma \cdot Q \cdot q_{p,k}) \cdot L_p}{A_{\text{a, col}} E_a + A_{\text{c, col}} E_{\text{c, dyn}40} + A_{\text{s, col}} E_s} \]

6.434-mm

Total deflection of floor structure:

\[ \delta_{\text{max}}: \delta_s + \delta_p + \delta_{\text{col}} \quad 9.98\text{-mm} \]

Natural frequency:

\[ f_n: 0.18 \cdot \sqrt{\frac{g}{\delta_{\text{max}}}} \quad 5.642\text{-Hz} \]

**Minimum Natural Frequency of the Floor Structure**

Forcing frequency:

First harmonic \( f_1: \quad 2.5\text{Hz} \)

Second harmonic \( f_2: \quad 2 \cdot f_1 \quad 5\text{-Hz} \)

Third harmonic \( f_3: \quad 3 \cdot f_1 \quad 7.5\text{-Hz} \)

Acceleration limit:

\[ a_0: \quad 5\% \cdot g \quad 0.49 \frac{m}{s^2} \]

\[ k: \quad 2.0 \]

Dynamic coefficient:

First harmonic \( \alpha_1: \quad 1.5 \)

Second harmonic \( \alpha_2: \quad 0.6 \)

Third harmonic \( \alpha_3: \quad 0.1 \)

Effective weight:

Participants \( w_p: \quad 0.2 \frac{kN}{m^2} \)

Floor structure + participants \( w_k: \quad \frac{B_{s,k} + \gamma \cdot Q \cdot q_{s,k}}{B_s} + w_p \quad 8.782 \frac{kN}{m^2} \)
First harmonic

\[ f_{n.min.1} : f_1 \cdot \sqrt{1 + \frac{k}{a_0} \cdot \frac{\alpha_1 \cdot w_p}{w_t} \cdot \frac{1}{g}} \] 3.846-Hz

Second harmonic

\[ f_{n.min.2} : f_2 \cdot \sqrt{1 + \frac{k}{a_0} \cdot \frac{\alpha_2 \cdot w_p}{w_t} \cdot \frac{1}{g}} \] 6.218-Hz

Third harmonic

\[ f_{n.min.3} : f_3 \cdot \sqrt{1 + \frac{k}{a_0} \cdot \frac{\alpha_3 \cdot w_p}{w_t} \cdot \frac{1}{g}} \] 7.834-Hz

Peak acceleration:

The normal frequency is close to the forcing frequency for the second harmonic.

\[ f_n > 1.2 \cdot f_2 \quad 0 \]

Damping ratio

\[ \zeta : 0.06 \]

\[ a_{p2} : \frac{1.3}{2 \cdot \zeta} \cdot \frac{\alpha_2 \cdot w_p}{w_t} \] 14.803-%

\[ a_{p1} : \frac{1.3}{\left( \frac{f_n}{f_1} \right)^2} \cdot \frac{\alpha_1 \cdot w_p}{w_t} \] 1.085-%

Effective maximum acceleration

\[ a_m : \left( a_{p1}^{1.5} + a_{p2}^{1.5} \right)^{1.5} \] 14.999-%
Appendix C

Acoustic Calculations

C.1 Concrete Structures

Table C.1: SPL, Point Evaluation when the Concrete Floor Structure is Subjected to a Tapping Machine

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Measurement (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(1.05, 1.1) (1.05, 3.1) (1.05, 5.1) (1.05, 7.1) (3.05, 1.1) (3.05, 3.1) (3.05, 5.1) (3.05, 7.1) Average</td>
</tr>
<tr>
<td>100</td>
<td>-1.15 7.23 17.38 8.30 17.11 7.59 17.82 24.04 17.4</td>
</tr>
<tr>
<td>125</td>
<td>14.09 32.31 29.78 28.54 17.76 31.44 29.10 28.80 28.0</td>
</tr>
<tr>
<td>160</td>
<td>62.04 29.76 59.44 60.65 61.24 33.12 58.21 60.87 59.3</td>
</tr>
<tr>
<td>200</td>
<td>24.55 24.27 1.92 8.76 32.30 35.53 32.63 30.29 30.4</td>
</tr>
<tr>
<td>250</td>
<td>24.27 27.77 30.99 33.46 25.70 45.57 42.42 36.31 38.9</td>
</tr>
<tr>
<td>315</td>
<td>30.32 43.44 35.92 52.20 36.38 44.04 51.81 43.09 48.0</td>
</tr>
<tr>
<td>400</td>
<td>52.17 55.20 54.56 35.84 52.06 41.35 50.84 41.69 51.4</td>
</tr>
<tr>
<td>500</td>
<td>38.40 44.00 35.14 17.35 41.67 48.26 47.18 33.90 43.3</td>
</tr>
<tr>
<td>630</td>
<td>58.18 51.34 49.69 37.51 56.55 42.45 46.49 47.70 52.6</td>
</tr>
<tr>
<td>800</td>
<td>44.38 39.88 38.27 35.81 29.89 39.57 27.86 44.97 40.5</td>
</tr>
<tr>
<td>1,000</td>
<td>59.09 70.02 62.01 72.46 61.06 61.37 66.75 72.12 68.3</td>
</tr>
<tr>
<td>1,250</td>
<td>25.42 69.54 35.57 37.61 79.89 55.08 78.60 59.88 73.5</td>
</tr>
<tr>
<td>1,600</td>
<td>23.12 21.67 -5.95 7.71 28.19 12.47 28.81 33.56 27.1</td>
</tr>
<tr>
<td>2,500</td>
<td>-29.47 -45.79 -41.66 -18.13 -22.95 -35.04 -32.89 -25.75 -25.0</td>
</tr>
<tr>
<td>3,150</td>
<td>-46.13 -40.63 -46.81 -49.94 -50.86 -60.01 -35.28 -64.06 -42.5</td>
</tr>
</tbody>
</table>
Table C.2: SPL Point Evaluation when the Concrete Floor Structure is Subjected to Rhythmic Excitation

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Measurement (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(1.05, 1.1)</td>
</tr>
<tr>
<td>16</td>
<td>96.02</td>
</tr>
<tr>
<td>20</td>
<td>93.44</td>
</tr>
<tr>
<td>25</td>
<td>82.48</td>
</tr>
<tr>
<td>31.5</td>
<td>68.38</td>
</tr>
<tr>
<td>40</td>
<td>70.49</td>
</tr>
<tr>
<td>50</td>
<td>48.14</td>
</tr>
<tr>
<td>63</td>
<td>53.72</td>
</tr>
<tr>
<td>80</td>
<td>64.98</td>
</tr>
<tr>
<td>100</td>
<td>66.39</td>
</tr>
<tr>
<td>125</td>
<td>43.22</td>
</tr>
<tr>
<td>160</td>
<td>89.29</td>
</tr>
<tr>
<td>200</td>
<td>61.42</td>
</tr>
<tr>
<td>250</td>
<td>54.41</td>
</tr>
<tr>
<td>315</td>
<td>44.00</td>
</tr>
<tr>
<td>400</td>
<td>96.87</td>
</tr>
<tr>
<td>500</td>
<td>50.99</td>
</tr>
<tr>
<td>630</td>
<td>83.46</td>
</tr>
<tr>
<td>800</td>
<td>51.04</td>
</tr>
<tr>
<td>1,000</td>
<td>79.06</td>
</tr>
<tr>
<td>1,250</td>
<td>105.22</td>
</tr>
<tr>
<td>1,600</td>
<td>69.22</td>
</tr>
<tr>
<td>2,000</td>
<td>28.61</td>
</tr>
<tr>
<td>2,500</td>
<td>-4.47</td>
</tr>
<tr>
<td>4,000</td>
<td>-88.81</td>
</tr>
<tr>
<td>5,000</td>
<td>-66.46</td>
</tr>
<tr>
<td>6,300</td>
<td>-103.39</td>
</tr>
<tr>
<td>8,000</td>
<td>-132.99</td>
</tr>
<tr>
<td>10,000</td>
<td>-144.04</td>
</tr>
<tr>
<td>12,500</td>
<td>-124.81</td>
</tr>
<tr>
<td>16,000</td>
<td>-135.68</td>
</tr>
<tr>
<td>20,000</td>
<td>-139.73</td>
</tr>
</tbody>
</table>
Table C.3: A-weighted Sound Level when the Concrete Floor Structure is Subjected to Rhythmic Excitation

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Measurement (dB)</th>
<th>A-weighting Relative Response (dB)</th>
<th>A-weighted Sound Level (dB(A))</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>92.8</td>
<td>-56.7</td>
<td>36.1</td>
</tr>
<tr>
<td>20</td>
<td>89.3</td>
<td>-50.5</td>
<td>38.8</td>
</tr>
<tr>
<td>25</td>
<td>83.5</td>
<td>-44.7</td>
<td>38.8</td>
</tr>
<tr>
<td>31.5</td>
<td>74.9</td>
<td>-39.4</td>
<td>35.5</td>
</tr>
<tr>
<td>40</td>
<td>74.3</td>
<td>-34.6</td>
<td>39.7</td>
</tr>
<tr>
<td>50</td>
<td>54.0</td>
<td>-30.2</td>
<td>23.8</td>
</tr>
<tr>
<td>63</td>
<td>57.8</td>
<td>-26.2</td>
<td>31.6</td>
</tr>
<tr>
<td>80</td>
<td>60.3</td>
<td>-22.5</td>
<td>37.8</td>
</tr>
<tr>
<td>100</td>
<td>65.0</td>
<td>-19.1</td>
<td>45.9</td>
</tr>
<tr>
<td>125</td>
<td>55.2</td>
<td>-16.1</td>
<td>39.1</td>
</tr>
<tr>
<td>160</td>
<td>86.5</td>
<td>-13.4</td>
<td>73.1</td>
</tr>
<tr>
<td>200</td>
<td>62.1</td>
<td>-10.9</td>
<td>51.2</td>
</tr>
<tr>
<td>250</td>
<td>61.3</td>
<td>-8.6</td>
<td>52.7</td>
</tr>
<tr>
<td>315</td>
<td>45.5</td>
<td>-6.6</td>
<td>38.9</td>
</tr>
<tr>
<td>400</td>
<td>95.3</td>
<td>-4.8</td>
<td>90.5</td>
</tr>
<tr>
<td>500</td>
<td>65.1</td>
<td>-3.2</td>
<td>61.9</td>
</tr>
<tr>
<td>630</td>
<td>80.9</td>
<td>-1.9</td>
<td>79.0</td>
</tr>
<tr>
<td>800</td>
<td>65.1</td>
<td>-0.8</td>
<td>64.3</td>
</tr>
<tr>
<td>1,000</td>
<td>75.1</td>
<td>0.0</td>
<td>75.1</td>
</tr>
<tr>
<td>1,250</td>
<td>105.0</td>
<td>0.6</td>
<td>105.6</td>
</tr>
<tr>
<td>1,600</td>
<td>73.3</td>
<td>1.0</td>
<td>74.3</td>
</tr>
<tr>
<td>2,000</td>
<td>29.5</td>
<td>1.2</td>
<td>30.7</td>
</tr>
<tr>
<td>2,500</td>
<td>3.9</td>
<td>1.3</td>
<td>5.2</td>
</tr>
<tr>
<td>3,150</td>
<td>-19.5</td>
<td>1.2</td>
<td>-18.3</td>
</tr>
<tr>
<td>4,000</td>
<td>-44.5</td>
<td>1.0</td>
<td>-43.5</td>
</tr>
<tr>
<td>5,000</td>
<td>-55.9</td>
<td>0.5</td>
<td>-55.4</td>
</tr>
<tr>
<td>6,300</td>
<td>-74.3</td>
<td>0.1</td>
<td>-74.4</td>
</tr>
<tr>
<td>8,000</td>
<td>-118.5</td>
<td>1.1</td>
<td>-119.6</td>
</tr>
<tr>
<td>10,000</td>
<td>-128.4</td>
<td>2.5</td>
<td>-130.9</td>
</tr>
<tr>
<td>12,500</td>
<td>-119.0</td>
<td>4.3</td>
<td>-123.3</td>
</tr>
<tr>
<td>16,000</td>
<td>-120.1</td>
<td>6.6</td>
<td>-126.7</td>
</tr>
<tr>
<td>20,000</td>
<td>-131.8</td>
<td>9.3</td>
<td>-141.1</td>
</tr>
</tbody>
</table>

105.8
C.2 Concrete Element Structures

Table C.4: SPL Point Evaluation when the Concrete Element Floor Structure is Subjected to a Tapping Machine

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Measurement (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(1.05, 1.1)</td>
</tr>
<tr>
<td>100</td>
<td>27.78</td>
</tr>
<tr>
<td>125</td>
<td>22.23</td>
</tr>
<tr>
<td>160</td>
<td>39.21</td>
</tr>
<tr>
<td>200</td>
<td>78.08</td>
</tr>
<tr>
<td>250</td>
<td>52.95</td>
</tr>
<tr>
<td>315</td>
<td>39.80</td>
</tr>
<tr>
<td>400</td>
<td>49.21</td>
</tr>
<tr>
<td>500</td>
<td>54.95</td>
</tr>
<tr>
<td>630</td>
<td>29.65</td>
</tr>
<tr>
<td>800</td>
<td>51.58</td>
</tr>
<tr>
<td>1,000</td>
<td>58.90</td>
</tr>
<tr>
<td>1,250</td>
<td>66.99</td>
</tr>
<tr>
<td>1,600</td>
<td>55.70</td>
</tr>
<tr>
<td>2,000</td>
<td>24.06</td>
</tr>
<tr>
<td>2,500</td>
<td>-1.35</td>
</tr>
<tr>
<td>3,150</td>
<td>10.26</td>
</tr>
</tbody>
</table>
Table C.5: SPL Point Evaluation when the Concrete Element Floor Structure is Subjected to Rhythmic Excitation

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>(0.85, 1.1)</th>
<th>(1.05, 1.31)</th>
<th>(1.05, 1.51)</th>
<th>(1.05, 1.71)</th>
<th>(3.05, 1.1)</th>
<th>(3.05, 1.31)</th>
<th>(3.05, 1.51)</th>
<th>(3.05, 1.71)</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>108.65</td>
<td>106.18</td>
<td>101.08</td>
<td>94.15</td>
<td>108.62</td>
<td>106.16</td>
<td>101.08</td>
<td>94.19</td>
<td>105.1</td>
</tr>
<tr>
<td>20</td>
<td>93.54</td>
<td>87.24</td>
<td>80.39</td>
<td>90.57</td>
<td>93.56</td>
<td>87.31</td>
<td>80.19</td>
<td>90.51</td>
<td>90.0</td>
</tr>
<tr>
<td>25</td>
<td>75.94</td>
<td>66.78</td>
<td>73.73</td>
<td>79.15</td>
<td>75.20</td>
<td>61.63</td>
<td>74.15</td>
<td>78.60</td>
<td>75.7</td>
</tr>
<tr>
<td>31.5</td>
<td>76.95</td>
<td>73.94</td>
<td>66.65</td>
<td>63.38</td>
<td>73.81</td>
<td>68.99</td>
<td>36.95</td>
<td>66.40</td>
<td>71.6</td>
</tr>
<tr>
<td>40</td>
<td>95.93</td>
<td>100.59</td>
<td>101.53</td>
<td>104.59</td>
<td>98.49</td>
<td>101.56</td>
<td>103.57</td>
<td>104.13</td>
<td>102.3</td>
</tr>
<tr>
<td>50</td>
<td>72.71</td>
<td>70.34</td>
<td>68.27</td>
<td>68.62</td>
<td>67.24</td>
<td>67.57</td>
<td>66.19</td>
<td>63.19</td>
<td>68.8</td>
</tr>
<tr>
<td>63</td>
<td>64.86</td>
<td>64.39</td>
<td>63.90</td>
<td>63.44</td>
<td>67.39</td>
<td>63.11</td>
<td>56.86</td>
<td>32.51</td>
<td>63.6</td>
</tr>
<tr>
<td>80</td>
<td>59.02</td>
<td>59.45</td>
<td>61.76</td>
<td>59.02</td>
<td>13.35</td>
<td>43.72</td>
<td>45.14</td>
<td>42.12</td>
<td>57.0</td>
</tr>
<tr>
<td>100</td>
<td>52.37</td>
<td>39.53</td>
<td>53.49</td>
<td>63.68</td>
<td>56.98</td>
<td>54.48</td>
<td>58.41</td>
<td>62.36</td>
<td>58.7</td>
</tr>
<tr>
<td>125</td>
<td>51.52</td>
<td>52.74</td>
<td>46.19</td>
<td>44.43</td>
<td>55.77</td>
<td>55.96</td>
<td>59.70</td>
<td>54.71</td>
<td>54.5</td>
</tr>
<tr>
<td>160</td>
<td>50.43</td>
<td>60.67</td>
<td>50.77</td>
<td>64.89</td>
<td>40.45</td>
<td>55.93</td>
<td>56.27</td>
<td>64.20</td>
<td>60.0</td>
</tr>
<tr>
<td>200</td>
<td>98.60</td>
<td>110.98</td>
<td>117.10</td>
<td>96.90</td>
<td>111.07</td>
<td>113.24</td>
<td>78.34</td>
<td>115.25</td>
<td>112.2</td>
</tr>
<tr>
<td>250</td>
<td>62.20</td>
<td>47.67</td>
<td>55.50</td>
<td>51.13</td>
<td>45.33</td>
<td>60.73</td>
<td>61.08</td>
<td>65.13</td>
<td>60.0</td>
</tr>
<tr>
<td>315</td>
<td>61.77</td>
<td>54.34</td>
<td>64.05</td>
<td>58.17</td>
<td>56.14</td>
<td>57.19</td>
<td>55.94</td>
<td>46.59</td>
<td>59.0</td>
</tr>
<tr>
<td>400</td>
<td>88.07</td>
<td>85.74</td>
<td>75.84</td>
<td>80.40</td>
<td>70.34</td>
<td>82.83</td>
<td>54.26</td>
<td>76.47</td>
<td>82.5</td>
</tr>
<tr>
<td>500</td>
<td>61.34</td>
<td>63.78</td>
<td>58.14</td>
<td>58.41</td>
<td>69.64</td>
<td>57.58</td>
<td>62.22</td>
<td>53.57</td>
<td>63.2</td>
</tr>
<tr>
<td>630</td>
<td>47.71</td>
<td>68.13</td>
<td>51.51</td>
<td>62.12</td>
<td>69.63</td>
<td>56.61</td>
<td>65.45</td>
<td>63.46</td>
<td>64.7</td>
</tr>
<tr>
<td>800</td>
<td>80.80</td>
<td>69.90</td>
<td>78.52</td>
<td>68.80</td>
<td>77.27</td>
<td>75.55</td>
<td>77.09</td>
<td>79.03</td>
<td>77.3</td>
</tr>
<tr>
<td>1,000</td>
<td>81.79</td>
<td>75.39</td>
<td>50.91</td>
<td>70.59</td>
<td>79.92</td>
<td>79.52</td>
<td>51.37</td>
<td>82.72</td>
<td>78.5</td>
</tr>
<tr>
<td>1,250</td>
<td>73.25</td>
<td>66.07</td>
<td>77.83</td>
<td>79.64</td>
<td>71.10</td>
<td>69.38</td>
<td>75.46</td>
<td>75.11</td>
<td>75.2</td>
</tr>
<tr>
<td>1,600</td>
<td>73.74</td>
<td>61.22</td>
<td>58.49</td>
<td>60.53</td>
<td>61.84</td>
<td>63.02</td>
<td>37.50</td>
<td>52.42</td>
<td>65.8</td>
</tr>
<tr>
<td>2,000</td>
<td>32.29</td>
<td>27.72</td>
<td>35.59</td>
<td>14.92</td>
<td>-3.53</td>
<td>-4.67</td>
<td>-6.29</td>
<td>-5.71</td>
<td>28.7</td>
</tr>
<tr>
<td>2,500</td>
<td>17.61</td>
<td>2.28</td>
<td>15.49</td>
<td>18.83</td>
<td>-37.86</td>
<td>-49.64</td>
<td>-52.81</td>
<td>-17.32</td>
<td>13.3</td>
</tr>
<tr>
<td>3,150</td>
<td>-24.06</td>
<td>2.73</td>
<td>-23.60</td>
<td>-8.51</td>
<td>-39.41</td>
<td>-77.28</td>
<td>-55.85</td>
<td>-34.65</td>
<td>-6.0</td>
</tr>
<tr>
<td>4,000</td>
<td>-3.67</td>
<td>9.92</td>
<td>-16.37</td>
<td>-2.82</td>
<td>-40.21</td>
<td>-57.86</td>
<td>-40.31</td>
<td>-62.41</td>
<td>1.3</td>
</tr>
<tr>
<td>5,000</td>
<td>-47.98</td>
<td>-24.61</td>
<td>-43.38</td>
<td>-41.18</td>
<td>-83.76</td>
<td>-85.36</td>
<td>-71.54</td>
<td>-61.18</td>
<td>-33.5</td>
</tr>
<tr>
<td>6,300</td>
<td>-93.51</td>
<td>-68.41</td>
<td>-100.01</td>
<td>-87.77</td>
<td>-136.34</td>
<td>-123.64</td>
<td>-122.90</td>
<td>-120.84</td>
<td>-77.4</td>
</tr>
<tr>
<td>8,000</td>
<td>-129.61</td>
<td>-105.50</td>
<td>-119.66</td>
<td>-112.01</td>
<td>-142.00</td>
<td>-156.02</td>
<td>-154.84</td>
<td>-144.89</td>
<td>-113.5</td>
</tr>
<tr>
<td>10,000</td>
<td>-114.58</td>
<td>-93.29</td>
<td>-137.01</td>
<td>-124.97</td>
<td>-141.06</td>
<td>-181.03</td>
<td>-165.66</td>
<td>-247.12</td>
<td>-102.3</td>
</tr>
<tr>
<td>12,500</td>
<td>-109.20</td>
<td>-85.42</td>
<td>-112.35</td>
<td>-99.00</td>
<td>-135.51</td>
<td>-160.50</td>
<td>-153.17</td>
<td>-141.86</td>
<td>-94.2</td>
</tr>
<tr>
<td>16,000</td>
<td>-113.54</td>
<td>-106.65</td>
<td>-119.00</td>
<td>-99.38</td>
<td>-152.54</td>
<td>-158.47</td>
<td>-146.71</td>
<td>-139.97</td>
<td>-107.5</td>
</tr>
<tr>
<td>20,000</td>
<td>-99.39</td>
<td>-80.72</td>
<td>-109.97</td>
<td>-98.45</td>
<td>-148.83</td>
<td>-143.81</td>
<td>-138.82</td>
<td>-152.80</td>
<td>-99.6</td>
</tr>
</tbody>
</table>
Table C.6: A-weighted Sound Level when the Concrete Element Floor Structure is Subjected to Rhythmic Excitation

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Measurement (dB)</th>
<th>A-weighting Relative Response (dB)</th>
<th>A-weighted Sound Level (dB(A))</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>105.1</td>
<td>-56.7</td>
<td>48.4</td>
</tr>
<tr>
<td>20</td>
<td>90.0</td>
<td>-50.5</td>
<td>39.5</td>
</tr>
<tr>
<td>25</td>
<td>75.7</td>
<td>-44.7</td>
<td>31.0</td>
</tr>
<tr>
<td>31.5</td>
<td>71.6</td>
<td>-39.4</td>
<td>32.2</td>
</tr>
<tr>
<td>40</td>
<td>102.3</td>
<td>-34.6</td>
<td>67.7</td>
</tr>
<tr>
<td>50</td>
<td>68.8</td>
<td>-30.2</td>
<td>38.6</td>
</tr>
<tr>
<td>63</td>
<td>63.6</td>
<td>-26.2</td>
<td>37.4</td>
</tr>
<tr>
<td>80</td>
<td>57.0</td>
<td>-22.5</td>
<td>34.5</td>
</tr>
<tr>
<td>100</td>
<td>58.7</td>
<td>-19.1</td>
<td>39.6</td>
</tr>
<tr>
<td>125</td>
<td>54.5</td>
<td>-16.1</td>
<td>38.4</td>
</tr>
<tr>
<td>160</td>
<td>60.0</td>
<td>-13.4</td>
<td>46.6</td>
</tr>
<tr>
<td>200</td>
<td>112.2</td>
<td>-10.9</td>
<td>101.3</td>
</tr>
<tr>
<td>250</td>
<td>60.0</td>
<td>-8.6</td>
<td>51.4</td>
</tr>
<tr>
<td>315</td>
<td>59.0</td>
<td>-6.6</td>
<td>52.4</td>
</tr>
<tr>
<td>400</td>
<td>82.5</td>
<td>-4.8</td>
<td>77.7</td>
</tr>
<tr>
<td>500</td>
<td>63.2</td>
<td>-3.2</td>
<td>60.0</td>
</tr>
<tr>
<td>630</td>
<td>64.7</td>
<td>-1.9</td>
<td>62.8</td>
</tr>
<tr>
<td>800</td>
<td>77.3</td>
<td>-0.8</td>
<td>76.5</td>
</tr>
<tr>
<td>1,000</td>
<td>78.5</td>
<td>0.0</td>
<td>78.5</td>
</tr>
<tr>
<td>1,250</td>
<td>75.2</td>
<td>0.6</td>
<td>75.8</td>
</tr>
<tr>
<td>1,600</td>
<td>65.8</td>
<td>1.0</td>
<td>66.8</td>
</tr>
<tr>
<td>2,000</td>
<td>28.7</td>
<td>1.2</td>
<td>29.9</td>
</tr>
<tr>
<td>2,500</td>
<td>13.3</td>
<td>1.3</td>
<td>14.6</td>
</tr>
<tr>
<td>3,150</td>
<td>-6.0</td>
<td>1.2</td>
<td>-4.8</td>
</tr>
<tr>
<td>4,000</td>
<td>1.3</td>
<td>1.0</td>
<td>2.3</td>
</tr>
<tr>
<td>5,000</td>
<td>-33.5</td>
<td>0.5</td>
<td>-33.0</td>
</tr>
<tr>
<td>6,300</td>
<td>-77.4</td>
<td>-0.1</td>
<td>-77.5</td>
</tr>
<tr>
<td>8,000</td>
<td>-113.5</td>
<td>-1.1</td>
<td>-114.6</td>
</tr>
<tr>
<td>10,000</td>
<td>-102.3</td>
<td>-2.5</td>
<td>-104.8</td>
</tr>
<tr>
<td>12,500</td>
<td>-94.2</td>
<td>-4.3</td>
<td>-98.5</td>
</tr>
<tr>
<td>16,000</td>
<td>-107.5</td>
<td>-6.6</td>
<td>-114.1</td>
</tr>
<tr>
<td>20,000</td>
<td>-89.6</td>
<td>-9.3</td>
<td>-98.9</td>
</tr>
</tbody>
</table>
### C.3 Steel-Concrete Composite Structures

*Table C.7: SPL Point Evaluation when the Steel-Concrete Composite Floor Structure is Subjected to a Tapping Machine*

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Measurement (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(1.05, 1.1)</td>
</tr>
<tr>
<td>100</td>
<td>-0.33</td>
</tr>
<tr>
<td>125</td>
<td>63.41</td>
</tr>
<tr>
<td>160</td>
<td>33.78</td>
</tr>
<tr>
<td>200</td>
<td>17.74</td>
</tr>
<tr>
<td>250</td>
<td>40.06</td>
</tr>
<tr>
<td>315</td>
<td>50.36</td>
</tr>
<tr>
<td>400</td>
<td>59.91</td>
</tr>
<tr>
<td>500</td>
<td>75.19</td>
</tr>
<tr>
<td>630</td>
<td>27.49</td>
</tr>
<tr>
<td>800</td>
<td>59.82</td>
</tr>
<tr>
<td>1,000</td>
<td>49.79</td>
</tr>
<tr>
<td>1,250</td>
<td>87.43</td>
</tr>
<tr>
<td>1,600</td>
<td>45.77</td>
</tr>
<tr>
<td>2,000</td>
<td>31.50</td>
</tr>
<tr>
<td>3,150</td>
<td>-34.36</td>
</tr>
</tbody>
</table>
Table C.8: SPL Point Evaluation when the Steel-Concrete Composite Floor Structure is Subjected to Rhythmic Excitation

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Measurement (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1.05, 1.1)</td>
<td>(1.05, 1.3)</td>
</tr>
<tr>
<td>16</td>
<td>97.45</td>
</tr>
<tr>
<td>20</td>
<td>97.14</td>
</tr>
<tr>
<td>25</td>
<td>72.71</td>
</tr>
<tr>
<td>31.5</td>
<td>77.91</td>
</tr>
<tr>
<td>40</td>
<td>88.72</td>
</tr>
<tr>
<td>50</td>
<td>34.51</td>
</tr>
<tr>
<td>63</td>
<td>58.47</td>
</tr>
<tr>
<td>80</td>
<td>74.63</td>
</tr>
<tr>
<td>100</td>
<td>63.46</td>
</tr>
<tr>
<td>125</td>
<td>88.40</td>
</tr>
<tr>
<td>160</td>
<td>53.48</td>
</tr>
<tr>
<td>200</td>
<td>56.61</td>
</tr>
<tr>
<td>250</td>
<td>59.29</td>
</tr>
<tr>
<td>315</td>
<td>54.56</td>
</tr>
<tr>
<td>400</td>
<td>87.64</td>
</tr>
<tr>
<td>500</td>
<td>86.07</td>
</tr>
<tr>
<td>630</td>
<td>73.07</td>
</tr>
<tr>
<td>800</td>
<td>87.08</td>
</tr>
<tr>
<td>1,000</td>
<td>69.45</td>
</tr>
<tr>
<td>1,250</td>
<td>71.77</td>
</tr>
<tr>
<td>1,600</td>
<td>83.96</td>
</tr>
<tr>
<td>2,000</td>
<td>36.55</td>
</tr>
<tr>
<td>2,500</td>
<td>7.32</td>
</tr>
<tr>
<td>3,150</td>
<td>-25.51</td>
</tr>
<tr>
<td>4,000</td>
<td>-41.98</td>
</tr>
<tr>
<td>5,000</td>
<td>-65.52</td>
</tr>
<tr>
<td>6,300</td>
<td>-97.80</td>
</tr>
<tr>
<td>8,000</td>
<td>-110.59</td>
</tr>
<tr>
<td>10,000</td>
<td>-122.44</td>
</tr>
<tr>
<td>12,500</td>
<td>-136.69</td>
</tr>
<tr>
<td>16,000</td>
<td>-122.44</td>
</tr>
<tr>
<td>20,000</td>
<td>-133.71</td>
</tr>
</tbody>
</table>

Average: 94.2
Table C.9: A-weighted Sound Level when the Steel-Concrete Composite Floor Structure is Subjected to Rhythmic Excitation

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Measurement (dB)</th>
<th>A-weighting Relative Response (dB)</th>
<th>A-weighted Sound Level (dB(A))</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>94.2</td>
<td>-56.7</td>
<td>37.5</td>
</tr>
<tr>
<td>20</td>
<td>93.1</td>
<td>-50.5</td>
<td>42.6</td>
</tr>
<tr>
<td>25</td>
<td>82.8</td>
<td>-44.7</td>
<td>38.1</td>
</tr>
<tr>
<td>31.5</td>
<td>81.2</td>
<td>-39.4</td>
<td>41.8</td>
</tr>
<tr>
<td>40</td>
<td>85.5</td>
<td>-34.6</td>
<td>50.9</td>
</tr>
<tr>
<td>50</td>
<td>60.6</td>
<td>-30.2</td>
<td>30.4</td>
</tr>
<tr>
<td>63</td>
<td>61.1</td>
<td>-26.2</td>
<td>34.9</td>
</tr>
<tr>
<td>80</td>
<td>76.6</td>
<td>-22.5</td>
<td>54.1</td>
</tr>
<tr>
<td>100</td>
<td>63.8</td>
<td>-19.1</td>
<td>44.7</td>
</tr>
<tr>
<td>125</td>
<td>86.7</td>
<td>-16.1</td>
<td>70.6</td>
</tr>
<tr>
<td>160</td>
<td>58.6</td>
<td>-13.4</td>
<td>45.2</td>
</tr>
<tr>
<td>200</td>
<td>56.9</td>
<td>-10.9</td>
<td>46.0</td>
</tr>
<tr>
<td>250</td>
<td>72.3</td>
<td>-8.6</td>
<td>63.7</td>
</tr>
<tr>
<td>315</td>
<td>66.8</td>
<td>-6.6</td>
<td>60.2</td>
</tr>
<tr>
<td>400</td>
<td>93.5</td>
<td>-4.8</td>
<td>88.7</td>
</tr>
<tr>
<td>500</td>
<td>81.6</td>
<td>-3.2</td>
<td>78.4</td>
</tr>
<tr>
<td>630</td>
<td>85.7</td>
<td>-1.9</td>
<td>83.8</td>
</tr>
<tr>
<td>800</td>
<td>87.1</td>
<td>-0.8</td>
<td>86.3</td>
</tr>
<tr>
<td>1,000</td>
<td>114.6</td>
<td>0.0</td>
<td>114.6</td>
</tr>
<tr>
<td>1,250</td>
<td>79.0</td>
<td>0.6</td>
<td>79.6</td>
</tr>
<tr>
<td>1,600</td>
<td>86.2</td>
<td>1.0</td>
<td>87.2</td>
</tr>
<tr>
<td>2,000</td>
<td>29.7</td>
<td>1.2</td>
<td>30.9</td>
</tr>
<tr>
<td>2,500</td>
<td>1.7</td>
<td>1.3</td>
<td>3.0</td>
</tr>
<tr>
<td>3,150</td>
<td>-28.0</td>
<td>1.2</td>
<td>-26.8</td>
</tr>
<tr>
<td>4,000</td>
<td>-26.1</td>
<td>1.0</td>
<td>-25.1</td>
</tr>
<tr>
<td>5,000</td>
<td>-54.4</td>
<td>0.5</td>
<td>-53.9</td>
</tr>
<tr>
<td>6,300</td>
<td>-75.7</td>
<td>0.1</td>
<td>-75.8</td>
</tr>
<tr>
<td>8,000</td>
<td>-86.7</td>
<td>-1.1</td>
<td>-87.8</td>
</tr>
<tr>
<td>10,000</td>
<td>-124.4</td>
<td>-2.5</td>
<td>-126.9</td>
</tr>
<tr>
<td>12,500</td>
<td>-134.3</td>
<td>-4.3</td>
<td>-138.6</td>
</tr>
<tr>
<td>16,000</td>
<td>-106.1</td>
<td>-6.6</td>
<td>-112.7</td>
</tr>
<tr>
<td>20,000</td>
<td>-130.2</td>
<td>-9.3</td>
<td>-139.5</td>
</tr>
</tbody>
</table>

114.6
### C.4 Steel-Concrete Composite Structures with a Resilient Floor Covering

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Transmissibility $\eta = 0.1$</th>
<th>Transmissibility $\eta = 0.2$</th>
<th>Transmissibility $\eta = 0.5$</th>
<th>Transmissibility $\eta = 1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>1.8062</td>
<td>1.7798</td>
<td>1.6358</td>
<td>1.3877</td>
</tr>
<tr>
<td>20</td>
<td>3.2402</td>
<td>2.9646</td>
<td>2.1087</td>
<td>1.4670</td>
</tr>
<tr>
<td>25</td>
<td>7.0566</td>
<td>4.4296</td>
<td>2.1200</td>
<td>1.3769</td>
</tr>
<tr>
<td>31.5</td>
<td>1.3401</td>
<td>1.3148</td>
<td>1.2075</td>
<td>1.0940</td>
</tr>
<tr>
<td>40</td>
<td>0.5586</td>
<td>0.5738</td>
<td>0.6549</td>
<td>0.7917</td>
</tr>
<tr>
<td>50</td>
<td>0.3011</td>
<td>0.3177</td>
<td>0.4085</td>
<td>0.5829</td>
</tr>
<tr>
<td>63</td>
<td>0.1732</td>
<td>0.1889</td>
<td>0.2710</td>
<td>0.4327</td>
</tr>
<tr>
<td>80</td>
<td>0.1030</td>
<td>0.1174</td>
<td>0.1882</td>
<td>0.3249</td>
</tr>
<tr>
<td>100</td>
<td>0.0655</td>
<td>0.0787</td>
<td>0.1392</td>
<td>0.2523</td>
</tr>
<tr>
<td>125</td>
<td>0.0427</td>
<td>0.0548</td>
<td>0.1056</td>
<td>0.1979</td>
</tr>
<tr>
<td>160</td>
<td>0.0274</td>
<td>0.0381</td>
<td>0.0794</td>
<td>0.1525</td>
</tr>
<tr>
<td>200</td>
<td>0.0189</td>
<td>0.0282</td>
<td>0.0621</td>
<td>0.1211</td>
</tr>
<tr>
<td>250</td>
<td>0.0133</td>
<td>0.0214</td>
<td>0.0490</td>
<td>0.0964</td>
</tr>
<tr>
<td>315</td>
<td>0.0096</td>
<td>0.0163</td>
<td>0.0385</td>
<td>0.0762</td>
</tr>
<tr>
<td>400</td>
<td>0.0070</td>
<td>0.0125</td>
<td>0.0301</td>
<td>0.0599</td>
</tr>
<tr>
<td>500</td>
<td>0.0053</td>
<td>0.0098</td>
<td>0.0240</td>
<td>0.0479</td>
</tr>
<tr>
<td>630</td>
<td>0.0041</td>
<td>0.0077</td>
<td>0.0190</td>
<td>0.0379</td>
</tr>
<tr>
<td>800</td>
<td>0.0031</td>
<td>0.0060</td>
<td>0.0150</td>
<td>0.0299</td>
</tr>
<tr>
<td>1,000</td>
<td>0.0025</td>
<td>0.0048</td>
<td>0.0120</td>
<td>0.0239</td>
</tr>
<tr>
<td>1,250</td>
<td>0.0019</td>
<td>0.0038</td>
<td>0.0096</td>
<td>0.0191</td>
</tr>
<tr>
<td>1,600</td>
<td>0.0015</td>
<td>0.0030</td>
<td>0.0075</td>
<td>0.0149</td>
</tr>
<tr>
<td>2,000</td>
<td>0.0012</td>
<td>0.0024</td>
<td>0.0060</td>
<td>0.0119</td>
</tr>
<tr>
<td>2,500</td>
<td>0.0010</td>
<td>0.0019</td>
<td>0.0048</td>
<td>0.0096</td>
</tr>
<tr>
<td>3,150</td>
<td>0.0008</td>
<td>0.0015</td>
<td>0.0038</td>
<td>0.0076</td>
</tr>
<tr>
<td>4,000</td>
<td>0.0006</td>
<td>0.0012</td>
<td>0.0030</td>
<td>0.0060</td>
</tr>
<tr>
<td>5,000</td>
<td>0.0005</td>
<td>0.0010</td>
<td>0.0024</td>
<td>0.0048</td>
</tr>
<tr>
<td>6,300</td>
<td>0.0004</td>
<td>0.0008</td>
<td>0.0019</td>
<td>0.0038</td>
</tr>
<tr>
<td>8,000</td>
<td>0.0003</td>
<td>0.0006</td>
<td>0.0015</td>
<td>0.0030</td>
</tr>
<tr>
<td>10,000</td>
<td>0.0002</td>
<td>0.0005</td>
<td>0.0012</td>
<td>0.0024</td>
</tr>
<tr>
<td>12,500</td>
<td>0.0002</td>
<td>0.0004</td>
<td>0.0010</td>
<td>0.0019</td>
</tr>
<tr>
<td>16,000</td>
<td>0.0002</td>
<td>0.0003</td>
<td>0.0008</td>
<td>0.0015</td>
</tr>
<tr>
<td>20,000</td>
<td>0.0001</td>
<td>0.0002</td>
<td>0.0006</td>
<td>0.0012</td>
</tr>
</tbody>
</table>

Table C.10: Force Transmissibility Magnitude at Each Center Frequency when the Dynamic Stiffness of the Resilient Floor Covering is 30 MN/m² with Loss Factors 0.1, 0.2, 0.5 and 1
<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Measurement η = 0.1 (dB)</th>
<th>Measurement η = 0.2 (dB)</th>
<th>Measurement η = 0.5 (dB)</th>
<th>Measurement η = 1 (dB)</th>
<th>A-weighting Relative Response</th>
<th>A-weighted Sound Level η = 0.1 (dB(A))</th>
<th>A-weighted Sound Level η = 0.2 (dB(A))</th>
<th>A-weighted Sound Level η = 0.5 (dB(A))</th>
<th>A-weighted Sound Level η = 1 (dB(A))</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>99.3</td>
<td>99.2</td>
<td>98.5</td>
<td>97.0</td>
<td>-56.7</td>
<td>42.6</td>
<td>42.5</td>
<td>41.8</td>
<td>40.3</td>
</tr>
<tr>
<td>20</td>
<td>103.3</td>
<td>102.5</td>
<td>99.6</td>
<td>96.4</td>
<td>-50.5</td>
<td>52.8</td>
<td>52.0</td>
<td>49.1</td>
<td>45.9</td>
</tr>
<tr>
<td>25</td>
<td>99.8</td>
<td>95.7</td>
<td>89.3</td>
<td>85.6</td>
<td>-44.7</td>
<td>55.1</td>
<td>51.0</td>
<td>44.6</td>
<td>40.9</td>
</tr>
<tr>
<td>31.5</td>
<td>83.7</td>
<td>83.6</td>
<td>82.8</td>
<td>82.0</td>
<td>-39.4</td>
<td>44.3</td>
<td>44.2</td>
<td>43.4</td>
<td>42.6</td>
</tr>
<tr>
<td>40</td>
<td>80.4</td>
<td>80.7</td>
<td>81.8</td>
<td>83.5</td>
<td>-34.6</td>
<td>45.8</td>
<td>46.1</td>
<td>47.2</td>
<td>48.9</td>
</tr>
<tr>
<td>50</td>
<td>50.2</td>
<td>50.6</td>
<td>52.8</td>
<td>55.9</td>
<td>-30.2</td>
<td>20.0</td>
<td>20.4</td>
<td>22.6</td>
<td>25.7</td>
</tr>
<tr>
<td>63</td>
<td>45.9</td>
<td>46.6</td>
<td>49.8</td>
<td>53.8</td>
<td>-26.2</td>
<td>13.7</td>
<td>19.4</td>
<td>23.6</td>
<td>27.6</td>
</tr>
<tr>
<td>80</td>
<td>56.9</td>
<td>58.0</td>
<td>62.1</td>
<td>66.8</td>
<td>-22.5</td>
<td>34.4</td>
<td>35.5</td>
<td>39.6</td>
<td>44.3</td>
</tr>
<tr>
<td>100</td>
<td>40.1</td>
<td>41.7</td>
<td>46.7</td>
<td>51.8</td>
<td>-19.1</td>
<td>21.0</td>
<td>22.6</td>
<td>27.6</td>
<td>32.7</td>
</tr>
<tr>
<td>125</td>
<td>59.3</td>
<td>61.5</td>
<td>67.2</td>
<td>72.6</td>
<td>-16.1</td>
<td>43.2</td>
<td>45.4</td>
<td>51.1</td>
<td>56.5</td>
</tr>
<tr>
<td>160</td>
<td>27.4</td>
<td>30.2</td>
<td>36.6</td>
<td>42.3</td>
<td>-13.4</td>
<td>14.0</td>
<td>16.8</td>
<td>23.2</td>
<td>28.9</td>
</tr>
<tr>
<td>200</td>
<td>22.4</td>
<td>25.9</td>
<td>32.8</td>
<td>38.6</td>
<td>-10.9</td>
<td>11.5</td>
<td>15.0</td>
<td>21.9</td>
<td>27.7</td>
</tr>
<tr>
<td>250</td>
<td>34.8</td>
<td>38.9</td>
<td>46.1</td>
<td>52.0</td>
<td>-8.6</td>
<td>26.2</td>
<td>30.3</td>
<td>37.5</td>
<td>43.4</td>
</tr>
<tr>
<td>315</td>
<td>26.4</td>
<td>31.0</td>
<td>38.5</td>
<td>44.4</td>
<td>-6.6</td>
<td>19.8</td>
<td>24.4</td>
<td>31.9</td>
<td>37.8</td>
</tr>
<tr>
<td>400</td>
<td>50.4</td>
<td>55.4</td>
<td>61.1</td>
<td>69.0</td>
<td>-4.8</td>
<td>45.6</td>
<td>50.6</td>
<td>58.3</td>
<td>64.2</td>
</tr>
<tr>
<td>500</td>
<td>36.1</td>
<td>41.4</td>
<td>49.2</td>
<td>55.2</td>
<td>-3.2</td>
<td>32.9</td>
<td>38.2</td>
<td>46.0</td>
<td>52.0</td>
</tr>
<tr>
<td>630</td>
<td>38.0</td>
<td>43.4</td>
<td>51.3</td>
<td>57.3</td>
<td>-1.9</td>
<td>36.1</td>
<td>41.5</td>
<td>49.4</td>
<td>55.4</td>
</tr>
<tr>
<td>800</td>
<td>36.9</td>
<td>42.7</td>
<td>50.6</td>
<td>56.6</td>
<td>-0.8</td>
<td>36.1</td>
<td>41.9</td>
<td>49.8</td>
<td>55.8</td>
</tr>
<tr>
<td>1,000</td>
<td>62.6</td>
<td>68.2</td>
<td>76.2</td>
<td>82.2</td>
<td>0.0</td>
<td>62.6</td>
<td>68.2</td>
<td>76.2</td>
<td>82.2</td>
</tr>
<tr>
<td>1,250</td>
<td>24.6</td>
<td>30.6</td>
<td>38.6</td>
<td>44.6</td>
<td>0.6</td>
<td>25.2</td>
<td>31.2</td>
<td>39.2</td>
<td>45.2</td>
</tr>
<tr>
<td>1,600</td>
<td>29.7</td>
<td>35.7</td>
<td>43.7</td>
<td>49.7</td>
<td>1.0</td>
<td>30.7</td>
<td>36.7</td>
<td>44.7</td>
<td>50.7</td>
</tr>
<tr>
<td>2,000</td>
<td>-28.7</td>
<td>-22.7</td>
<td>-14.7</td>
<td>-8.8</td>
<td>1.2</td>
<td>-27.5</td>
<td>-21.5</td>
<td>-13.5</td>
<td>-7.6</td>
</tr>
<tr>
<td>2,500</td>
<td>-58.3</td>
<td>-52.7</td>
<td>-44.7</td>
<td>-38.7</td>
<td>1.3</td>
<td>-57.0</td>
<td>-51.4</td>
<td>-43.4</td>
<td>-37.4</td>
</tr>
<tr>
<td>3,150</td>
<td>-89.9</td>
<td>-84.5</td>
<td>-76.4</td>
<td>-70.4</td>
<td>-1.2</td>
<td>-88.7</td>
<td>-83.3</td>
<td>-75.2</td>
<td>-69.2</td>
</tr>
<tr>
<td>4,000</td>
<td>-90.5</td>
<td>-85.5</td>
<td>-76.6</td>
<td>-70.5</td>
<td>0.1</td>
<td>-89.5</td>
<td>-83.5</td>
<td>-75.6</td>
<td>-69.5</td>
</tr>
<tr>
<td>5,000</td>
<td>-120.4</td>
<td>-114.4</td>
<td>-106.8</td>
<td>-100.8</td>
<td>0.5</td>
<td>-119.9</td>
<td>-113.9</td>
<td>-106.3</td>
<td>-100.3</td>
</tr>
<tr>
<td>6,300</td>
<td>-143.7</td>
<td>-137.6</td>
<td>-130.1</td>
<td>-124.1</td>
<td>-0.1</td>
<td>-143.8</td>
<td>-137.7</td>
<td>-130.2</td>
<td>-124.2</td>
</tr>
<tr>
<td>8,000</td>
<td>-157.2</td>
<td>-151.1</td>
<td>-143.2</td>
<td>-137.2</td>
<td>-1.1</td>
<td>-158.3</td>
<td>-152.2</td>
<td>-144.3</td>
<td>-138.3</td>
</tr>
<tr>
<td>10,000</td>
<td>-198.4</td>
<td>-190.4</td>
<td>-182.8</td>
<td>-176.8</td>
<td>-2.5</td>
<td>-200.9</td>
<td>-192.9</td>
<td>-185.3</td>
<td>-179.3</td>
</tr>
<tr>
<td>12,500</td>
<td>-208.3</td>
<td>-202.3</td>
<td>-194.3</td>
<td>-188.7</td>
<td>-4.3</td>
<td>-212.6</td>
<td>-206.6</td>
<td>-198.6</td>
<td>-193.0</td>
</tr>
<tr>
<td>16,000</td>
<td>-180.1</td>
<td>-176.6</td>
<td>-160.0</td>
<td>-152.6</td>
<td>-6.6</td>
<td>-186.7</td>
<td>-183.2</td>
<td>-174.6</td>
<td>-169.2</td>
</tr>
<tr>
<td>20,000</td>
<td>-210.2</td>
<td>-204.2</td>
<td>-194.6</td>
<td>-188.6</td>
<td>-9.3</td>
<td>-219.5</td>
<td>-213.5</td>
<td>-203.9</td>
<td>-197.9</td>
</tr>
</tbody>
</table>

| 63.9 | 68.6 | 76.3 | 82.3 |
### C.5 Steel-Concrete Composite Structures with a Floating Floor

**Table C.12: SPL Point Evaluation when the Steel-Concrete Composite Floor Structure with a Floating Floor is Subjected to Rhythmic Excitation**

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Measurement (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(1.05, 1.1)</td>
</tr>
<tr>
<td>16</td>
<td>94.40</td>
</tr>
<tr>
<td>20</td>
<td>96.77</td>
</tr>
<tr>
<td>25</td>
<td>76.12</td>
</tr>
<tr>
<td>31.5</td>
<td>83.66</td>
</tr>
<tr>
<td>40</td>
<td>104.72</td>
</tr>
<tr>
<td>50</td>
<td>53.89</td>
</tr>
<tr>
<td>63</td>
<td>46.31</td>
</tr>
<tr>
<td>80</td>
<td>64.97</td>
</tr>
<tr>
<td>100</td>
<td>44.79</td>
</tr>
<tr>
<td>125</td>
<td>81.61</td>
</tr>
<tr>
<td>160</td>
<td>33.06</td>
</tr>
<tr>
<td>200</td>
<td>33.45</td>
</tr>
<tr>
<td>250</td>
<td>56.22</td>
</tr>
<tr>
<td>315</td>
<td>17.11</td>
</tr>
<tr>
<td>400</td>
<td>65.06</td>
</tr>
<tr>
<td>500</td>
<td>2.33</td>
</tr>
<tr>
<td>630</td>
<td>8.61</td>
</tr>
<tr>
<td>800</td>
<td>38.27</td>
</tr>
<tr>
<td>1,000</td>
<td>16.63</td>
</tr>
<tr>
<td>1,250</td>
<td>49.20</td>
</tr>
<tr>
<td>1,600</td>
<td>25.84</td>
</tr>
<tr>
<td>2,000</td>
<td>24.52</td>
</tr>
<tr>
<td>2,500</td>
<td>-39.47</td>
</tr>
<tr>
<td>3,150</td>
<td>-101.21</td>
</tr>
<tr>
<td>4,000</td>
<td>-60.48</td>
</tr>
<tr>
<td>5,000</td>
<td>-73.64</td>
</tr>
<tr>
<td>6,300</td>
<td>-109.29</td>
</tr>
<tr>
<td>8,000</td>
<td>-124.86</td>
</tr>
<tr>
<td>10,000</td>
<td>-146.91</td>
</tr>
<tr>
<td>12,500</td>
<td>-160.58</td>
</tr>
<tr>
<td>16,000</td>
<td>-127.85</td>
</tr>
<tr>
<td>20,000</td>
<td>-143.10</td>
</tr>
</tbody>
</table>
Table C.13: A-weighted Sound Level when the Steel-Concrete Composite Floor Structure with a Floating Floor is Subjected to Rhythmic Excitation

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Measurement</th>
<th>A-weighting Relative Response (dB)</th>
<th>A-weighted Sound Level (dB(A))</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>91.1</td>
<td>-56.7</td>
<td>34.4</td>
</tr>
<tr>
<td>20</td>
<td>92.8</td>
<td>-50.5</td>
<td>42.3</td>
</tr>
<tr>
<td>25</td>
<td>84.6</td>
<td>-44.7</td>
<td>39.9</td>
</tr>
<tr>
<td>31.5</td>
<td>86.8</td>
<td>-39.4</td>
<td>47.4</td>
</tr>
<tr>
<td>40</td>
<td>101.5</td>
<td>-34.6</td>
<td>66.9</td>
</tr>
<tr>
<td>50</td>
<td>63.6</td>
<td>-30.2</td>
<td>33.4</td>
</tr>
<tr>
<td>63</td>
<td>52.9</td>
<td>-26.2</td>
<td>26.7</td>
</tr>
<tr>
<td>80</td>
<td>62.6</td>
<td>-22.5</td>
<td>40.1</td>
</tr>
<tr>
<td>100</td>
<td>49.6</td>
<td>-19.1</td>
<td>30.5</td>
</tr>
<tr>
<td>125</td>
<td>79.6</td>
<td>-16.1</td>
<td>63.5</td>
</tr>
<tr>
<td>160</td>
<td>34.3</td>
<td>-13.4</td>
<td>20.9</td>
</tr>
<tr>
<td>200</td>
<td>35.2</td>
<td>-10.9</td>
<td>24.3</td>
</tr>
<tr>
<td>250</td>
<td>57.6</td>
<td>-8.6</td>
<td>49.0</td>
</tr>
<tr>
<td>315</td>
<td>26.6</td>
<td>-6.6</td>
<td>20.0</td>
</tr>
<tr>
<td>400</td>
<td>62.9</td>
<td>-4.8</td>
<td>58.1</td>
</tr>
<tr>
<td>500</td>
<td>25.6</td>
<td>-3.2</td>
<td>22.4</td>
</tr>
<tr>
<td>630</td>
<td>34.9</td>
<td>-1.9</td>
<td>33.0</td>
</tr>
<tr>
<td>800</td>
<td>58.0</td>
<td>-0.8</td>
<td>57.2</td>
</tr>
<tr>
<td>1,000</td>
<td>29.8</td>
<td>0.0</td>
<td>29.8</td>
</tr>
<tr>
<td>1,250</td>
<td>44.9</td>
<td>0.6</td>
<td>45.5</td>
</tr>
<tr>
<td>1,600</td>
<td>30.7</td>
<td>1.0</td>
<td>31.7</td>
</tr>
<tr>
<td>2,000</td>
<td>-20.9</td>
<td>1.2</td>
<td>-19.7</td>
</tr>
<tr>
<td>2,500</td>
<td>-43.1</td>
<td>1.3</td>
<td>-41.8</td>
</tr>
<tr>
<td>3,150</td>
<td>-80.3</td>
<td>1.2</td>
<td>-79.1</td>
</tr>
<tr>
<td>4,000</td>
<td>-68.9</td>
<td>1.0</td>
<td>-67.9</td>
</tr>
<tr>
<td>5,000</td>
<td>-80.3</td>
<td>0.5</td>
<td>-79.8</td>
</tr>
<tr>
<td>6,300</td>
<td>-114.4</td>
<td>-0.1</td>
<td>-114.5</td>
</tr>
<tr>
<td>8,000</td>
<td>-132.5</td>
<td>-1.1</td>
<td>-133.6</td>
</tr>
<tr>
<td>10,000</td>
<td>-139.5</td>
<td>-2.5</td>
<td>-142.0</td>
</tr>
<tr>
<td>12,500</td>
<td>-156.2</td>
<td>-4.3</td>
<td>-160.5</td>
</tr>
<tr>
<td>16,000</td>
<td>-129.0</td>
<td>-6.6</td>
<td>-135.6</td>
</tr>
<tr>
<td>20,000</td>
<td>-147.1</td>
<td>-9.3</td>
<td>-156.4</td>
</tr>
</tbody>
</table>

69.3