Human-Induced Vibrations in Timber Floor Systems

Master Thesis

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Abstract

This thesis focuses on the vibration performance of timber floor systems. The timber floor systems is becoming increasingly popular in the construction sector. However, these floor systems face challenges regarding vibration performance due to their low self-weight. To solve these problems, ballast is added to the floor system. This results in significantly more material usage for the floor system. Therefore, the goal of this research is to reduce the ballast in a floor system, while maintaining the desired level of vibration performance. The research is divided into three different phases: literature study, analytical analysis, and numerical analysis. The latter phase includes the analysis of the proposed ballast optimisations.

The literature research focuses on the behaviour of timber floors during vibrations. This also includes the human perception aspect of vibrations. The literature research also focuses on the OS-RMS$_{90}$ method, which is a commonly used assessment method for vibrations in floors. This method is used throughout the research.

During the analytical analysis a research is performed on the vibration performance of four different timber floor systems: Joist, Cross Laminated Timber (CLT), Lignatur, and Kerto Ripa Rib. This research is done following the OS-RMS$_{90}$ method. Based on this analysis, it is clear that the CLT and Lignatur floor systems outperform the Joist and Kerto Ripa floors in terms of vibration performance. This can be explained by their higher self-weight and higher transverse stiffness. The Lignatur floor system was chosen for the optimisation methods, due to its performance and the possibility to apply ballast inside the floor elements.

The numerical analysis is divided into two parts. The first part is the validation of the model with respect to the analytical analysis. The numerical model yields the same results as the analytical analysis. The only found difference was the reduced stiffness of the numerical model due to shear deformations.

The second part is a study on the ballast optimisations proposed for the floor system. The optimisation using strategically placed mass shows that the ballast on the floor can be reduced by 36% for a Lignatur floor system. A change in span, damping, or function does not influence the ability to reduce ballast. A change in width does allow a higher reduction in ballast, yielding reduction values up to 70%. When placing the ballast on top of a spring system, a total reduction in ballast of 50% is possible for the floor system. When combining both optimisation methods, a reduction in mass of 52% is possible.

Implementation of these options shows that there are limitations to the reduction in mass. The space that is needed inside the Lignatur floor element often exceeds the available space. To solve this issue, a lower concentration of ballast needs to be used. When accounting for these issues, a reduction of 33% is possible for the strategically placed mass. For the ballast placed on springs, a reduction of 25% is possible.

Preface

Innovative Structural Design has always had my interests during my studies. For this reason I was immediately interested by the RESED (Resource Efficient Structural Engineering and Design) group of ir. A.P.H.W. (Arjan) Habraken. A discussion on the subject for the graduation project led to the subject of human-induced vibrations in timber floors. This subject is relatively new in the RESED group and therefore has a lot of research potential.

I would like to thank me supervisors for their support and feedback during the graduation project. In particularly, ir. A.P.H.W. Habraken for his knowledge on optimising structures and his enthusiasm for the project during the whole process. At the beginning of the project we were not sure where the project would end due to the fact that subject was relatively new. However, during the process we created a clear picture of what we wanted to achieve. I would also like to thank dr. ir. S.P.G. (Faas) Moonen for his general knowledge and feedback. And lastly, I would like to thank dr. ir. S. (Susanne) Bron-van der Jagt for her expertise on the subject of vibrations.

Thijmen van de Goor

Veldhoven, July 2024

Contents

1 Introduction

1.1 Problem Definition

When it comes to construction, timber is highly in demand. The reasons behind its soaring popularity are threefold: timber presents a range of ecological, economical, and practical perks that other building materials cannot rival [3]. This trend can also be observed in the use of floor systems. An increasing variety of timber floor systems are being developed and used in buildings. Floor structures are designed to meet the ultimate limit-state and serviceability limit state criteria. Ultimate limit-state criteria are related to strength and stability, while serviceability limit state criteria are related to comfort [10].

Human-induced vibrations are a serviceability problem when looking at the structural design of floors. For heavy floors, which typically use concrete as a deck, vibrations produced by humans are generally less noticeable. For timber floor structures, the vibration response is relatively high. This can be explained by the fact that the amplitude of the response is inversely proportional to the self-weight of the structure being vibrated. This causes an issue for timber floors, due to the low self-weight of the floors [12].

Humans sense low-frequency vibrations in three ways: acceleration, visual cues, and audio cues. Since vibration in floors is a serviceability problem, it is difficult to set a limit on the amount of vibration that is accepted. Different persons experience different feelings concerning vibrations. In general, people are more susceptible to low frequencies. On the other hand, the activity of the person experiencing the vibration is important. When a person walks across a floor, he or she will tolerate much larger amplitude vibrations than when sitting or lying down [20]. Therefore, buildings that are most problematic concerning vibrations are residential buildings and offices.

Human-induced vibrations are mainly based on walking vibrations in buildings. Walking frequencies are around 2,0 Hz. This means that floors with a low fundamental frequency are more susceptible to resonance. This is the case for floors with a frequency around 2,0 Hz, but, also the 2nd, 3rd, and 4th harmonic frequencies can cause problems with resonance. The walking frequency, however, is a variable, because of that floor systems should be tested for a range of walking frequencies. The same goes for the weight of the person walking on the floor. The weight of a person and the walking frequency are not found to be in correlation [12].

At the moment, vibration problems are mostly solved by over-dimensioning the structure of timber floors. The two parameters, fundamental frequency and modal mass mainly control vibrations. Increasing the frequency reduces the sensitivity of vibrations. As a solution, the floor is often constructed with larger structural elements to address this issue. The result is using more material in order to meet serviceability requirements. The same goes for the modal mass, a higher modal mass decreases the amplitude of the vibrations. Additional mass is added to structures, resulting in larger structural elements to accommodate the mass. In this way, more materials are used to build the floor structures.

1.2 Objective

The goal of this research is to get more knowledge on vibrations in different types of timber floor systems. With the knowledge obtained, the objective is to search for solutions that decrease the material usage of the floors, while maintaining the same vibration levels. In general, two solutions will be addressed. The first is the strategic placement of mass on and/or in the floor structure. The second is the use of springs under the ballast situated on and/or in the floor structure. The following research question is formulated:

"Can the placement of strategic mass and/or the appliance of spring and tuned mass dampers, be used to improve the serviceability performance of timber floor systems in residential or office buildings, with regards to human-induced vibrations?"

Alongside the research question, there are several sub-questions to elaborate on the subject:

- *What are different timber floor systems and what are their characteristics?*
- *What do humans experience regarding vibrations in floors?*
- *What type of vibrations are caused by humans on floors?*
- *What influences the vibrational performance of floors?*
- *Can strategically placed mass be used to improve the vibrational performance?*
- *What effect can tuned mass and damping have on vibrations in timber floors?*

1.3 Outline Thesis

The thesis consists of three parts. The first part is the literature research. This phase is used to obtain more knowledge about vibrations. With a focus on the following subjects: Vibrations in general, Human-induced vibrations, Human perception, Vibrations in floors, and the OS-RMS$_{90}$ calculation method.

The second part of the research will be based on an analytical analysis of several different timber floor systems. The goal of this part is to create a database, with all information needed to assess the vibration performance of different commonly used types of timber floor systems. From this, a floor system can be chosen to use for the optimisations.

The third part will consist of creating a 3D Finite Element modelling (FEM) model. The timber floor system chosen in the second part will be modelled in GSA. This model will be used to research the vibration performance of the proposed optimisations that are applied to the floor. This is done by performing a study on the different parameters of the floor. Finally, the practical implementation of these optimisations will be researched.

The thesis is finalized with a conclusion and a recommendation. At the end of the thesis, the references and the appendices are found.

2 Literature

2.1 Vibrations

A vibration can be described as a periodic back-and-forth motion of particles in an elastic body or medium, resulting when almost any physical system is displaced from the equilibrium condition and allowed to respond to the forces that restore equilibrium [8].

A vibration system stores two types of energy. The structure itself stores potential energy due to the stiffness of the structure. This can be seen as a spring. The kinetic energy is stored in the mass and the inertia of the system during a vibration. When the system is damped, energy is lost during the vibration. During a vibration, an energy transfer takes place from potential energy to kinetic energy and vice versa. The damping of the structure dissipates a part of the energy at each vibration cycle [22].

Mechanical vibration, the vibration type of interest, can be categorized into two types. Firstly, there is free vibration; a system can vibrate without the initial force still acting on the system. Secondly, the system is in vibration due to a continuously acting force on the system, so-called forced vibration [27].

The free vibration response of a structure occurs when an initial excitation (typically an imposed force or displacement) disturbs the system from an equilibrium state, and is then allowed to vibrate freely. In the ideal conditions of linear stiffness and no damping, this movement is sinusoidal and characterized by two parameters: the amplitude of the peak response (displacement, velocity, or acceleration) and the amount of time between peaks (the natural period of vibration), T_n. The inverse of the natural period is the natural frequency of vibration ($f_n = 1/T_n$). To illustrate undamped free vibration, consider a single degree of freedom (SDOF) dynamic system with a mass (M) and spring with stiffness (K). If this system is acted on by an impulsive load or displacement, the system will oscillate around its equilibrium point [4]. An illustration of a SDOF vibration can be seen in Figure 1.

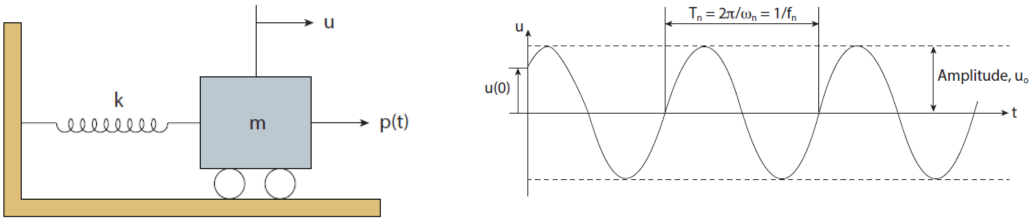


Figure 1: Single degree of freedom vibration [4]

2.2 Human-Induced Vibrations

When looking at vibrations in floor systems, the main source of vibration is human-induced. This includes all movements of humans acting on the floor system, such as walking, running, jumping, etc. For residential and office buildings, the key movement is walking. Therefore, a focus on human-induced vibrations due to walking was chosen for this research.

Walking differs from running as one foot keeps continuous contact with the ground while the other foot moves. The movement can be described by the time history of walking-induced contact forces [12]. The forces depend upon many factors, the characteristics of the person or persons, the number of people, and the activity being undertaken. While the focus is solely on walking-induced vibrations, there still is a wide range of walking characteristics that need to be addressed. Walking characteristics are measured and shown in Table 1 [13].

Activity	Pacing frequency f (Hz)	Speed V (m/s)	Stride length L (m)
Slow walk	1.7	1.1	0.60
Normal walk	2.0	1.5	0.75
Fast walk	2.3	2.2	1.00

Table 1: Data on walking [12]

The movement of a single leg is illustrated in Figure 2. The following phases can be determined for a walking motion:

1 The right foot touches the ground with the heel. This is the starting point of the contact forces.

2 The right leg is stretched; it transmits the full body weight.

3 Rocking: the right foot rocks while the left leg swings forward.

4 The left foot touches the ground while the right leg swings forward [9]

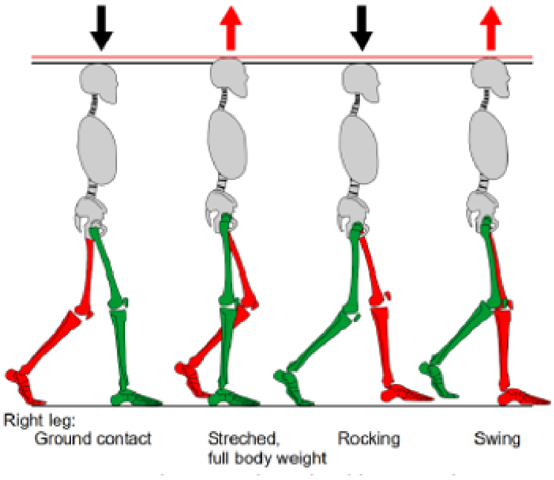


Figure 2: Movement of a single leg during walking [12]

Because of the repeated nature of the contact forces on the floor, it is possible to consider the walking load as a periodic function with a period, T, equal to the inverse of the step frequency, f$_s$:

$$T = \frac{1}{fs} \tag{1}$$

A standard walking load is defined as a series of consecutive steps whereby each step load, also called a footfall, is described by a polynomial [12]. The normalized step load is given by:

$$Sn(t) = \frac{S(t)}{G} = \begin{cases} \sum_{i=1}^{8} K_i t^i, & 0 \leq t < t_s \\ 0, & t < 0; t \geq t_s \end{cases} \tag{2}$$

Where G is the mass of the person and t_s is the total time during which one foot is in contact with the ground. The coefficients K1 to K8 depend on the step frequency, f$_s$, and are given in Table 2. The duration of a single step t$_s$, is given by the following formula: [12] [9]

$$t_s = 2.6606 - 1.757 \cdot f_s + 0.3844 \cdot f_s^2 \tag{3}$$

	$f_s \leq 1.75$	$1.75 < f_s < 2$	$f_s \geq 2$
K_1	-8 x f_s + 38	24 x f_s - 18	75 x f_s - 120.4
K_2	376 x f_s - 844	-404 x f_s + 521	-1720 x f_s - 3153
K_3	-2804 x f_s + 6025	4224 x f_s - 6274	17055 x f_s - 31936
K_4	6308 x f_s - 16573	-29144 x f_s + 45468	-94265 x f_s + 175710
K_5	1732 x f_s + 13619	109976 x f_s - 175808	298940 x f_s - 553736
K_6	-24648 x f_s + 16045	-217424 x f_s + 353403	-529390 x f_s + 977335
K_7	31836 x f_s - 33614	212776 x f_s - 350259	481665 x f_s - 888037
K_8	-12948 x f_s + 15532	-81572 x f_s + 135624	-174265 x f_s + 321008

Table 2: K coefficients [12]

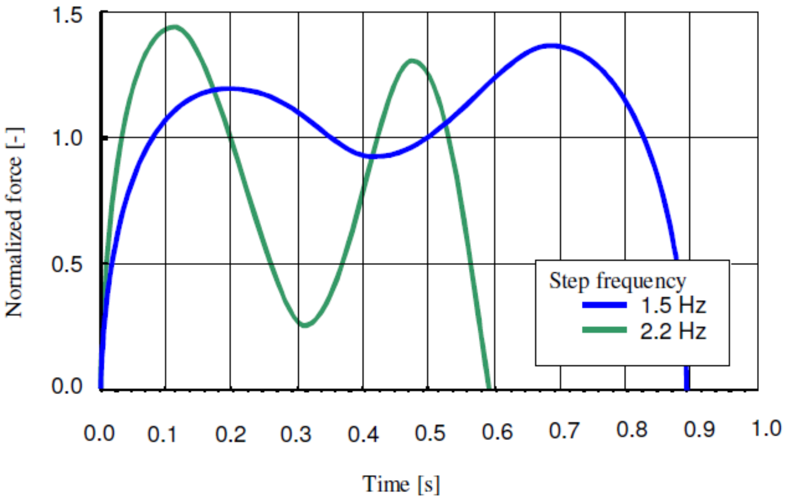


Figure 3: Force-time diagram for different step frequencies [12]

2.3 Human Perception

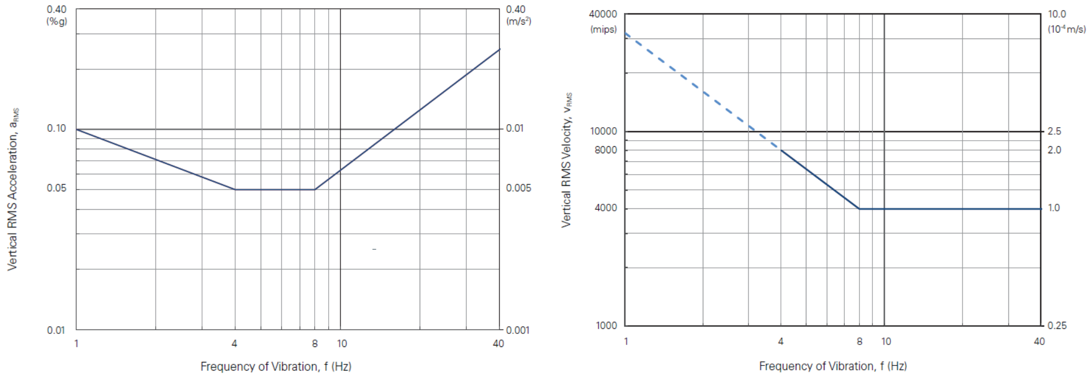
The human perception of vibrations presents a vital aspect in the research of vibrations in floor systems. Vibration is almost always a serviceability problem, meaning that it is based on the comfort of the users. The response of humans to vibrations is highly subjective and difficult to quantify. The main parameters that influence vibration response are the direction, amplitude, frequency, duration, orientation and the activity of the observer. Because floor vibration problems occur in the vertical direction, the main focus is on the vertical motion normal to the floor plane [4]. As an example, human sensitivities to horizontal vibrations are important for wind-induced vibrations on tall structures.

In buildings and other engineered structures, humans sense low-frequency motions in three ways:

- Acceleration causes forces on the body that are felt by the balance organs.
- Visual cues (movement of the structure relative to fixed objects).
- Audio cues (creaking or rattling created by the movement of the structure).

In some situations, the person experiencing the vibration is also the source of the vibration. In other situations, it is the activities of other users that are the source of the vibration. A person walking on a floor will tolerate much larger amplitudes than a person sitting or lying down. Therefore, human perception of vibrations needs to include the activity of the user and the relation between the source and the receiver [20]. Next to that, for a short-lasting vibration, a larger amplitude is tolerated compared to a long-lasting vibration.

The amplitude of vibration has the largest impact on perception. The baseline Root Mean Square (RMS) acceleration perceptible by humans is 0,0005*g (0,05% g). Humans are not able to perceive small changes in amplitude; the vibration amplitude often has to be doubled before the change is perceived [4].



(a) Acceleration

(b) Velocity

Figure 4: Human limits of perception for acceleration and velocity [4]

Human sensitivity to vibration also depends on the frequency at which it occurs. Vibrations in the vertical direction are best felt between a frequency of 4 and 8

Hz; these frequencies are in line with the frequencies people feel in their gut [4]. To account for this sensibility, a weighting curve is applied to the baseline RMS acceleration. The resulting curve can be seen in Figure 4a. Accelerations below this curve are generally not perceptible for humans. Next to acceleration, velocity can also be used to measure human perception. As for acceleration, it depends on the frequency of the vibration. The perception of velocity is assumed to be constant above a frequency of 8 Hz, with an RMS velocity of 0,001 m/s. This RMS velocity increases proportionally with frequencies under 8 Hz. The adapted curve for velocity perception is shown in the right graph of Figure 4b [4].

From Figure 4, it can be seen that there are two frequency ranges where the sensitivity for humans is constant. Between 4 and 8 Hz for acceleration and above 8 Hz for velocity. These frequency ranges can be used to determine which measurement is more suitable to assess floor performance. Acceleration is typically used to assess low-frequency floors, with a fundamental frequency under 8 Hz. Velocity is used for high-frequency floors, with a fundamental frequency above 8 Hz. For both situations, the frequency weighting curves can be used to define limits on vibrations.

2.4 Vibration in Floors

To analyse the vibration performance of a specific floor system, the first step is to determine the floor characteristics, particularly the dynamic properties of the floor. The following three dynamic properties are key properties during vibrations:

- The eigenfrequency
- The modal mass
- The damping value

2.4.1 Eigenfrequency

The eigenfrequencies, which can also be called natural frequencies, are certain frequencies at which a system is prone to vibrate. When a structure vibrates at a certain frequency, similar to its eigenfrequency, the system changes shape. This shape is called the eigenmode. The lowest eigenfrequency of a system is called the fundamental frequency. The fundamental frequency is also the first harmonic of the system [6].

Two types of vibrations can be observed, due to a person walking on the floor:

- Transient vibrations immediately following a single footfall
- Resonant vibrations resulting from the build-up of multiple footfalls

The two types of vibrations can be seen in Figure 5. Whether transient or resonant vibration is governing depends on the fundamental frequency of the floor. Walking frequencies commonly occur in the range of 1,7 to 2,3 Hz (Table 1). The fundamental frequency of the floor system is the primary determinant for the response of the floor concerning the vibration type. Fundamental frequencies of floors are in the range of 3 Hz to over 20 Hz [4].

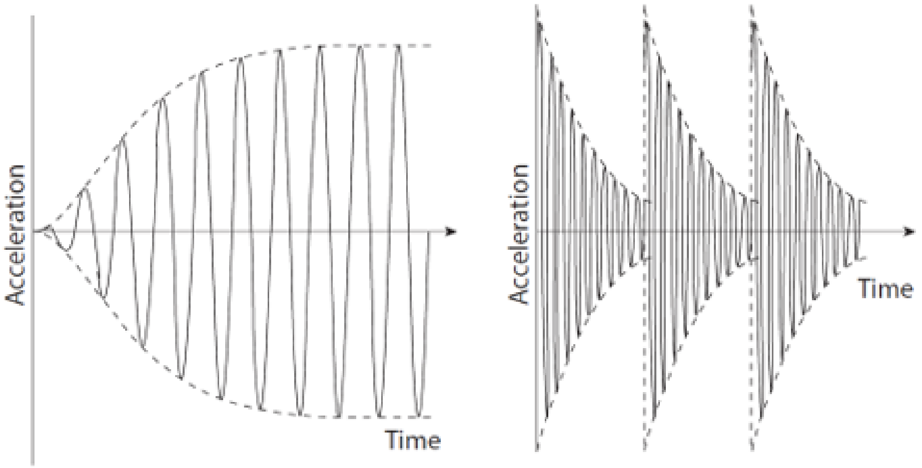


Figure 5: Transient and Resonant floor response respectively [4]

A resonant response will be more perceptible than any transient response that occurs on the floor. Therefore, the elimination of possible resonant build-up in the floor is a key aspect. Resonance takes place when the excitation frequency is similar to or close to the fundamental frequency of the floor system. It can also appear at higher natural frequencies, however, then the impact will be lower. Walking frequencies consist of several frequencies instead of a single frequency. Resonance can occur when the fundamental frequency of a floor system is harmonic with one or more walking frequencies acting on the floor. The harmonic frequencies of an excitation frequency are the integer multiples of the walking frequency. For example, if the walking frequency is 2 Hz, the second, third, and fourth harmonics of the walking frequency are respectively 4, 6, and 8 Hz. Due to this, a floor structure with a natural frequency near 4, 6, or 8 Hz may be prone to resonance when subjected to a walking frequency of 2 Hz. The magnitude of resonance decreases at higher harmonics. Beyond the fourth harmonic of the walking frequency, the resonant build-up of a structure will generally be small and damped out between two excitations. Floors with a fundamental frequency lower than the fourth harmonic frequency are called low-frequency floor systems and need to be assessed on the effects of resonant vibrations [4].

2.4.2 Modal Mass

The modal mass is the mass activated in a specific mode shape [10]. Therefore, the modal mass states how much of the total floor mass contributes to the vibrational performance of the floor system. The modal mass changes for each mode shape of the floor system. Thus, the amount of modal mass on a floor system is strongly dependent on the mode shape. An example of different mode shapes for a simply supported beam can be seen in Figure 6. The mode shape itself depends on the number of supports present in the floor system [23]. Next to the number of supports, also the type of support is important; a distinction needs to be made between hinged and fixed supports.

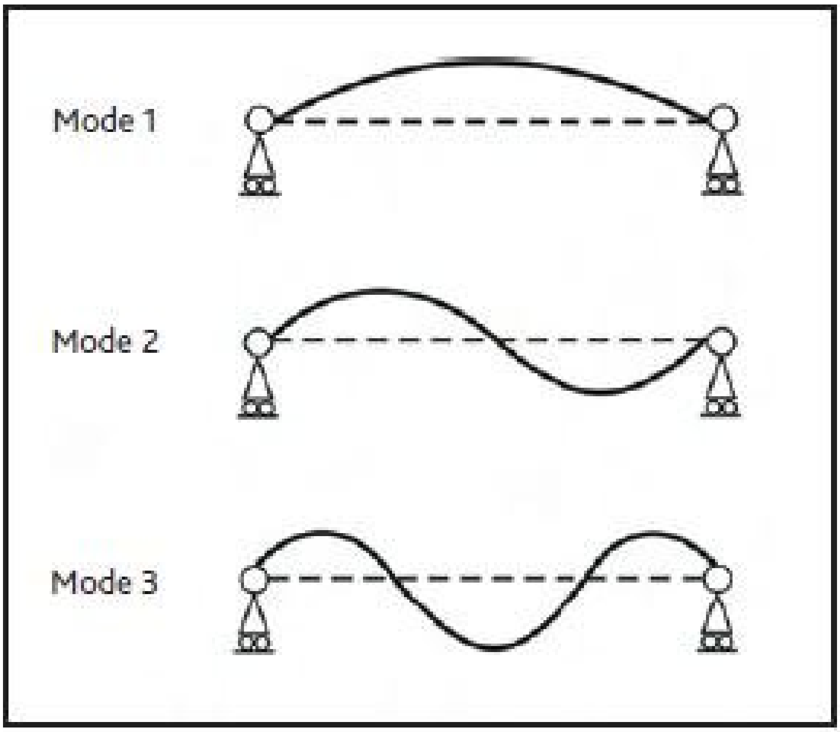


Figure 6: Mode shapes of a simply supported beam [23]

The modal mass has a positive impact on the vibrational performance of floor systems. The ratio between the mass of the exciter to the mass of the excited floor is a key parameter for the dynamic response of a floor system. The sensitivity to floor vibrations increases with increasing ratio of exciter mass and floor mass. The exciter mass is the mass of a person walking on the floor. The excited mass is defined as the modal mass of the floor [16]. A higher amount of excited mass means that there is more energy needed to move the floor system, resulting in a lower amplitude for the vibration.

2.4.3 Damping

Damping is the reduction in the amplitude of a vibration, because of energy being dissipated. There are three types of damping for a mechanical system. These types are illustrated in Figure 7. An overdamped system will not have a form of vibration, meaning there is no negative deflection. A critically damped system is a system that is on the border of oscillation; any decay in damping would create a vibration. An underdamped system is a system where vibrations are present and the system dissipates energy over multiple oscillations.

Damping has a high impact on the human perception of vibration in a floor system. Damping belongs to the property of a structural system that influences oscillation amplitudes and the rate of decay under forced and free vibrations, respectively. This means that the level of damping of a floor system is a key aspect for structural designers, while vibrations are more tolerable for floor systems with a higher damping value [12].

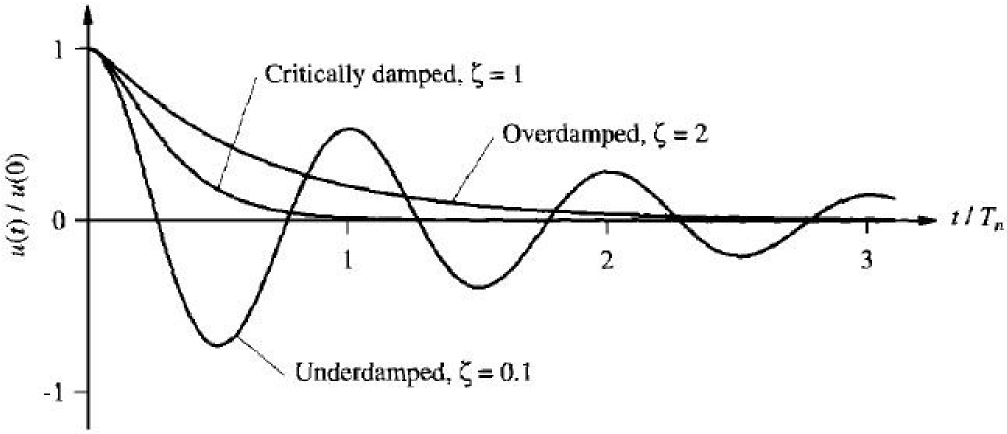


Figure 7: Damping ratio [25]

The total damping value of a floor system depends on the sum of three separate damping values. First, the structural material of the floor. This type of damping comes from inner friction within the floor structure or from connections of the floor to other structural components such as supports. The second damping value is due to furniture and other equipment on the floor. While the last damping value comes from permanent installations and finishing of the floor [9]. The damping values are presented as a percentage of the critical damping value. Values can be found for different types of structural materials, furniture, and finishings in Table 3.

2.4.4 Timber Floors

Timber floor systems are in general lightweight floor systems in comparison to steel/concrete floors. For lightweight floor structures like timber floors, the vibration response is high. This can be explained by the fact that amplitudes of response are inversely proportional to the self-weight of the structure being vibrated [12].

Timber has a high strength-to-weight ratio, with relatively high stiffness. However, this is not desirable for vibration control of floors. Common practice is to use larger dimensions for the structural elements of the timber floor systems. Next to that, ballast can be added on top of the floor structure to increase the modal mass. This could, for example, be a layer of cement. These types of measures have to be taken to comply with the vibration performance criteria.

2.5 OS-RMS$_{90}$

The OS-RMS$_{90}$ is a method to determine the floor response values for vertical vibrations. This method is presented in the HiVoSS Guideline and stems from the ECSC research project ”Vibration of Floors” [17]. OS-RMS$_{90}$ stands for the One-Step Root-Mean-Square value larger than the 90% fractile of people walking on the floor. The response value of a floor system depends on the fundamental frequency, the modal mass, and the damping of the floor [1]. The OS-RMS$_{90}$ method is well-known and used in the building industry to assess the vibrational performance of floors.

Type	Damping (% of critical damping)
Structural damping D_1	
Wood	6%
Concrete	2%
Steel	1%
Composite (Steel-Concrete	1%
Damping due to furniture D_2	
Traditional office with separation walls	2%
Paperless office	0%
Open plan office	1%
Library	1%
Residential	1%
Schools	0%
Gymnastics rooms	0%
Damping due to finishes D_3	
Ceiling under the floor	1%
Free-floating floor	0%
Swimming screed	1%
Total damping $D = D_1 + D_2 + D_3$	

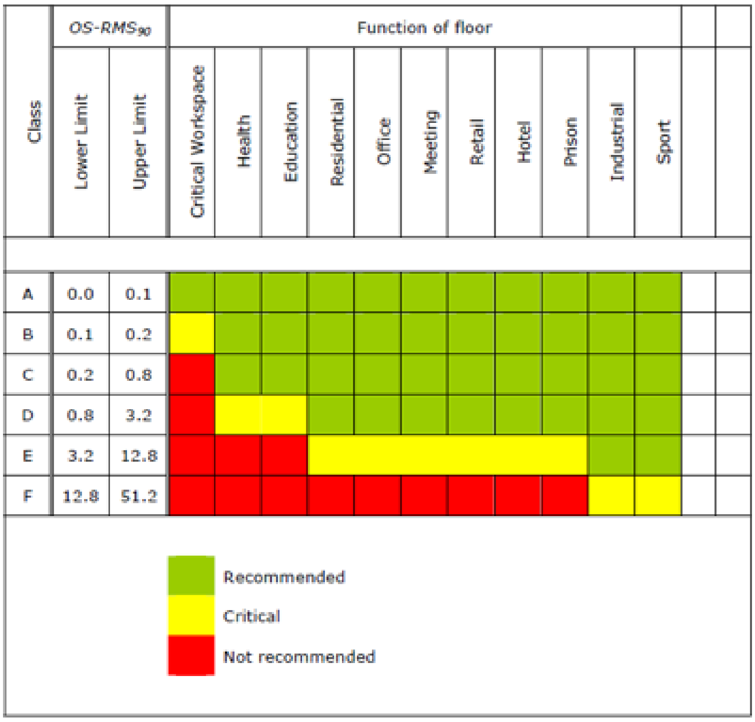
Table 3: Damping values [16]

2.5.1 Response Classes

The response value obtained from the assessment fits into one of the 6 response classes, A to F. The response classes have an upper and lower bound concerning the response value of the OS-RMS$_{90}$ method and can be seen in Figure 8. Since the perception of vibrations is dependent on the activities carried out by users, different building functions are assigned different recommended floor response classes [12]. The goal of the method is to design a floor system where human-induced floor vibrations do not cause comfort issues for users.

2.5.2 Loading Probability

In the OS-RMS$_{90}$ method, the loading on the floor is a statistical distribution. Persons walking on the floor have different masses and walking frequencies. This influences the load on the floor system. Information on the statistical distributions of walking frequencies f_s and body weights G of persons is obtained by measurements. These measurements for the step frequencies were carried out in the entrance area of the TNO building in Delft. The step frequency for 700 people was measured. The distribution of step frequencies was correlated with the distribution of body mass, as published for Europe, assuming statistical independence between the step frequency and the body mass of a person [9]. Figure 9 gives the distribution of step frequencies and body mass, and in Appendix A.1 the associated cumulative distributions can be found.



Class	$OS\text{-}RMS_{90}$		Function of floor												
	Lower Limit	Upper Limit	Critical Workspace	Health	Education	Residential	Office	Meeting	Retail	Hotel	Prison	Industrial	Sport		
A	0.0	0.1	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩		
B	0.1	0.2	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩		
C	0.2	0.8	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩		
D	0.8	3.2	🟥	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩		
E	3.2	12.8	🟥	🟥	🟥	🟨	🟨	🟨	🟨	🟨	🟨	🟩	🟩		
F	12.8	51.2	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟨		

🟩 Recommended
🟨 Critical
🟥 Not recommended

Figure 8: Response classes [12]

2.5.3 RMS-Value

The peak value of a measurement is often used for analysis. However, judgments of performance based on peak values can sometimes be misleading, since the peak value does not consider response duration or decay. A peak value can also be a result of a specific event that is normally not experienced by a typical user [9]. The peak values of a measurement can be used in situations where the response of a floor is resonance-governed. In this situation, the response of a single step will not be governing compared to the resonant build-up of multiple steps.

The Root Mean Square (RMS) is a technique that accounts for changes in amplitude over time and can be applied to both transient and resonant vibration problems. An RMS value is a weighted average of a sample over a specific period. The value can be defined in the following way for both velocity and acceleration: [9]

$$v_{rms} = \sqrt{1/T \int_T^0 v(t)^2 \, dt} \tag{4}$$

$$a_{rms} = \sqrt{1/T \int_T^0 a(t)^2 \, dt} \tag{5}$$

The RMS value over a period will always be lower than the peak value. For example, the RMS of a pure sinusoidal response is $1/\sqrt{2}$ which is approximately 71% times the peak response. The RMS response value is sensitive to the sampling period [9].

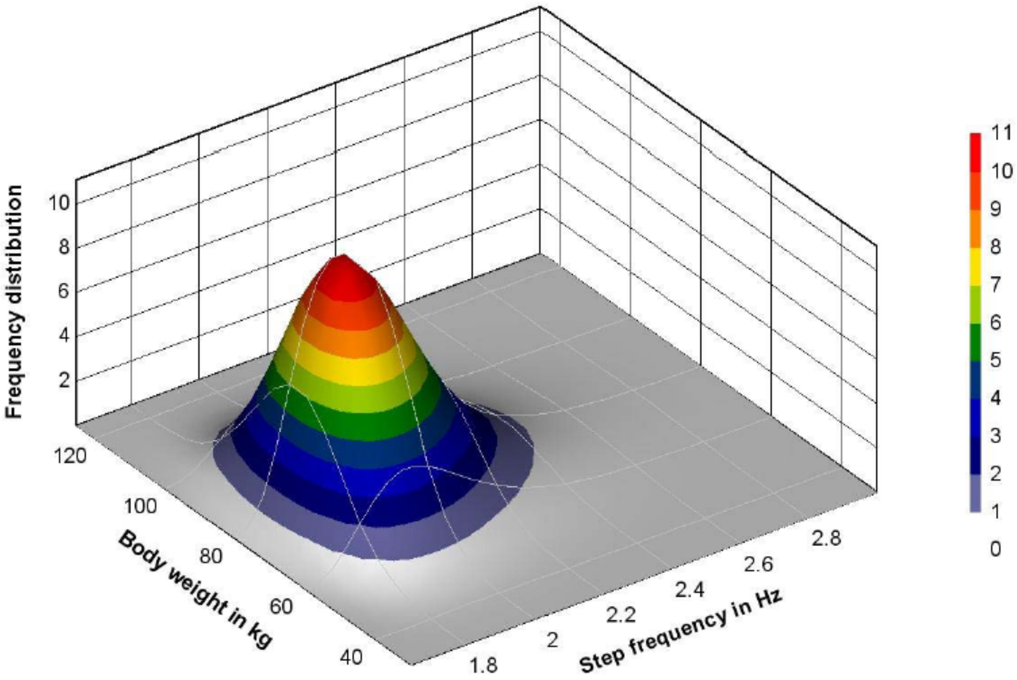


Figure 9: Frequency distribution of body mass and step frequency for a population data of 700 [12]

2.5.4 Design Diagram

The hand calculation method of the OS-RMS$_{90}$ can be described in three steps; these steps can be seen in Figure 10. The OS-RMS$_{90}$ value can be obtained from design diagrams. These diagrams are based on natural frequency, modal mass, and damping. The range of the y-axis is between 0 and 20 Hz for the natural frequency. For the x-axis, there is a range between 100 and 100.000 kg for the modal mass. In total, there are nine different graphs for each of the damping ratios, ranging from 1% to 9%. From the diagrams, the floor response can be read off regarding the OS-RMS$_{90}$ value. With coloured ranges, the corresponding floor response classes are indicated. The design graphs can be found in Appendix A.2.

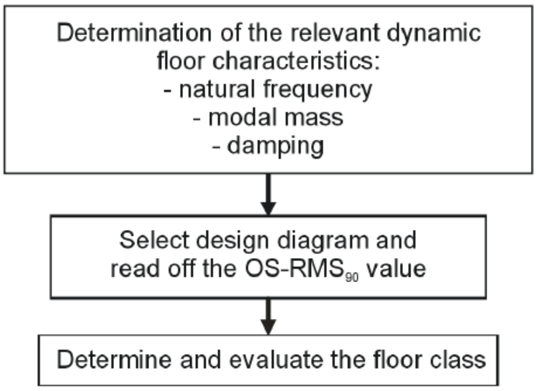


Figure 10: Design steps hand calculation [12]

3 Analytical Analysis

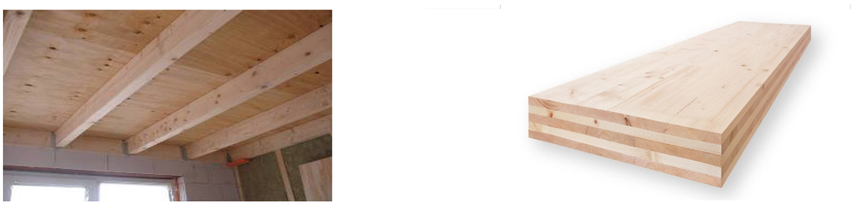
The analytical analysis is the first part of the vibration analysis. This analysis consists of hand calculations based on the OS-RMS$_{90}$ method. The goal of this analysis is to find the difference in structural height for a floor designed with and without vibration requirements. For this analysis, four different timber floor systems will be analysed. The analytical part will also be used to validate the numerical results and give more insights into the vibrational behaviour of timber floors.

3.1 Floor Systems

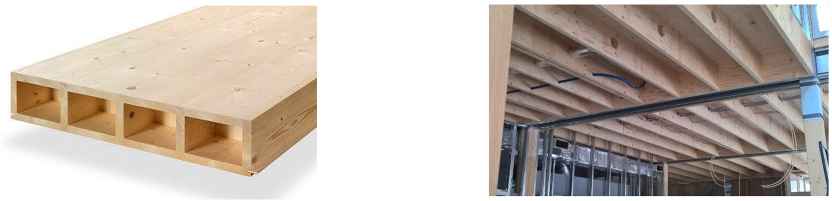
An analytical analysis will be performed on four types of timber floor systems found in residential and office buildings. These floor systems have vastly different characteristics. The results of the different floor systems can be used to assess the influence of different aspects on vibrations.

The finishing of the floor systems will not be described specifically. A predetermined mass per square meter will be taken as constant for the finishing layer of the floors. This incorporates the standard buildup of a floor. For the analytical analysis, a permanent load of 50 kg/m^2 is taken on top of the floor.

For the live load, a difference will be made between the two building functions. The floors in a residential building will have a live load of 175 kg/m^2, while the office building will have a live load of 250 kg/m^2. For a vibration analysis, only 20% of the live load may be used, because the live load acts favourably for the vibration analysis. It cannot be assumed that the live load will always be present on the structure, therefore a reduction is applied. For the ULS+deflection analysis, the full live load will be considered [16].



(a) Joist floor [19]   (b) CLT floor [24]



(c) Lignatur floor [26]   (d) Kerto Ripa Rib floor [2]

Figure 11: Timber floor systems

3.1.1 Joist floor

A joist floor is a lightweight timber floor system, with joists of solid structural timber and timber sheeting on top of these joists. The quality of timber used for this floor is C24. The joists have a wide range of dimensions. These standardized dimensions can be seen in Appendix B.3.1. A centre-to-centre distance of 610 mm is taken for the joists. The sheeting thickness for this floor will be 18 mm. The sheeting is connected to the joists by screws. This type of floor structure is normally found in single-family houses and typically spans up to 5 meters. The properties of C24 timber can be found in Appendix B.1.

3.1.2 CLT

Cross-laminated timber (CLT) is a mass timber floor system. The timber chosen for the analytical analysis has the timber quality C24. CLT floors can span up to 6 meters and are typically used in residential buildings and offices. A CLT floor has a relatively high transverse stiffness. CLT floor panels can be built up with numerous possibilities, regarding the number of layers, their orientation, and their thickness. For the analytical analysis, a CLT panel with five equally sized layers is chosen. For this panel, three layers are orientated in the longitudinal direction, while the other two layers are oriented in the transverse direction. Appendix B.3.2 shows the standardized dimensions of the CLT used in the analytical analysis [14].

3.1.3 Lignatur

Lignatur is a company that designs timber floor systems. A Lignatur floor system consists of box elements, With this box structure, different floor systems are created. For the analytical analysis, an LFE Lignatur floor is chosen. This floor system consists of a top and bottom plate with five ribs in between these plates. These elements have a width of one meter. An LFE system is typically used in residential and office buildings and can span up to 9 meters. For the analysis, timber with quality C24 is chosen for the Lignatur floor. In Appendix B.3.3 the standardized dimensions of a Lignatur LFE floor are shown [26].

3.1.4 Kerto Ripa Rib

Kerto Ripa is a floor system with laminated veneer lumber (LVL). For this analysis, a Kerto Ripa rib floor is chosen. This floor consists of Kerto-S ribs with a top plate of Kerto-Q. The chosen strength class is LVL36, the properties of this class can be seen in Appendix B.2. The floor system can be used for residential and office buildings and can span up to 12 meters. A top plate with a thickness of 25 mm is chosen. The ribs have a centre-to-centre distance of 610 mm. The standardized dimensions of the ribs can be seen in Appendix B.3.4 [11].

3.2 Methods

The following methods are used to calculate the vibrational performance of the timber floor systems based on the OS-RMS$_{90}$ method. This calculation method is explained in 2.5.

3.2.1 Formulae OS-RMS90

3.2.1.1 Natural Frequency

$$f_1 = \frac{\pi}{2l^2}\sqrt{\frac{(EI)_L}{m}} \tag{6}$$

Where:

- f_1 = the natural frequency in Hz
- l = the span of the floor system in m
- EI_L = the bending stiffness in the longitudinal direction in Nm^2
- m = the mass of the floor systems per unit area in kg/m^2

This formula applies to a floor system with a single span in one direction. The supports of the floor system have a hinge on one side and a roller support on the other side. For the floor system, a realistic mass should be used. The realistic mass consists of the permanent loads and 20% of the live loads on the floor.

3.2.1.2 Modal Mass

$$M^* = 0,5\, l\, b_{eff}\, m \tag{7}$$

Where:

- M^* = the modal mass in kg
- b_{eff} = the effective width of the floor in m

$$b_{eff} = \frac{l}{1,1}\frac{EI_T}{EI_L}^{0,25} \tag{8}$$

The effective width is introduced in the formula of the modal mass instead of using the actual width of the floor. By using the actual width of the floor, it is assumed that the whole of the floor is active during a vibration. This is not the case. Human-induced vibrations are caused by a point load. This point load is the foot of the person walking on the floor. This point load only excites a vibration in a specific floor part. The dimensions of the excited area depend on the relation between the transverse stiffness and the longitudinal stiffness of the floor system. This is incorporated in equation 8.

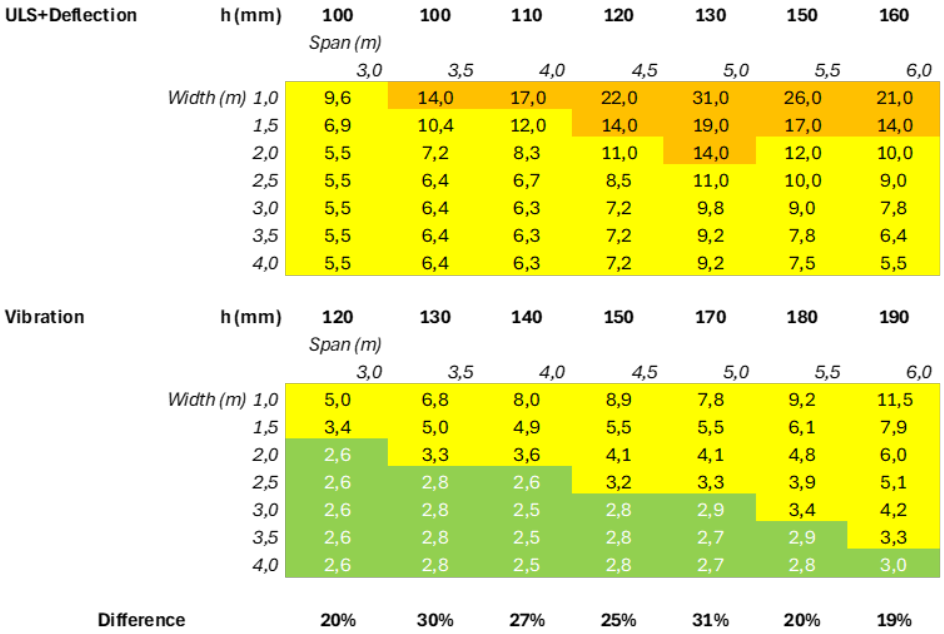
3.2.1.3 Damping

The damping is based on the total damping presented in Table 3. The resulting damping value from that table will determine the OS-RMS$_{90}$ graph that needs to be used for the particular situation.

3.2.2 Analysis

The first step of the analytical analysis is to calculate the minimal structural height needed for the floor system, based on the Ultimate Limit State and the deflection criteria given by Eurocode 5 [18]. As an example, the ULS+Deflection calculations for a Joist floor system can be seen in Appendix E. From this, the structural height of the floor systems will be chosen based on the standardized dimensions for the specific floor system.

The second step is to determine the OS-RMS$_{90}$ value based on the chosen structural dimensions of the floor system. This value is determined for seven spans and seven widths of the floor. All values are presented in a table. An example of this table can be seen in Figure 12.



ULS+Deflection	**h (mm)**	**100**	**100**	**110**	**120**	**130**	**150**	**160**
	Span (m)	*3,0*	*3,5*	*4,0*	*4,5*	*5,0*	*5,5*	*6,0*
	Width (m) 1,0	9,6	14,0	17,0	22,0	31,0	26,0	21,0
	1,5	6,9	10,4	12,0	14,0	19,0	17,0	14,0
	2,0	5,5	7,2	8,3	11,0	14,0	12,0	10,0
	2,5	5,5	6,4	6,7	8,5	11,0	10,0	9,0
	3,0	5,5	6,4	6,3	7,2	9,8	9,0	7,8
	3,5	5,5	6,4	6,3	7,2	9,2	7,8	6,4
	4,0	5,5	6,4	6,3	7,2	9,2	7,5	5,5
Vibration	**h (mm)**	**120**	**130**	**140**	**150**	**170**	**180**	**190**
	Span (m)	*3,0*	*3,5*	*4,0*	*4,5*	*5,0*	*5,5*	*6,0*
	Width (m) 1,0	5,0	6,8	8,0	8,9	7,8	9,2	11,5
	1,5	3,4	5,0	4,9	5,5	5,5	6,1	7,9
	2,0	2,6	3,3	3,6	4,1	4,1	4,8	6,0
	2,5	2,6	2,8	2,6	3,2	3,3	3,9	5,1
	3,0	2,6	2,8	2,5	2,8	2,9	3,4	4,2
	3,5	2,6	2,8	2,5	2,8	2,7	2,9	3,3
	4,0	2,6	2,8	2,5	2,8	2,7	2,8	3,0
Difference		**20%**	**30%**	**27%**	**25%**	**31%**	**20%**	**19%**

Figure 12: OS-RMS$_{90}$ analysis of a CLT floor with a damping of 7%

The next step is to increase the structural height of the floor while keeping the loads on the floor constant until the floor complies with the utility class of the OS-RMS$_{90}$ method. A similar table is created for the new structural height. A comparison can be made between the two structural heights for both situations. The value for the largest width of the floor is taken as the deciding value when determining the vibration class.

The structural height is used as a measuring value for both the CLT and Lignatur floors. However, this value is not representative for the Joist and Kerto Ripa rib floor. For these floors, not only the structural height of the beams is decisive, but also the width of the beams. This is why the measuring value for these floors is the second moment of area, while this takes into account both the height and the width of the beams. The top plate of both these joist floors is practically chosen and will not differ during the analysis.

The analysis will be performed with several ranging parameters. The parameters span and width are already incorporated in the tables. The other parameters are the building function (office or residential) and the damping value of the floor system. For these parameters, different tables are created.

3.2.2.1 Additional Mass

After the analytical analysis for all the floors is completed, the analysis will be performed again. However, this time additional mass will be added to the floors. Using additional mass can decrease acceleration and therefore improve the performance of the floor system. Adding more mass to the floor system decreases the natural frequency of the floor, resulting in a worse vibration performance of the floor. Finding the optimal solution for the floor systems is a balancing act between the natural frequency and the modal mass of the floor system. Therefore, the additional mass will only be applied when it decreases the structural height or second moment of area of the floor.

3.3 Results

The tables of the results for all different floors and parameters can be found in Appendix C.

3.3.1 General Results

From the analytical analysis, some general results not related to the different floor systems can be discovered. The standardized dimensions of the different floor systems influence the RMS value. The structural height is chosen as close as possible to the unity check of 1,0 for the ULS and the deflection. However, due to the standardized dimensions, the floor system sometimes needs an increase in structural height. When a floor has a unity check of 1,01, an increase in structural height is needed, which will result in a unity check of 0,85. This results in a significantly better RMS value for this floor in comparison to a floor with a unity check above 0,95 for example.

For the analysis with additional mass, it can also be observed that floors with additional mass will always have a smaller difference in structural height. Due to more mass, the ULS and deflection calculations will already yield a higher structural height when more mass is added to the floor system, bringing it closer to the structural height optimized for floor vibrations.

3.3.1.1 Joist

The main conclusion that can be drawn from the analytical analysis of the joist floor, is that the vibration performance of these types of floors is low. This can all be put down to the low self-weight of the floor. Due to this low self-weight, the OS-RMS value obtained from the graphs will always be high. When the natural frequency is high, it is still difficult to meet the required vibration class. An increase in the width of the floor also has a marginal effect on the modal mass of the floor. Due to the low transverse stiffness, the effective width is small. This is more pronounced for floors with a larger span. The effective width depends on the relation between the longitudinal and transverse stiffness. For larger spans, longitudinal stiffness will increase. However, the transverse stiffness will be the same because the top plate of the floor structure does not change. For spans of 4 meters or larger, it is not possible to meet the required vibration class with the standardized dimensions of the joist floor.

3.3.1.2 CLT

The performance of the CLT floor is the best, looking at the difference in structural height. This can be explained by the high transverse stiffness of the CLT floors. This allows for a larger effective width, resulting in a higher modal mass. In the tables, this can be seen by the fact that the RMS value decreases when the structural width is increased, even for the larger widths of the floor. The CLT floor also has a high self-weight in comparison to the other three floor systems. This not only results in a higher structural height in the ULS, but it also works positively in the vibration evaluation. This explains the relatively low difference in structural height for CLT floors.

3.3.1.3 Lignatur

The vibration performance of the Lignatur floor system is comparable to the CLT floors. The OS-RMS values for the ULS+deflection analysis are similar for both floors. When optimizing the structural height of the floor systems for the vibration analysis, some differences can be seen for the floor types. Due to the higher self-weight and the larger transverse stiffness, the CLT floors perform better than the Lignatur floors. Resulting in a smaller increase in structural height for the CLT floors. Next to that, the standardized dimensions of the Lignatur floors present some larger jumps in structural height. As a result, less effective optimisation of structural height is possible.

3.3.1.4 Kerto Ripa Rib

The Kerto Ripa Rib floor can be compared to the Joist floor with respect to the vibration performance. There is a wide variety of standardized dimensions for the beams of the Kerto Ripa Rib floor. This means that the floor is always close to a unity check of 1,0. This also allows for an effective optimisation of the second moment of area in the vibration analysis. This also means that the damping has a significant influence on the second moment of area of the floor. An increase in damping leads more often than not to a decrease in cross-section of the beams, due to the wide variety of dimensions. Furthermore, the Kerto Ripa Rib floor can also be optimised regarding vibrations for spans larger than 4 meters, in contrast to the Joist floor. The downside of the Kerto Ripa Rib floor is the usage of LVL. LVL has a higher strength class while maintaining the same material stiffness as C24. This means that a smaller second moment of area can be used in the ULS analysis. The second moment of area cannot be decreased for the vibrations analysis because this analysis is based on the stiffness of the floor system. The result is a larger difference in the second moment of area to reach the required vibration class.

4 Numerical Analysis

For the numerical analysis, a single floor type is chosen from the analytical analysis. This floor type is analysed numerically using Finite Element Modeling (FEM). GSA will be used as FEM software. The chosen floor will create a basic model to apply solutions, which will improve the vibration performance of the floor. To validate the FEM software, a comparison is made between a hand calculation, originating from the analytical analysis, and the values obtained from GSA.

4.1 Floor Choice

The choice of floor system for the numerical analysis is based on two aspects. The first aspect is the vibration performance in the analytical study, the second aspect is the potential to improve the performance of the floor. The analytical analysis shows that the CLT and the Lignatur floor systems perform significantly better than the Joist and Kerto Ripa Rib floors. Due to their higher self-weight and larger transverse stiffness. It is chosen to use the Lignatur floor for the numerical analysis. The Lignatur floor has a higher potential to improve the vibration performance. The box structure of the Lignatur floor allows for the possibility of applying ballast inside the floor system. For a CLT floor, there is only the possibility of applying the ballast on top of the floor. Therefore, the Lignatur floor system will be chosen for the numerical analysis.

4.2 Methods

The following methods are used to validate the numerical model.

4.2.1 Hand Calculation

The results of the footfall analysis in GSA are expressed in acceleration or velocity. For the validation, it is chosen to use the acceleration value, while the floor systems generally have a natural frequency under 8 Hz. Specifically, the acceleration will be expressed as peak acceleration. To validate the GSA results, an elaboration needs to be made on the OS-RMS$_{90}$ method. This is done by calculating the peak acceleration by hand using the methods explained in the next paragraphs. This hand calculation is only used to validate the numerical model.

4.2.1.1 Excitation

The calculation of the peak acceleration concerns a resonant response analysis. This analysis applies to low-frequency floors (where the natural frequency is lower than four times the walking frequency). For a specific walking frequency, a hand calculation starts by calculating, for each mode, a harmonic force, F_h, for the first four harmonics of the walking frequency. F_h is the total excited force applied by the person walking on the floor. F_h is expressed in equation 9, where α_h is the harmonic coefficient presented in Table 4, and P is the static weight of the person walking on the floor.

$$F_h = \alpha_h P \tag{9}$$

Harmonic Number, h	Harmonic Coefficient, α_h
1	$0,41(f_h - 0,95) \leq 0,56$
2	$0,069 + 0,0056 f_h$
3	$0,033 + 0,0064 f_h$
4	$0,013 + 0,0065 f_h$
$h > 4$	0

Table 4: Design value of footfall harmonic coefficients (CCIP-016) [4]

The harmonic loading functions are based on the full steady-state resonant response. However, a steady-state response is not always achieved. Considering the walking path, a person can cross the complete floor before the needed amount of steps for a full steady-state response is reached. CCIP-016 proposes a correction factor, $p_{h,m}$ to account for this effect [4].

$$\rho_{h,m} = 1 - e^{-2\pi\zeta_m N_h} \tag{10}$$

- ζ_m is the modal damping ratio
- N_h is the calculated number of steps:

$$N_h = 0,55h\frac{L}{l} \tag{11}$$

- L is the length of the floor
- l is the stride length

4.2.1.2 Modal Response

With the excitation forces, the resonant acceleration for each mode and harmonic can be calculated. The steady-state acceleration response is at the same frequency as the forcing function, but its magnitude and phase are shifted for each mode of the structure, in comparison to the forcing function. For mathematical convenience, the response is expressed in terms of real and imaginary components of acceleration, instead of magnitude and phase [4].

The following formulae calculate the resonant response accelerations for a given mode and harmonic of the walking frequency:

$$a_{real,h,m} = (\frac{f_h}{f_m})^2 \frac{F_h \mu_{r,m} \mu e, m \rho_{h,m}}{M_m} \frac{A_m}{(A_m^2 + B_m^2)} \tag{12}$$

$$a_{imag,h,m} = (\frac{f_h}{f_m})^2 \frac{F_h \mu_{r,m} \mu e, m \rho_{h,m}}{M_m} \frac{B_m}{(A_m^2 + B_m^2)} \tag{13}$$

Where:

$$A_m = 1 - (\frac{f_h}{f_m})^2 \tag{14}$$

$$B_m = 2\zeta_m \frac{f_h}{f_m} \tag{15}$$

and:

- h is the harmonic number (1 to 4)
- m is the mode number
- f_m is the natural frequency of the mode under consideration
- ζ_m is the modal damping ratio
- M_m is the modal mass
- $\mu_{e,m}$ is the modal amplitude at the excitation location
- $\mu_{r,m}$ is the modal amplitude at the receiver location
- $\rho_{h,m}$ is the correction factor for sub-resonant response

For a single harmonic, the real and imaginary acceleration components are summed separately across all modes considered. The real and imaginary accelerations are then combined to determine the acceleration response for the specific walking frequency harmonic, following equation 16. This acceleration component is calculated for each harmonic [4].

$$a_h = \sqrt{a_{real,h}^2 + a_{imag,h}^2} \tag{16}$$

4.2.1.3 Evaluating Response

To calculate the total peak acceleration of the floor for the specific walking frequency, the acceleration response from the four harmonics needs to be combined using the square root sum of the squares method [4].

As explained in 2.3, human perception is not similar at all frequencies, for this reason, a frequency-weighted peak acceleration needs to be calculated. A corresponding weighting factor is calculated for each harmonic following Table 5. This factor is multiplied by the acceleration for each harmonic:

$$a_{h,fw} = a_h x w_f \tag{17}$$

The peak acceleration for the specific walking frequency can then be calculated by combining all the harmonic responses:

Harmonic frequency	Weighting factor w_f
f_h <4 Hz	$\frac{\sqrt{f_h}}{2}$
4 Hz≤ f_h ≤8 Hz	1
f_h >8 Hz	$\frac{8}{f_h}$

Table 5: Frequency weighting factors [6]

$$a_{peak} = \sqrt{\sum_{n=1}^{4} a_{h,fw}^2} \tag{18}$$

4.2.2 GSA

GSA is a finite element software package developed by Oasys, which is part of Arup. Oasys GSA allows analysis of the structural design of any type of structure. The main choice for the usage of GSA is the ability for a dynamic analysis and response analysis. The dynamic aspect of GSA also has the option of performing a Footfall analysis, which allows for research regarding human-induced vibrations in floors.

4.2.2.1 Modeling Floors

When modelling the Lignatur floor in GSA, there are multiple parameters that need to be considered. Firstly, the support conditions. In the analytical analysis, the supports are hinged on one side of the floor and roller supports on the other side. Secondly, the additional mass on/in the floor needs to be modelled as mass only. The mass should not contribute to the structural performance of the floor. Finally, a Lignatur element has a width of one meter; for floors with a width larger than one meter, multiple Lignatur elements need to be used. In practice, these elements have a hinged connection. This connection will be modelled in GSA by placing small bars between the floor elements. These bars are hinged on one side and fixed on the other side. This creates a vertical connection between the elements and does not transfer any moments.

4.2.2.2 Dynamic Analysis

A dynamic analysis can be performed in GSA. This analysis will yield the different vibration modes of the floor structure. From the different modes, the mode shapes, the frequency, and the modal mass can be obtained. This dynamic analysis is the input for the footfall analysis.

4.2.2.3 Footfall Analysis

The footfall analysis yields multiple values to analyse the performance of the floor: peak acceleration, RMS acceleration, peak velocity, and RMS velocity. Next to that, there is the response factor. The response factor is a factor that indicates the vibration performance of the floor. The response factor combines the acceleration and velocity response from the floor into a single value.

4.3 Results

The results from the dynamic and footfall analysis will be compared to the results of the analytical analysis. This will be done for a residential Lignatur floor with 50 kg/m^2 of permanent mass. The structural height of the floor for the different spans depends on the height chosen in the analytical analysis.

4.3.1 Validation GSA

In the following paragraphs, the comparison is made between the hand calculations and GSA. The comparison will be based on the natural frequency, modal mass, and the peak acceleration values.

4.3.1.1 Natural Frequency

The calculated natural frequencies for both the analytical and numerical analysis can be seen in Figure 13. There is a difference between both methods visible in the graph. The difference between the two methods is consistent for the different spans. An explanation for this difference is the fact that GSA considers the shear deformations of the structure, this is not the case for the hand calculations. Due to this aspect, the frequencies of the numerical analysis are somewhat lower than the frequencies of the analytical calculations.

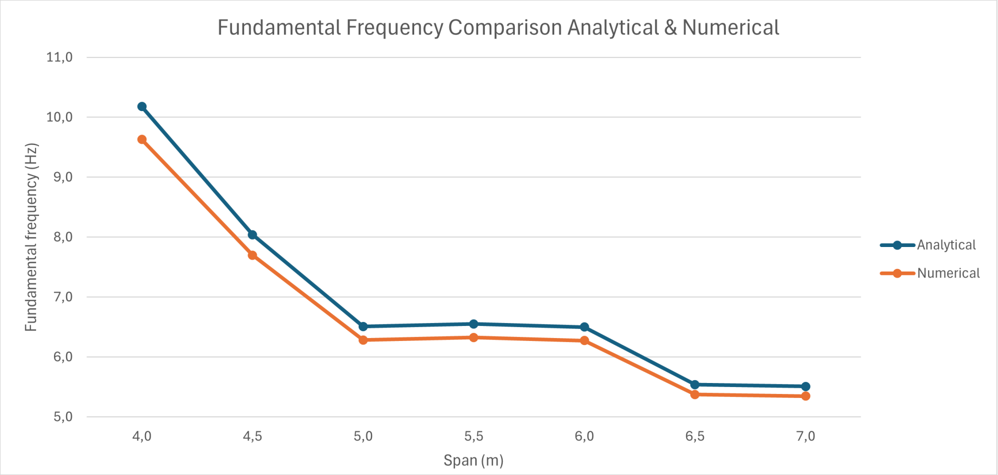


Figure 13: Comparison natural frequency between the analytical and numerical analysis

4.3.1.2 Modal Mass

The modal mass calculated for both situations can be seen in Figure 14. Both methods yield the same modal mass for the different spans. From this, it can be concluded that both the calculation methods use the same formula.

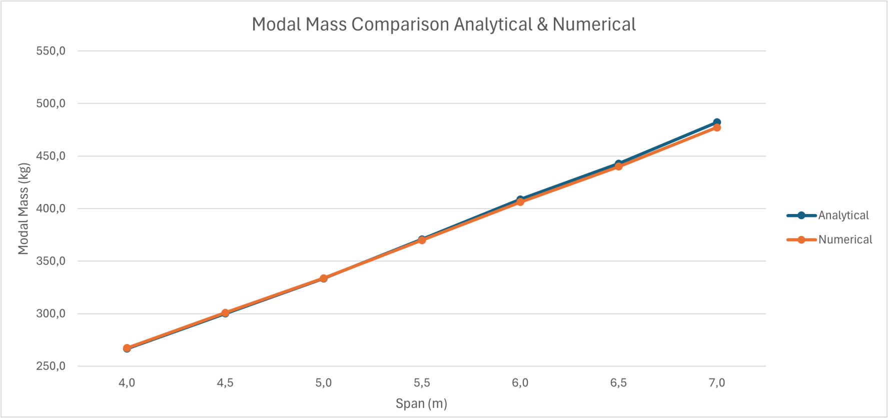


Figure 14: Comparison modal mass between the analytical and numerical analysis

4.3.1.3 Peak acceleration

The hand calculation of the peak acceleration calculates the acceleration values for each walking frequency separately. The acceleration values in the numerical analysis were therefore also divided into the different walking frequencies to validate the results from GSA. The walking frequency ranges from 1,7 Hz to 2,3 Hz, with steps of 0,1 Hz. The values were tested on a Lignatur 140 floor element with a span of 5,5 meters. The results can be seen in Figure 15.

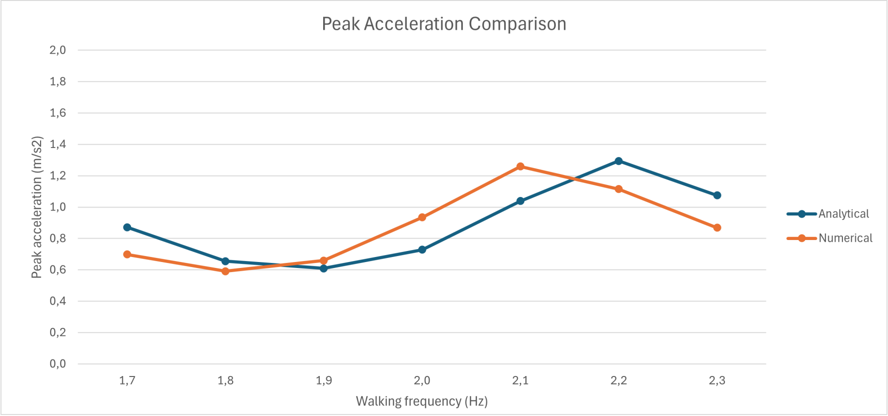


Figure 15: Comparison peak acceleration between the analytical and numerical analysis

From the graph, it can be seen that both calculation methods have the same trend, however, the lines are shifted on the horizontal axis. This can be explained by the difference in natural frequency observed in 4.3.1.1. There is a strong connection between the walking frequency and the natural frequency of the floor. A floor with a natural frequency of 8 Hz has a peak acceleration value at a walking frequency of 2,0 Hz. This is exactly the fourth harmonic frequency. When the numerically calculated natural frequency is used in the hand calculation of the peak acceleration, both methods yield the same values. This can be seen in Figure 16.

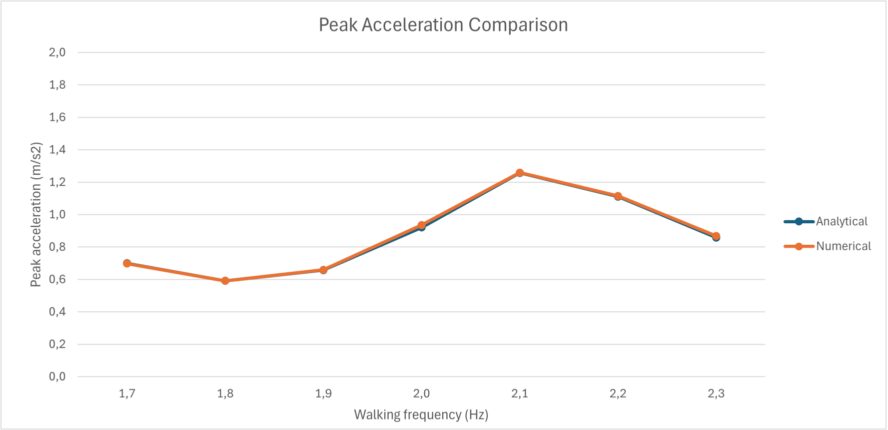


Figure 16: Comparison peak acceleration between the analytical and numerical analysis using the numerical frequency

4.3.1.4 Conclusion

From the previous paragraphs, it can be concluded that the GSA model is valid for further research because it yields the same values as the analytical analysis.

5 Optimisations

During this research, two different design optimisations are researched for the timber floor systems. The main goal of these optimisations is to reduce the mass that is needed to meet the vibration requirements. Both optimisation methods are introduced in the introduction and will be further explained in the following Chapter.

5.1 Strategic Mass

Strategic mass is a concept that only applies mass at the most efficient locations. Instead of adding mass to the whole floor area, mass will only be applied to parts of the floor where mass is needed the most. Leading to a reduction in the total mass used on the floor. Next to the location of the mass, also changing the concentration of the mass at certain areas of the floor is part of the concept. The additional mass can be applied on the floor or in the case of the Lignatur floor, also inside the floor. In Figure 17 an illustration of the strategic mass can be seen with the several options.

There are several boundaries for the optimisation of this concept. First, there should always be a permanent mass of 50 kg/m^2 on the whole area of the floor. This permanent mass is the finishing layer on top of the Lignatur floor. A second boundary is the limit on Unity Check for the floor structure. A high concentration of additional mass in the middle of the floor span results in a high point load at the least favourable position. The unity check of the complete floor system should always be under 1.0 even with the additional mass.

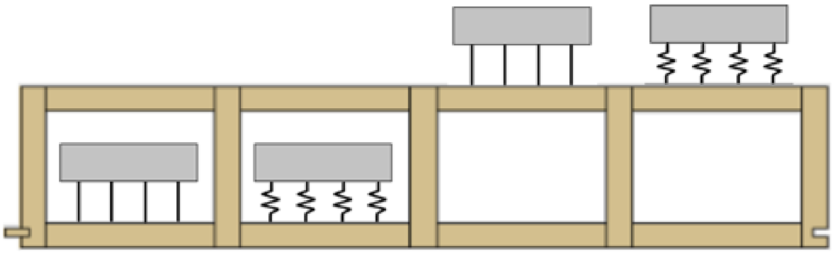


Figure 17: Strategic mass

5.2 Mass on Springs

The concept of tuned mass is an optimisation proposal in which the additional mass on the floor is placed on springs. The mass on springs has a damping effect on the vibrations of the floor. In this way, the mass can be used more efficiently than the normally placed mass. This can lead to a reduction in additional mass on the floor system. Figure 17 illustrates the additional mass on top of springs.

5.3 Mass in/on the Floor

Due to the box-shaped geometry of the Lignatur floor, it is possible to add mass inside the floor system. The effects of the placement on top or inside the floor need to be researched. If one of the concepts is more efficient, this concept should be used for the optimisations.

The effect of the mass inside the floor will be researched for a Lignatur 180 floor. This floor has a span of 5 meters and a width of 1 meter. The floor is longitudinally divided into 17 segments. The peak acceleration is calculated for every different segment, during the calculation, mass is only applied to the segment that is being calculated. The calculation is performed separately for both mass on and inside the floor. The resulting graph can be seen in Figure 18.

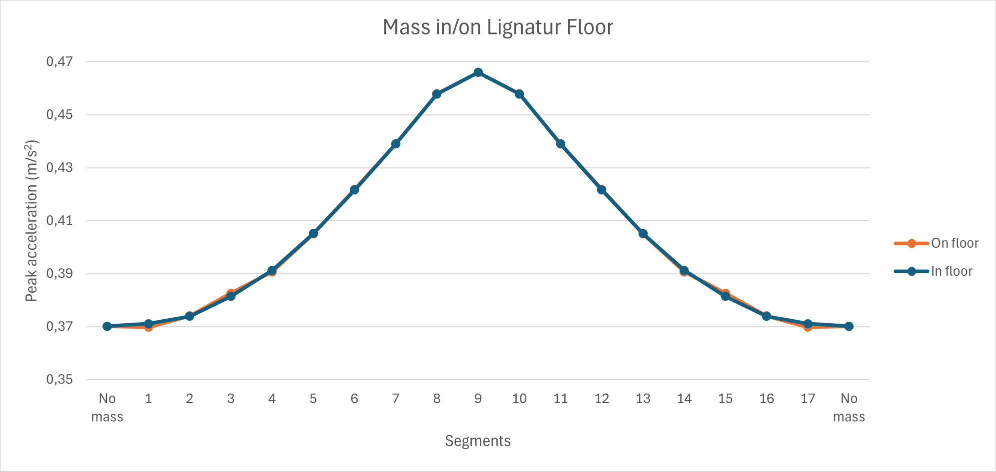


Figure 18: Peak acceleration comparison for mass in/on the Lignatur floor

5.3.1 Conclusion

From the graph, it can be seen that there is no significant difference between the additional mass on or inside the Lignatur floor system. Following this research, it can be concluded that both methods can be used for the optimisations. The choice of mass inside the floor system can be a practical choice. Mass inside the floor decreases the total height of the floor. It also allows for differently distributed mass over the area of the floor system. The mass on top of the floor needs to be in a flat plane for the users of the floor.

5.4 Methods

GSA will be used to analyse the floor systems, however, the floors are designed using the OS-RMS$_{90}$ method. First, a floor system is designed to comply with vibration class D of the OS-RMS$_{90}$ method. When the appropriate section and additional mass for this floor is obtained, the floor system is modelled in GSA with the same parameters. In GSA, a footfall analysis is performed, yielding peak acceleration values. Because this specific floor complies with vibration class D, the peak acceleration value obtained, can be used as upper limit value (benchmark value) for the specific floor system. A flow chart of the design process of a floor can be seen in Figure 19.

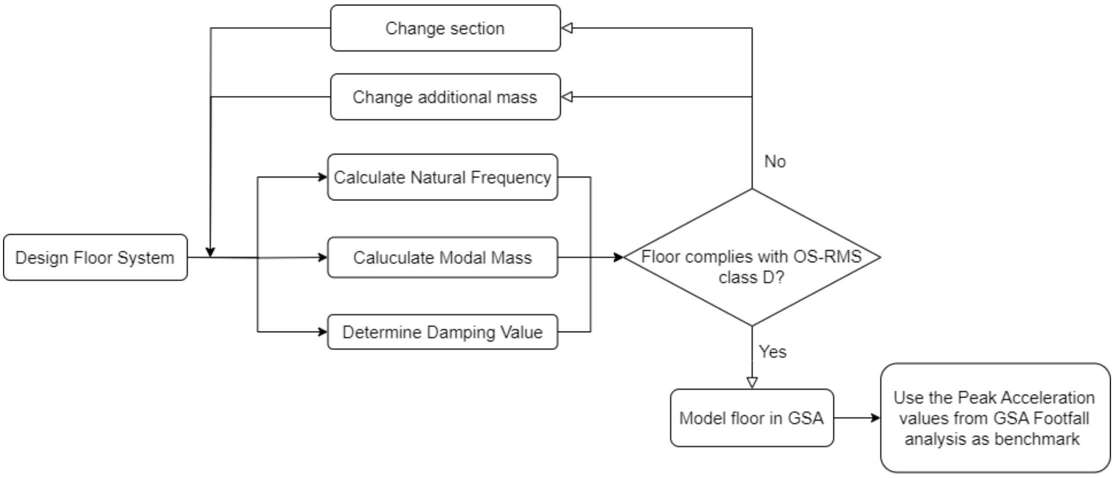


Figure 19: Floor Design Process

The optimisations of the two concepts are based on several parameters. These parameters are differentiated from a standard floor system. This floor system is the core of the optimisation analysis.

5.4.1 Standard Floor

The floor chosen as the standard floor is a Lignatur 200 floor, with a span of 6 meters and a width of 3 meters. The floor is an office floor and has a damping percentage of 8%. On top of the floor is the minimal permanent mass of 50 kg/m^2, on top of that will be an additional mass of 150 kg/m^2 resulting in a total mass of 200 kg/m^2. This mass is needed to comply with the requirements of class D of the OS-RMS$_{90}$ calculation. Alongside that, on the floor is also 20% of the live load of 250 kg/m^2. The OS-RMS$_{90}$ calculation of the standard floor can be seen in Appendix D.

5.4.2 Parameter Analysis

The standard Lignatur floor system is the core of the optimisation process. For this floor, five different parameters will be varied to see the effect of the different parameters on the vibration performance of the floors. The following parameters will be considered:

- Span
- Width
- Damping
- Function
- Mass on springs

The parameters can be seen illustrated in Figure 20, structured around the standard Lignatur floor. The goal for all researched floors is to decrease additional mass while maintaining the same level of vibration performance as the standard floor.

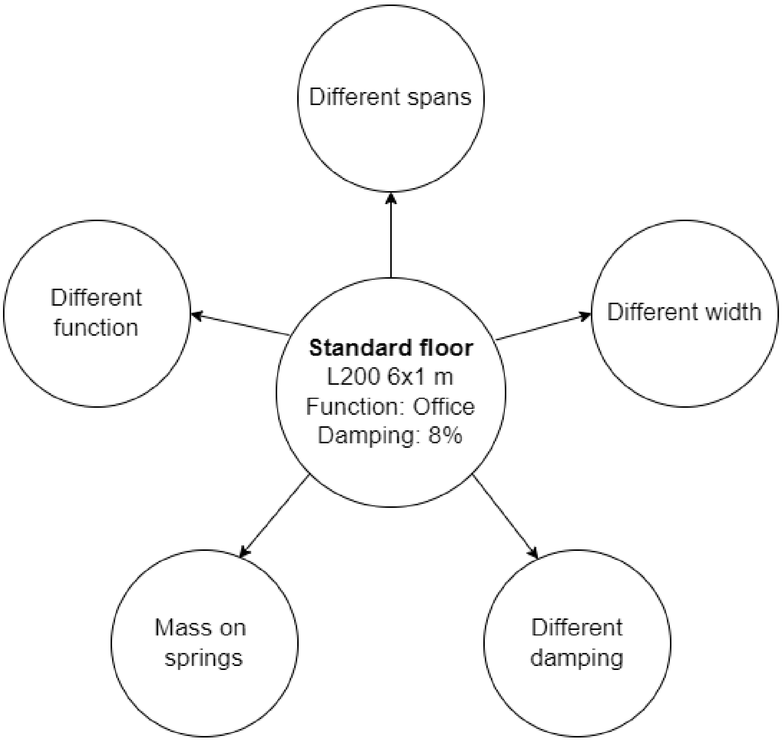


Figure 20: Different optimisation parameters for the standard floor

5.4.3 Optimisation Method

The benchmark value obtained following the design process explained in 5.4 is used in the optimisation. This value is the upper limit peak acceleration value for the specific floor. With the proposed optimisation methods, the goal is to decrease the mass needed for the floor system, while staying below the benchmark value, and thus maintaining the desired comfort levels concerning vibrations.

5.4.3.1 Longitudinal Variable Mass

The additional mass on the floor calculated to comply with the vibration requirements, will be taken as the start value for the optimisation. This mass per square meter is applied to a small area in the middle of the floor, over the full width of the floor. This coverage area on the floor is increased step by step towards the supports until the full floor is covered with the mass. This means that the floor's total mass increases with each step. Areas not covered with the additional mass will always have the minimal 50 kg/m^2 of permanent mass. Different steps in the progress of applying the longitudinal variable mass can be seen in Figure 21, this figure shows a top view of the standard Lignatur floor. From this method, a certain amount of mass can be found. This mass needs to be present on the floor to meet or come close to the acceleration benchmark. This will be the additional mass in kg.

5.4.3.2 Concentrated Additional Mass

The total additional mass found in the longitudinal variable mass method will be concentrated in the middle of the floor. The total mass will be applied to a small

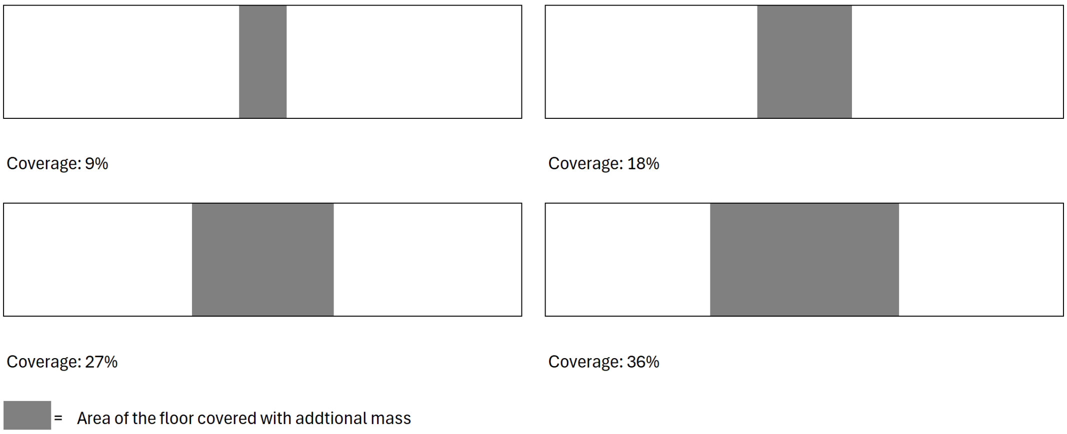


Figure 21: Longitudinal variable mass

area in the middle, which covers the full width of the floor. Step by step this area is increased, lowering the concentration of the mass, but keeping the total mass the same. The mass is always applied over the full width of the floor element of one meter. To increase the area, the length is increased towards the supports. If the acceleration of the floor is still under the benchmark for a larger area, the total additional mass on the floor can be decreased until it exceeds the benchmark. An example of the concentrated mass can be seen in Figure 22.

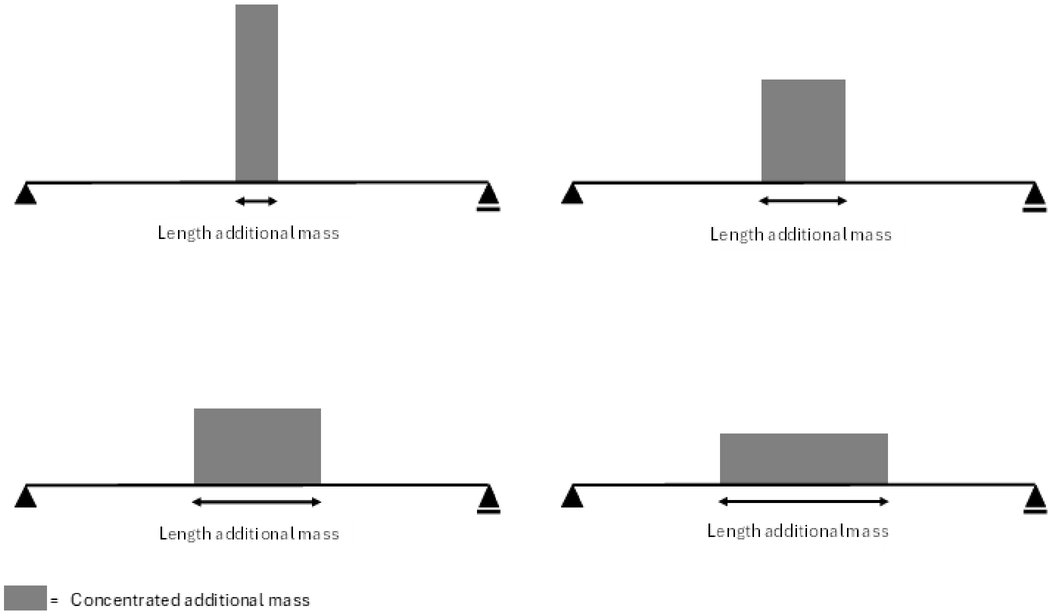


Figure 22: Concentrated mass

5.4.3.3 Decrease in Mass

From the total additional mass found in the previous method, the decrease in mass for the specific floor can be calculated. The total additional mass needs to be added to the already present 50 kg/m^2 on the floor. This yields the total mass on the new floor. The total mass of the old floor can be calculated by multiplying the required mass in kg/m^2 times the area of the floor. A decrease in the percentage of the total mass can be calculated from the values for the old and the new floor.

6 Results

The results from the footfall analysis in GSA will be used to create an optimisation model for the standard floor with different parameters. The main goal is to decrease the additional mass on the floor structure while maintaining the acceleration values at the desired level following the OS-RMS$_{90}$ method.

6.1 Standard Floor

The standard floor complies with the requirements for a class D floor following the OS-RMS$_{90}$ calculation, meaning that the peak acceleration value resulting from the footfall analysis can be taken as the benchmark. A one-meter-wide Lignatur element is taken from the standard floor to simplify the results from the analysis. The peak acceleration for the one-meter-wide Lignatur element of the standard floor is 0,399 m/s^2. This value is taken as the benchmark peak acceleration value.

6.1.1 Longitudinal Variable Mass

For the standard floor, the mass will be increased from the middle of the floor as was explained in 5.4.3.1. The values resulting from this analysis can be seen in Figure 23. From this figure, it can be seen that the increase in mass has a positive effect on the acceleration as is to be expected. However, from an area coverage of 65% and higher, the peak acceleration decrease is only marginal. At only 65% of the additional mass on the floor, the benchmark acceleration level is almost matched. This shows that the mass is mostly needed in the middle of the floor where the deformations due to the vibrations are the highest. For the standard floor, the 65% coverage of the floor will result in an additional mass of 585 kg.

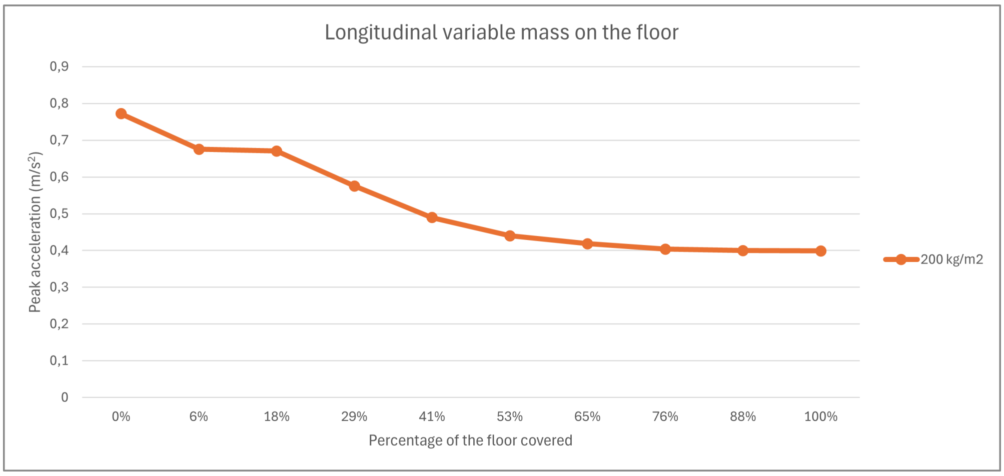


Figure 23: Longitudinal variable mass on the standard floor

6.1.2 Concentrated Additional Mass

The additional mass found in the longitudinal variable mass analysis will be concentrated in the middle of the floor. First, the total amount of additional mass will be applied as a highly concentrated load over the full width of the floor. This results in a length of 0,1 meters. After that, the mass will be spread out over a length of 0,3 meters. This results in a lower concentration of mass, while the total mass stays the same. The sequence is applied with steps of 0,2 meters until a length of 1,5 meters is reached. The results of this analysis can be seen in Figure 24. When the 580 kg of additional mass is concentrated in the middle of the floor, the peak accelerations are below the benchmark of 0,399 m/s^2. The mass can be decreased to 460 kg for the standard floor when applied over a maximum length of 0,9 meters.

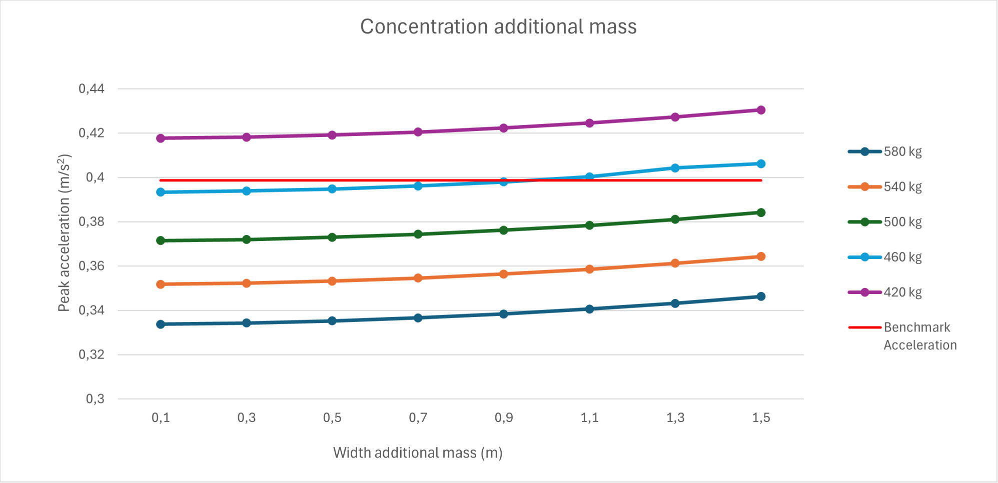
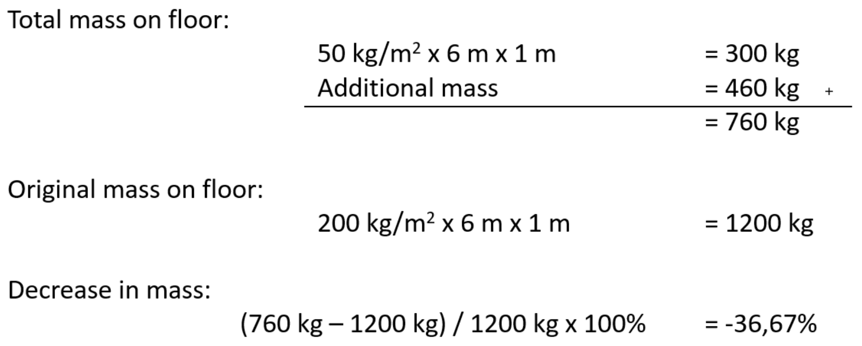


Figure 24: Concentrated additional mass on the standard floor

6.1.3 Decrease in Mass



Total mass on floor:

50 kg/m² x 6 m x 1 m = 300 kg
Additional mass = 460 kg +
= 760 kg

Original mass on floor:

200 kg/m² x 6 m x 1 m = 1200 kg

Decrease in mass:

(760 kg – 1200 kg) / 1200 kg x 100% = -36,67%

6.2 Different Spans

The optimisation method is tested for different spans. For every span, the Lignatur section is calculated using the OS-RMS$_{90}$, as was also performed for the standard floor. The variability in longitudinal mass is applied to the different floor spans. The results can be seen in Figure 25. From this graph, it can be observed that all of the floors follow the same trend for adding mass to the floor. After coverage of 65% of the mass from the middle of the floor, the additional mass does not influence the peak acceleration anymore. Following this conclusion, 65% of the mass can be used for all of the spans. The total amount of additional mass is calculated and concentrated on the middle of the floor as is also done in 6.1.2. From this, the minimal amount of additional mass is calculated for all different spans.

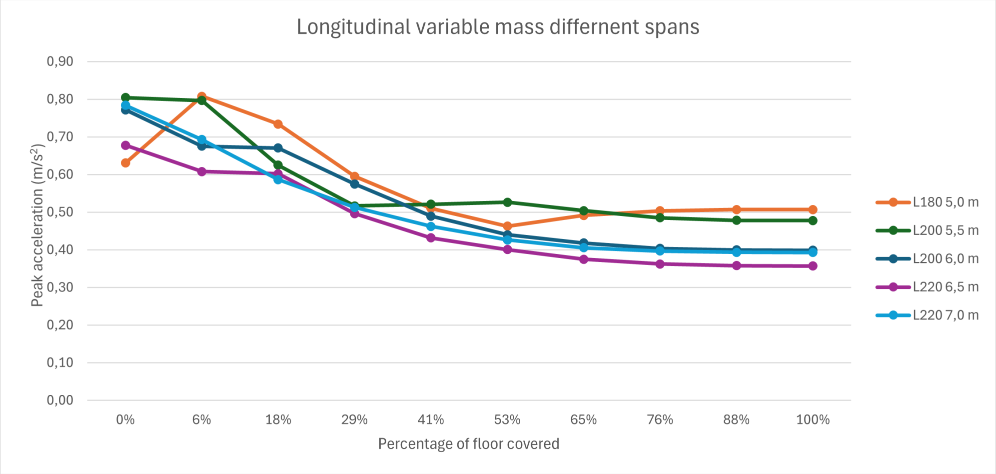


Figure 25: Longitudinal variable mass for different floor spans

6.2.1 Decrease in Mass

The decrease of mass for the calculated floors can be seen in Figure 26. The Lignatur floors with a span of 5,5 meters to 7 meters result in a decrease of mass around 36%. The only exception is for the five-meter floor span. This floor results in a decrease of 47% when compared to the original floor.

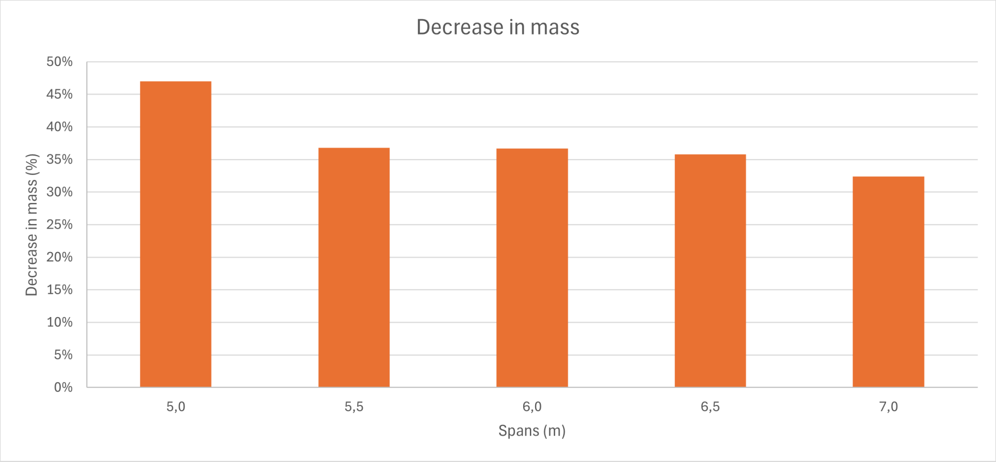


Figure 26: Decrease in mass for the different spans

6.2.2 Five Meter Span

The five-meter span floor is analysed separately to find the reason for the large decrease in mass. This specific floor has a five-meter span and a Lignatur 180 section. All other aspects are similar to the other floors. The reason for the outlier value can be found in the analysis of longitudinal variable mass. As can be seen in Figure 27, the peak acceleration has a minimum at 53% of floor coverage. After this, the additional mass on the floor causes an increase in peak acceleration. This increase in acceleration causes a higher-than-expected benchmark value of 0,507 m/s^2 at the 100% floor coverage. This is significantly higher than the benchmark value of 0,399 m/s^2 found for the standard floor. This means staying under the benchmark value is easier, resulting in less additional mass on the floor.

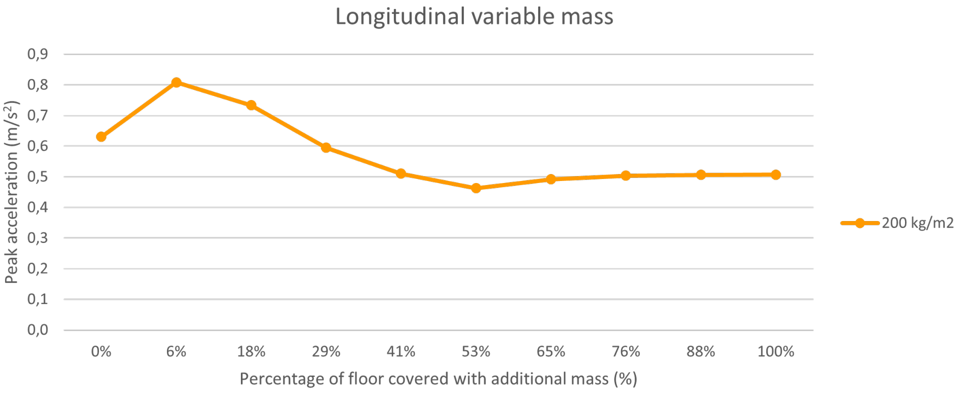


Figure 27: Concentrated additional mass on the standard floor

6.3 Different Width

The parameter floor width influences the modal mass of the floor significantly, while only having a small effect on the natural frequency of the floor. Floors with a width of 3 and 5 meters will be analysed and compared to the 1-meter-wide standard Lignatur floor element. As was explained in 6.1.1 only 65% of the additional mass in the middle of the floor influences the acceleration. Therefore, the 65% of additional mass is also taken as starting point for this analysis.

6.3.1 Transverse Variable Mass

The same principle that was used in paragraph 6.1.1 will be used in the transverse direction of the floor. The coverage of the additional mass on the floor area gradually increases in the transverse direction. The resulting graph with the peak acceleration plotted against the coverage of the additional mass can be seen in Figure 28. The one-meter-wide Lignatur floor element follows the expected path, with a decrease in peak acceleration for an increase in mass. The three-meter-wide floor shows a different behaviour, with a minimum at 33% of the total mass. For this floor system, this would mean that only the middle of the three Lignatur elements is covered with the additional mass. Covering more areas of the floor towards the edges has a negative effect on acceleration values. For the five-meter-wide floor, covering the first 20% of the floor area with the additional mass does not positively affect the acceleration value. From the graph, it can be seen that the acceleration decreases between 20% and 60%. This means that only Lignatur element 2 and 4 need to be covered with the additional mass to reach the most optimal solution. This will yield a lower peak acceleration value, while only covering the floor with 40% of the total additional mass.

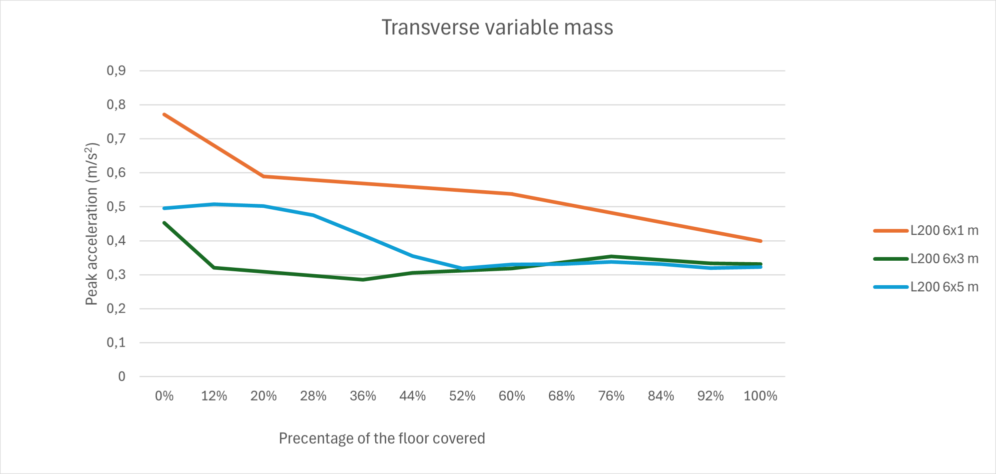


Figure 28: Transverse variable mass for different floor width

6.3.2 Decrease in Mass

The mass decrease for the floor systems can be calculated in the same fashion as was done in 6.1.3. For this calculation, the variable mass in both the longitudinal and transverse directions will be considered. The results are illustrated in Figure 29. From the results, the difference in comparison to the standard floor can be seen. The floors with a width of three and five meters give a significantly higher decrease in mass because the mass is not needed over the complete width of the floor. This can be explained by the different mode shapes that act on the floor structure during vibrations.

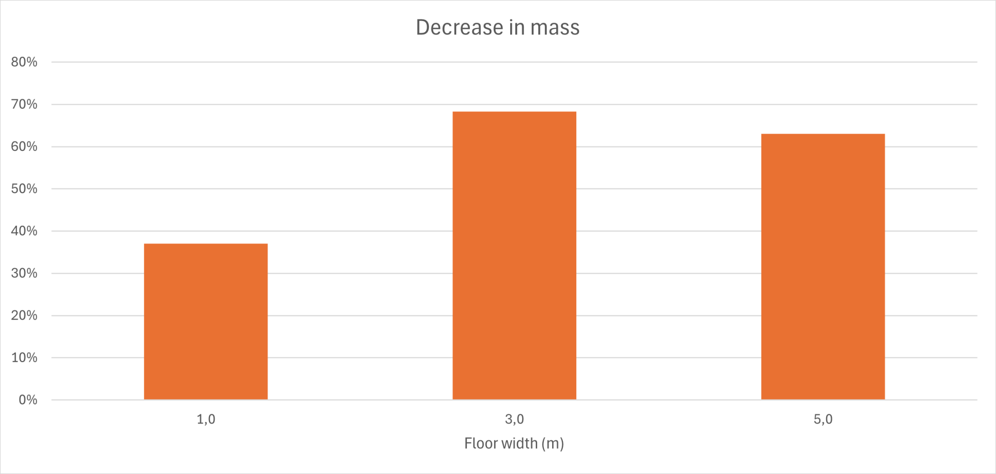


Figure 29: Decrease in mass for the different floor width

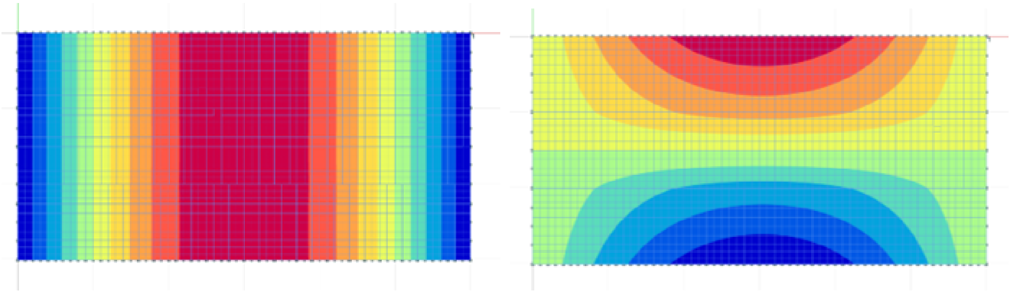
6.3.3 Mode Shapes

The mode shape of a vibration describes the specific way of deflecting when an element is subjected to excitation. An element has one or more mode shapes, with different excitation forces. Harmonic vibrations will take place inside the mode shape when the element is deflected according to that shape. However, real load scenarios often combine several mode shapes, which leads to a more complex overall vibration [7].

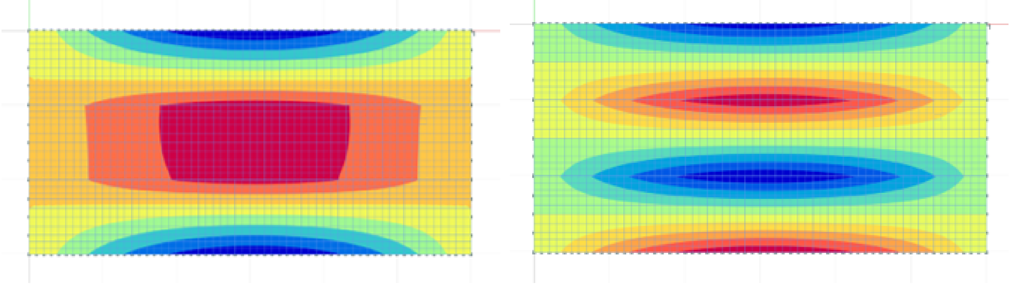
6.3.3.1 Mode Shape Contribution

From the dynamic analysis in GSA, the 10 mode shapes with the lowest excitation force can be obtained, with their corresponding frequency and modal mass. The footfall analysis used in GSA provides the contribution of different mode shapes to peak acceleration values.

When analysing a one-meter-wide Lignatur element of the standard floor, it can be observed that only the lowest mode shape contributes to the peak acceleration of the floor. This mode shape is illustrated in Figure 30a in which it can be seen that the deformation is constant over the width of the floor. A red colour indicates a positive deformation, while a blue colour indicates a negative deformation. In this case, the location of the mass in the transverse direction has close to no effect on the acceleration of the floor.



(a) Mode shape 1 (b) Mode shape 2



(c) Mode shape 3 (d) Mode shape 4

Figure 30: Mode shapes for a 3-meter wide Lignatur floor

The same results can be seen for the three-meter-wide floor when a person is placed in the middle of the floor. However, when a person is placed on the edge of the floor, the mode contribution changes. In Figure 31 it can be seen that mode shape one is still dominant, but now mode shape two, three, and four also influence the acceleration value. Due to the different deformation behaviour of the edges, the mode shapes that contribute to the acceleration are not constant over the width of the floor. An overview of these mode shapes can be seen in Figure 30.

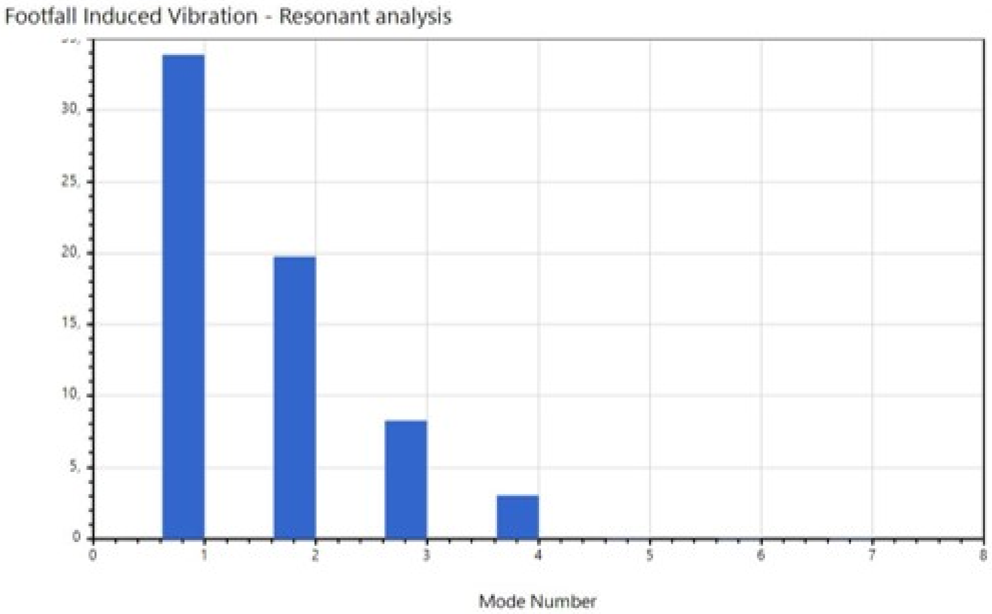


Figure 31: Contribution of each mode shape to the peak acceleration

6.3.3.2 Acceleration Values

An analysis is made based on natural frequency and modal mass. This analysis is used to explain the increase in acceleration that results from additional mass being placed at the edge of the floor. The analysis will be divided into 8 steps. The first analysis is performed in the middle of the floor. After that, the location of the analysis is moved towards the edge of the floor with 8 equally divided steps of 0,2 meters. For all these steps, the natural frequency and modal mass are calculated. This gives an insight into the contribution of the different mode shapes.

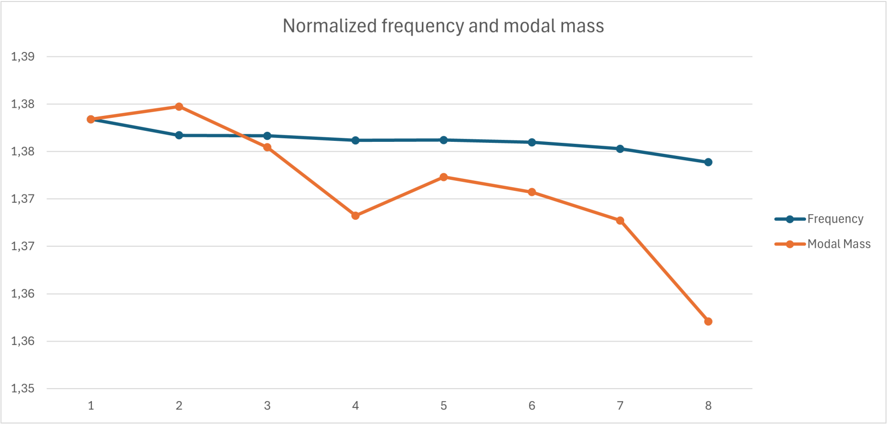


Figure 32: Natural frequency and modal mass for different locations on the floor

In Figure 32 the results of the 8 steps can be seen. The values of the natural frequency and modal mass are normalized to visualize them in one graph. For the natural frequency, it is observed that the frequency decreases when the person on the floor is moved towards the edge of the floor. This can be explained by the slightly lower transverse stiffness of the floor edge in comparison to the middle of the floor. For the modal mass, it can be seen that the location of the floor is important. At some locations, particularly closer to the edge, the mass of the person does not contribute as much to the modal mass of the floor.

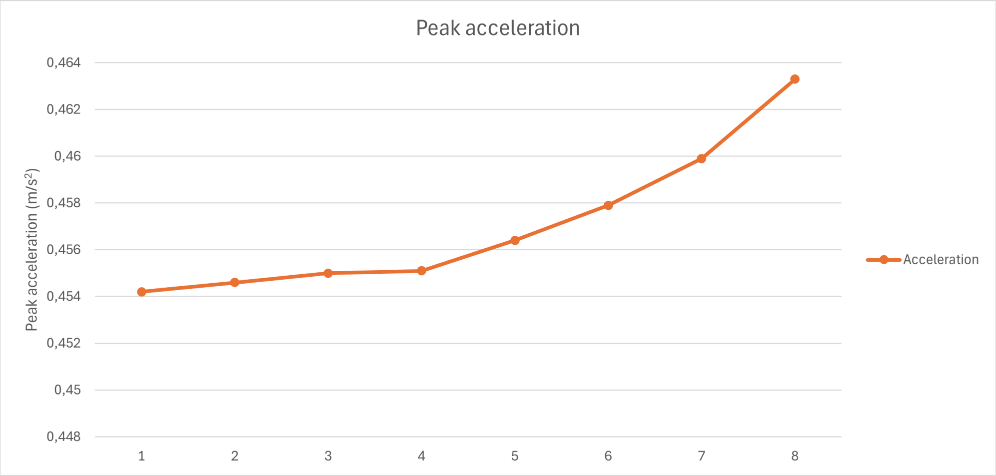


Figure 33: Peak acceleration for different locations on the floor

6.4 Different Damping

The parameter damping can vary for the standard floor. The damping values lie in a range of 6% to 9% for the office and residential functions. These values can be determined following Table 3. In Figure 34, the peak acceleration value is plotted on the vertical axis, with the total permanent mass on the floor plotted on the horizontal axis. As expected, a higher damping value will lead to a lower peak acceleration value. However, it can be seen that for a higher permanent mass, the influence of the damping is lower. Damping influences the response amplitude of the vibration. For higher permanent mass values, the response amplitude is lower, meaning that the effect of the higher damping is relatively low.

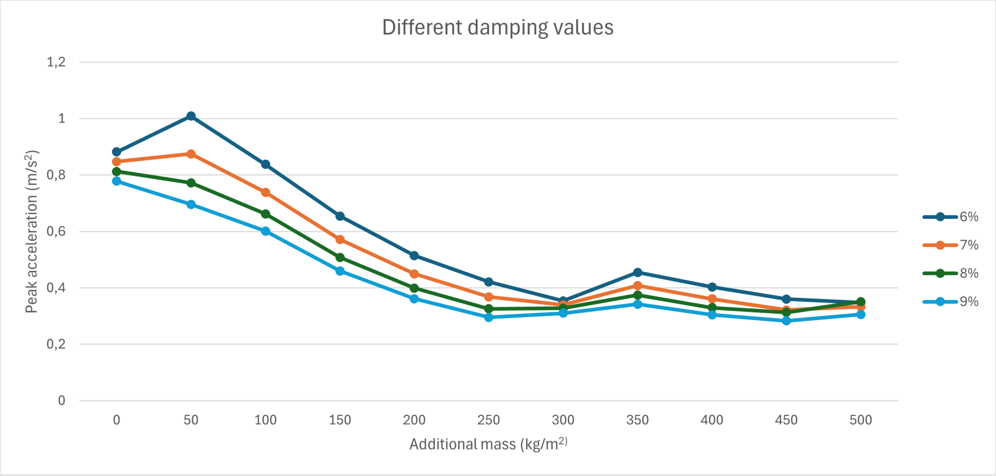


Figure 34: Different damping values for the standard floor

In Figure 35, the longitudinal variable mass on the floor can be seen for different damping values. This graph shows that the damping value influences peak acceleration. However, the damping value does not influence the decrease in mass, as floors with different damping values follow the same trend.

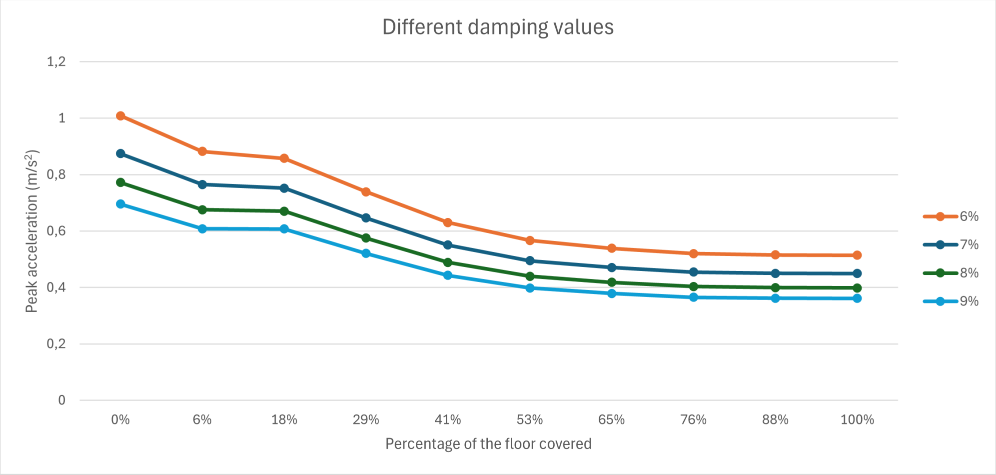


Figure 35: Longitudinal variable mass for different damping values

6.5 Different Function

The standard floor has an office function. The influence of the function on the mass decrease of the floor will be tested for the residential function as well.

First, the floor should be redesigned using the OS-RMS$_{90}$ method, while the loading is changed for the residential function. A live load of 175 kg/m^2 is stated for a residential floor. Applying the reduction for the live load as was explained in 3.1, the live load acting in the vibration analysis is 35 kg/m^2. This is a decrease of 15 kg/m^2 when compared to the office floor. The lower live load results in an increase in permanent mass needed on the floor to comply with vibration class D. An additional mass of 200 kg/m^2 plus the 50 kg/m^2 of permanent mass is needed on the floor. This is instead of the 150 kg/m^2 plus 50 kg/m^2 that was used for the standard floor.

Performing the longitudinal variable mass and the concentrated mass methods. The residential floor yields a decrease in mass of 38%. This is in line with the values found for the office floor. Although more additional mass is needed at the beginning of the optimisation, the reduction in mass is similar to the results found for the office floor.

6.6 Mass on Springs

The additional mass can be placed on springs to counteract the movement of the floor system. In this way, mass can act as a damper for the structure. The springs can be added underneath the mass for both the mass in and on the floor. In the FEM model, each mass is placed on top of an individual axial spring, which only allows for vertical movement.

6.6.1 Spring Stiffness

The spring stiffness dictates the amount of damping added to the floor system due to the springs. A low stiffness allows for a lot of movement of the mass, dissipating a lot of energy from the vibrating floor system. On the other hand, a high stiffness only allows a small mass movement, resulting in less energy reduction of the vibrating system. The higher the stiffness, the closer the behaviour of the floor system is to a floor system without springs.

The results of the standard floor including springs can be seen in Figure 36. On the horizontal axis, a variability in spring stiffness is used. The peak acceleration values are calculated for the top plate of the floor and for the mass itself. As was explained earlier, a low stiffness results in a high mass acceleration on top of the springs. Due to the high energy dissipation, the peak acceleration at the floor plate will remain low. As the spring stiffness is increased, the difference between the two acceleration values disappears and finds an equilibrium, with the same value as a system without springs.

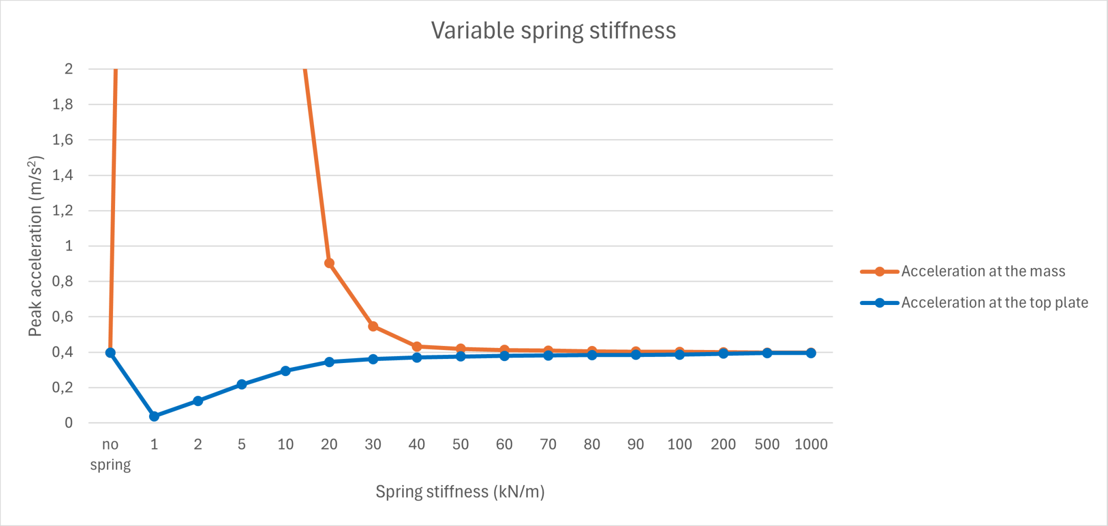


Figure 36: Variable spring stiffness standard floor

6.6.2 Location Springs

The low spring stiffness presents an issue concerning the application of the springs. Due to the movement of the mass on top of the spring, the mass cannot be placed on top of the floor, while the users of the floor would feel the displacement of the mass when walking on the floor. This results in a decrease in comfort. At a high spring stiffness, the movement of the springs can be neglected, however, the addition of springs is not effective for high stiffness, as can be seen in Figure 36. Therefore, it is chosen that mass on springs can only be applied inside the Lignatur floor system.

Adding mass inside the floor is less effective concerning the application of springs. The minimum permanent mass of 50 kg/m^2 is always placed on top of the floor because it represents the finishing of the floor. When adding 200 kg/m^2 to the floor, 150 kg/m^2 can be placed inside the floor on the springs while the 50 kg/m^2 will be placed on top of the floor without springs. This is considered for the following calculations.

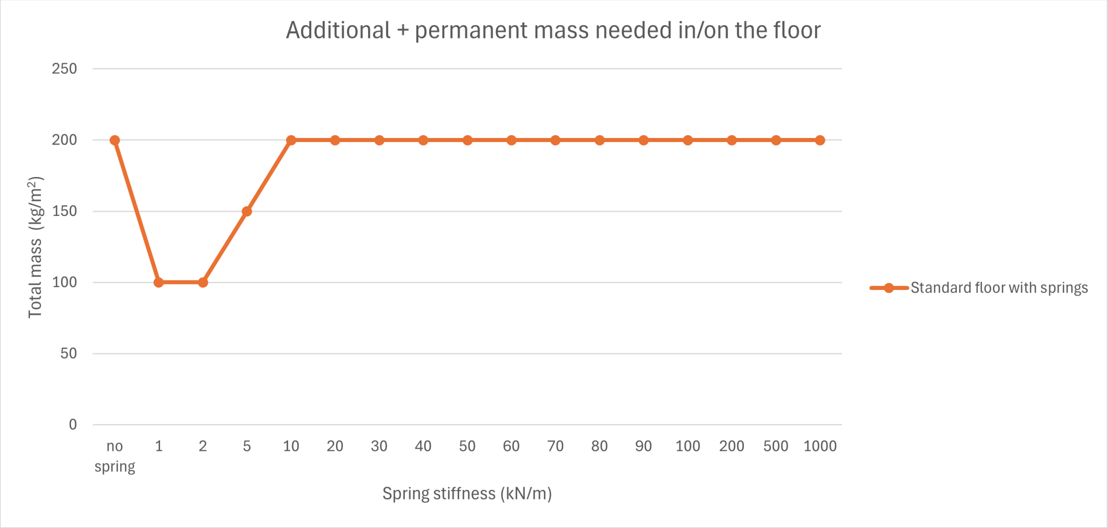


Figure 37: Additional mass needed on the springs

6.6.3 Decrease in Mass

For the standard floor, the decrease in mass can be calculated for the different spring stiffness. The acceleration benchmark is set as the result of the standard floor without springs, which was determined to be 0,399 m/s^2, following 6.1. The goal is to reduce the mass needed by using springs. In Figure 37, the mass needed for each spring stiffness to remain under the benchmark is shown. The resulting decrease in mass is calculated and presented in Table 6.

Spring stiffness (kN/m)	Total decrease in mass (%)
1	50%
2	50%
5	25%
10	0%
20	0%
30	0%

Table 6: Decrease in mass for the standard floor

6.7 Combining Optimisations

Both of the proposed optimisations yield a positive result concerning the decrease in additional mass in the floor system. These optimisations can also be combined. The methods of longitudinal variable mass and concentrated mass will be used for the standard Lignatur floor, with ballast on springs inside the floor. A spring stiffness of 5 kN/m will be chosen for the floor. This spring stiffness allows for a reduction in mass of 25%. Therefore, an additional mass of 100 kg/m^2 is chosen next to the 50 kg/m^2 of permanent mass, resulting in a total mass of 150 kg/m^2 for the floor system. The benchmark of the floor is still stated at the original level of 0,399 m/s^2.

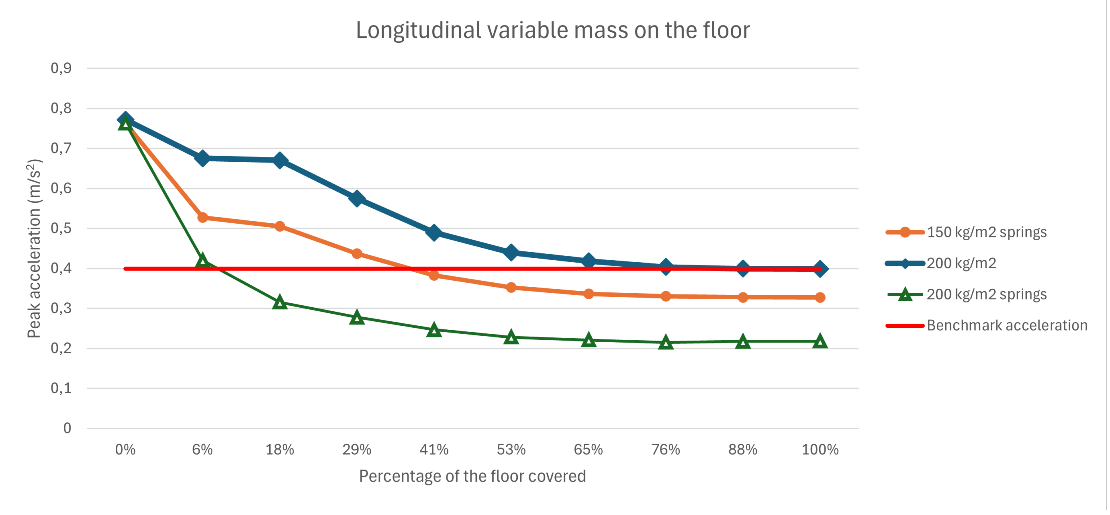


Figure 38: Mass on springs; longitudinal variable mass

From the analysis of the longitudinal variable mass, it can be observed that the peak acceleration only has a marginal decrease after a coverage of 65% and higher. This can be seen in Figure 38. This is inline with the earlier found results of the standard floor. However, due to the springs, a total mass of 150 kg/m^2 is used instead of 200 kg/m^2, which is normally used for the standard floor. Even with the decrease in mass the peak acceleration levels are still below the benchmark. From the 65% coverage a total additional mass of 390 kg is found.

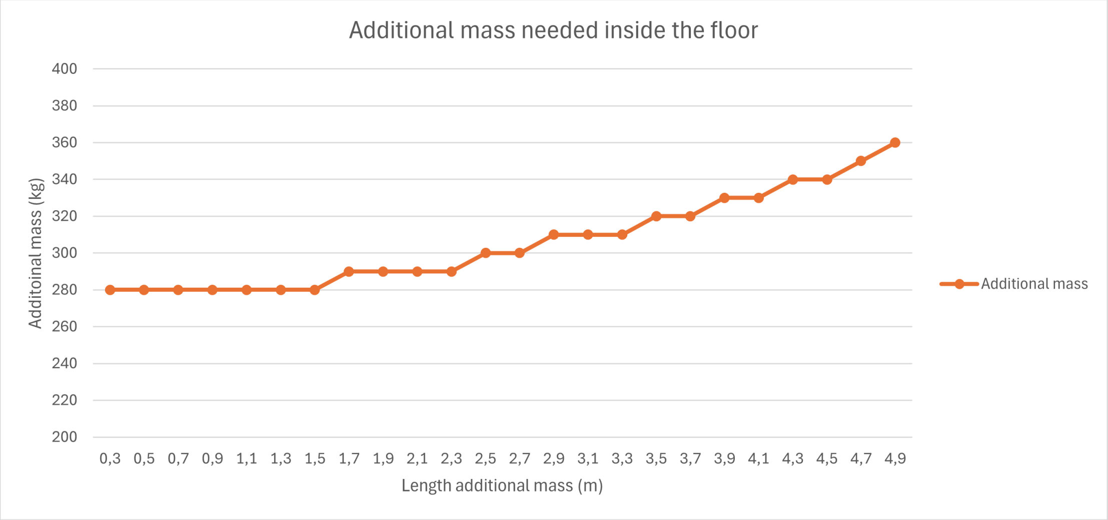


Figure 39: Total amount of additional mass needed for the floor system

The 390 kg of additional mass is used as starting point for the concentrated mass method, this method is explained in 5.4.3.2. When applying the mass over a larger area on the floor, the effectiveness of the mass decreases. For a small area less mass on the springs is needed. The width over which the concentrated mass is applied is constant, the width is the same as the floor width of 1 meter. This means that only the length of the area of concentrated mass can change. From the analysis a minimal amount of mass needed for a specific length can be calculated. The results can be seen in Figure 39. One additional aspect applicable to the concentrated mass method is the variable spring stiffness. For a small area of mass, only several springs are activated, reducing the total spring stiffness. To keep the spring stiffness at 5 kN/m the spring stiffness is adjusted according to the area covered with mass. This results in the unit $kN/m/m^2$ for the spring stiffness.

6.7.1 Decrease in Mass

Both optimisations methods strengthen each other, resulting in less additional mass for the floor system. The decrease in mass for all different lengths is calculated and presented in Table 7.

Length of additional mass	Total decrease in mass (%)
0,3	52%
0,5	52%
0,7	52%
0,9	52%
1,1	52%
1,3	52%
1,5	52%
1,7	51%
1,9	51%
2,1	51%
2,3	51%
2,5	50%
2,7	50%
2,9	49%
3,1	49%
3,3	49%
3,5	48%
3,7	48%
3,9	48%
4,1	48%
4,3	47%
4,5	47%
4,7	46%
4,9	45%

Table 7: Decrease in mass for the standard floor using springs

7 Practical Implementation

This chapter will research the practical implementation of the proposed optimisations. Following the optimisations, a specific amount of additional mass is needed on or inside the floor system. For the strategically placed mass, the additional mass is often concentrated, requiring space on or inside the floor to apply this mass. This additional mass is also called ballast.

Inside the Lignatur floor elements, there is limited space to add ballast. The amount of space depends on the height of the cross-section. As well as a limitation on the height, also the width of the Lignatur element has a restriction on the amount of ballast that can be added inside the floor, due to the vertical ribs of the Lignatur floor which take up space. On top of the floor, the full width of the Lignatur element can be used to apply ballast. There is also no hard limitation on the height of the ballast. However, when the ballast is only placed on specific areas of the floor, the other areas of the floor need to be raised to meet the higher floor level resulting from the ballast. Therefore, to implement the optimisations practically, the ballast should be placed inside the Lignatur floor element.

7.1 Ballast Types

Several ballast types are suitable for adding to a Lignatur floor system. Ballast materials with high density are desirable because they use less space on/in the floor. The standard ballast materials used for a Lignatur floor can be seen in Table 8. Insitu concrete has the highest density, however, it is difficult to apply inside the Lignatur floor, especially when it only needs to be applied to certain areas of the floor. Therefore, concrete blocks are often chosen as ballast material [21]. They have a high density and are practical in use. These blocks can be placed at specific locations in the Lignatur floor element. Aggregates are also used as a cheap and practical solution, however, they have a lower density and will therefore have a higher volume. For highly concentrated mass, concrete blocks can best be applied to the floor system.

Ballast material	Density (kg/m^3)
Insitu concrete	2400
Concrete blocks	2250
Aggregates	1900

Table 8: Density mass applications

7.2 Standard Floor

The standard floor is a Lignatur 200 floor, which has a height of 200 mm and a width of 1000 mm. The free space inside the floor can be calculated by subtracting the top and bottom plates of the Lignatur element from the total section height. The plates have a thickness of 31 mm, resulting in a free space of 138 mm. The ribs of the Lignatur element reduce the width on which the ballast can be placed. There are five ribs with a thickness of 31 mm, giving a usable width of 845 mm for the ballast inside the Lignatur floor element.

7.3 Strategic Mass

Following the optimisations found in 6.1, the needed concentration of mass can be found for the standard floor, 460 kg of ballast is needed over 0,9 meters length in the middle of the floor. This results in an area of 0,9 m^2 on which the ballast can be placed.

$$\frac{total\,ballast}{length\,*\,usable\,width} - permanent\,mass = concentrated\,mass \tag{19}$$

Where:

- Length is the length of the area on which the ballast can be placed equal to 900 millimeters for this situation
- Usable width is the free space inside the floor equal to 845 mm for the standard floor
- Permanent mass is the finishing of the floor equal to 50 kg/m^2

Using equation 19 a concentrated ballast of 555 kg/m^2 can be found. Using the concrete blocks, this results in a height of 246 mm for the concrete blocks. With only a height of 138 mm available for the Lignatur 200 floor, this concentrated load cannot be applied.

Looking at 6.1.2 a total additional mass of 500 kg can be applied over a length of 1,7 meters in the middle of the floor. Applying this ballast to equation 19, a concentrated ballast of 298 kg/m^2 can be found. This results in a height of 130 mm for the concrete blocks, which fit inside the Lignatur 200 element.

The use of 500 kg of ballast results in a decrease in mass of 33,33% for the standard floor. This is less than the 36,67% calculated in 6.1.3, however, for that situation, the concentrated ballast is too high and cannot be applied inside the floor.

7.4 Mass on Springs

The same principle can be applied to the mass on springs, however, the ballast on springs poses a new challenge regarding the free space inside the Lignatur element. For the ballast to be effective as a damper, the ballast needs to be able to move freely inside the floor element. So, the deformation of the ballast also needs to be taken into account, this results in equation 20.

$$\frac{ballast}{concrete\,blocks} - deformation\,ballast = free\,space\,needed \tag{20}$$

Where:

- Ballast is the needed ballast in kg/m^2
- Concrete blocks is the density of the concrete blocks in kg/m^3

- Deformation ballast is the deformation of the ballast on top of the spring in m

As was determined earlier, the free space for the standard floor is 138 mm. For the configuration with springs, less ballast is required inside the floor compared to the highly concentrated ballast, resulting in a lower height for the concrete blocks.

As was found in 6.6.1, a low spring stiffness results in a low acceleration value. But, the low stiffness also results in a high deformation of the ballast. When the results of 6.6.2 for a spring stiffness of 1 kN/m are applied, a total ballast of 100 kg/m2 is needed on the floor. This gives a height of 53 mm for the concrete blocks, the deformation of the ballast on the springs will be 60 mm. The free space needed for this system is 113 mm, meaning that there is space left for 25 mm for a spring system which needs to deform 60 mm. This would need a complex spring system which is outside the scope of this research.

When applying a spring stiffness of 10 kN/m, a ballast of 150 kg/m2 is needed. To apply this ballast, a height of 78 mm is needed for the concrete blocks. With the springs stiffness of 10 kN/m the ballast will deform 5 mm, so, the free space needed inside the floor is 83 mm. This means that there is 55 mm of free space left for a spring system that needs to deform 5 mm. This can for example be achieved by a rubber strip, with the appropriate spring stiffness.

7.5 Combined Optimisations

The practical application of the combined optimisations is limited. The high concentrated mass already takes up all the available space inside the floor elements. There is no space left to apply the springs inside the floor, while these also require a significant amount of height inside the floor.

8 Conclusion

The main goal of this research is to decrease the additional mass needed on timber floor systems to comply with the vibration requirements. The following research question was formulated:

"Can the placement of strategic mass and/or the appliance of spring and tuned mass dampers, be used to improve the serviceability performance of timber floor systems in residential or office buildings, with regards to human-induced vibrations?"

The first part of the research focused on the analytical vibration analysis of four different timber floor systems. From this phase, it can be concluded that when the floors are designed based on the ULS + deflection, the vibration performance is not in line with the requirements. To comply with the right vibration class, an increase in section height and/or an increase in mass is needed.

The performance of the CLT and Lignatur floor systems is comparable with respect to the vibration performance. The CLT has slightly better performance due to the higher effective width that can be taken into account. However, the Lignatur floor has a higher potential due to the possibility of applying ballast inside the floor system.

Both the Joist and Kerto Ripa Rib floors have difficulties reaching the desired vibration class. Due to their low self-weight, the modal mass of these floors will always be low. Next to the low self-weight, the modal mass is also low due to the small effective width that can be taken into account. These floor types need a significant increase in structural section height to comply with the vibration requirements. For the joist floor, the desired vibration class cannot be reached for spans of 4 meters and larger with the standardized dimensions.

During the second part, optimisations of the mass applied to the floor systems are researched. Two different optimization types can be distinguished: strategically placed mass and mass on springs. The goal of the optimizations is to reduce the amount of mass in the floor system while maintaining the desired acceleration level.

For the strategically placed mass, it was found that a decrease in mass of 36,67% is theoretically possible for the standard floor, when the ballast is concentrated in the middle of the floor. When applying this in practice, only a decrease of 33,33% is possible. This is due to the fact that the volume of the ballast will not fit inside the floor for highly concentrated ballast.

When changing the spans and corresponding sections of the floors, the amount of mass reduction is in a similar range as the standard floor. A change in user function from office to residential results in a higher permanent mass on the floor. However, the reduction in mass is still comparable to the office floor. An increase in damping value has a positive effect on the vibration performance of the floor in general. However, the change in damping value does still yield the same mass reduction for the floor.

The width of the floor has a significant impact on the reduction in mass. Due to the different mode shapes, the mass in the transverse direction is also variable. When designing for each specific floor, a reduction in mass up to 68,00% is feasible. However, the decrease is different depending on the floor width.

The mass on springs can theoretically reduce the additional mass by 50,00%. However, practically this would result in a complex spring system. A reduction of 25,00% is possible with a higher spring stiffness. This solution is practically possible.

The combination of both optimisations methods results in an even larger decrease of additional mass for the Lignatur floor system. This however is a theoretical reduction, while this solution would take up to much space inside the floor system.

In conclusion, when answering the research question, it can be said that for both of the optimisation methods, a reduction in mass is possible while maintaining the desired acceleration level for the timber floor system.

9 Recommendation

The results following from this thesis allow for further research. Different aspects can be recommended for further research. These aspects are explained in the following chapter.

9.1 Variable Floor Width

As was found in the research, the width of the timber floor system has a large impact on the potential mass decrease of the system. For floor structures, which are more than one Lignatur element wide, the location of the mass in the transverse direction becomes critical. This can be explained due to the different mode shapes acting on the wider floor structures. The research was only performed on floors with a width of 1, 3 and 5 meters. The results for the 3 and 5-meter-wide floors showed a large decrease in ballast on the floor. This, however, is floor-specific and a separate vibration analysis needs to be performed for every individual floor. For the different spans of the Lignatur floor, a common thread was found, which could be applied to calculate the reduction in mass for the floors. Further research of different widths is recommended so that a common thread can also be found for the location of the strategic mass in the transverse direction.

9.2 Implementation of Springs

The ballast placed on springs can have a positive effect on the vibration performance of a timber floor system. Especially, when springs with a low stiffness are applied, a significant reduction in ballast is possible. However, the implementation of these springs in practice is a difficult aspect. A spring system should be created that is compact so it can fit inside the Lignatur floor elements, while also allowing for large deformations of the ballast. When the ballast cannot deform at the desired amplitude, the reduction of vibration is less effective. Further research for this thesis could be the design of such a spring system that can be applied in practice.

9.3 Acoustic Analysis

The reduction of mass calculated in this research complies with the vibrations caused by humans walking on the floor. However, another serviceability criterion for a floor is acoustic performance. For the acoustic performance, there is also mass needed on or in the floor system to reduce the propagation of sound. When the mass is concentrated and placed in the middle of the floor, the edges have significantly less mass, which can negatively affect acoustic performance at these specific locations. More research is needed to determine the impact of the proposed optimisations on the acoustic performance of timber floor systems. So that in practice, all the serviceability criteria can be considered when applying mass optimisations.

9.4 Floor Boundary Conditions

In this research, the timber floor elements are modelled as one-way spanning. They have a hinged support on one side and a roller support on the other side. The edges of all the floors are modelled freely. In practice, different boundary conditions are present for a floor element. For example, the edges may be horizontally or vertically supported. For a CLT floor, the floor can be designed as two-way spanning instead of one. The support conditions also influence vibration performance. A fixed connection will yield completely different frequencies and mode shapes for the floor. The boundary conditions in practice are often different from the conditions used for the theoretical analysis. Therefore, the effects of these changes in boundary conditions can be used for further research.

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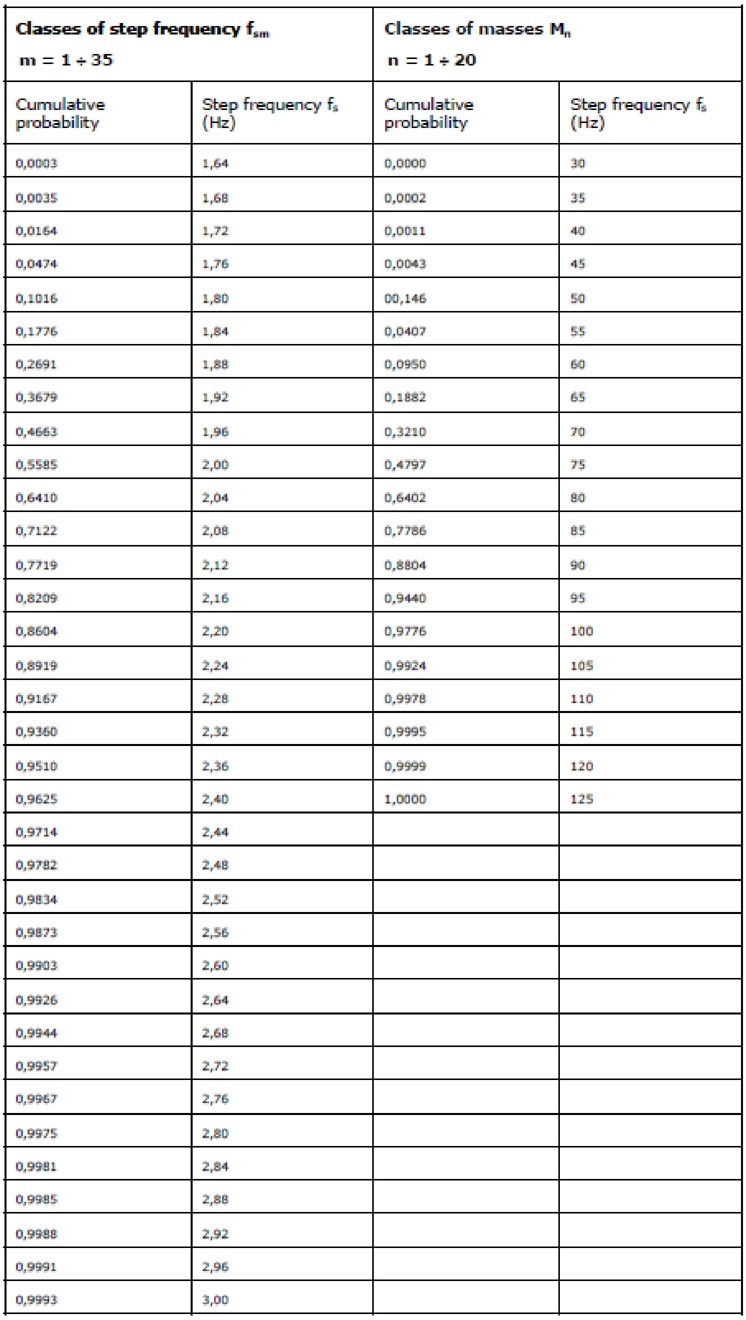
A OS-RMS Data

A.1 Cumulative distributions of frequency and body mass



Classes of step frequency f_{sm} m = 1 ÷ 35		Classes of masses M_n n = 1 ÷ 20	
Cumulative probability	Step frequency f_s (Hz)	Cumulative probability	Step frequency f_s (Hz)
0,0003	1,64	0,0000	30
0,0035	1,68	0,0002	35
0,0164	1,72	0,0011	40
0,0474	1,76	0,0043	45
0,1016	1,80	00,146	50
0,1776	1,84	0,0407	55
0,2691	1,88	0,0950	60
0,3679	1,92	0,1882	65
0,4663	1,96	0,3210	70
0,5585	2,00	0,4797	75
0,6410	2,04	0,6402	80
0,7122	2,08	0,7786	85
0,7719	2,12	0,8804	90
0,8209	2,16	0,9440	95
0,8604	2,20	0,9776	100
0,8919	2,24	0,9924	105
0,9167	2,28	0,9978	110
0,9360	2,32	0,9995	115
0,9510	2,36	0,9999	120
0,9625	2,40	1,0000	125
0,9714	2,44		
0,9782	2,48		
0,9834	2,52		
0,9873	2,56		
0,9903	2,60		
0,9926	2,64		
0,9944	2,68		
0,9957	2,72		
0,9967	2,76		
0,9975	2,80		
0,9981	2,84		
0,9985	2,88		
0,9988	2,92		
0,9991	2,96		
0,9993	3,00		

Figure 40: [9]

A.2 OS-RMS graphs

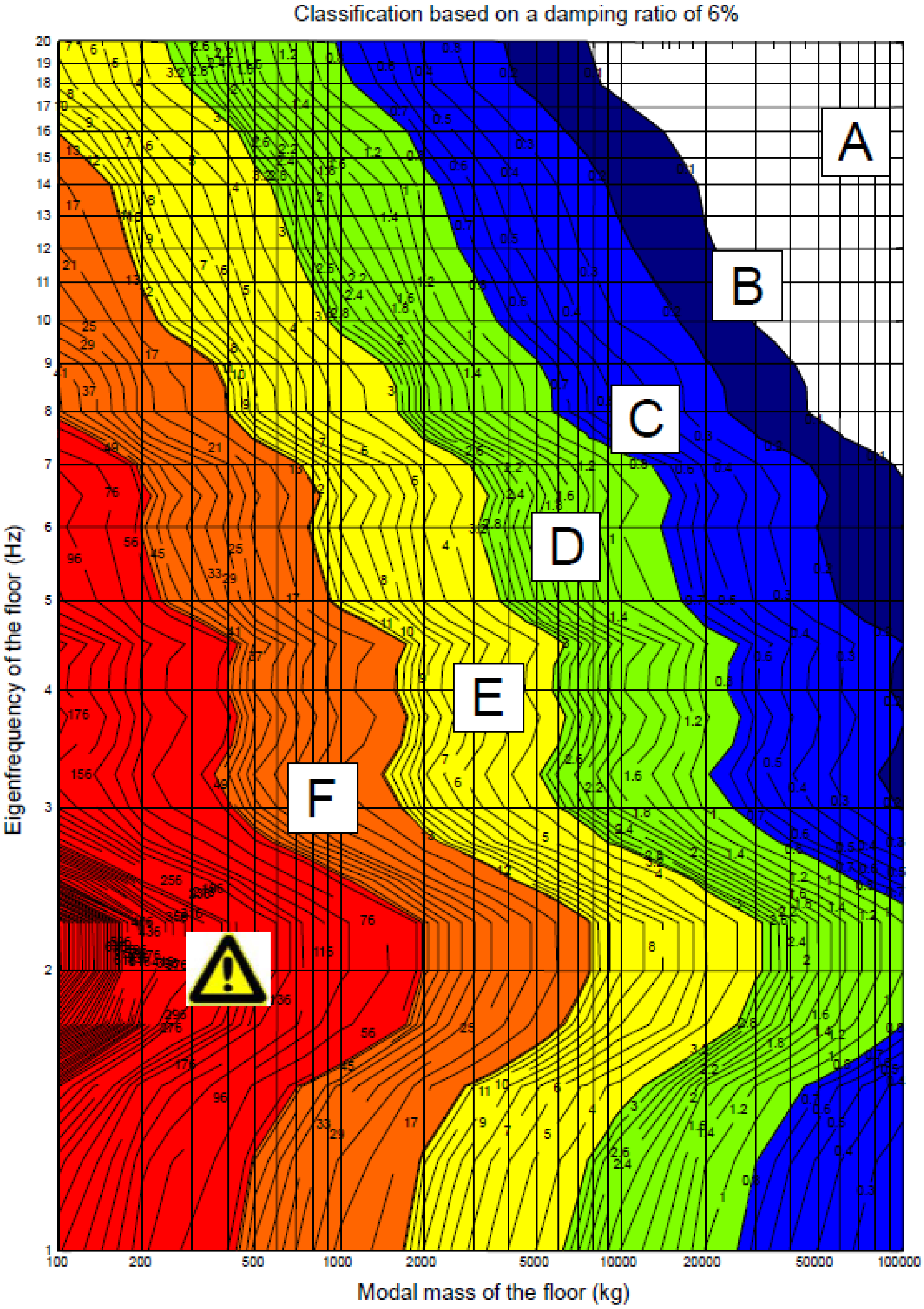


Figure 41: [9]

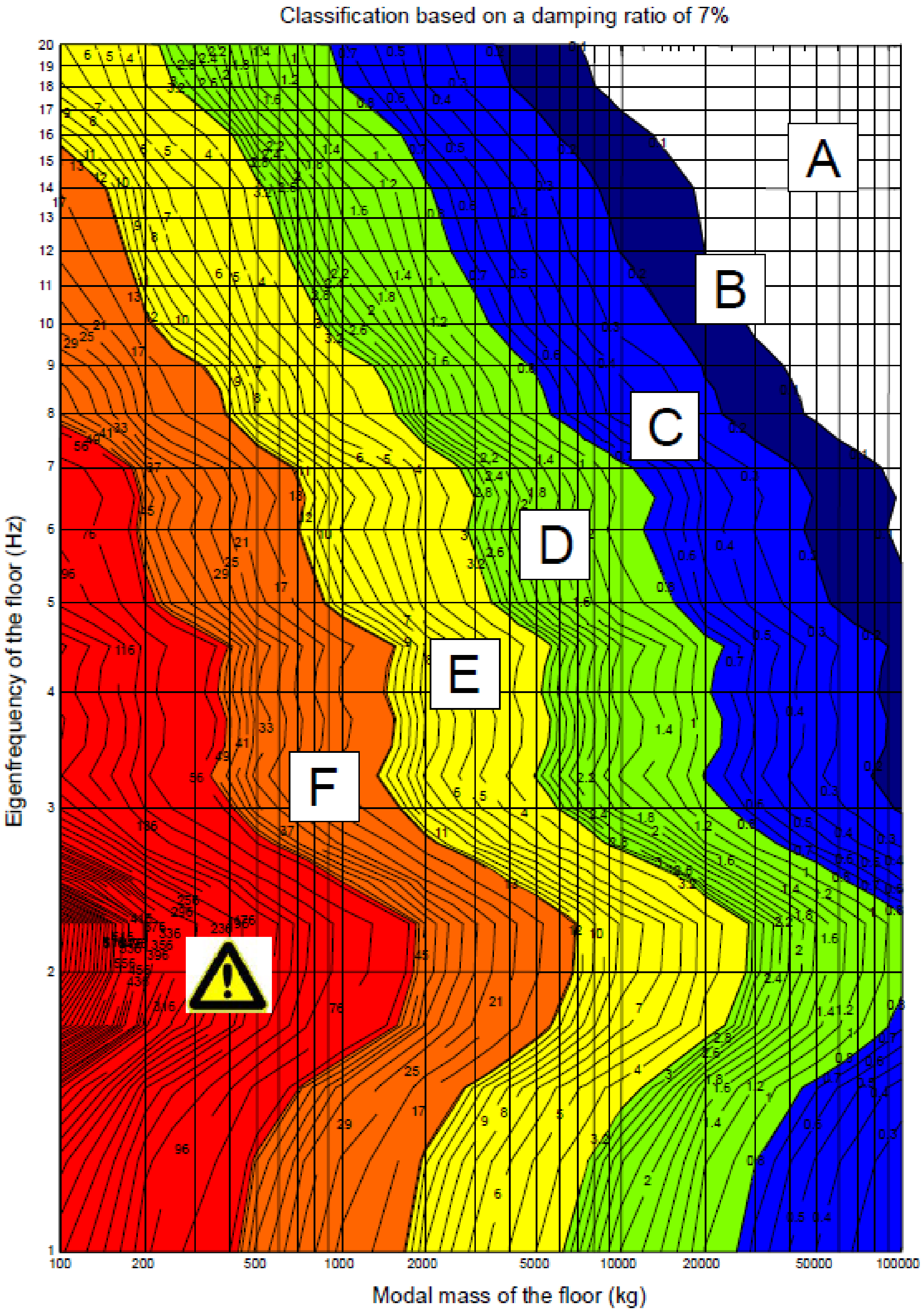

Classification based on a damping ratio of 7%
Eigenfrequency of the floor (Hz)
Modal mass of the floor (kg)
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
100
200
500
1000
2000
5000
10000
20000
50000
100000
A
B
C
D
E
F

Figure 42: [9]

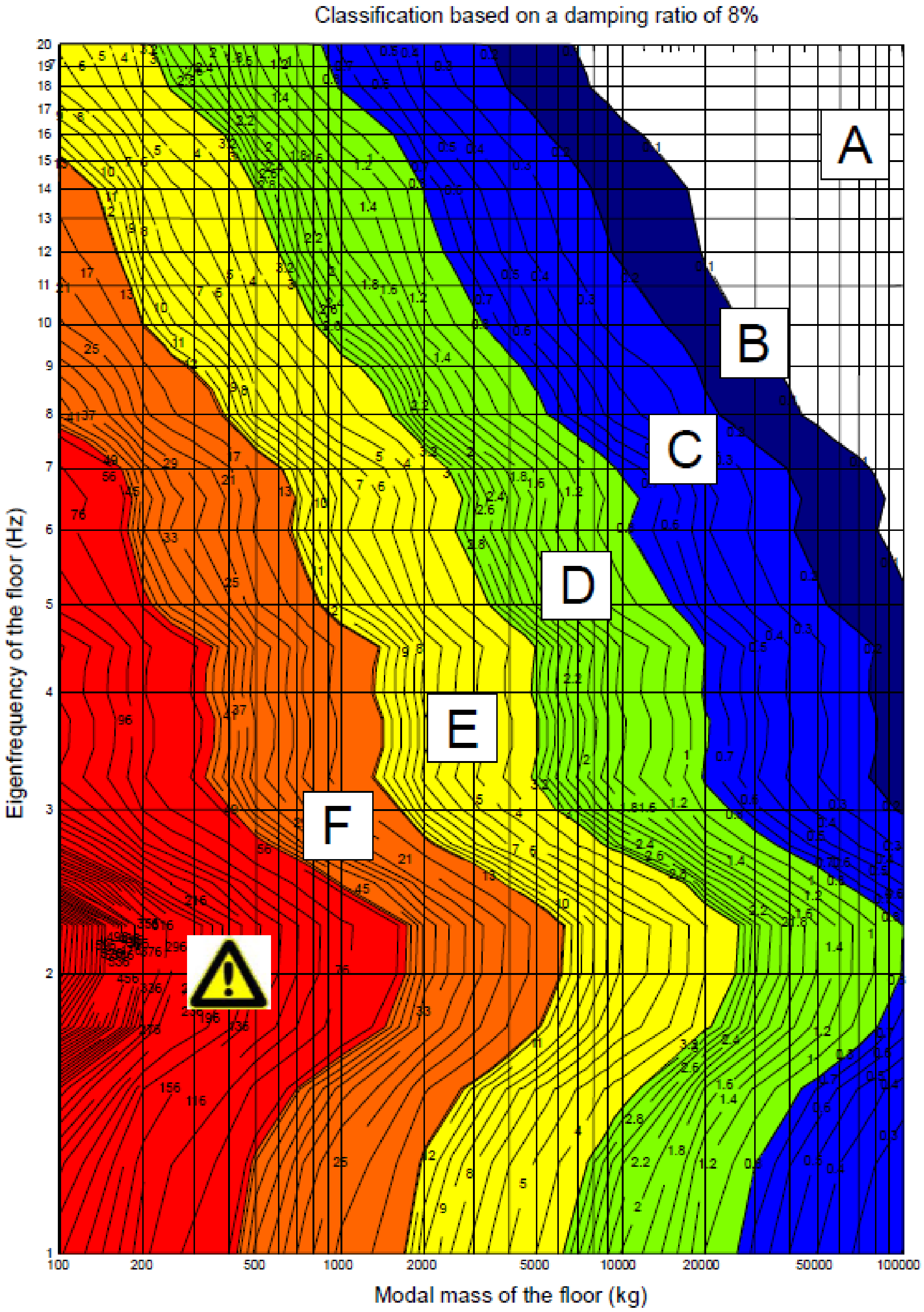

Classification based on a damping ratio of 8%
Eigenfrequency of the floor (Hz)
Modal mass of the floor (kg)
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
100
200
500
1000
2000
5000
10000
20000
50000
100000
A
B
C
D
E
F

Figure 43: [9]

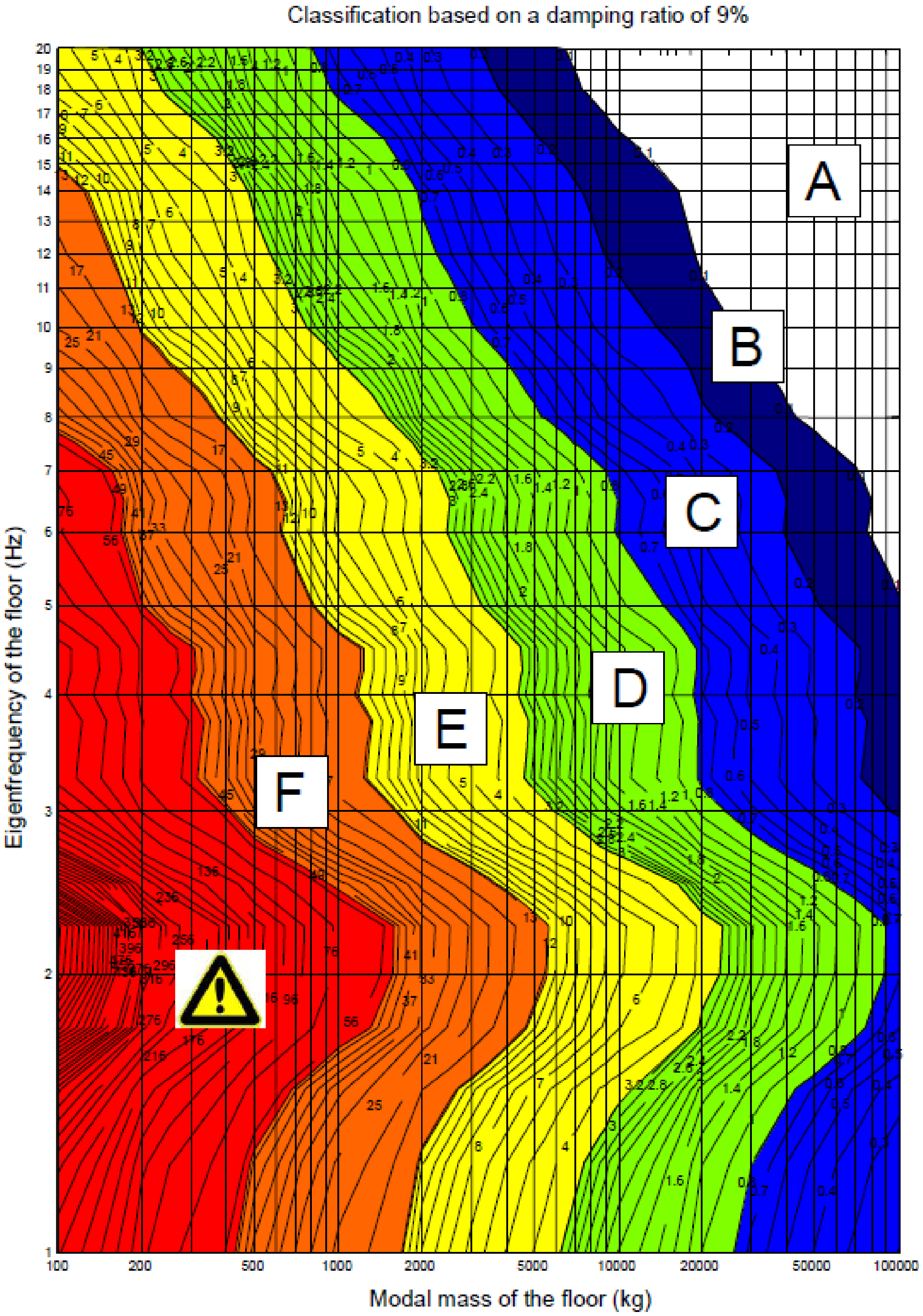
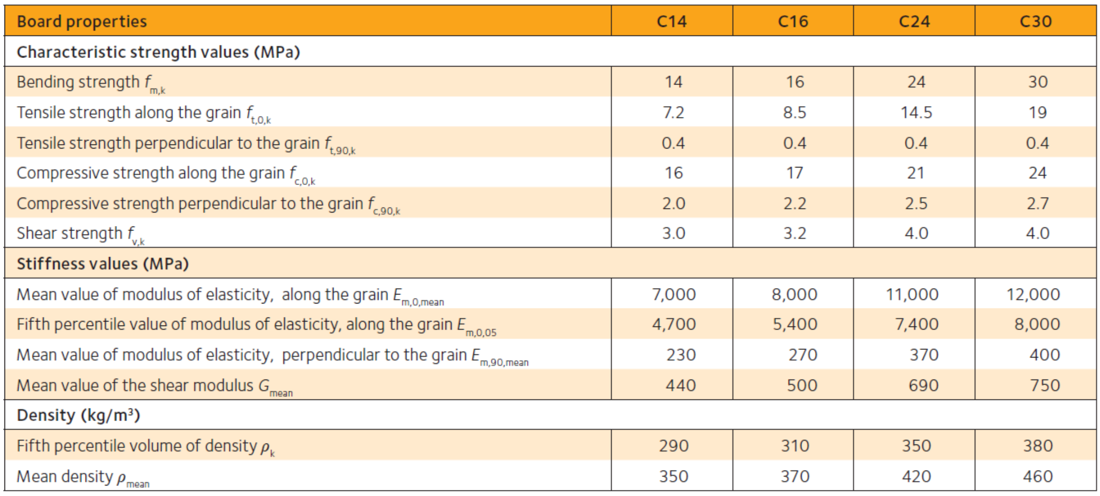

Classification based on a damping ratio of 9%
Eigenfrequency of the floor (Hz)
Modal mass of the floor (kg)
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
100
200
500
1000
2000
5000
10000
20000
50000
100000
A
B
C
D
E
F

Figure 44: [9]

B Timber Floor Systems

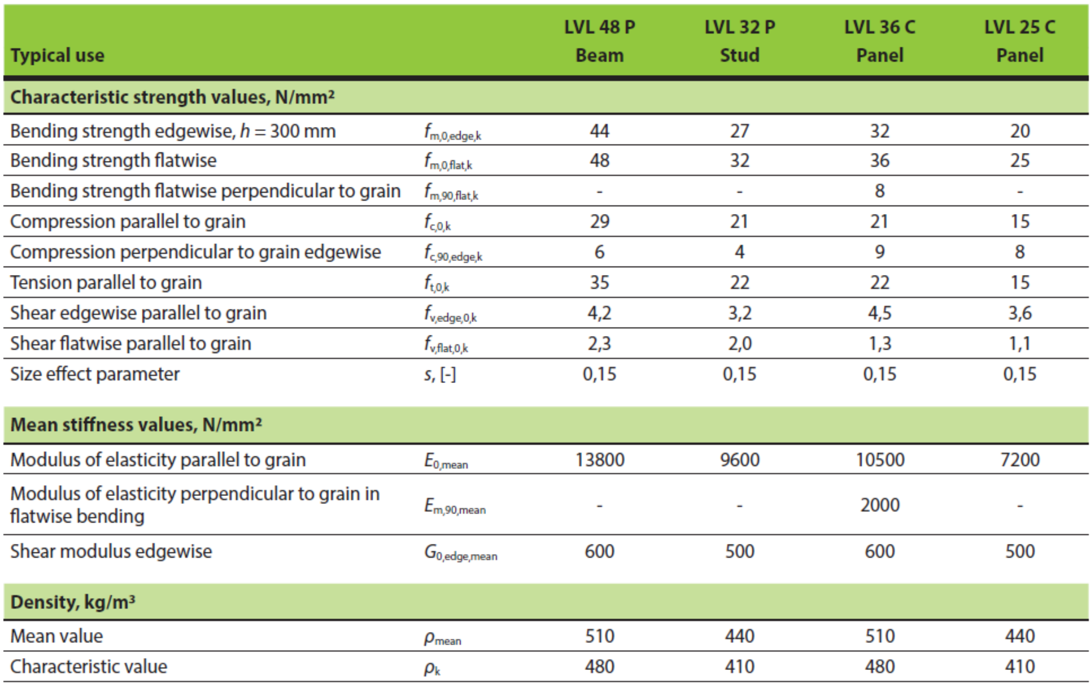
B.1 C24 timber properties



Board properties	C14	C16	C24	C30
Characteristic strength values (MPa)				
Bending strength $f_{m,k}$	14	16	24	30
Tensile strength along the grain $f_{t,0,k}$	7.2	8.5	14.5	19
Tensile strength perpendicular to the grain $f_{t,90,k}$	0.4	0.4	0.4	0.4
Compressive strength along the grain $f_{c,0,k}$	16	17	21	24
Compressive strength perpendicular to the grain $f_{c,90,k}$	2.0	2.2	2.5	2.7
Shear strength $f_{v,k}$	3.0	3.2	4.0	4.0
Stiffness values (MPa)				
Mean value of modulus of elasticity, along the grain $E_{m,0,mean}$	7,000	8,000	11,000	12,000
Fifth percentile value of modulus of elasticity, along the grain $E_{m,0,05}$	4,700	5,400	7,400	8,000
Mean value of modulus of elasticity, perpendicular to the grain $E_{m,90,mean}$	230	270	370	400
Mean value of the shear modulus G_{mean}	440	500	690	750
Density (kg/m³)				
Fifth percentile volume of density ρ_k	290	310	350	380
Mean density ρ_{mean}	350	370	420	460

Figure 45: [14]

B.2 LVL timber properties

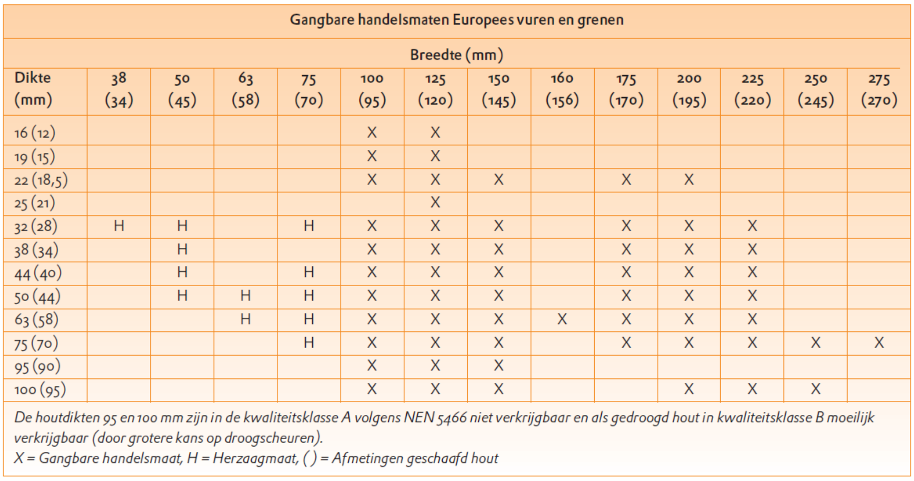


Typical use		LVL 48 P Beam	LVL 32 P Stud	LVL 36 C Panel	LVL 25 C Panel
Characteristic strength values, N/mm²					
Bending strength edgewise, $h = 300$ mm	$f_{m,0,edge,k}$	44	27	32	20
Bending strength flatwise	$f_{m,0,flat,k}$	48	32	36	25
Bending strength flatwise perpendicular to grain	$f_{m,90,flat,k}$	-	-	8	-
Compression parallel to grain	$f_{c,0,k}$	29	21	21	15
Compression perpendicular to grain edgewise	$f_{c,90,edge,k}$	6	4	9	8
Tension parallel to grain	$f_{t,0,k}$	35	22	22	15
Shear edgewise parallel to grain	$f_{v,edge,0,k}$	4,2	3,2	4,5	3,6
Shear flatwise parallel to grain	$f_{v,flat,0,k}$	2,3	2,0	1,3	1,1
Size effect parameter	s, [-]	0,15	0,15	0,15	0,15
Mean stiffness values, N/mm²					
Modulus of elasticity parallel to grain	$E_{0,mean}$	13800	9600	10500	7200
Modulus of elasticity perpendicular to grain in flatwise bending	$E_{m,90,mean}$	-	-	2000	-
Shear modulus edgewise	$G_{0,edge,mean}$	600	500	600	500
Density, kg/m³					
Mean value	ρ_{mean}	510	440	510	440
Characteristic value	ρ_k	480	410	480	410

Figure 46: [15]

B.3 Standardized dimensions

B.3.1 Joist floor



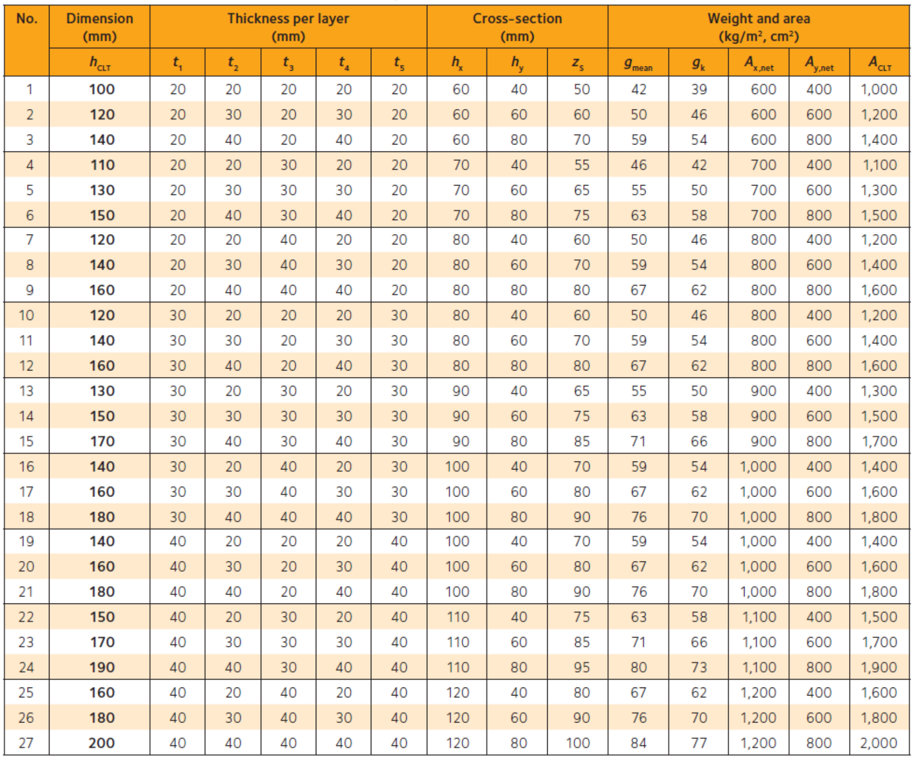
Gangbare handelsmaten Europees vuren en grenen

Dikte (mm)	Breedte (mm) 38 (34)	50 (45)	63 (58)	75 (70)	100 (95)	125 (120)	150 (145)	160 (156)	175 (170)	200 (195)	225 (220)	250 (245)	275 (270)
16 (12)					X	X							
19 (15)					X	X							
22 (18,5)					X	X	X		X	X			
25 (21)						X							
32 (28)	H	H		H	X	X	X		X	X	X		
38 (34)		H			X	X	X		X	X	X		
44 (40)		H		H	X	X	X		X	X	X		
50 (44)		H	H	H	X	X	X		X	X	X		
63 (58)			H	H	X	X	X	X	X	X	X		
75 (70)				H	X	X	X		X	X	X	X	X
95 (90)					X	X	X						
100 (95)					X	X	X			X	X	X	

De houtdikten 95 en 100 mm zijn in de kwaliteitsklasse A volgens NEN 5466 niet verkrijgbaar en als gedroogd hout in kwaliteitsklasse B moeilijk verkrijgbaar (door grotere kans op droogscheuren).
X = Gangbare handelsmaat, H = Herzaagmaat, ( ) = Afmetingen geschaafd hout

Figure 47: [5]

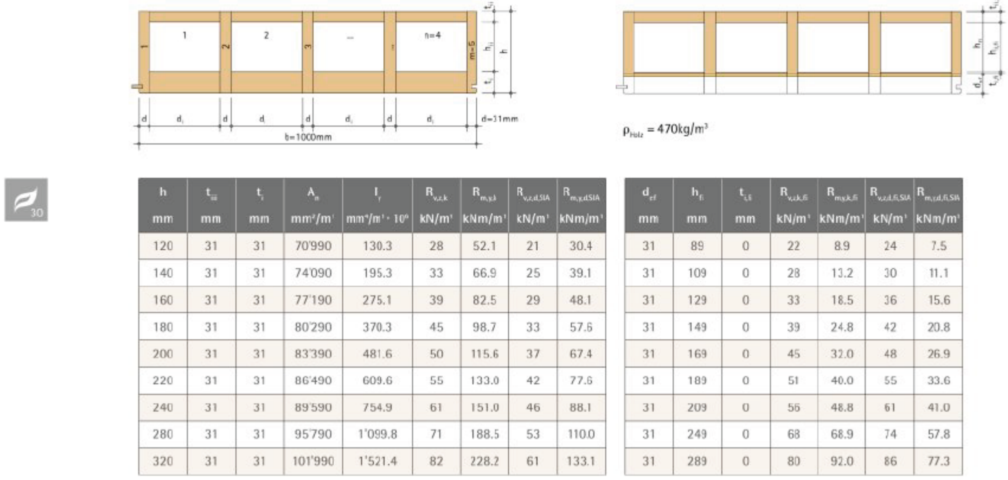
B.3.2 CLT floor



No.	Dimension (mm)	Thickness per layer (mm)					Cross-section (mm)			Weight and area (kg/m², cm²)				
	h_{CLT}	t_1	t_2	t_3	t_4	t_5	h_x	h_y	z_s	g_{mean}	g_k	$A_{x,net}$	$A_{y,net}$	A_{CLT}
1	**100**	20	20	20	20	20	60	40	50	42	39	600	400	1,000
2	**120**	20	30	20	30	20	60	60	60	50	46	600	600	1,200
3	**140**	20	40	20	40	20	60	80	70	59	54	600	800	1,400
4	**110**	20	20	30	20	20	70	40	55	46	42	700	400	1,100
5	**130**	20	30	30	30	20	70	60	65	55	50	700	600	1,300
6	**150**	20	40	30	40	20	70	80	75	63	58	700	800	1,500
7	**120**	20	20	40	20	20	80	40	60	50	46	800	400	1,200
8	**140**	20	30	40	30	20	80	60	70	59	54	800	600	1,400
9	**160**	20	40	40	40	20	80	80	80	67	62	800	800	1,600
10	**120**	30	20	20	20	30	80	40	60	50	46	800	400	1,200
11	**140**	30	30	20	30	30	80	60	70	59	54	800	600	1,400
12	**160**	30	40	20	40	30	80	80	80	67	62	800	800	1,600
13	**130**	30	20	30	20	30	90	40	65	55	50	900	400	1,300
14	**150**	30	30	30	30	30	90	60	75	63	58	900	600	1,500
15	**170**	30	40	30	40	30	90	80	85	71	66	900	800	1,700
16	**140**	30	20	40	20	30	100	40	70	59	54	1,000	400	1,400
17	**160**	30	30	40	30	30	100	60	80	67	62	1,000	600	1,600
18	**180**	30	40	40	40	30	100	80	90	76	70	1,000	800	1,800
19	**140**	40	20	20	20	40	100	40	70	59	54	1,000	400	1,400
20	**160**	40	30	20	30	40	100	60	80	67	62	1,000	600	1,600
21	**180**	40	40	20	40	40	100	80	90	76	70	1,000	800	1,800
22	**150**	40	20	30	20	40	110	40	75	63	58	1,100	400	1,500
23	**170**	40	30	30	30	40	110	60	85	71	66	1,100	600	1,700
24	**190**	40	40	30	40	40	110	80	95	80	73	1,100	800	1,900
25	**160**	40	20	40	20	40	120	40	80	67	62	1,200	400	1,600
26	**180**	40	30	40	30	40	120	60	90	76	70	1,200	600	1,800
27	**200**	40	40	40	40	40	120	80	100	84	77	1,200	800	2,000

Figure 48: [14]

B.3.3 Lignatur floor

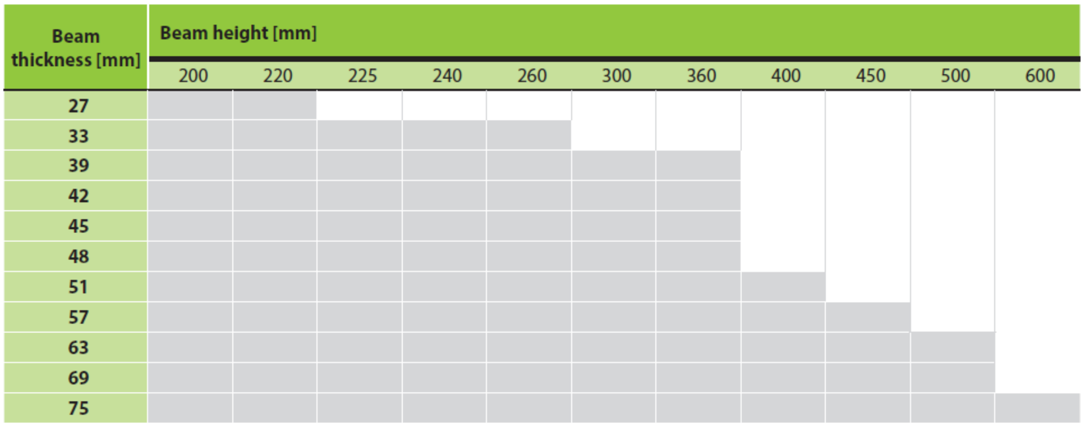


h mm	t_u mm	t_l mm	A_n mm²/m'	I_y mm⁴/m' · 10⁶	$R_{v,z,k}$ kN/m'	$R_{m,y,k}$ kNm/m'	$R_{v,z,d,SIA}$ kN/m'	$R_{m,y,d,SIA}$ kNm/m'
120	31	31	70'990	130.3	28	52.1	21	30.4
140	31	31	74'090	195.3	33	66.9	25	39.1
160	31	31	77'190	275.1	39	82.5	29	48.1
180	31	31	80'290	370.3	45	98.7	33	57.6
200	31	31	83'390	481.6	50	115.6	37	67.4
220	31	31	86'490	609.6	55	133.0	42	77.6
240	31	31	89'590	754.9	61	151.0	46	88.1
280	31	31	95'790	1'099.8	71	188.5	53	110.0
320	31	31	101'990	1'521.4	82	228.2	61	133.1

d_{ef} mm	h_{fi} mm	$t_{l,fi}$ mm	$R_{v,z,k,fi}$ kN/m'	$R_{m,y,k,fi}$ kNm/m'	$R_{v,z,d,fi,SIA}$ kN/m'	$R_{m,y,d,fi,SIA}$ kNm/m'
31	89	0	22	8.9	24	7.5
31	109	0	28	13.2	30	11.1
31	129	0	33	18.5	36	15.6
31	149	0	39	24.8	42	20.8
31	169	0	45	32.0	48	26.9
31	189	0	51	40.0	55	33.6
31	209	0	56	48.8	61	41.0
31	249	0	68	68.9	74	57.8
31	289	0	80	92.0	86	77.3

Figure 49: [21]

B.3.4 Kerto Ripa Rib floor



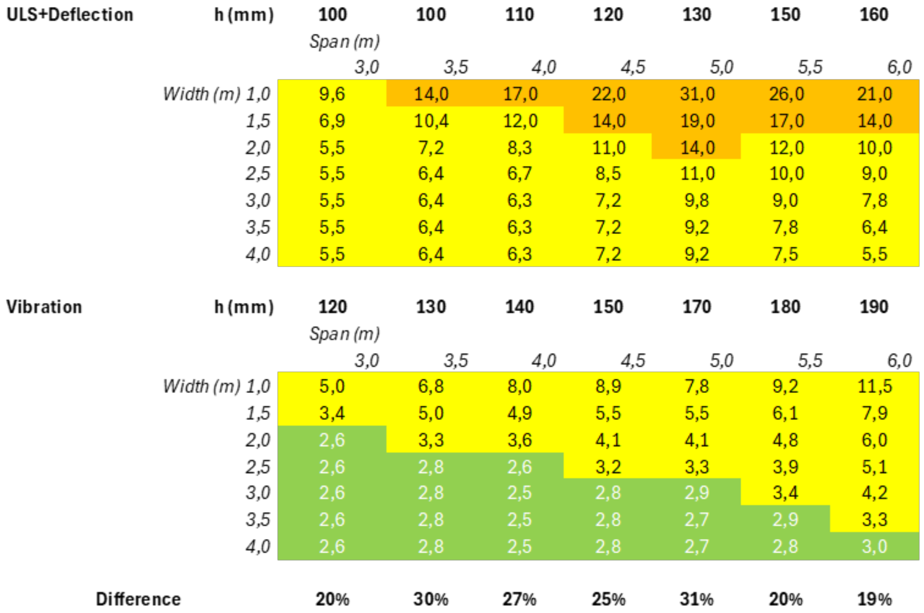
Beam thickness [mm]	Beam height [mm] 200	220	225	240	260	300	360	400	450	500	600
27	▨	▨									
33	▨	▨	▨	▨	▨						
39	▨	▨	▨	▨	▨	▨	▨				
42	▨	▨	▨	▨	▨	▨	▨				
45	▨	▨	▨	▨	▨	▨	▨				
48	▨	▨	▨	▨	▨	▨	▨				
51	▨	▨	▨	▨	▨	▨	▨	▨			
57	▨	▨	▨	▨	▨	▨	▨	▨	▨		
63	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	
69	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	
75	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨

Figure 50: [15]

C Results Analytical Analysis

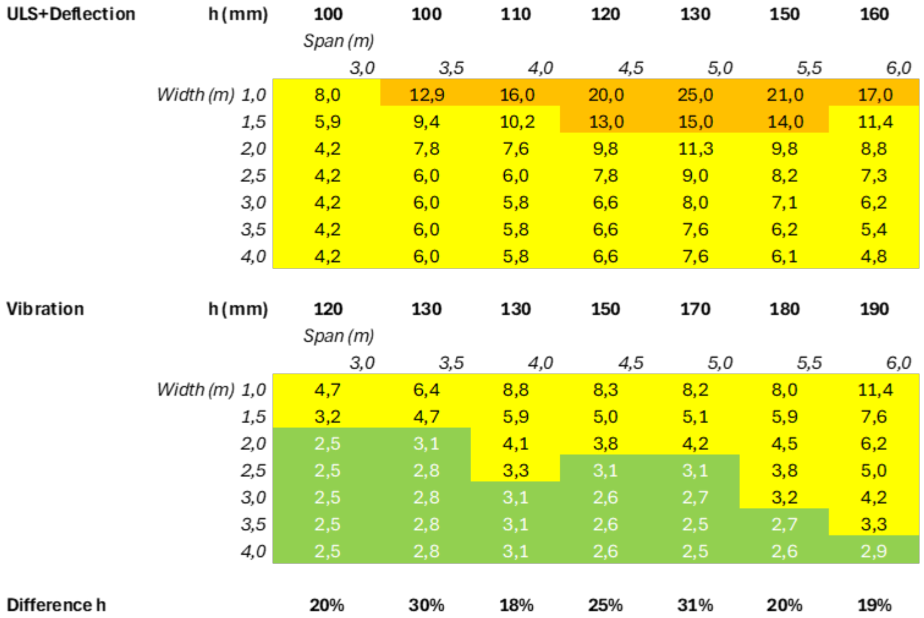
C.1 No additional mass

C.1.1 CLT



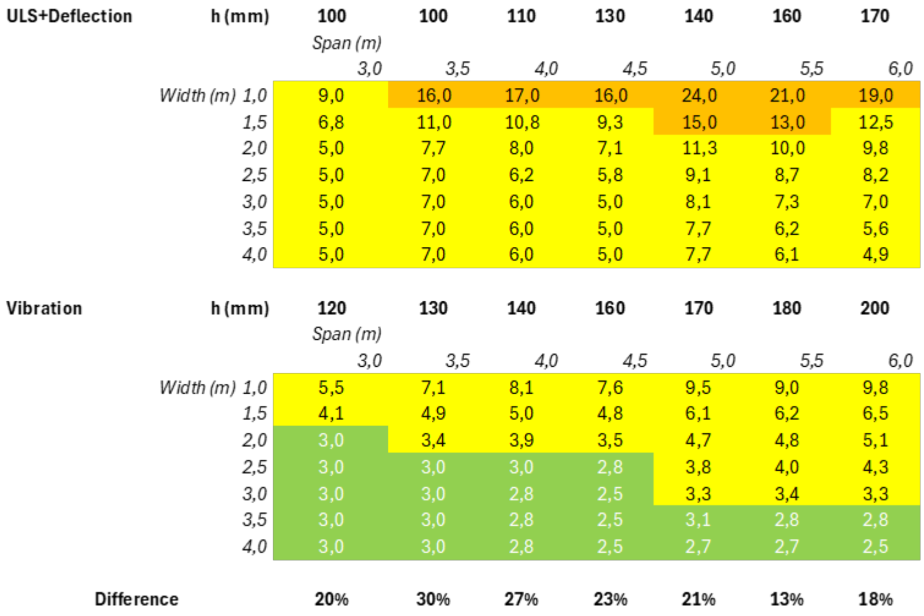
ULS+Deflection	h (mm)	100	100	110	120	130	150	160
	Span (m)	3,0	3,5	4,0	4,5	5,0	5,5	6,0
	Width (m) 1,0	9,6	14,0	17,0	22,0	31,0	26,0	21,0
	1,5	6,9	10,4	12,0	14,0	19,0	17,0	14,0
	2,0	5,5	7,2	8,3	11,0	14,0	12,0	10,0
	2,5	5,5	6,4	6,7	8,5	11,0	10,0	9,0
	3,0	5,5	6,4	6,3	7,2	9,8	9,0	7,8
	3,5	5,5	6,4	6,3	7,2	9,2	7,8	6,4
	4,0	5,5	6,4	6,3	7,2	9,2	7,5	5,5
Vibration	h (mm)	120	130	140	150	170	180	190
	Span (m)	3,0	3,5	4,0	4,5	5,0	5,5	6,0
	Width (m) 1,0	5,0	6,8	8,0	8,9	7,8	9,2	11,5
	1,5	3,4	5,0	4,9	5,5	5,5	6,1	7,9
	2,0	2,6	3,3	3,6	4,1	4,1	4,8	6,0
	2,5	2,6	2,8	2,6	3,2	3,3	3,9	5,1
	3,0	2,6	2,8	2,5	2,8	2,9	3,4	4,2
	3,5	2,6	2,8	2,5	2,8	2,7	2,9	3,3
	4,0	2,6	2,8	2,5	2,8	2,7	2,8	3,0
Difference		20%	30%	27%	25%	31%	20%	19%

Figure 51: CLT Residential 7% damping



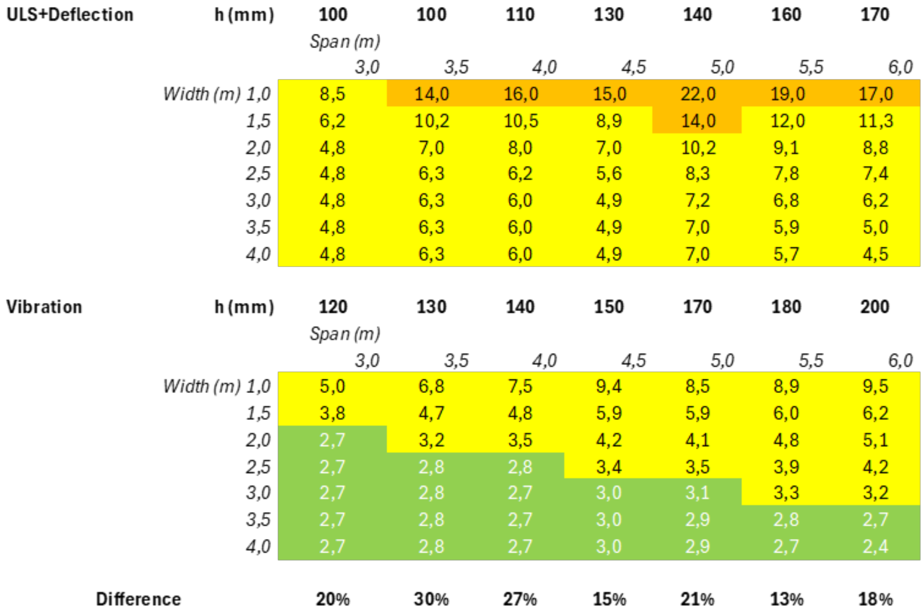
ULS+Deflection	h (mm)	100	100	110	120	130	150	160
	Span (m)	3,0	3,5	4,0	4,5	5,0	5,5	6,0
	Width (m) 1,0	8,0	12,9	16,0	20,0	25,0	21,0	17,0
	1,5	5,9	9,4	10,2	13,0	15,0	14,0	11,4
	2,0	4,2	7,8	7,6	9,8	11,3	9,8	8,8
	2,5	4,2	6,0	6,0	7,8	9,0	8,2	7,3
	3,0	4,2	6,0	5,8	6,6	8,0	7,1	6,2
	3,5	4,2	6,0	5,8	6,6	7,6	6,2	5,4
	4,0	4,2	6,0	5,8	6,6	7,6	6,1	4,8
Vibration	h (mm)	120	130	130	150	170	180	190
	Span (m)	3,0	3,5	4,0	4,5	5,0	5,5	6,0
	Width (m) 1,0	4,7	6,4	8,8	8,3	8,2	8,0	11,4
	1,5	3,2	4,7	5,9	5,0	5,1	5,9	7,6
	2,0	2,5	3,1	4,1	3,8	4,2	4,5	6,2
	2,5	2,5	2,8	3,3	3,1	3,1	3,8	5,0
	3,0	2,5	2,8	3,1	2,6	2,7	3,2	4,2
	3,5	2,5	2,8	3,1	2,6	2,5	2,7	3,3
	4,0	2,5	2,8	3,1	2,6	2,5	2,6	2,9
Difference h		20%	30%	18%	25%	31%	20%	19%

Figure 52: CLT Residential 8% damping



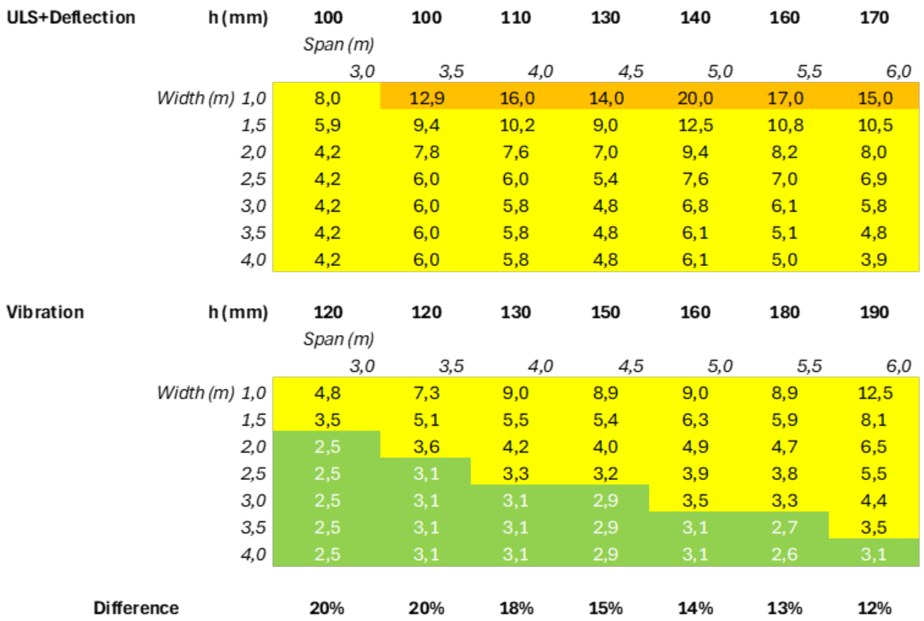
ULS+Deflection	h (mm)	100	100	110	130	140	160	170
	Span (m)	3,0	3,5	4,0	4,5	5,0	5,5	6,0
	Width (m) 1,0	9,0	16,0	17,0	16,0	24,0	21,0	19,0
	1,5	6,8	11,0	10,8	9,3	15,0	13,0	12,5
	2,0	5,0	7,7	8,0	7,1	11,3	10,0	9,8
	2,5	5,0	7,0	6,2	5,8	9,1	8,7	8,2
	3,0	5,0	7,0	6,0	5,0	8,1	7,3	7,0
	3,5	5,0	7,0	6,0	5,0	7,7	6,2	5,6
	4,0	5,0	7,0	6,0	5,0	7,7	6,1	4,9
Vibration	**h (mm)**	**120**	**130**	**140**	**160**	**170**	**180**	**200**
	Span (m)	3,0	3,5	4,0	4,5	5,0	5,5	6,0
	Width (m) 1,0	5,5	7,1	8,1	7,6	9,5	9,0	9,8
	1,5	4,1	4,9	5,0	4,8	6,1	6,2	6,5
	2,0	3,0	3,4	3,9	3,5	4,7	4,8	5,1
	2,5	3,0	3,0	3,0	2,8	3,8	4,0	4,3
	3,0	3,0	3,0	2,8	2,5	3,3	3,4	3,3
	3,5	3,0	3,0	2,8	2,5	3,1	2,8	2,8
	4,0	3,0	3,0	2,8	2,5	2,7	2,7	2,5
Difference		**20%**	**30%**	**27%**	**23%**	**21%**	**13%**	**18%**

Figure 53: CLT Office 6% damping



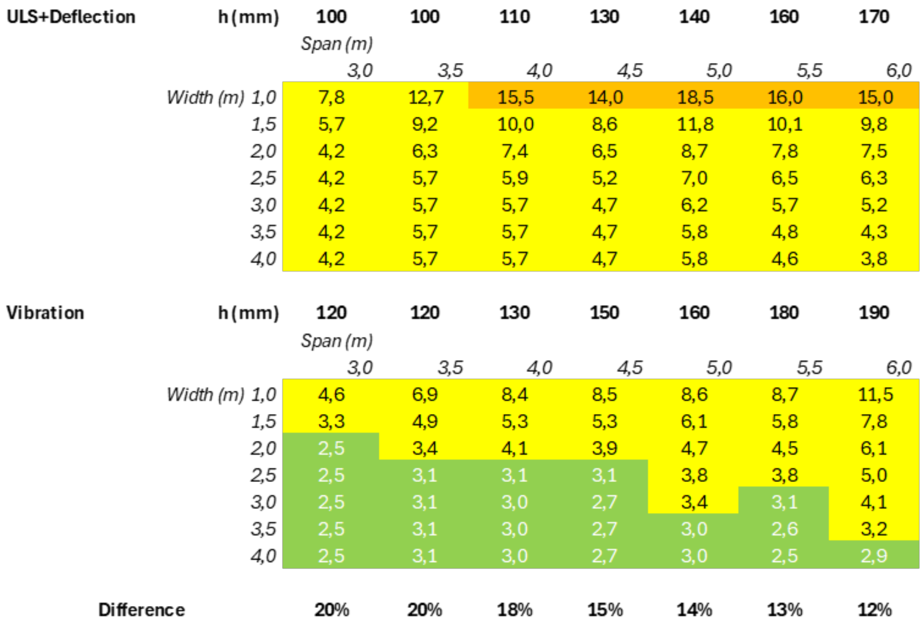
ULS+Deflection	h (mm)	100	100	110	130	140	160	170
	Span (m)	3,0	3,5	4,0	4,5	5,0	5,5	6,0
	Width (m) 1,0	8,5	14,0	16,0	15,0	22,0	19,0	17,0
	1,5	6,2	10,2	10,5	8,9	14,0	12,0	11,3
	2,0	4,8	7,0	8,0	7,0	10,2	9,1	8,8
	2,5	4,8	6,3	6,2	5,6	8,3	7,8	7,4
	3,0	4,8	6,3	6,0	4,9	7,2	6,8	6,2
	3,5	4,8	6,3	6,0	4,9	7,0	5,9	5,0
	4,0	4,8	6,3	6,0	4,9	7,0	5,7	4,5
Vibration	**h (mm)**	**120**	**130**	**140**	**150**	**170**	**180**	**200**
	Span (m)	3,0	3,5	4,0	4,5	5,0	5,5	6,0
	Width (m) 1,0	5,0	6,8	7,5	9,4	8,5	8,9	9,5
	1,5	3,8	4,7	4,8	5,9	5,9	6,0	6,2
	2,0	2,7	3,2	3,5	4,2	4,1	4,8	5,1
	2,5	2,7	2,8	2,8	3,4	3,5	3,9	4,2
	3,0	2,7	2,8	2,7	3,0	3,1	3,3	3,2
	3,5	2,7	2,8	2,7	3,0	2,9	2,8	2,7
	4,0	2,7	2,8	2,7	3,0	2,9	2,7	2,4
Difference		**20%**	**30%**	**27%**	**15%**	**21%**	**13%**	**18%**

Figure 54: CLT Office 7% damping



ULS+Deflection	h (mm)	100	100	110	130	140	160	170
	Span (m)	*3,0*	*3,5*	*4,0*	*4,5*	*5,0*	*5,5*	*6,0*
	Width (m) 1,0	8,0	12,9	16,0	14,0	20,0	17,0	15,0
	1,5	5,9	9,4	10,2	9,0	12,5	10,8	10,5
	2,0	4,2	7,8	7,6	7,0	9,4	8,2	8,0
	2,5	4,2	6,0	6,0	5,4	7,6	7,0	6,9
	3,0	4,2	6,0	5,8	4,8	6,8	6,1	5,8
	3,5	4,2	6,0	5,8	4,8	6,1	5,1	4,8
	4,0	4,2	6,0	5,8	4,8	6,1	5,0	3,9
Vibration	**h (mm)**	**120**	**120**	**130**	**150**	**160**	**180**	**190**
	Span (m)	*3,0*	*3,5*	*4,0*	*4,5*	*5,0*	*5,5*	*6,0*
	Width (m) 1,0	4,8	7,3	9,0	8,9	9,0	8,9	12,5
	1,5	3,5	5,1	5,5	5,4	6,3	5,9	8,1
	2,0	2,5	3,6	4,2	4,0	4,9	4,7	6,5
	2,5	2,5	3,1	3,3	3,2	3,9	3,8	5,5
	3,0	2,5	3,1	3,1	2,9	3,5	3,3	4,4
	3,5	2,5	3,1	3,1	2,9	3,1	2,7	3,5
	4,0	2,5	3,1	3,1	2,9	3,1	2,6	3,1
Difference		**20%**	**20%**	**18%**	**15%**	**14%**	**13%**	**12%**

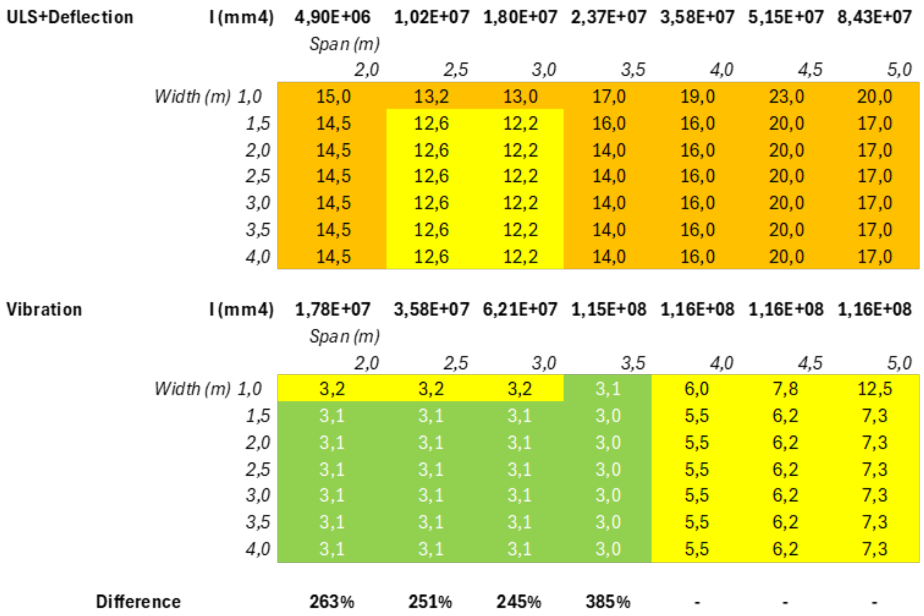
Figure 55: CLT Office 8% damping



ULS+Deflection	h (mm)	100	100	110	130	140	160	170
	Span (m)	*3,0*	*3,5*	*4,0*	*4,5*	*5,0*	*5,5*	*6,0*
	Width (m) 1,0	7,8	12,7	15,5	14,0	18,5	16,0	15,0
	1,5	5,7	9,2	10,0	8,6	11,8	10,1	9,8
	2,0	4,2	6,3	7,4	6,5	8,7	7,8	7,5
	2,5	4,2	5,7	5,9	5,2	7,0	6,5	6,3
	3,0	4,2	5,7	5,7	4,7	6,2	5,7	5,2
	3,5	4,2	5,7	5,7	4,7	5,8	4,8	4,3
	4,0	4,2	5,7	5,7	4,7	5,8	4,6	3,8
Vibration	**h (mm)**	**120**	**120**	**130**	**150**	**160**	**180**	**190**
	Span (m)	*3,0*	*3,5*	*4,0*	*4,5*	*5,0*	*5,5*	*6,0*
	Width (m) 1,0	4,6	6,9	8,4	8,5	8,6	8,7	11,5
	1,5	3,3	4,9	5,3	5,3	6,1	5,8	7,8
	2,0	2,5	3,4	4,1	3,9	4,7	4,5	6,1
	2,5	2,5	3,1	3,1	3,1	3,8	3,8	5,0
	3,0	2,5	3,1	3,0	2,7	3,4	3,1	4,1
	3,5	2,5	3,1	3,0	2,7	3,0	2,6	3,2
	4,0	2,5	3,1	3,0	2,7	3,0	2,5	2,9
Difference		**20%**	**20%**	**18%**	**15%**	**14%**	**13%**	**12%**

Figure 56: CLT Office 9% damping

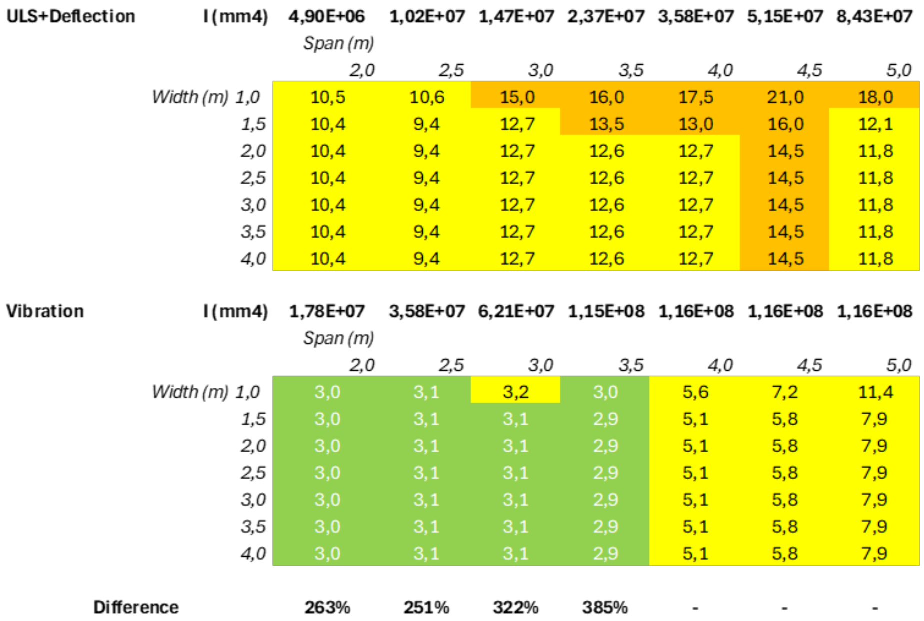
C.1.2 Joist



ULS+Deflection	**I (mm4)**	**4,90E+06**	**1,02E+07**	**1,80E+07**	**2,37E+07**	**3,58E+07**	**5,15E+07**	**8,43E+07**
		Span (m)						
		2,0	*2,5*	*3,0*	*3,5*	*4,0*	*4,5*	*5,0*
	Width (m) 1,0	15,0	13,2	13,0	17,0	19,0	23,0	20,0
	1,5	14,5	12,6	12,2	16,0	16,0	20,0	17,0
	2,0	14,5	12,6	12,2	14,0	16,0	20,0	17,0
	2,5	14,5	12,6	12,2	14,0	16,0	20,0	17,0
	3,0	14,5	12,6	12,2	14,0	16,0	20,0	17,0
	3,5	14,5	12,6	12,2	14,0	16,0	20,0	17,0
	4,0	14,5	12,6	12,2	14,0	16,0	20,0	17,0

Vibration	**I (mm4)**	**1,78E+07**	**3,58E+07**	**6,21E+07**	**1,15E+08**	**1,16E+08**	**1,16E+08**	**1,16E+08**
		Span (m)						
		2,0	*2,5*	*3,0*	*3,5*	*4,0*	*4,5*	*5,0*
	Width (m) 1,0	3,2	3,2	3,2	3,1	6,0	7,8	12,5
	1,5	3,1	3,1	3,1	3,0	5,5	6,2	7,3
	2,0	3,1	3,1	3,1	3,0	5,5	6,2	7,3
	2,5	3,1	3,1	3,1	3,0	5,5	6,2	7,3
	3,0	3,1	3,1	3,1	3,0	5,5	6,2	7,3
	3,5	3,1	3,1	3,1	3,0	5,5	6,2	7,3
	4,0	3,1	3,1	3,1	3,0	5,5	6,2	7,3
Difference		**263%**	**251%**	**245%**	**385%**	**-**	**-**	**-**

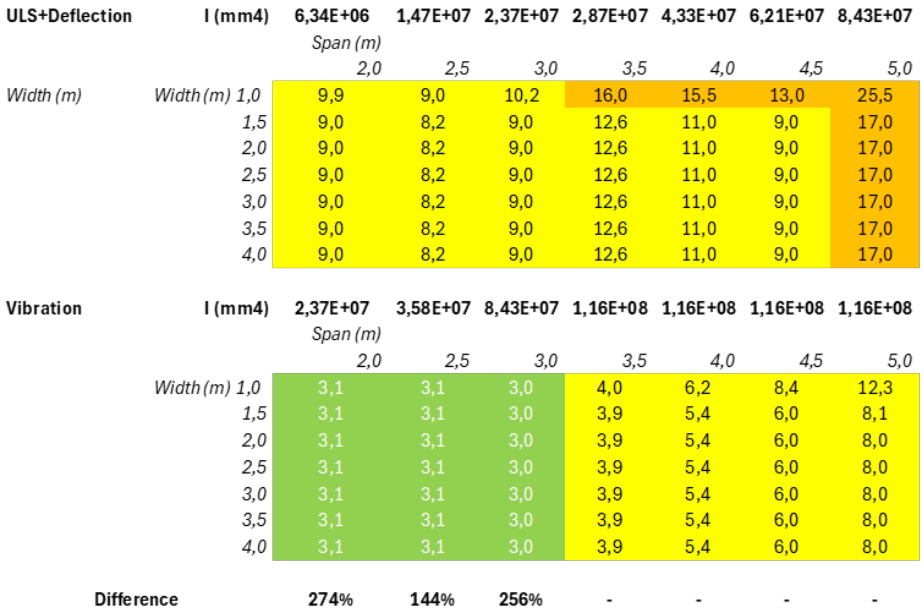
Figure 57: Joist Residential 7% damping



ULS+Deflection	**I (mm4)**	**4,90E+06**	**1,02E+07**	**1,47E+07**	**2,37E+07**	**3,58E+07**	**5,15E+07**	**8,43E+07**
		Span (m)						
		2,0	*2,5*	*3,0*	*3,5*	*4,0*	*4,5*	*5,0*
	Width (m) 1,0	10,5	10,6	15,0	16,0	17,5	21,0	18,0
	1,5	10,4	9,4	12,7	13,5	13,0	16,0	12,1
	2,0	10,4	9,4	12,7	12,6	12,7	14,5	11,8
	2,5	10,4	9,4	12,7	12,6	12,7	14,5	11,8
	3,0	10,4	9,4	12,7	12,6	12,7	14,5	11,8
	3,5	10,4	9,4	12,7	12,6	12,7	14,5	11,8
	4,0	10,4	9,4	12,7	12,6	12,7	14,5	11,8

Vibration	**I (mm4)**	**1,78E+07**	**3,58E+07**	**6,21E+07**	**1,15E+08**	**1,16E+08**	**1,16E+08**	**1,16E+08**
		Span (m)						
		2,0	*2,5*	*3,0*	*3,5*	*4,0*	*4,5*	*5,0*
	Width (m) 1,0	3,0	3,1	3,2	3,0	5,6	7,2	11,4
	1,5	3,0	3,1	3,1	2,9	5,1	5,8	7,9
	2,0	3,0	3,1	3,1	2,9	5,1	5,8	7,9
	2,5	3,0	3,1	3,1	2,9	5,1	5,8	7,9
	3,0	3,0	3,1	3,1	2,9	5,1	5,8	7,9
	3,5	3,0	3,1	3,1	2,9	5,1	5,8	7,9
	4,0	3,0	3,1	3,1	2,9	5,1	5,8	7,9
Difference		**263%**	**251%**	**322%**	**385%**	**-**	**-**	**-**

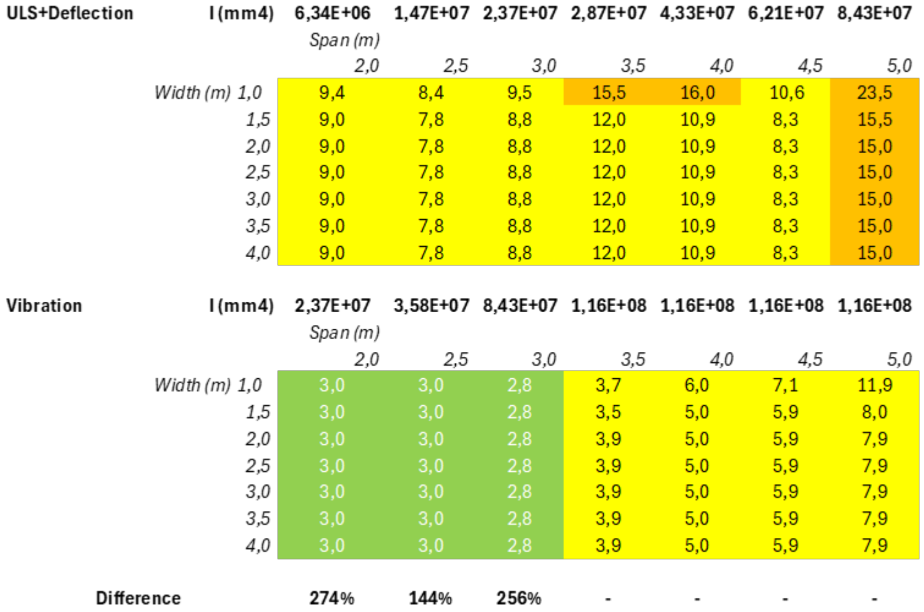
Figure 58: Joist Residential 8% damping



ULS+Deflection	**I (mm4)**	**6,34E+06**	**1,47E+07**	**2,37E+07**	**2,87E+07**	**4,33E+07**	**6,21E+07**	**8,43E+07**
		Span (m)						
		2,0	*2,5*	*3,0*	*3,5*	*4,0*	*4,5*	*5,0*
Width (m)	*Width (m) 1,0*	9,9	9,0	10,2	16,0	15,5	13,0	25,5
	1,5	9,0	8,2	9,0	12,6	11,0	9,0	17,0
	2,0	9,0	8,2	9,0	12,6	11,0	9,0	17,0
	2,5	9,0	8,2	9,0	12,6	11,0	9,0	17,0
	3,0	9,0	8,2	9,0	12,6	11,0	9,0	17,0
	3,5	9,0	8,2	9,0	12,6	11,0	9,0	17,0
	4,0	9,0	8,2	9,0	12,6	11,0	9,0	17,0

Vibration	**I (mm4)**	**2,37E+07**	**3,58E+07**	**8,43E+07**	**1,16E+08**	**1,16E+08**	**1,16E+08**	**1,16E+08**
		Span (m)						
		2,0	*2,5*	*3,0*	*3,5*	*4,0*	*4,5*	*5,0*
	Width (m) 1,0	3,1	3,1	3,0	4,0	6,2	8,4	12,3
	1,5	3,1	3,1	3,0	3,9	5,4	6,0	8,1
	2,0	3,1	3,1	3,0	3,9	5,4	6,0	8,0
	2,5	3,1	3,1	3,0	3,9	5,4	6,0	8,0
	3,0	3,1	3,1	3,0	3,9	5,4	6,0	8,0
	3,5	3,1	3,1	3,0	3,9	5,4	6,0	8,0
	4,0	3,1	3,1	3,0	3,9	5,4	6,0	8,0
Difference		**274%**	**144%**	**256%**	-	-	-	-

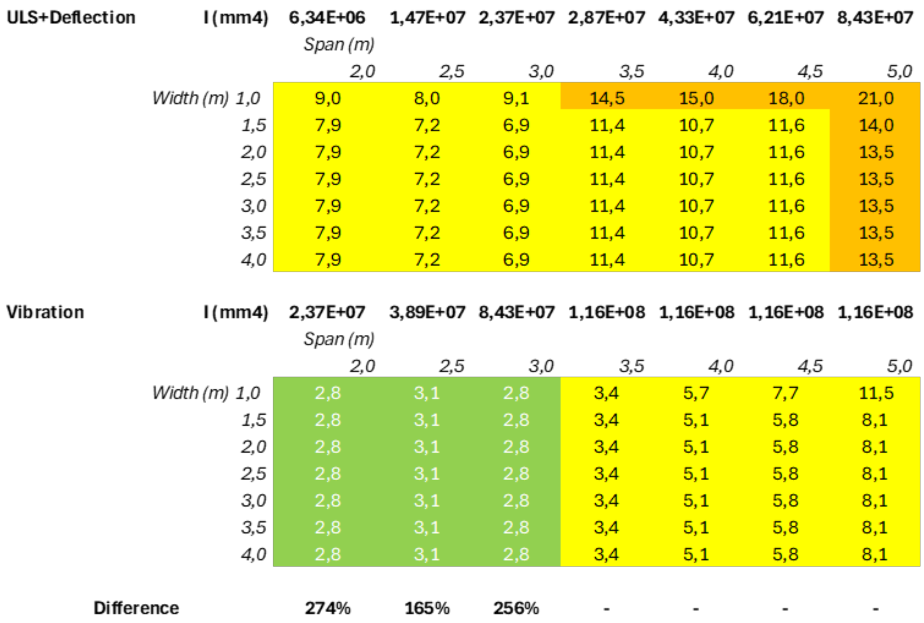
Figure 59: Joist Office 6% damping



ULS+Deflection	**I (mm4)**	**6,34E+06**	**1,47E+07**	**2,37E+07**	**2,87E+07**	**4,33E+07**	**6,21E+07**	**8,43E+07**
		Span (m)						
		2,0	*2,5*	*3,0*	*3,5*	*4,0*	*4,5*	*5,0*
	Width (m) 1,0	9,4	8,4	9,5	15,5	16,0	10,6	23,5
	1,5	9,0	7,8	8,8	12,0	10,9	8,3	15,5
	2,0	9,0	7,8	8,8	12,0	10,9	8,3	15,0
	2,5	9,0	7,8	8,8	12,0	10,9	8,3	15,0
	3,0	9,0	7,8	8,8	12,0	10,9	8,3	15,0
	3,5	9,0	7,8	8,8	12,0	10,9	8,3	15,0
	4,0	9,0	7,8	8,8	12,0	10,9	8,3	15,0

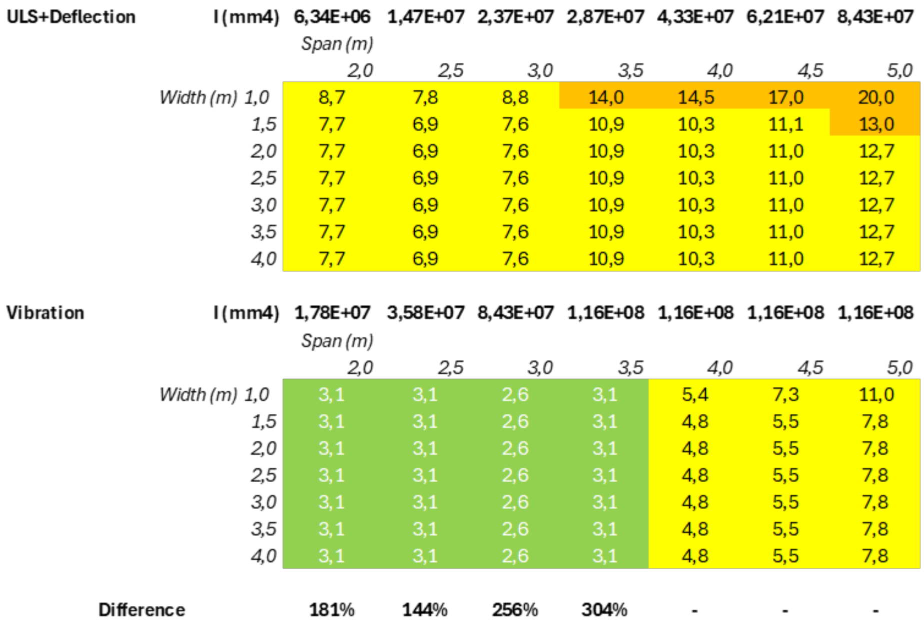
Vibration	**I (mm4)**	**2,37E+07**	**3,58E+07**	**8,43E+07**	**1,16E+08**	**1,16E+08**	**1,16E+08**	**1,16E+08**
		Span (m)						
		2,0	*2,5*	*3,0*	*3,5*	*4,0*	*4,5*	*5,0*
	Width (m) 1,0	3,0	3,0	2,8	3,7	6,0	7,1	11,9
	1,5	3,0	3,0	2,8	3,5	5,0	5,9	8,0
	2,0	3,0	3,0	2,8	3,9	5,0	5,9	7,9
	2,5	3,0	3,0	2,8	3,9	5,0	5,9	7,9
	3,0	3,0	3,0	2,8	3,9	5,0	5,9	7,9
	3,5	3,0	3,0	2,8	3,9	5,0	5,9	7,9
	4,0	3,0	3,0	2,8	3,9	5,0	5,9	7,9
Difference		**274%**	**144%**	**256%**	-	-	-	-

Figure 60: Joist Office 7% damping



ULS+Deflection	I (mm4)	6,34E+06	1,47E+07	2,37E+07	2,87E+07	4,33E+07	6,21E+07	8,43E+07
		Span (m)						
		2,0	*2,5*	*3,0*	*3,5*	*4,0*	*4,5*	*5,0*
	Width (m) 1,0	9,0	8,0	9,1	14,5	15,0	18,0	21,0
	1,5	7,9	7,2	6,9	11,4	10,7	11,6	14,0
	2,0	7,9	7,2	6,9	11,4	10,7	11,6	13,5
	2,5	7,9	7,2	6,9	11,4	10,7	11,6	13,5
	3,0	7,9	7,2	6,9	11,4	10,7	11,6	13,5
	3,5	7,9	7,2	6,9	11,4	10,7	11,6	13,5
	4,0	7,9	7,2	6,9	11,4	10,7	11,6	13,5
Vibration	**I (mm4)**	**2,37E+07**	**3,89E+07**	**8,43E+07**	**1,16E+08**	**1,16E+08**	**1,16E+08**	**1,16E+08**
		Span (m)						
		2,0	*2,5*	*3,0*	*3,5*	*4,0*	*4,5*	*5,0*
	Width (m) 1,0	2,8	3,1	2,8	3,4	5,7	7,7	11,5
	1,5	2,8	3,1	2,8	3,4	5,1	5,8	8,1
	2,0	2,8	3,1	2,8	3,4	5,1	5,8	8,1
	2,5	2,8	3,1	2,8	3,4	5,1	5,8	8,1
	3,0	2,8	3,1	2,8	3,4	5,1	5,8	8,1
	3,5	2,8	3,1	2,8	3,4	5,1	5,8	8,1
	4,0	2,8	3,1	2,8	3,4	5,1	5,8	8,1
Difference		**274%**	**165%**	**256%**	**-**	**-**	**-**	**-**

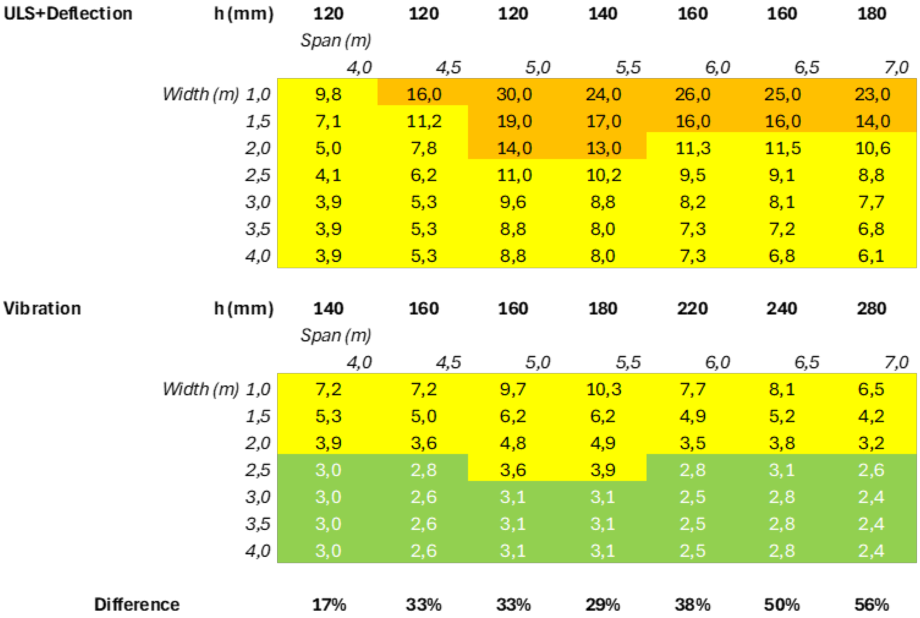
Figure 61: Joist Office 8% damping



ULS+Deflection	I (mm4)	6,34E+06	1,47E+07	2,37E+07	2,87E+07	4,33E+07	6,21E+07	8,43E+07
		Span (m)						
		2,0	*2,5*	*3,0*	*3,5*	*4,0*	*4,5*	*5,0*
	Width (m) 1,0	8,7	7,8	8,8	14,0	14,5	17,0	20,0
	1,5	7,7	6,9	7,6	10,9	10,3	11,1	13,0
	2,0	7,7	6,9	7,6	10,9	10,3	11,0	12,7
	2,5	7,7	6,9	7,6	10,9	10,3	11,0	12,7
	3,0	7,7	6,9	7,6	10,9	10,3	11,0	12,7
	3,5	7,7	6,9	7,6	10,9	10,3	11,0	12,7
	4,0	7,7	6,9	7,6	10,9	10,3	11,0	12,7
Vibration	**I (mm4)**	**1,78E+07**	**3,58E+07**	**8,43E+07**	**1,16E+08**	**1,16E+08**	**1,16E+08**	**1,16E+08**
		Span (m)						
		2,0	*2,5*	*3,0*	*3,5*	*4,0*	*4,5*	*5,0*
	Width (m) 1,0	3,1	3,1	2,6	3,1	5,4	7,3	11,0
	1,5	3,1	3,1	2,6	3,1	4,8	5,5	7,8
	2,0	3,1	3,1	2,6	3,1	4,8	5,5	7,8
	2,5	3,1	3,1	2,6	3,1	4,8	5,5	7,8
	3,0	3,1	3,1	2,6	3,1	4,8	5,5	7,8
	3,5	3,1	3,1	2,6	3,1	4,8	5,5	7,8
	4,0	3,1	3,1	2,6	3,1	4,8	5,5	7,8
Difference		**181%**	**144%**	**256%**	**304%**	**-**	**-**	**-**

Figure 62: Joist Office 9% damping

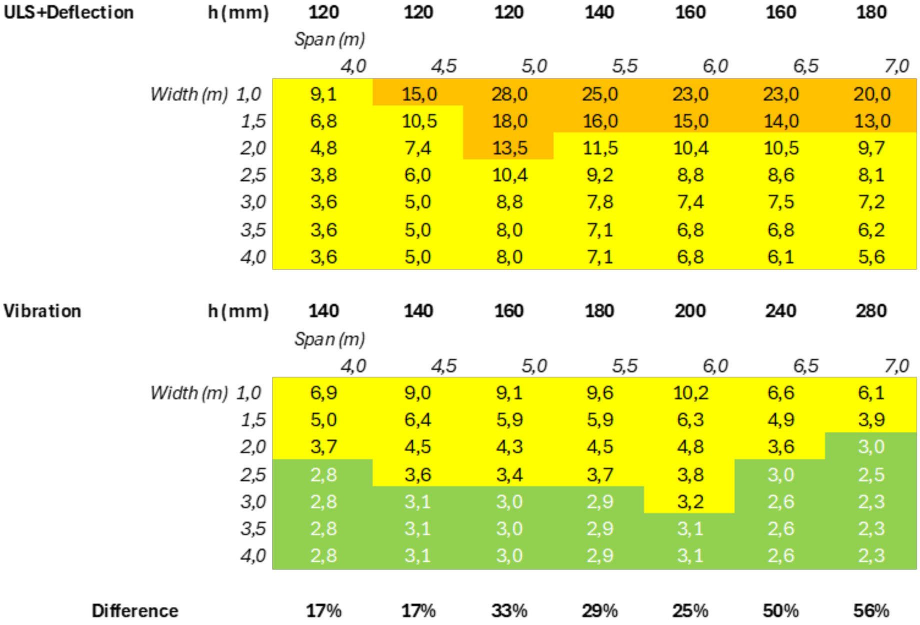
C.1.3 Lignatur



ULS+Deflection	h (mm)	120	120	120	140	160	160	180
	Span (m)	4,0	4,5	5,0	5,5	6,0	6,5	7,0
Width (m)	1,0	9,8	16,0	30,0	24,0	26,0	25,0	23,0
	1,5	7,1	11,2	19,0	17,0	16,0	16,0	14,0
	2,0	5,0	7,8	14,0	13,0	11,3	11,5	10,6
	2,5	4,1	6,2	11,0	10,2	9,5	9,1	8,8
	3,0	3,9	5,3	9,6	8,8	8,2	8,1	7,7
	3,5	3,9	5,3	8,8	8,0	7,3	7,2	6,8
	4,0	3,9	5,3	8,8	8,0	7,3	6,8	6,1

Vibration	h (mm)	140	160	160	180	220	240	280
	Span (m)	4,0	4,5	5,0	5,5	6,0	6,5	7,0
Width (m)	1,0	7,2	7,2	9,7	10,3	7,7	8,1	6,5
	1,5	5,3	5,0	6,2	6,2	4,9	5,2	4,2
	2,0	3,9	3,6	4,8	4,9	3,5	3,8	3,2
	2,5	3,0	2,8	3,6	3,9	2,8	3,1	2,6
	3,0	3,0	2,6	3,1	3,1	2,5	2,8	2,4
	3,5	3,0	2,6	3,1	3,1	2,5	2,8	2,4
	4,0	3,0	2,6	3,1	3,1	2,5	2,8	2,4
Difference		17%	33%	33%	29%	38%	50%	56%

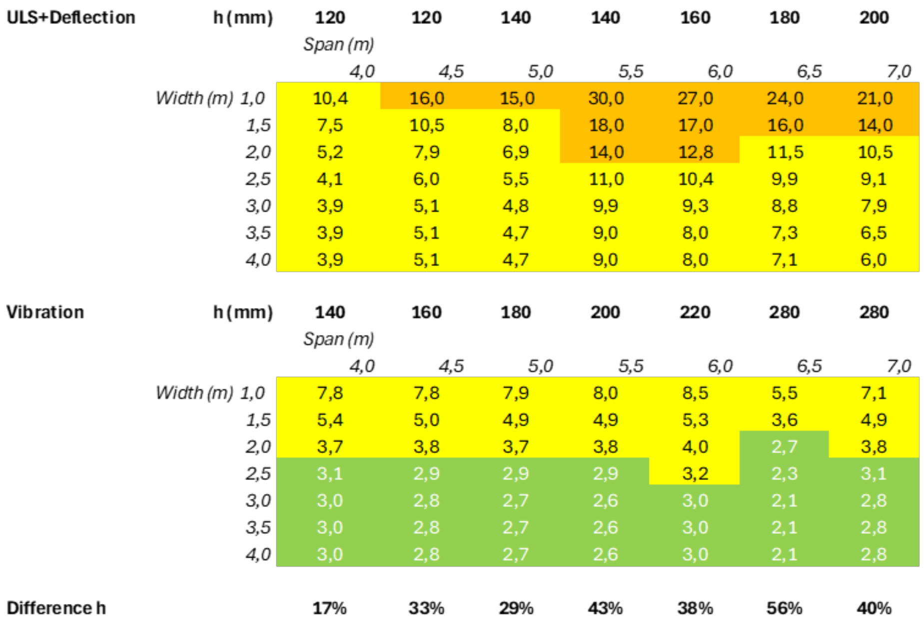
Figure 63: Lignatur Residential 7% damping



ULS+Deflection	h (mm)	120	120	120	140	160	160	180
	Span (m)	4,0	4,5	5,0	5,5	6,0	6,5	7,0
Width (m)	1,0	9,1	15,0	28,0	25,0	23,0	23,0	20,0
	1,5	6,8	10,5	18,0	16,0	15,0	14,0	13,0
	2,0	4,8	7,4	13,5	11,5	10,4	10,5	9,7
	2,5	3,8	6,0	10,4	9,2	8,8	8,6	8,1
	3,0	3,6	5,0	8,8	7,8	7,4	7,5	7,2
	3,5	3,6	5,0	8,0	7,1	6,8	6,8	6,2
	4,0	3,6	5,0	8,0	7,1	6,8	6,1	5,6

Vibration	h (mm)	140	140	160	180	200	240	280
	Span (m)	4,0	4,5	5,0	5,5	6,0	6,5	7,0
Width (m)	1,0	6,9	9,0	9,1	9,6	10,2	6,6	6,1
	1,5	5,0	6,4	5,9	5,9	6,3	4,9	3,9
	2,0	3,7	4,5	4,3	4,5	4,8	3,6	3,0
	2,5	2,8	3,6	3,4	3,7	3,8	3,0	2,5
	3,0	2,8	3,1	3,0	2,9	3,2	2,6	2,3
	3,5	2,8	3,1	3,0	2,9	3,1	2,6	2,3
	4,0	2,8	3,1	3,0	2,9	3,1	2,6	2,3
Difference		17%	17%	33%	29%	25%	50%	56%

Figure 64: Lignatur Residential 8% damping

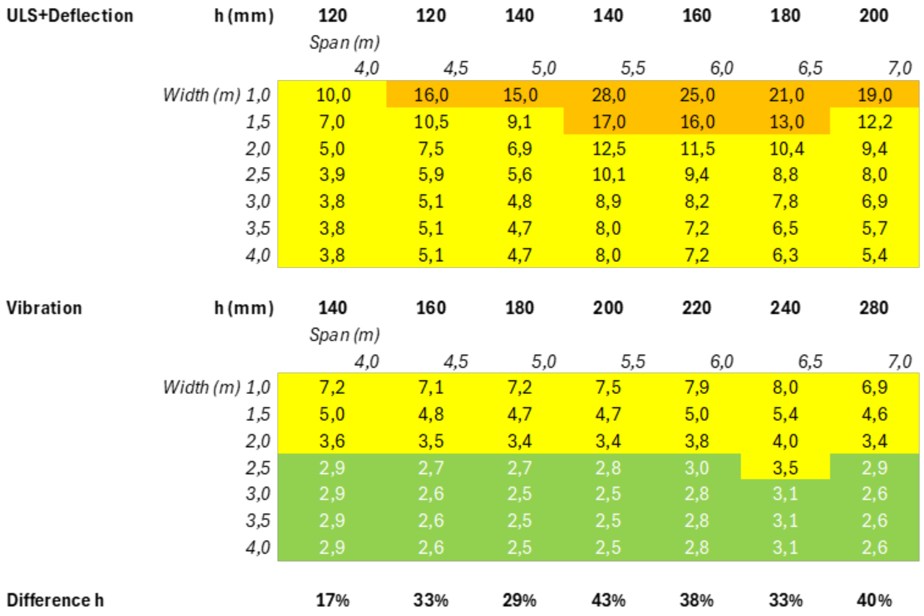


ULS+Deflection	h (mm)	120	120	140	140	160	180	200
	Span (m)	4,0	4,5	5,0	5,5	6,0	6,5	7,0
	Width (m) 1,0	10,4	16,0	15,0	30,0	27,0	24,0	21,0
	1,5	7,5	10,5	8,0	18,0	17,0	16,0	14,0
	2,0	5,2	7,9	6,9	14,0	12,8	11,5	10,5
	2,5	4,1	6,0	5,5	11,0	10,4	9,9	9,1
	3,0	3,9	5,1	4,8	9,9	9,3	8,8	7,9
	3,5	3,9	5,1	4,7	9,0	8,0	7,3	6,5
	4,0	3,9	5,1	4,7	9,0	8,0	7,1	6,0

Vibration	h (mm)	140	160	180	200	220	280	280
	Span (m)	4,0	4,5	5,0	5,5	6,0	6,5	7,0
	Width (m) 1,0	7,8	7,8	7,9	8,0	8,5	5,5	7,1
	1,5	5,4	5,0	4,9	4,9	5,3	3,6	4,9
	2,0	3,7	3,8	3,7	3,8	4,0	2,7	3,8
	2,5	3,1	2,9	2,9	2,9	3,2	2,3	3,1
	3,0	3,0	2,8	2,7	2,6	3,0	2,1	2,8
	3,5	3,0	2,8	2,7	2,6	3,0	2,1	2,8
	4,0	3,0	2,8	2,7	2,6	3,0	2,1	2,8

Difference h		17%	33%	29%	43%	38%	56%	40%

Figure 65: Lignatur Office 6% damping

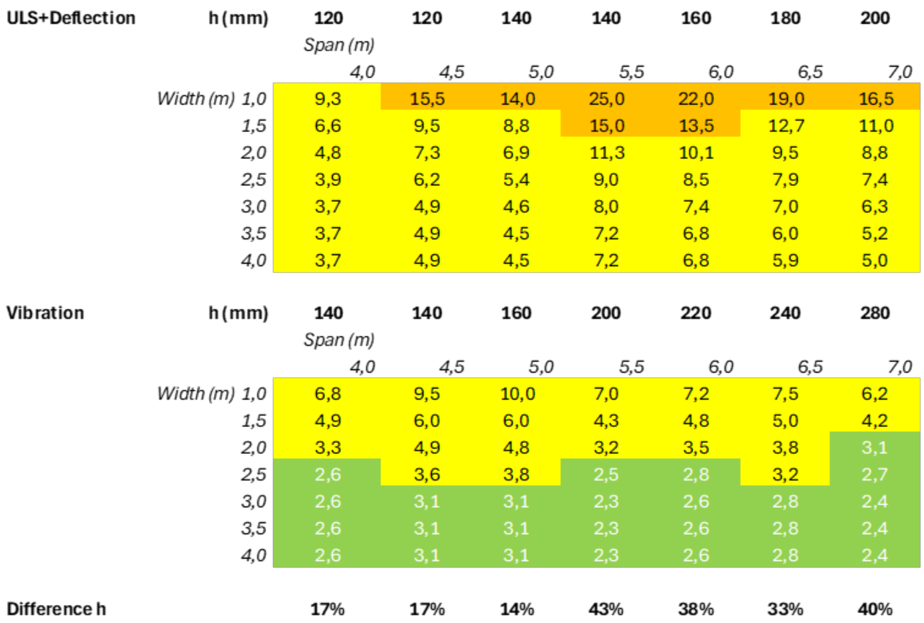


ULS+Deflection	h (mm)	120	120	140	140	160	180	200
	Span (m)	4,0	4,5	5,0	5,5	6,0	6,5	7,0
	Width (m) 1,0	10,0	16,0	15,0	28,0	25,0	21,0	19,0
	1,5	7,0	10,5	9,1	17,0	16,0	13,0	12,2
	2,0	5,0	7,5	6,9	12,5	11,5	10,4	9,4
	2,5	3,9	5,9	5,6	10,1	9,4	8,8	8,0
	3,0	3,8	5,1	4,8	8,9	8,2	7,8	6,9
	3,5	3,8	5,1	4,7	8,0	7,2	6,5	5,7
	4,0	3,8	5,1	4,7	8,0	7,2	6,3	5,4

Vibration	h (mm)	140	160	180	200	220	240	280
	Span (m)	4,0	4,5	5,0	5,5	6,0	6,5	7,0
	Width (m) 1,0	7,2	7,1	7,2	7,5	7,9	8,0	6,9
	1,5	5,0	4,8	4,7	4,7	5,0	5,4	4,6
	2,0	3,6	3,5	3,4	3,4	3,8	4,0	3,4
	2,5	2,9	2,7	2,7	2,8	3,0	3,5	2,9
	3,0	2,9	2,6	2,5	2,5	2,8	3,1	2,6
	3,5	2,9	2,6	2,5	2,5	2,8	3,1	2,6
	4,0	2,9	2,6	2,5	2,5	2,8	3,1	2,6

Difference h		17%	33%	29%	43%	38%	33%	40%

Figure 66: Lignatur Office 7% damping



ULS+Deflection	h (mm)	120	120	140	140	160	180	200
	Span (m)	*4,0*	*4,5*	*5,0*	*5,5*	*6,0*	*6,5*	*7,0*
Width (m)	*1,0*	9,3	15,5	14,0	25,0	22,0	19,0	16,5
	1,5	6,6	9,5	8,8	15,0	13,5	12,7	11,0
	2,0	4,8	7,3	6,9	11,3	10,1	9,5	8,8
	2,5	3,9	6,2	5,4	9,0	8,5	7,9	7,4
	3,0	3,7	4,9	4,6	8,0	7,4	7,0	6,3
	3,5	3,7	4,9	4,5	7,2	6,8	6,0	5,2
	4,0	3,7	4,9	4,5	7,2	6,8	5,9	5,0

Vibration	h (mm)	140	140	160	200	220	240	280
	Span (m)	*4,0*	*4,5*	*5,0*	*5,5*	*6,0*	*6,5*	*7,0*
Width (m)	*1,0*	6,8	9,5	10,0	7,0	7,2	7,5	6,2
	1,5	4,9	6,0	6,0	4,3	4,8	5,0	4,2
	2,0	3,3	4,9	4,8	3,2	3,5	3,8	3,1
	2,5	2,6	3,6	3,8	2,5	2,8	3,2	2,7
	3,0	2,6	3,1	3,1	2,3	2,6	2,8	2,4
	3,5	2,6	3,1	3,1	2,3	2,6	2,8	2,4
	4,0	2,6	3,1	3,1	2,3	2,6	2,8	2,4
Difference h		**17%**	**17%**	**14%**	**43%**	**38%**	**33%**	**40%**

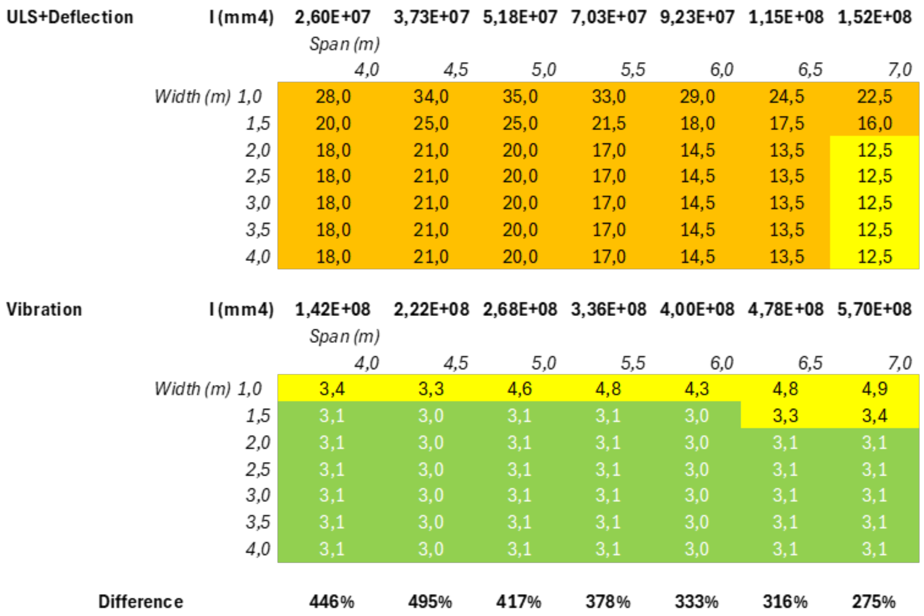
Figure 67: Lignatur Office 8% damping

ULS+Deflection	h (mm)	120	120	140	140	160	180	200
	Span (m)	*4,0*	*4,5*	*5,0*	*5,5*	*6,0*	*6,5*	*7,0*
Width (m)	*1,0*	8,9	15,0	14,0	22,0	20,5	17,5	16,0
	1,5	6,2	9,1	8,5	14,0	13,0	11,7	10,5
	2,0	4,5	7,0	6,4	10,4	9,6	8,9	7,9
	2,5	3,6	5,5	5,2	8,4	7,8	7,2	6,9
	3,0	3,3	4,8	4,5	7,3	6,9	6,3	5,8
	3,5	3,3	4,8	4,3	6,7	6,0	5,5	5,0
	4,0	3,3	4,8	4,3	6,7	6,0	5,4	4,8

Vibration	h (mm)	140	140	160	180	200	220	280
	Span (m)	*4,0*	*4,5*	*5,0*	*5,5*	*6,0*	*6,5*	*7,0*
Width (m)	*1,0*	6,4	9,0	9,4	9,6	9,5	9,0	5,9
	1,5	4,6	5,9	5,8	6,0	6,0	5,9	4,0
	2,0	3,1	4,2	4,3	4,6	4,5	4,5	3,0
	2,5	2,5	3,4	3,5	3,6	3,8	3,8	2,6
	3,0	2,5	3,0	2,9	3,1	3,2	3,3	2,3
	3,5	2,5	3,0	2,9	3,1	3,1	3,1	2,3
	4,0	2,5	3,0	2,9	3,1	3,1	3,1	2,3
Difference h		**17%**	**17%**	**14%**	**29%**	**25%**	**22%**	**40%**

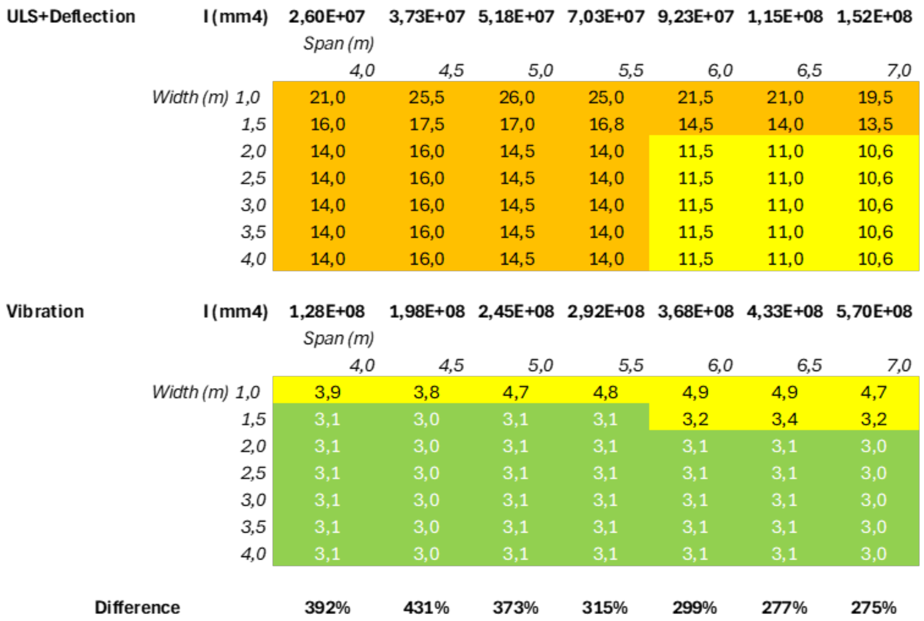
Figure 68: Lignatur Office 9% damping

C.1.4 Kerto Ripa Rib



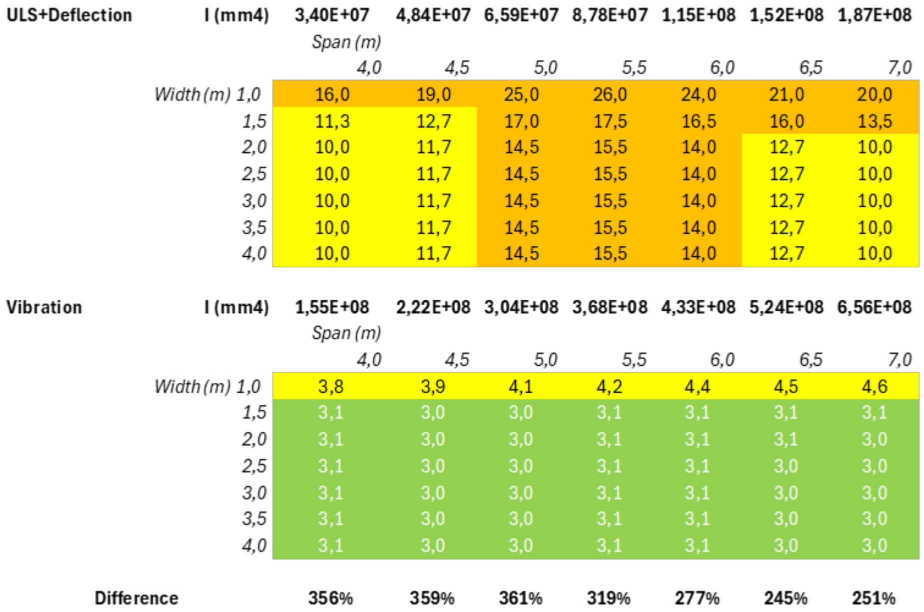
ULS+Deflection	I (mm4)	2,60E+07	3,73E+07	5,18E+07	7,03E+07	9,23E+07	1,15E+08	1,52E+08
		Span (m)						
		4,0	*4,5*	*5,0*	*5,5*	*6,0*	*6,5*	*7,0*
	Width (m) 1,0	28,0	34,0	35,0	33,0	29,0	24,5	22,5
	1,5	20,0	25,0	25,0	21,5	18,0	17,5	16,0
	2,0	18,0	21,0	20,0	17,0	14,5	13,5	12,5
	2,5	18,0	21,0	20,0	17,0	14,5	13,5	12,5
	3,0	18,0	21,0	20,0	17,0	14,5	13,5	12,5
	3,5	18,0	21,0	20,0	17,0	14,5	13,5	12,5
	4,0	18,0	21,0	20,0	17,0	14,5	13,5	12,5
Vibration	**I (mm4)**	**1,42E+08**	**2,22E+08**	**2,68E+08**	**3,36E+08**	**4,00E+08**	**4,78E+08**	**5,70E+08**
		Span (m)						
		4,0	*4,5*	*5,0*	*5,5*	*6,0*	*6,5*	*7,0*
	Width (m) 1,0	3,4	3,3	4,6	4,8	4,3	4,8	4,9
	1,5	3,1	3,0	3,1	3,1	3,0	3,3	3,4
	2,0	3,1	3,0	3,1	3,1	3,0	3,1	3,1
	2,5	3,1	3,0	3,1	3,1	3,0	3,1	3,1
	3,0	3,1	3,0	3,1	3,1	3,0	3,1	3,1
	3,5	3,1	3,0	3,1	3,1	3,0	3,1	3,1
	4,0	3,1	3,0	3,1	3,1	3,0	3,1	3,1
Difference		**446%**	**495%**	**417%**	**378%**	**333%**	**316%**	**275%**

Figure 69: Kerto Ripa Rib Residential 7% damping



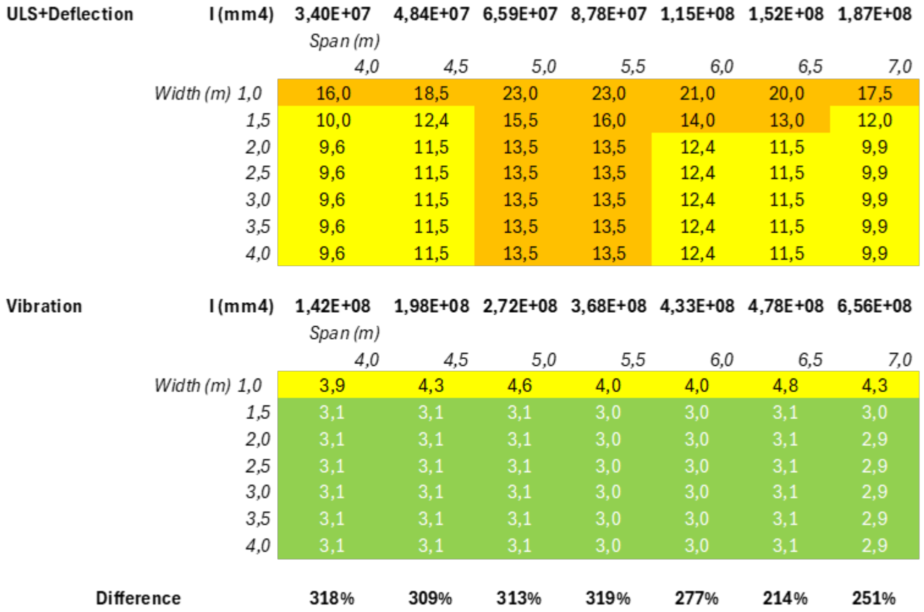
ULS+Deflection	I (mm4)	2,60E+07	3,73E+07	5,18E+07	7,03E+07	9,23E+07	1,15E+08	1,52E+08
		Span (m)						
		4,0	*4,5*	*5,0*	*5,5*	*6,0*	*6,5*	*7,0*
	Width (m) 1,0	21,0	25,5	26,0	25,0	21,5	21,0	19,5
	1,5	16,0	17,5	17,0	16,8	14,5	14,0	13,5
	2,0	14,0	16,0	14,5	14,0	11,5	11,0	10,6
	2,5	14,0	16,0	14,5	14,0	11,5	11,0	10,6
	3,0	14,0	16,0	14,5	14,0	11,5	11,0	10,6
	3,5	14,0	16,0	14,5	14,0	11,5	11,0	10,6
	4,0	14,0	16,0	14,5	14,0	11,5	11,0	10,6
Vibration	**I (mm4)**	**1,28E+08**	**1,98E+08**	**2,45E+08**	**2,92E+08**	**3,68E+08**	**4,33E+08**	**5,70E+08**
		Span (m)						
		4,0	*4,5*	*5,0*	*5,5*	*6,0*	*6,5*	*7,0*
	Width (m) 1,0	3,9	3,8	4,7	4,8	4,9	4,9	4,7
	1,5	3,1	3,0	3,1	3,1	3,2	3,4	3,2
	2,0	3,1	3,0	3,1	3,1	3,1	3,1	3,0
	2,5	3,1	3,0	3,1	3,1	3,1	3,1	3,0
	3,0	3,1	3,0	3,1	3,1	3,1	3,1	3,0
	3,5	3,1	3,0	3,1	3,1	3,1	3,1	3,0
	4,0	3,1	3,0	3,1	3,1	3,1	3,1	3,0
Difference		**392%**	**431%**	**373%**	**315%**	**299%**	**277%**	**275%**

Figure 70: Kerto Ripa Rib Residential 8% damping



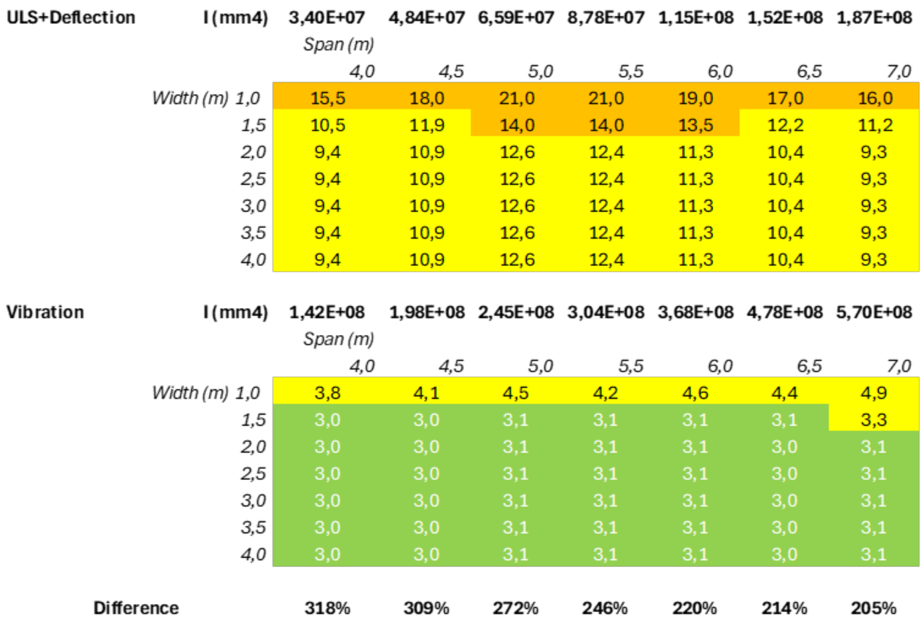
ULS+Deflection	**I (mm4)**	**3,40E+07**	**4,84E+07**	**6,59E+07**	**8,78E+07**	**1,15E+08**	**1,52E+08**	**1,87E+08**
		Span (m)						
		4,0	*4,5*	*5,0*	*5,5*	*6,0*	*6,5*	*7,0*
	Width (m) 1,0	16,0	19,0	25,0	26,0	24,0	21,0	20,0
	1,5	11,3	12,7	17,0	17,5	16,5	16,0	13,5
	2,0	10,0	11,7	14,5	15,5	14,0	12,7	10,0
	2,5	10,0	11,7	14,5	15,5	14,0	12,7	10,0
	3,0	10,0	11,7	14,5	15,5	14,0	12,7	10,0
	3,5	10,0	11,7	14,5	15,5	14,0	12,7	10,0
	4,0	10,0	11,7	14,5	15,5	14,0	12,7	10,0
Vibration	**I (mm4)**	**1,55E+08**	**2,22E+08**	**3,04E+08**	**3,68E+08**	**4,33E+08**	**5,24E+08**	**6,56E+08**
		Span (m)						
		4,0	*4,5*	*5,0*	*5,5*	*6,0*	*6,5*	*7,0*
	Width (m) 1,0	3,8	3,9	4,1	4,2	4,4	4,5	4,6
	1,5	3,1	3,0	3,0	3,1	3,1	3,1	3,1
	2,0	3,1	3,0	3,0	3,1	3,1	3,1	3,0
	2,5	3,1	3,0	3,0	3,1	3,1	3,0	3,0
	3,0	3,1	3,0	3,0	3,1	3,1	3,0	3,0
	3,5	3,1	3,0	3,0	3,1	3,1	3,0	3,0
	4,0	3,1	3,0	3,0	3,1	3,1	3,0	3,0
Difference		**356%**	**359%**	**361%**	**319%**	**277%**	**245%**	**251%**

Figure 71: Kerto Ripa Rib Office 6% damping



ULS+Deflection	**I (mm4)**	**3,40E+07**	**4,84E+07**	**6,59E+07**	**8,78E+07**	**1,15E+08**	**1,52E+08**	**1,87E+08**
		Span (m)						
		4,0	*4,5*	*5,0*	*5,5*	*6,0*	*6,5*	*7,0*
	Width (m) 1,0	16,0	18,5	23,0	23,0	21,0	20,0	17,5
	1,5	10,0	12,4	15,5	16,0	14,0	13,0	12,0
	2,0	9,6	11,5	13,5	13,5	12,4	11,5	9,9
	2,5	9,6	11,5	13,5	13,5	12,4	11,5	9,9
	3,0	9,6	11,5	13,5	13,5	12,4	11,5	9,9
	3,5	9,6	11,5	13,5	13,5	12,4	11,5	9,9
	4,0	9,6	11,5	13,5	13,5	12,4	11,5	9,9
Vibration	**I (mm4)**	**1,42E+08**	**1,98E+08**	**2,72E+08**	**3,68E+08**	**4,33E+08**	**4,78E+08**	**6,56E+08**
		Span (m)						
		4,0	*4,5*	*5,0*	*5,5*	*6,0*	*6,5*	*7,0*
	Width (m) 1,0	3,9	4,3	4,6	4,0	4,0	4,8	4,3
	1,5	3,1	3,1	3,1	3,0	3,0	3,1	3,0
	2,0	3,1	3,1	3,1	3,0	3,0	3,1	2,9
	2,5	3,1	3,1	3,1	3,0	3,0	3,1	2,9
	3,0	3,1	3,1	3,1	3,0	3,0	3,1	2,9
	3,5	3,1	3,1	3,1	3,0	3,0	3,1	2,9
	4,0	3,1	3,1	3,1	3,0	3,0	3,1	2,9
Difference		**318%**	**309%**	**313%**	**319%**	**277%**	**214%**	**251%**

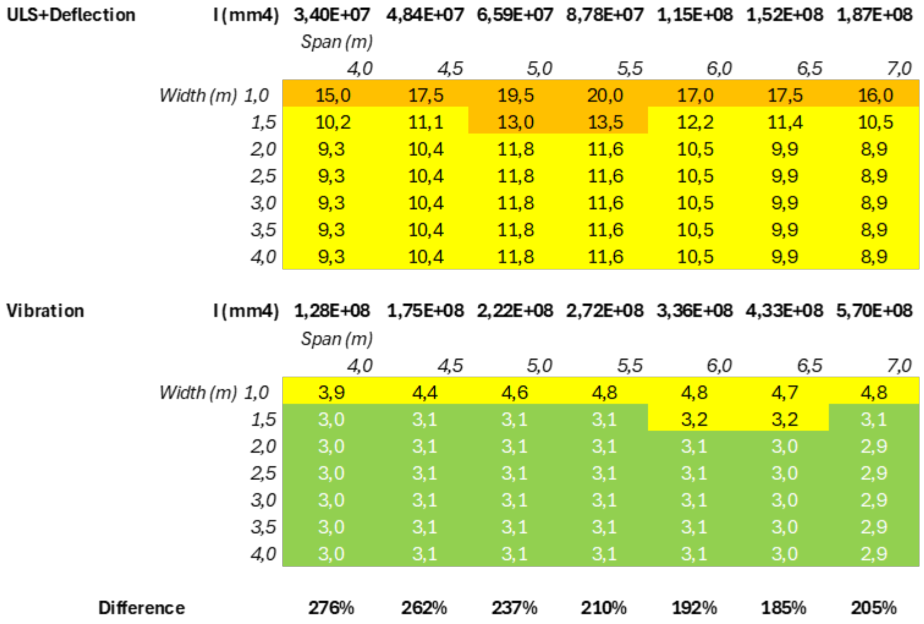
Figure 72: Kerto Ripa Rib Office 7% damping



ULS+Deflection	**I (mm4)**	**3,40E+07**	**4,84E+07**	**6,59E+07**	**8,78E+07**	**1,15E+08**	**1,52E+08**	**1,87E+08**
		Span (m)						
		4,0	*4,5*	*5,0*	*5,5*	*6,0*	*6,5*	*7,0*
	Width (m) 1,0	15,5	18,0	21,0	21,0	19,0	17,0	16,0
	1,5	10,5	11,9	14,0	14,0	13,5	12,2	11,2
	2,0	9,4	10,9	12,6	12,4	11,3	10,4	9,3
	2,5	9,4	10,9	12,6	12,4	11,3	10,4	9,3
	3,0	9,4	10,9	12,6	12,4	11,3	10,4	9,3
	3,5	9,4	10,9	12,6	12,4	11,3	10,4	9,3
	4,0	9,4	10,9	12,6	12,4	11,3	10,4	9,3

Vibration	**I (mm4)**	**1,42E+08**	**1,98E+08**	**2,45E+08**	**3,04E+08**	**3,68E+08**	**4,78E+08**	**5,70E+08**
		Span (m)						
		4,0	*4,5*	*5,0*	*5,5*	*6,0*	*6,5*	*7,0*
	Width (m) 1,0	3,8	4,1	4,5	4,2	4,6	4,4	4,9
	1,5	3,0	3,0	3,1	3,1	3,1	3,1	3,3
	2,0	3,0	3,0	3,1	3,1	3,1	3,0	3,1
	2,5	3,0	3,0	3,1	3,1	3,1	3,0	3,1
	3,0	3,0	3,0	3,1	3,1	3,1	3,0	3,1
	3,5	3,0	3,0	3,1	3,1	3,1	3,0	3,1
	4,0	3,0	3,0	3,1	3,1	3,1	3,0	3,1
Difference		**318%**	**309%**	**272%**	**246%**	**220%**	**214%**	**205%**

Figure 73: Kerto Ripa Rib Office 8% damping



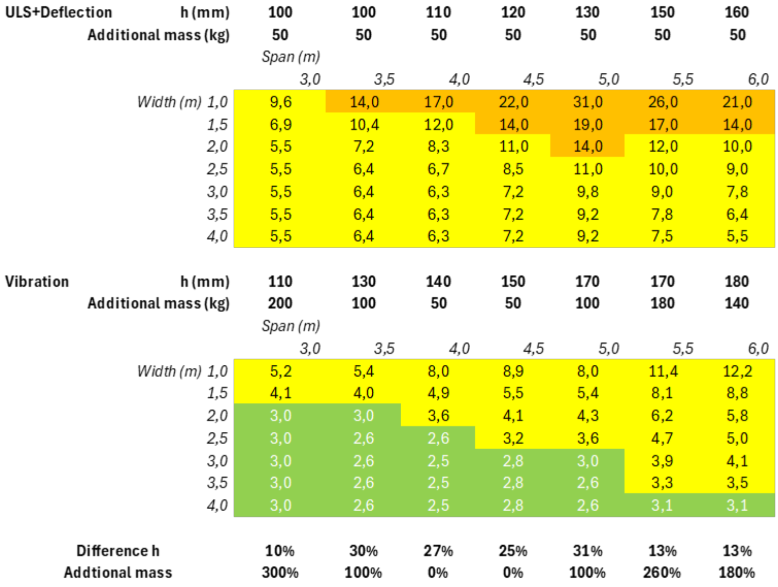
ULS+Deflection	**I (mm4)**	**3,40E+07**	**4,84E+07**	**6,59E+07**	**8,78E+07**	**1,15E+08**	**1,52E+08**	**1,87E+08**
		Span (m)						
		4,0	*4,5*	*5,0*	*5,5*	*6,0*	*6,5*	*7,0*
	Width (m) 1,0	15,0	17,5	19,5	20,0	17,0	17,5	16,0
	1,5	10,2	11,1	13,0	13,5	12,2	11,4	10,5
	2,0	9,3	10,4	11,8	11,6	10,5	9,9	8,9
	2,5	9,3	10,4	11,8	11,6	10,5	9,9	8,9
	3,0	9,3	10,4	11,8	11,6	10,5	9,9	8,9
	3,5	9,3	10,4	11,8	11,6	10,5	9,9	8,9
	4,0	9,3	10,4	11,8	11,6	10,5	9,9	8,9

Vibration	**I (mm4)**	**1,28E+08**	**1,75E+08**	**2,22E+08**	**2,72E+08**	**3,36E+08**	**4,33E+08**	**5,70E+08**
		Span (m)						
		4,0	*4,5*	*5,0*	*5,5*	*6,0*	*6,5*	*7,0*
	Width (m) 1,0	3,9	4,4	4,6	4,8	4,8	4,7	4,8
	1,5	3,0	3,1	3,1	3,1	3,2	3,2	3,1
	2,0	3,0	3,1	3,1	3,1	3,1	3,0	2,9
	2,5	3,0	3,1	3,1	3,1	3,1	3,0	2,9
	3,0	3,0	3,1	3,1	3,1	3,1	3,0	2,9
	3,5	3,0	3,1	3,1	3,1	3,1	3,0	2,9
	4,0	3,0	3,1	3,1	3,1	3,1	3,0	2,9
Difference		**276%**	**262%**	**237%**	**210%**	**192%**	**185%**	**205%**

Figure 74: Kerto Ripa Rib Office 9% damping

C.2 Additional mass

C.2.1 CLT

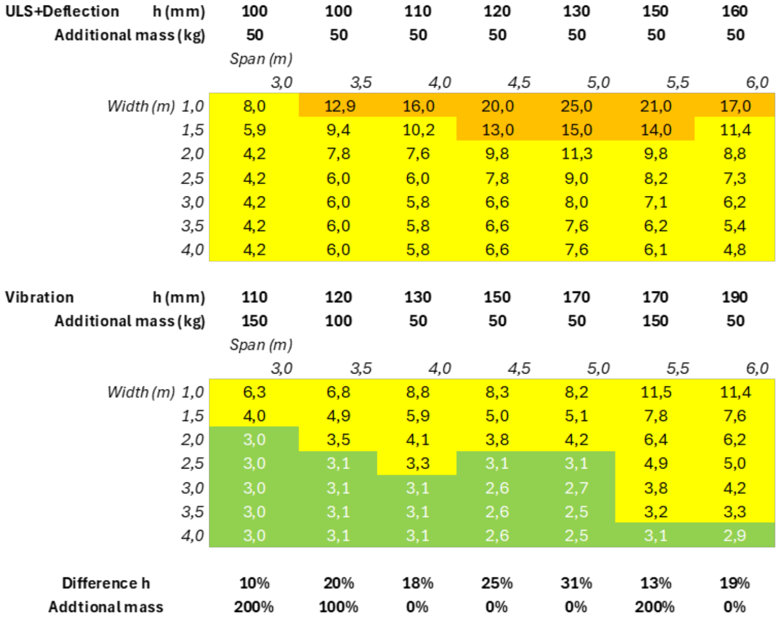


ULS+Deflection	h (mm)	100	100	110	120	130	150	160
	Additional mass (kg)	50	50	50	50	50	50	50
		Span (m)						
		3,0	3,5	4,0	4,5	5,0	5,5	6,0
Width (m)	1,0	9,6	14,0	17,0	22,0	31,0	26,0	21,0
	1,5	6,9	10,4	12,0	14,0	19,0	17,0	14,0
	2,0	5,5	7,2	8,3	11,0	14,0	12,0	10,0
	2,5	5,5	6,4	6,7	8,5	11,0	10,0	9,0
	3,0	5,5	6,4	6,3	7,2	9,8	9,0	7,8
	3,5	5,5	6,4	6,3	7,2	9,2	7,8	6,4
	4,0	5,5	6,4	6,3	7,2	9,2	7,5	5,5

Vibration	h (mm)	110	130	140	150	170	170	180
	Additional mass (kg)	200	100	50	50	100	180	140
		Span (m)						
		3,0	3,5	4,0	4,5	5,0	5,5	6,0
Width (m)	1,0	5,2	5,4	8,0	8,9	8,0	11,4	12,2
	1,5	4,1	4,0	4,9	5,5	5,4	8,1	8,8
	2,0	3,0	3,0	3,6	4,1	4,3	6,2	5,8
	2,5	3,0	2,6	2,6	3,2	3,6	4,7	5,0
	3,0	3,0	2,6	2,5	2,8	3,0	3,9	4,1
	3,5	3,0	2,6	2,5	2,8	2,6	3,3	3,5
	4,0	3,0	2,6	2,5	2,8	2,6	3,1	3,1

Difference h	10%	30%	27%	25%	31%	13%	13%
Addtional mass	300%	100%	0%	0%	100%	260%	180%

Figure 75: CLT Residential 7% damping

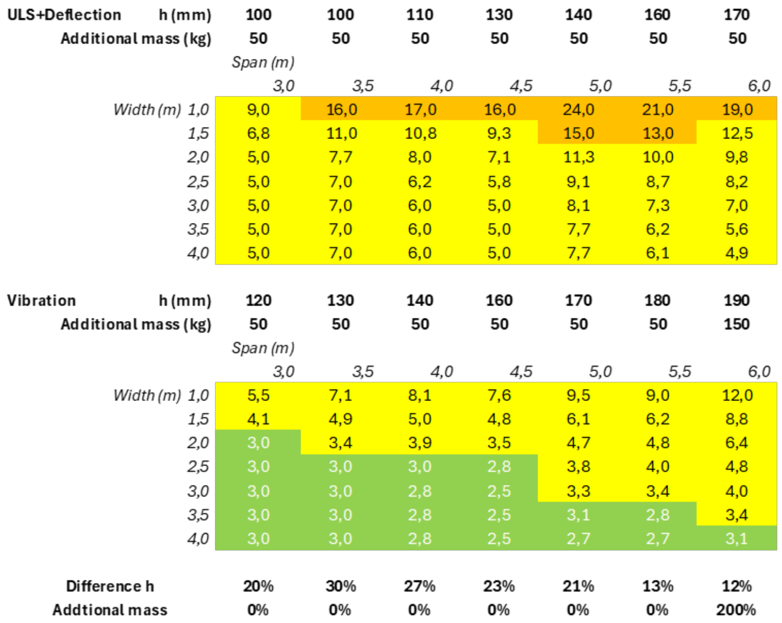


ULS+Deflection	h (mm)	100	100	110	120	130	150	160
	Additional mass (kg)	50	50	50	50	50	50	50
		Span (m)						
		3,0	3,5	4,0	4,5	5,0	5,5	6,0
Width (m)	1,0	8,0	12,9	16,0	20,0	25,0	21,0	17,0
	1,5	5,9	9,4	10,2	13,0	15,0	14,0	11,4
	2,0	4,2	7,8	7,6	9,8	11,3	9,8	8,8
	2,5	4,2	6,0	6,0	7,8	9,0	8,2	7,3
	3,0	4,2	6,0	5,8	6,6	8,0	7,1	6,2
	3,5	4,2	6,0	5,8	6,6	7,6	6,2	5,4
	4,0	4,2	6,0	5,8	6,6	7,6	6,1	4,8

Vibration	h (mm)	110	120	130	150	170	170	190
	Additional mass (kg)	150	100	50	50	50	150	50
		Span (m)						
		3,0	3,5	4,0	4,5	5,0	5,5	6,0
Width (m)	1,0	6,3	6,8	8,8	8,3	8,2	11,5	11,4
	1,5	4,0	4,9	5,9	5,0	5,1	7,8	7,6
	2,0	3,0	3,5	4,1	3,8	4,2	6,4	6,2
	2,5	3,0	3,1	3,3	3,1	3,1	4,9	5,0
	3,0	3,0	3,1	3,1	2,6	2,7	3,8	4,2
	3,5	3,0	3,1	3,1	2,6	2,5	3,2	3,3
	4,0	3,0	3,1	3,1	2,6	2,5	3,1	2,9

Difference h	10%	20%	18%	25%	31%	13%	19%
Addtional mass	200%	100%	0%	0%	0%	200%	0%

Figure 76: CLT Residential 8% damping

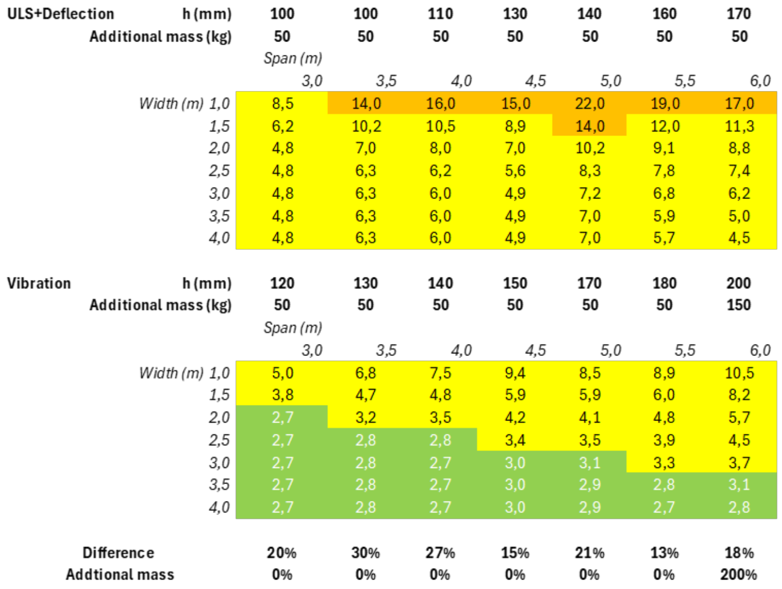


ULS+Deflection	h (mm)	100	100	110	130	140	160	170
	Additional mass (kg)	50	50	50	50	50	50	50
		Span (m)						
		3,0	3,5	4,0	4,5	5,0	5,5	6,0
	Width (m) 1,0	9,0	16,0	17,0	16,0	24,0	21,0	19,0
	1,5	6,8	11,0	10,8	9,3	15,0	13,0	12,5
	2,0	5,0	7,7	8,0	7,1	11,3	10,0	9,8
	2,5	5,0	7,0	6,2	5,8	9,1	8,7	8,2
	3,0	5,0	7,0	6,0	5,0	8,1	7,3	7,0
	3,5	5,0	7,0	6,0	5,0	7,7	6,2	5,6
	4,0	5,0	7,0	6,0	5,0	7,7	6,1	4,9

Vibration	h (mm)	120	130	140	160	170	180	190
	Additional mass (kg)	50	50	50	50	50	50	150
		Span (m)						
		3,0	3,5	4,0	4,5	5,0	5,5	6,0
	Width (m) 1,0	5,5	7,1	8,1	7,6	9,5	9,0	12,0
	1,5	4,1	4,9	5,0	4,8	6,1	6,2	8,8
	2,0	3,0	3,4	3,9	3,5	4,7	4,8	6,4
	2,5	3,0	3,0	3,0	2,8	3,8	4,0	4,8
	3,0	3,0	3,0	2,8	2,5	3,3	3,4	4,0
	3,5	3,0	3,0	2,8	2,5	3,1	2,8	3,4
	4,0	3,0	3,0	2,8	2,5	2,7	2,7	3,1

Difference h	20%	30%	27%	23%	21%	13%	12%
Addtional mass	0%	0%	0%	0%	0%	0%	200%

Figure 77: CLT Office 6% damping

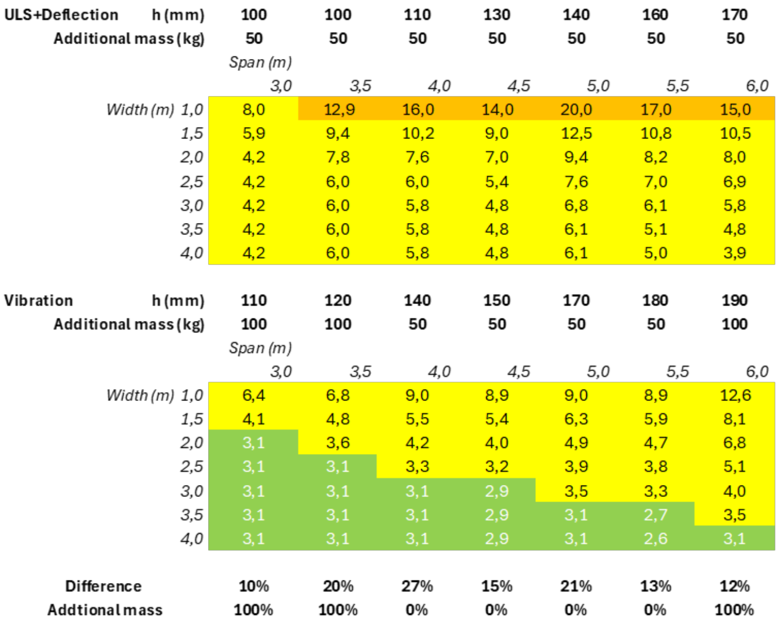


ULS+Deflection	h (mm)	100	100	110	130	140	160	170
	Additional mass (kg)	50	50	50	50	50	50	50
		Span (m)						
		3,0	3,5	4,0	4,5	5,0	5,5	6,0
	Width (m) 1,0	8,5	14,0	16,0	15,0	22,0	19,0	17,0
	1,5	6,2	10,2	10,5	8,9	14,0	12,0	11,3
	2,0	4,8	7,0	8,0	7,0	10,2	9,1	8,8
	2,5	4,8	6,3	6,2	5,6	8,3	7,8	7,4
	3,0	4,8	6,3	6,0	4,9	7,2	6,8	6,2
	3,5	4,8	6,3	6,0	4,9	7,0	5,9	5,0
	4,0	4,8	6,3	6,0	4,9	7,0	5,7	4,5

Vibration	h (mm)	120	130	140	150	170	180	200
	Additional mass (kg)	50	50	50	50	50	50	150
		Span (m)						
		3,0	3,5	4,0	4,5	5,0	5,5	6,0
	Width (m) 1,0	5,0	6,8	7,5	9,4	8,5	8,9	10,5
	1,5	3,8	4,7	4,8	5,9	5,9	6,0	8,2
	2,0	2,7	3,2	3,5	4,2	4,1	4,8	5,7
	2,5	2,7	2,8	2,8	3,4	3,5	3,9	4,5
	3,0	2,7	2,8	2,7	3,0	3,1	3,3	3,7
	3,5	2,7	2,8	2,7	3,0	2,9	2,8	3,1
	4,0	2,7	2,8	2,7	3,0	2,9	2,7	2,8

Difference	20%	30%	27%	15%	21%	13%	18%
Addtional mass	0%	0%	0%	0%	0%	0%	200%

Figure 78: CLT Office 7% damping

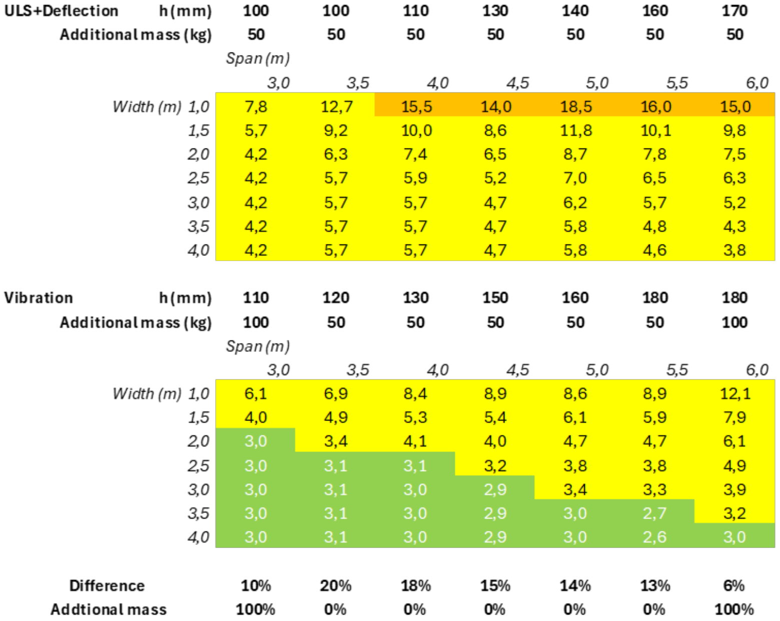


ULS+Deflection	h (mm)	100	100	110	130	140	160	170
	Additional mass (kg)	50	50	50	50	50	50	50
		Span (m)						
		3,0	*3,5*	*4,0*	*4,5*	*5,0*	*5,5*	*6,0*
Width (m)	*1,0*	8,0	12,9	16,0	14,0	20,0	17,0	15,0
	1,5	5,9	9,4	10,2	9,0	12,5	10,8	10,5
	2,0	4,2	7,8	7,6	7,0	9,4	8,2	8,0
	2,5	4,2	6,0	6,0	5,4	7,6	7,0	6,9
	3,0	4,2	6,0	5,8	4,8	6,8	6,1	5,8
	3,5	4,2	6,0	5,8	4,8	6,1	5,1	4,8
	4,0	4,2	6,0	5,8	4,8	6,1	5,0	3,9

Vibration	h (mm)	110	120	140	150	170	180	190
	Additional mass (kg)	100	100	50	50	50	50	100
		Span (m)						
		3,0	*3,5*	*4,0*	*4,5*	*5,0*	*5,5*	*6,0*
Width (m)	*1,0*	6,4	6,8	9,0	8,9	9,0	8,9	12,6
	1,5	4,1	4,8	5,5	5,4	6,3	5,9	8,1
	2,0	3,1	3,6	4,2	4,0	4,9	4,7	6,8
	2,5	3,1	3,1	3,3	3,2	3,9	3,8	5,1
	3,0	3,1	3,1	3,1	2,9	3,5	3,3	4,0
	3,5	3,1	3,1	3,1	2,9	3,1	2,7	3,5
	4,0	3,1	3,1	3,1	2,9	3,1	2,6	3,1

Difference	10%	20%	27%	15%	21%	13%	12%
Addtional mass	100%	100%	0%	0%	0%	0%	100%

Figure 79: CLT Office 8% damping



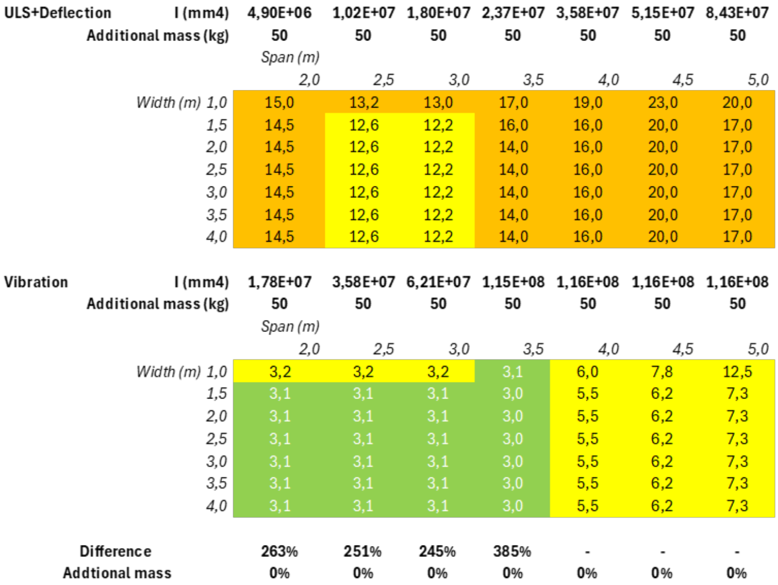
ULS+Deflection	h (mm)	100	100	110	130	140	160	170
	Additional mass (kg)	50	50	50	50	50	50	50
		Span (m)						
		3,0	*3,5*	*4,0*	*4,5*	*5,0*	*5,5*	*6,0*
Width (m)	*1,0*	7,8	12,7	15,5	14,0	18,5	16,0	15,0
	1,5	5,7	9,2	10,0	8,6	11,8	10,1	9,8
	2,0	4,2	6,3	7,4	6,5	8,7	7,8	7,5
	2,5	4,2	5,7	5,9	5,2	7,0	6,5	6,3
	3,0	4,2	5,7	5,7	4,7	6,2	5,7	5,2
	3,5	4,2	5,7	5,7	4,7	5,8	4,8	4,3
	4,0	4,2	5,7	5,7	4,7	5,8	4,6	3,8

Vibration	h (mm)	110	120	130	150	160	180	180
	Additional mass (kg)	100	50	50	50	50	50	100
		Span (m)						
		3,0	*3,5*	*4,0*	*4,5*	*5,0*	*5,5*	*6,0*
Width (m)	*1,0*	6,1	6,9	8,4	8,9	8,6	8,9	12,1
	1,5	4,0	4,9	5,3	5,4	6,1	5,9	7,9
	2,0	3,0	3,4	4,1	4,0	4,7	4,7	6,1
	2,5	3,0	3,1	3,1	3,2	3,8	3,8	4,9
	3,0	3,0	3,1	3,0	2,9	3,4	3,3	3,9
	3,5	3,0	3,1	3,0	2,9	3,0	2,7	3,2
	4,0	3,0	3,1	3,0	2,9	3,0	2,6	3,0

Difference	10%	20%	18%	15%	14%	13%	6%
Addtional mass	100%	0%	0%	0%	0%	0%	100%

Figure 80: CLT Office 9% damping

C.2.2 Joist

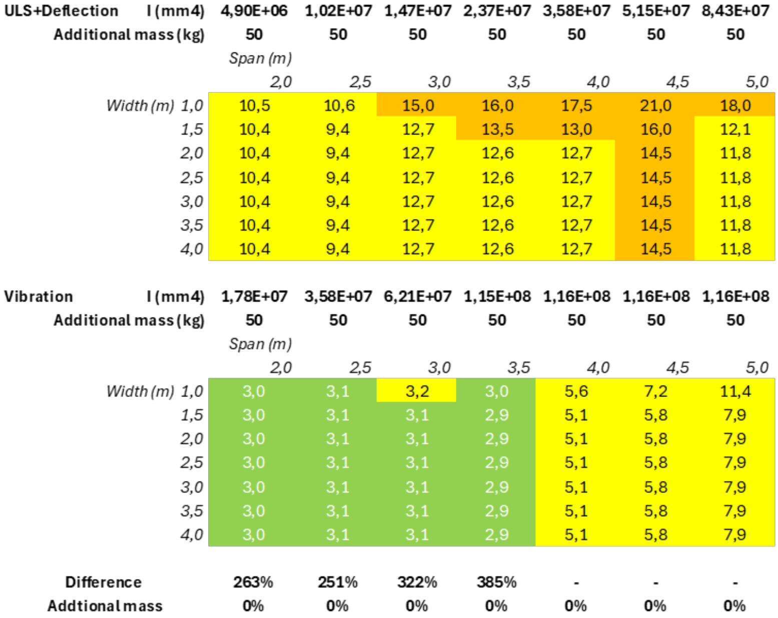


ULS+Deflection	I (mm4)	4,90E+06	1,02E+07	1,80E+07	2,37E+07	3,58E+07	5,15E+07	8,43E+07
	Additional mass (kg)	50	50	50	50	50	50	50
		Span (m)						
		2,0	*2,5*	*3,0*	*3,5*	*4,0*	*4,5*	*5,0*
	Width (m) 1,0	15,0	13,2	13,0	17,0	19,0	23,0	20,0
	1,5	14,5	12,6	12,2	16,0	16,0	20,0	17,0
	2,0	14,5	12,6	12,2	14,0	16,0	20,0	17,0
	2,5	14,5	12,6	12,2	14,0	16,0	20,0	17,0
	3,0	14,5	12,6	12,2	14,0	16,0	20,0	17,0
	3,5	14,5	12,6	12,2	14,0	16,0	20,0	17,0
	4,0	14,5	12,6	12,2	14,0	16,0	20,0	17,0

Vibration	I (mm4)	1,78E+07	3,58E+07	6,21E+07	1,15E+08	1,16E+08	1,16E+08	1,16E+08
	Additional mass (kg)	50	50	50	50	50	50	50
		Span (m)						
		2,0	*2,5*	*3,0*	*3,5*	*4,0*	*4,5*	*5,0*
	Width (m) 1,0	3,2	3,2	3,2	3,1	6,0	7,8	12,5
	1,5	3,1	3,1	3,1	3,0	5,5	6,2	7,3
	2,0	3,1	3,1	3,1	3,0	5,5	6,2	7,3
	2,5	3,1	3,1	3,1	3,0	5,5	6,2	7,3
	3,0	3,1	3,1	3,1	3,0	5,5	6,2	7,3
	3,5	3,1	3,1	3,1	3,0	5,5	6,2	7,3
	4,0	3,1	3,1	3,1	3,0	5,5	6,2	7,3

Difference		263%	251%	245%	385%	-	-	-
Addtional mass		0%	0%	0%	0%	0%	0%	0%

Figure 81: Joist Residential 7% damping

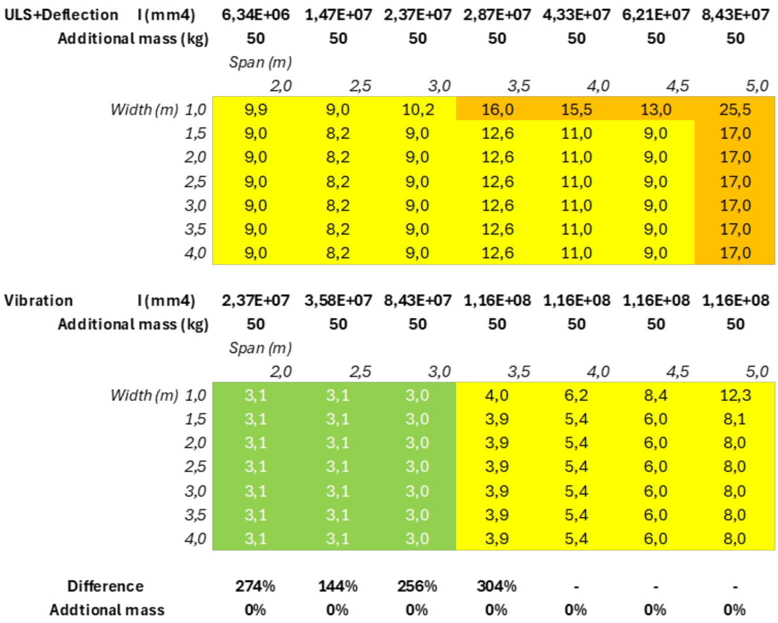


ULS+Deflection	I (mm4)	4,90E+06	1,02E+07	1,47E+07	2,37E+07	3,58E+07	5,15E+07	8,43E+07
	Additional mass (kg)	50	50	50	50	50	50	50
		Span (m)						
		2,0	*2,5*	*3,0*	*3,5*	*4,0*	*4,5*	*5,0*
	Width (m) 1,0	10,5	10,6	15,0	16,0	17,5	21,0	18,0
	1,5	10,4	9,4	12,7	13,5	13,0	16,0	12,1
	2,0	10,4	9,4	12,7	12,6	12,7	14,5	11,8
	2,5	10,4	9,4	12,7	12,6	12,7	14,5	11,8
	3,0	10,4	9,4	12,7	12,6	12,7	14,5	11,8
	3,5	10,4	9,4	12,7	12,6	12,7	14,5	11,8
	4,0	10,4	9,4	12,7	12,6	12,7	14,5	11,8

Vibration	I (mm4)	1,78E+07	3,58E+07	6,21E+07	1,15E+08	1,16E+08	1,16E+08	1,16E+08
	Additional mass (kg)	50	50	50	50	50	50	50
		Span (m)						
		2,0	*2,5*	*3,0*	*3,5*	*4,0*	*4,5*	*5,0*
	Width (m) 1,0	3,0	3,1	3,2	3,0	5,6	7,2	11,4
	1,5	3,0	3,1	3,1	2,9	5,1	5,8	7,9
	2,0	3,0	3,1	3,1	2,9	5,1	5,8	7,9
	2,5	3,0	3,1	3,1	2,9	5,1	5,8	7,9
	3,0	3,0	3,1	3,1	2,9	5,1	5,8	7,9
	3,5	3,0	3,1	3,1	2,9	5,1	5,8	7,9
	4,0	3,0	3,1	3,1	2,9	5,1	5,8	7,9

Difference		263%	251%	322%	385%	-	-	-
Addtional mass		0%	0%	0%	0%	0%	0%	0%

Figure 82: Joist Residential 8% damping

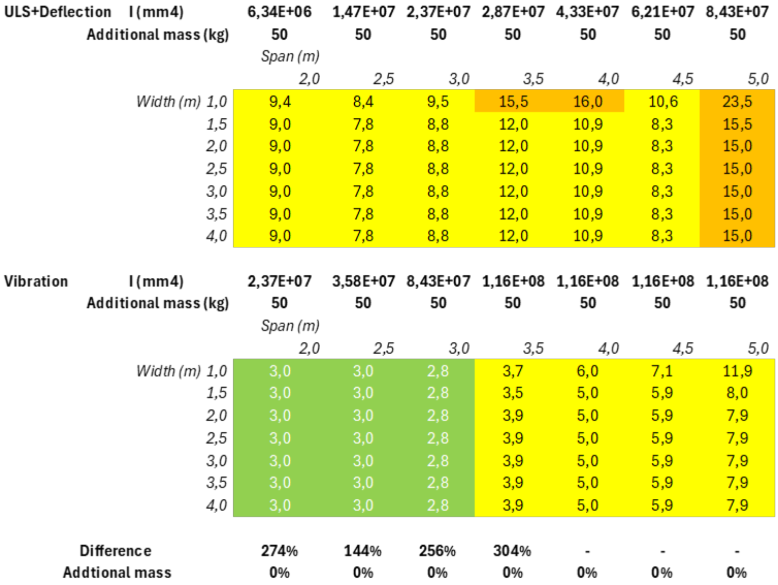


ULS+Deflection	I (mm4)	6,34E+06	1,47E+07	2,37E+07	2,87E+07	4,33E+07	6,21E+07	8,43E+07
	Additional mass (kg)	50	50	50	50	50	50	50
		Span (m)						
		2,0	2,5	3,0	3,5	4,0	4,5	5,0
Width (m)	1,0	9,9	9,0	10,2	16,0	15,5	13,0	25,5
	1,5	9,0	8,2	9,0	12,6	11,0	9,0	17,0
	2,0	9,0	8,2	9,0	12,6	11,0	9,0	17,0
	2,5	9,0	8,2	9,0	12,6	11,0	9,0	17,0
	3,0	9,0	8,2	9,0	12,6	11,0	9,0	17,0
	3,5	9,0	8,2	9,0	12,6	11,0	9,0	17,0
	4,0	9,0	8,2	9,0	12,6	11,0	9,0	17,0

Vibration	I (mm4)	2,37E+07	3,58E+07	8,43E+07	1,16E+08	1,16E+08	1,16E+08	1,16E+08
	Additional mass (kg)	50	50	50	50	50	50	50
		Span (m)						
		2,0	2,5	3,0	3,5	4,0	4,5	5,0
Width (m)	1,0	3,1	3,1	3,0	4,0	6,2	8,4	12,3
	1,5	3,1	3,1	3,0	3,9	5,4	6,0	8,1
	2,0	3,1	3,1	3,0	3,9	5,4	6,0	8,0
	2,5	3,1	3,1	3,0	3,9	5,4	6,0	8,0
	3,0	3,1	3,1	3,0	3,9	5,4	6,0	8,0
	3,5	3,1	3,1	3,0	3,9	5,4	6,0	8,0
	4,0	3,1	3,1	3,0	3,9	5,4	6,0	8,0

Difference	274%	144%	256%	304%	-	-	-
Addtional mass	0%	0%	0%	0%	0%	0%	0%

Figure 83: Joist Office 6% damping

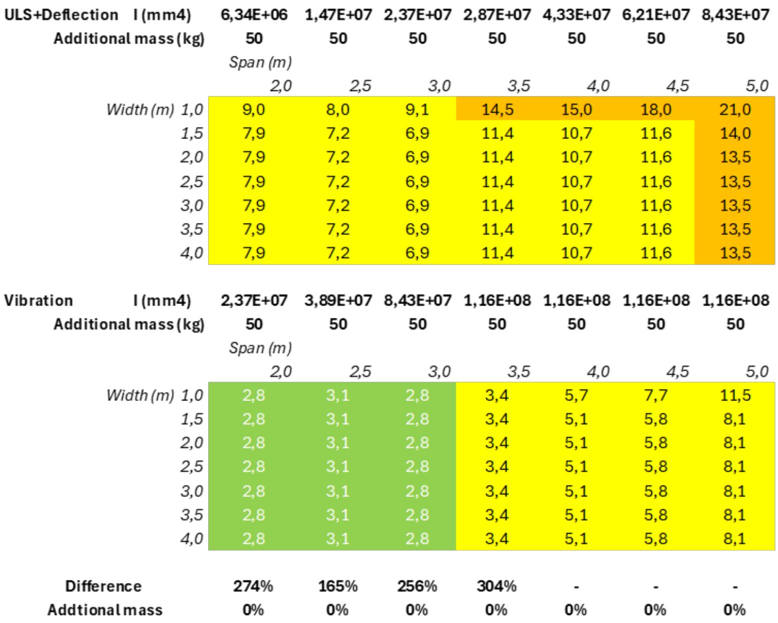


ULS+Deflection	I (mm4)	6,34E+06	1,47E+07	2,37E+07	2,87E+07	4,33E+07	6,21E+07	8,43E+07
	Additional mass (kg)	50	50	50	50	50	50	50
		Span (m)						
		2,0	2,5	3,0	3,5	4,0	4,5	5,0
Width (m)	1,0	9,4	8,4	9,5	15,5	16,0	10,6	23,5
	1,5	9,0	7,8	8,8	12,0	10,9	8,3	15,5
	2,0	9,0	7,8	8,8	12,0	10,9	8,3	15,0
	2,5	9,0	7,8	8,8	12,0	10,9	8,3	15,0
	3,0	9,0	7,8	8,8	12,0	10,9	8,3	15,0
	3,5	9,0	7,8	8,8	12,0	10,9	8,3	15,0
	4,0	9,0	7,8	8,8	12,0	10,9	8,3	15,0

Vibration	I (mm4)	2,37E+07	3,58E+07	8,43E+07	1,16E+08	1,16E+08	1,16E+08	1,16E+08
	Additional mass (kg)	50	50	50	50	50	50	50
		Span (m)						
		2,0	2,5	3,0	3,5	4,0	4,5	5,0
Width (m)	1,0	3,0	3,0	2,8	3,7	6,0	7,1	11,9
	1,5	3,0	3,0	2,8	3,5	5,0	5,9	8,0
	2,0	3,0	3,0	2,8	3,9	5,0	5,9	7,9
	2,5	3,0	3,0	2,8	3,9	5,0	5,9	7,9
	3,0	3,0	3,0	2,8	3,9	5,0	5,9	7,9
	3,5	3,0	3,0	2,8	3,9	5,0	5,9	7,9
	4,0	3,0	3,0	2,8	3,9	5,0	5,9	7,9

Difference	274%	144%	256%	304%	-	-	-
Addtional mass	0%	0%	0%	0%	0%	0%	0%

Figure 84: Joist Office 7% damping

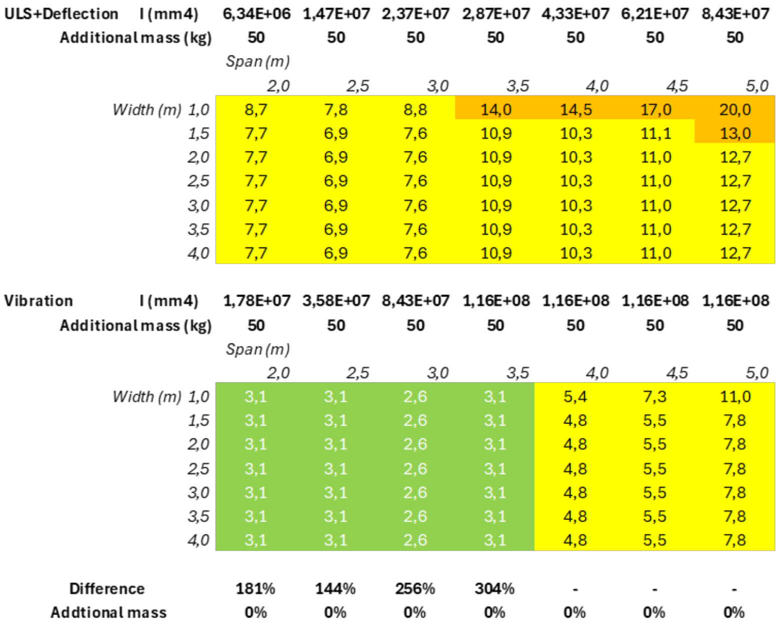


ULS+Deflection	I (mm4)	6,34E+06	1,47E+07	2,37E+07	2,87E+07	4,33E+07	6,21E+07	8,43E+07
	Additional mass (kg)	50	50	50	50	50	50	50
		Span (m)						
		2,0	*2,5*	*3,0*	*3,5*	*4,0*	*4,5*	*5,0*
	Width (m) 1,0	9,0	8,0	9,1	14,5	15,0	18,0	21,0
	1,5	7,9	7,2	6,9	11,4	10,7	11,6	14,0
	2,0	7,9	7,2	6,9	11,4	10,7	11,6	13,5
	2,5	7,9	7,2	6,9	11,4	10,7	11,6	13,5
	3,0	7,9	7,2	6,9	11,4	10,7	11,6	13,5
	3,5	7,9	7,2	6,9	11,4	10,7	11,6	13,5
	4,0	7,9	7,2	6,9	11,4	10,7	11,6	13,5

Vibration	I (mm4)	2,37E+07	3,89E+07	8,43E+07	1,16E+08	1,16E+08	1,16E+08	1,16E+08
	Additional mass (kg)	50	50	50	50	50	50	50
		Span (m)						
		2,0	*2,5*	*3,0*	*3,5*	*4,0*	*4,5*	*5,0*
	Width (m) 1,0	2,8	3,1	2,8	3,4	5,7	7,7	11,5
	1,5	2,8	3,1	2,8	3,4	5,1	5,8	8,1
	2,0	2,8	3,1	2,8	3,4	5,1	5,8	8,1
	2,5	2,8	3,1	2,8	3,4	5,1	5,8	8,1
	3,0	2,8	3,1	2,8	3,4	5,1	5,8	8,1
	3,5	2,8	3,1	2,8	3,4	5,1	5,8	8,1
	4,0	2,8	3,1	2,8	3,4	5,1	5,8	8,1

Difference	274%	165%	256%	304%	-	-	-
Addtional mass	0%	0%	0%	0%	0%	0%	0%

Figure 85: Joist Office 8% damping



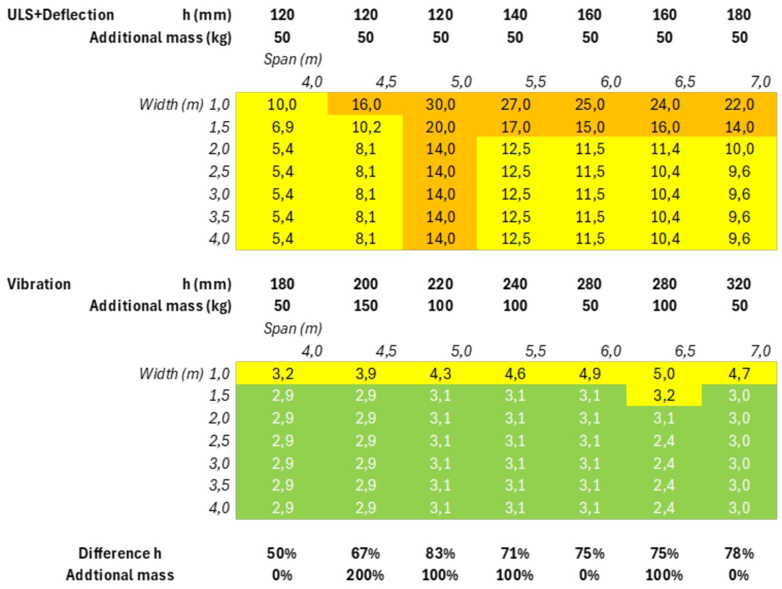
ULS+Deflection	I (mm4)	6,34E+06	1,47E+07	2,37E+07	2,87E+07	4,33E+07	6,21E+07	8,43E+07
	Additional mass (kg)	50	50	50	50	50	50	50
		Span (m)						
		2,0	*2,5*	*3,0*	*3,5*	*4,0*	*4,5*	*5,0*
	Width (m) 1,0	8,7	7,8	8,8	14,0	14,5	17,0	20,0
	1,5	7,7	6,9	7,6	10,9	10,3	11,1	13,0
	2,0	7,7	6,9	7,6	10,9	10,3	11,0	12,7
	2,5	7,7	6,9	7,6	10,9	10,3	11,0	12,7
	3,0	7,7	6,9	7,6	10,9	10,3	11,0	12,7
	3,5	7,7	6,9	7,6	10,9	10,3	11,0	12,7
	4,0	7,7	6,9	7,6	10,9	10,3	11,0	12,7

Vibration	I (mm4)	1,78E+07	3,58E+07	8,43E+07	1,16E+08	1,16E+08	1,16E+08	1,16E+08
	Additional mass (kg)	50	50	50	50	50	50	50
		Span (m)						
		2,0	*2,5*	*3,0*	*3,5*	*4,0*	*4,5*	*5,0*
	Width (m) 1,0	3,1	3,1	2,6	3,1	5,4	7,3	11,0
	1,5	3,1	3,1	2,6	3,1	4,8	5,5	7,8
	2,0	3,1	3,1	2,6	3,1	4,8	5,5	7,8
	2,5	3,1	3,1	2,6	3,1	4,8	5,5	7,8
	3,0	3,1	3,1	2,6	3,1	4,8	5,5	7,8
	3,5	3,1	3,1	2,6	3,1	4,8	5,5	7,8
	4,0	3,1	3,1	2,6	3,1	4,8	5,5	7,8

Difference	181%	144%	256%	304%	-	-	-
Addtional mass	0%	0%	0%	0%	0%	0%	0%

Figure 86: Joist Office 9% damping

C.2.3 Lignatur

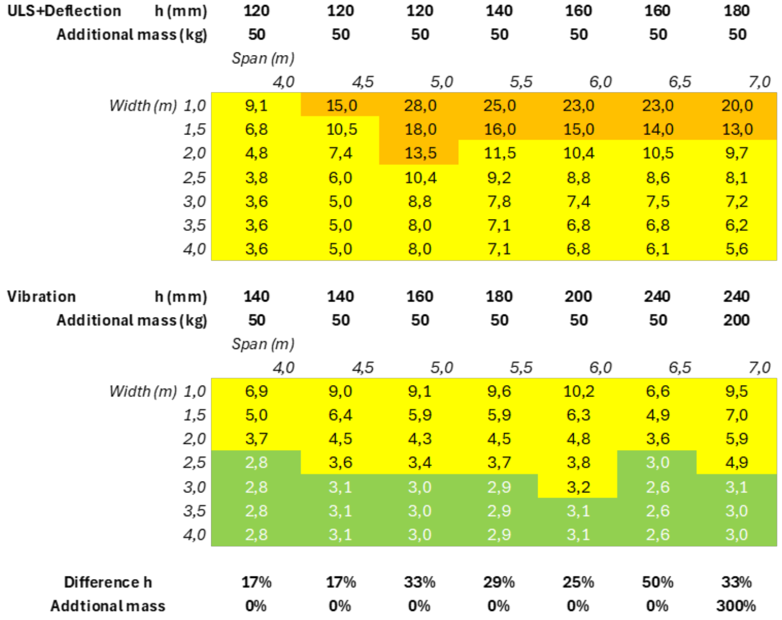


ULS+Deflection	h (mm)	120	120	120	140	160	160	180
	Additional mass (kg)	50	50	50	50	50	50	50
	Span (m)	4,0	4,5	5,0	5,5	6,0	6,5	7,0
Width (m)	1,0	10,0	16,0	30,0	27,0	25,0	24,0	22,0
	1,5	6,9	10,2	20,0	17,0	15,0	16,0	14,0
	2,0	5,4	8,1	14,0	12,5	11,5	11,4	10,0
	2,5	5,4	8,1	14,0	12,5	11,5	10,4	9,6
	3,0	5,4	8,1	14,0	12,5	11,5	10,4	9,6
	3,5	5,4	8,1	14,0	12,5	11,5	10,4	9,6
	4,0	5,4	8,1	14,0	12,5	11,5	10,4	9,6

Vibration	h (mm)	180	200	220	240	280	280	320
	Additional mass (kg)	50	150	100	100	50	100	50
	Span (m)	4,0	4,5	5,0	5,5	6,0	6,5	7,0
Width (m)	1,0	3,2	3,9	4,3	4,6	4,9	5,0	4,7
	1,5	2,9	2,9	3,1	3,1	3,1	3,2	3,0
	2,0	2,9	2,9	3,1	3,1	3,1	3,1	3,0
	2,5	2,9	2,9	3,1	3,1	3,1	2,4	3,0
	3,0	2,9	2,9	3,1	3,1	3,1	2,4	3,0
	3,5	2,9	2,9	3,1	3,1	3,1	2,4	3,0
	4,0	2,9	2,9	3,1	3,1	3,1	2,4	3,0

Difference h	50%	67%	83%	71%	75%	75%	78%
Addtional mass	0%	200%	100%	100%	0%	100%	0%

Figure 87: Lignatur Residential 7% damping

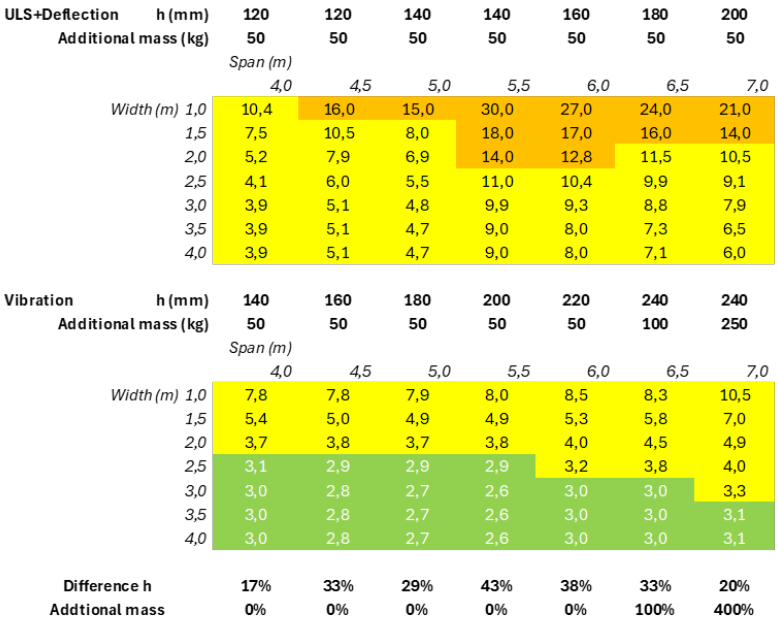


ULS+Deflection	h (mm)	120	120	120	140	160	160	180
	Additional mass (kg)	50	50	50	50	50	50	50
	Span (m)	4,0	4,5	5,0	5,5	6,0	6,5	7,0
Width (m)	1,0	9,1	15,0	28,0	25,0	23,0	23,0	20,0
	1,5	6,8	10,5	18,0	16,0	15,0	14,0	13,0
	2,0	4,8	7,4	13,5	11,5	10,4	10,5	9,7
	2,5	3,8	6,0	10,4	9,2	8,8	8,6	8,1
	3,0	3,6	5,0	8,8	7,8	7,4	7,5	7,2
	3,5	3,6	5,0	8,0	7,1	6,8	6,8	6,2
	4,0	3,6	5,0	8,0	7,1	6,8	6,1	5,6

Vibration	h (mm)	140	140	160	180	200	240	240
	Additional mass (kg)	50	50	50	50	50	50	200
	Span (m)	4,0	4,5	5,0	5,5	6,0	6,5	7,0
Width (m)	1,0	6,9	9,0	9,1	9,6	10,2	6,6	9,5
	1,5	5,0	6,4	5,9	5,9	6,3	4,9	7,0
	2,0	3,7	4,5	4,3	4,5	4,8	3,6	5,9
	2,5	2,8	3,6	3,4	3,7	3,8	3,0	4,9
	3,0	2,8	3,1	3,0	2,9	3,2	2,6	3,1
	3,5	2,8	3,1	3,0	2,9	3,1	2,6	3,0
	4,0	2,8	3,1	3,0	2,9	3,1	2,6	3,0

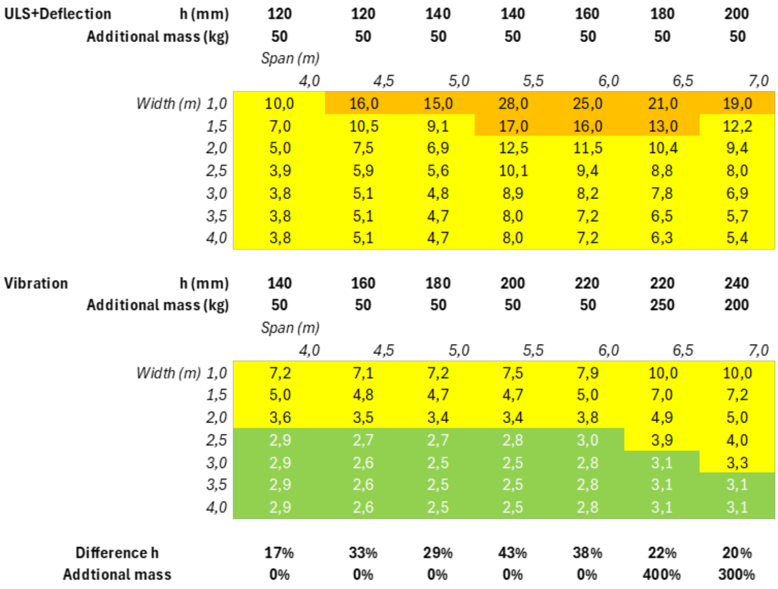
Difference h	17%	17%	33%	29%	25%	50%	33%
Addtional mass	0%	0%	0%	0%	0%	0%	300%

Figure 88: Lignatur Residential 8% damping



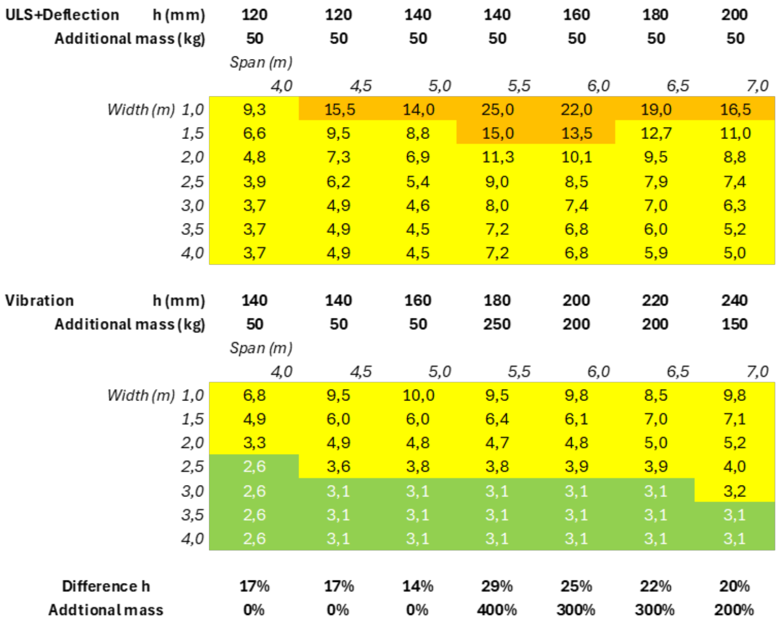
ULS+Deflection	**h (mm)**	**120**	**120**	**140**	**140**	**160**	**180**	**200**
	Additional mass (kg)	**50**	**50**	**50**	**50**	**50**	**50**	**50**
		Span (m)						
		4,0	*4,5*	*5,0*	*5,5*	*6,0*	*6,5*	*7,0*
Width (m)	*1,0*	10,4	16,0	15,0	30,0	27,0	24,0	21,0
	1,5	7,5	10,5	8,0	18,0	17,0	16,0	14,0
	2,0	5,2	7,9	6,9	14,0	12,8	11,5	10,5
	2,5	4,1	6,0	5,5	11,0	10,4	9,9	9,1
	3,0	3,9	5,1	4,8	9,9	9,3	8,8	7,9
	3,5	3,9	5,1	4,7	9,0	8,0	7,3	6,5
	4,0	3,9	5,1	4,7	9,0	8,0	7,1	6,0
Vibration	**h (mm)**	**140**	**160**	**180**	**200**	**220**	**240**	**240**
	Additional mass (kg)	**50**	**50**	**50**	**50**	**50**	**100**	**250**
		Span (m)						
		4,0	*4,5*	*5,0*	*5,5*	*6,0*	*6,5*	*7,0*
Width (m)	*1,0*	7,8	7,8	7,9	8,0	8,5	8,3	10,5
	1,5	5,4	5,0	4,9	4,9	5,3	5,8	7,0
	2,0	3,7	3,8	3,7	3,8	4,0	4,5	4,9
	2,5	3,1	2,9	2,9	2,9	3,2	3,8	4,0
	3,0	3,0	2,8	2,7	2,6	3,0	3,0	3,3
	3,5	3,0	2,8	2,7	2,6	3,0	3,0	3,1
	4,0	3,0	2,8	2,7	2,6	3,0	3,0	3,1
Difference h		**17%**	**33%**	**29%**	**43%**	**38%**	**33%**	**20%**
Addtional mass		**0%**	**0%**	**0%**	**0%**	**0%**	**100%**	**400%**

Figure 89: Lignatur Office 6% damping



ULS+Deflection	**h (mm)**	**120**	**120**	**140**	**140**	**160**	**180**	**200**
	Additional mass (kg)	**50**	**50**	**50**	**50**	**50**	**50**	**50**
		Span (m)						
		4,0	*4,5*	*5,0*	*5,5*	*6,0*	*6,5*	*7,0*
Width (m)	*1,0*	10,0	16,0	15,0	28,0	25,0	21,0	19,0
	1,5	7,0	10,5	9,1	17,0	16,0	13,0	12,2
	2,0	5,0	7,5	6,9	12,5	11,5	10,4	9,4
	2,5	3,9	5,9	5,6	10,1	9,4	8,8	8,0
	3,0	3,8	5,1	4,8	8,9	8,2	7,8	6,9
	3,5	3,8	5,1	4,7	8,0	7,2	6,5	5,7
	4,0	3,8	5,1	4,7	8,0	7,2	6,3	5,4
Vibration	**h (mm)**	**140**	**160**	**180**	**200**	**220**	**220**	**240**
	Additional mass (kg)	**50**	**50**	**50**	**50**	**50**	**250**	**200**
		Span (m)						
		4,0	*4,5*	*5,0*	*5,5*	*6,0*	*6,5*	*7,0*
Width (m)	*1,0*	7,2	7,1	7,2	7,5	7,9	10,0	10,0
	1,5	5,0	4,8	4,7	4,7	5,0	7,0	7,2
	2,0	3,6	3,5	3,4	3,4	3,8	4,9	5,0
	2,5	2,9	2,7	2,7	2,8	3,0	3,9	4,0
	3,0	2,9	2,6	2,5	2,5	2,8	3,1	3,3
	3,5	2,9	2,6	2,5	2,5	2,8	3,1	3,1
	4,0	2,9	2,6	2,5	2,5	2,8	3,1	3,1
Difference h		**17%**	**33%**	**29%**	**43%**	**38%**	**22%**	**20%**
Addtional mass		**0%**	**0%**	**0%**	**0%**	**0%**	**400%**	**300%**

Figure 90: Lignatur Office 7% damping

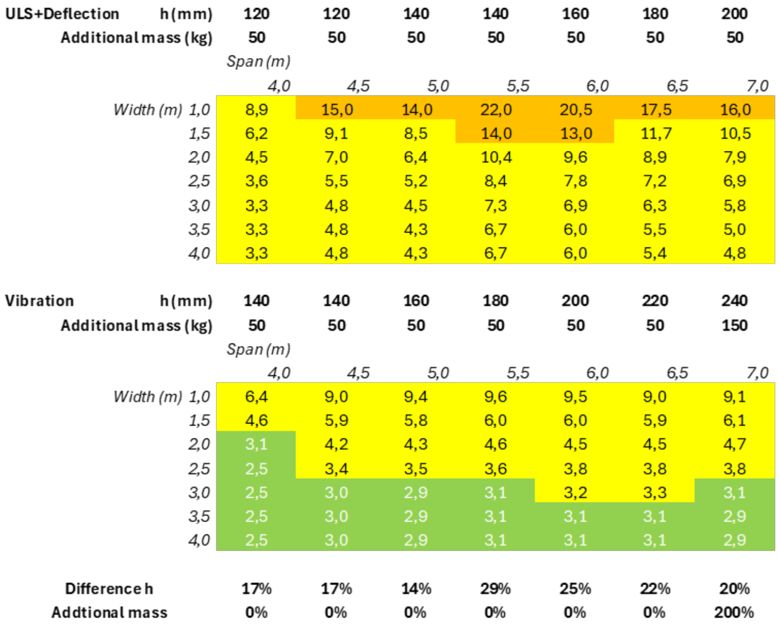


ULS+Deflection	**h (mm)**	**120**	**120**	**140**	**140**	**160**	**180**	**200**
	Additional mass (kg)	**50**	**50**	**50**	**50**	**50**	**50**	**50**
		Span (m)						
		4,0	*4,5*	*5,0*	*5,5*	*6,0*	*6,5*	*7,0*
	Width (m) 1,0	9,3	15,5	14,0	25,0	22,0	19,0	16,5
	1,5	6,6	9,5	8,8	15,0	13,5	12,7	11,0
	2,0	4,8	7,3	6,9	11,3	10,1	9,5	8,8
	2,5	3,9	6,2	5,4	9,0	8,5	7,9	7,4
	3,0	3,7	4,9	4,6	8,0	7,4	7,0	6,3
	3,5	3,7	4,9	4,5	7,2	6,8	6,0	5,2
	4,0	3,7	4,9	4,5	7,2	6,8	5,9	5,0

Vibration	**h (mm)**	**140**	**140**	**160**	**180**	**200**	**220**	**240**
	Additional mass (kg)	**50**	**50**	**50**	**250**	**200**	**200**	**150**
		Span (m)						
		4,0	*4,5*	*5,0*	*5,5*	*6,0*	*6,5*	*7,0*
	Width (m) 1,0	6,8	9,5	10,0	9,5	9,8	8,5	9,8
	1,5	4,9	6,0	6,0	6,4	6,1	7,0	7,1
	2,0	3,3	4,9	4,8	4,7	4,8	5,0	5,2
	2,5	2,6	3,6	3,8	3,8	3,9	3,9	4,0
	3,0	2,6	3,1	3,1	3,1	3,1	3,1	3,2
	3,5	2,6	3,1	3,1	3,1	3,1	3,1	3,1
	4,0	2,6	3,1	3,1	3,1	3,1	3,1	3,1

Difference h	**17%**	**17%**	**14%**	**29%**	**25%**	**22%**	**20%**
Addtional mass	**0%**	**0%**	**0%**	**400%**	**300%**	**300%**	**200%**

Figure 91: Lignatur Office 8% damping



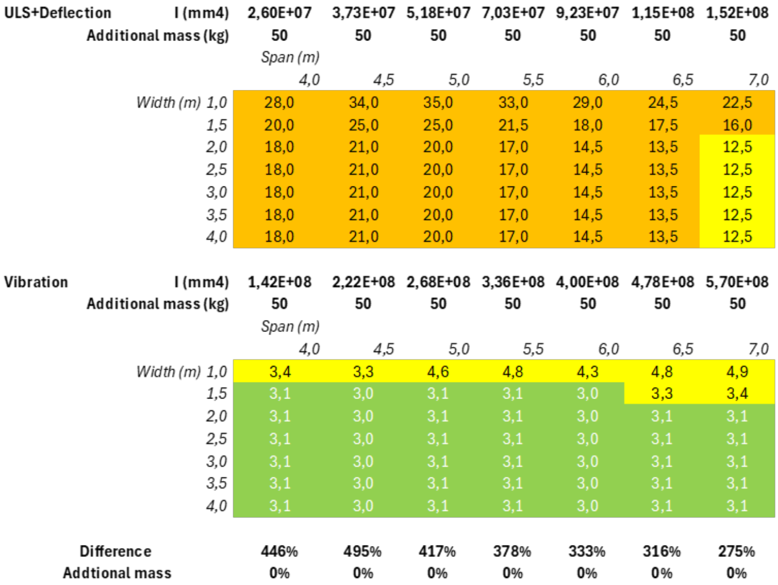
ULS+Deflection	**h (mm)**	**120**	**120**	**140**	**140**	**160**	**180**	**200**
	Additional mass (kg)	**50**	**50**	**50**	**50**	**50**	**50**	**50**
		Span (m)						
		4,0	*4,5*	*5,0*	*5,5*	*6,0*	*6,5*	*7,0*
	Width (m) 1,0	8,9	15,0	14,0	22,0	20,5	17,5	16,0
	1,5	6,2	9,1	8,5	14,0	13,0	11,7	10,5
	2,0	4,5	7,0	6,4	10,4	9,6	8,9	7,9
	2,5	3,6	5,5	5,2	8,4	7,8	7,2	6,9
	3,0	3,3	4,8	4,5	7,3	6,9	6,3	5,8
	3,5	3,3	4,8	4,3	6,7	6,0	5,5	5,0
	4,0	3,3	4,8	4,3	6,7	6,0	5,4	4,8

Vibration	**h (mm)**	**140**	**140**	**160**	**180**	**200**	**220**	**240**
	Additional mass (kg)	**50**	**50**	**50**	**50**	**50**	**50**	**150**
		Span (m)						
		4,0	*4,5*	*5,0*	*5,5*	*6,0*	*6,5*	*7,0*
	Width (m) 1,0	6,4	9,0	9,4	9,6	9,5	9,0	9,1
	1,5	4,6	5,9	5,8	6,0	6,0	5,9	6,1
	2,0	3,1	4,2	4,3	4,6	4,5	4,5	4,7
	2,5	2,5	3,4	3,5	3,6	3,8	3,8	3,8
	3,0	2,5	3,0	2,9	3,1	3,2	3,3	3,1
	3,5	2,5	3,0	2,9	3,1	3,1	3,1	2,9
	4,0	2,5	3,0	2,9	3,1	3,1	3,1	2,9

Difference h	**17%**	**17%**	**14%**	**29%**	**25%**	**22%**	**20%**
Addtional mass	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**	**200%**

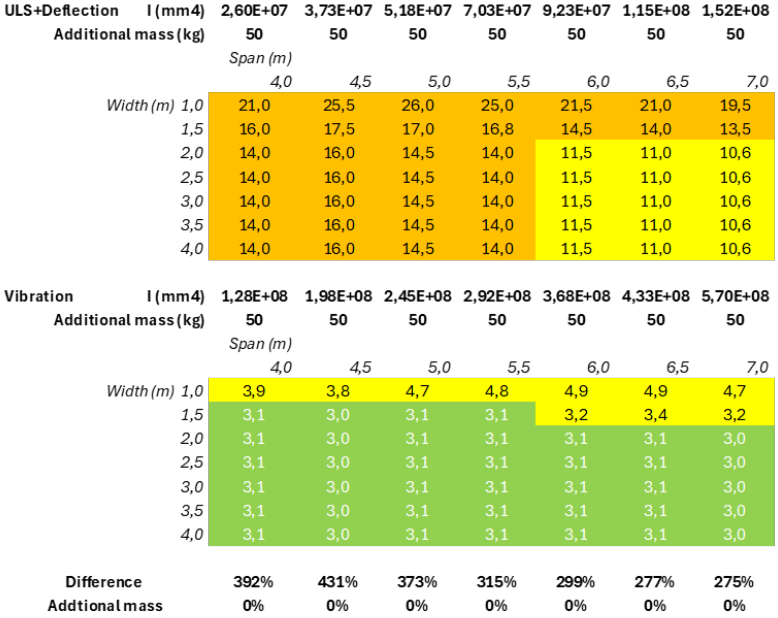
Figure 92: Lignatur Office 9% damping

C.2.4 Kerto Ripa Rib



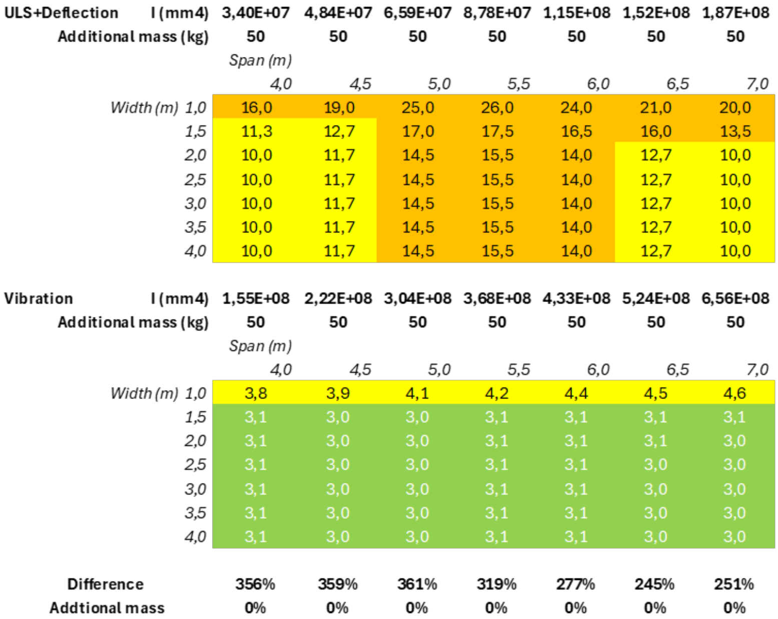
ULS+Deflection	I (mm4)	2,60E+07	3,73E+07	5,18E+07	7,03E+07	9,23E+07	1,15E+08	1,52E+08
	Additional mass (kg)	50	50	50	50	50	50	50
		Span (m)						
		4,0	4,5	5,0	5,5	6,0	6,5	7,0
Width (m)	1,0	28,0	34,0	35,0	33,0	29,0	24,5	22,5
	1,5	20,0	25,0	25,0	21,5	18,0	17,5	16,0
	2,0	18,0	21,0	20,0	17,0	14,5	13,5	12,5
	2,5	18,0	21,0	20,0	17,0	14,5	13,5	12,5
	3,0	18,0	21,0	20,0	17,0	14,5	13,5	12,5
	3,5	18,0	21,0	20,0	17,0	14,5	13,5	12,5
	4,0	18,0	21,0	20,0	17,0	14,5	13,5	12,5
Vibration	I (mm4)	1,42E+08	2,22E+08	2,68E+08	3,36E+08	4,00E+08	4,78E+08	5,70E+08
	Additional mass (kg)	50	50	50	50	50	50	50
		Span (m)						
		4,0	4,5	5,0	5,5	6,0	6,5	7,0
Width (m)	1,0	3,4	3,3	4,6	4,8	4,3	4,8	4,9
	1,5	3,1	3,0	3,1	3,1	3,0	3,3	3,4
	2,0	3,1	3,0	3,1	3,1	3,0	3,1	3,1
	2,5	3,1	3,0	3,1	3,1	3,0	3,1	3,1
	3,0	3,1	3,0	3,1	3,1	3,0	3,1	3,1
	3,5	3,1	3,0	3,1	3,1	3,0	3,1	3,1
	4,0	3,1	3,0	3,1	3,1	3,0	3,1	3,1
Difference		446%	495%	417%	378%	333%	316%	275%
Addtional mass		0%	0%	0%	0%	0%	0%	0%

Figure 93: Kerto Ripa Rib Residential 7% damping



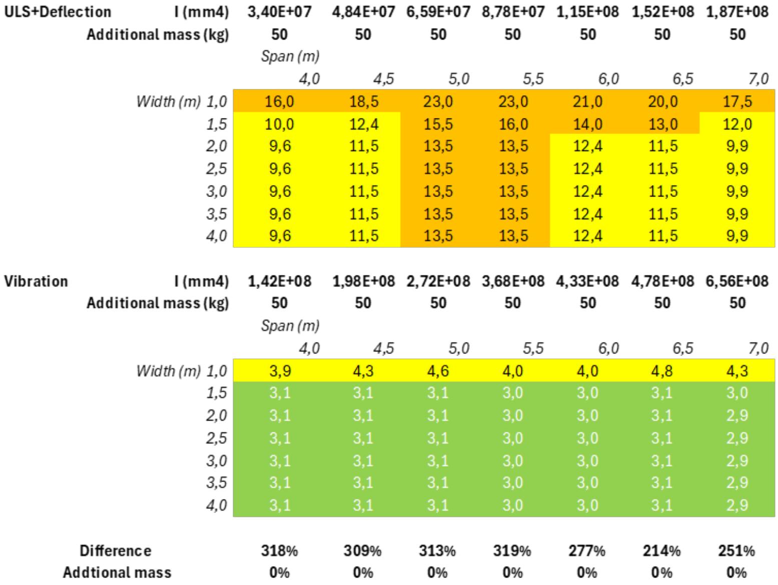
ULS+Deflection	I (mm4)	2,60E+07	3,73E+07	5,18E+07	7,03E+07	9,23E+07	1,15E+08	1,52E+08
	Additional mass (kg)	50	50	50	50	50	50	50
		Span (m)						
		4,0	4,5	5,0	5,5	6,0	6,5	7,0
Width (m)	1,0	21,0	25,5	26,0	25,0	21,5	21,0	19,5
	1,5	16,0	17,5	17,0	16,8	14,5	14,0	13,5
	2,0	14,0	16,0	14,5	14,0	11,5	11,0	10,6
	2,5	14,0	16,0	14,5	14,0	11,5	11,0	10,6
	3,0	14,0	16,0	14,5	14,0	11,5	11,0	10,6
	3,5	14,0	16,0	14,5	14,0	11,5	11,0	10,6
	4,0	14,0	16,0	14,5	14,0	11,5	11,0	10,6
Vibration	I (mm4)	1,28E+08	1,98E+08	2,45E+08	2,92E+08	3,68E+08	4,33E+08	5,70E+08
	Additional mass (kg)	50	50	50	50	50	50	50
		Span (m)						
		4,0	4,5	5,0	5,5	6,0	6,5	7,0
Width (m)	1,0	3,9	3,8	4,7	4,8	4,9	4,9	4,7
	1,5	3,1	3,0	3,1	3,1	3,2	3,4	3,2
	2,0	3,1	3,0	3,1	3,1	3,1	3,1	3,0
	2,5	3,1	3,0	3,1	3,1	3,1	3,1	3,0
	3,0	3,1	3,0	3,1	3,1	3,1	3,1	3,0
	3,5	3,1	3,0	3,1	3,1	3,1	3,1	3,0
	4,0	3,1	3,0	3,1	3,1	3,1	3,1	3,0
Difference		392%	431%	373%	315%	299%	277%	275%
Addtional mass		0%	0%	0%	0%	0%	0%	0%

Figure 94: Kerto Ripa Rib Residential 8% damping



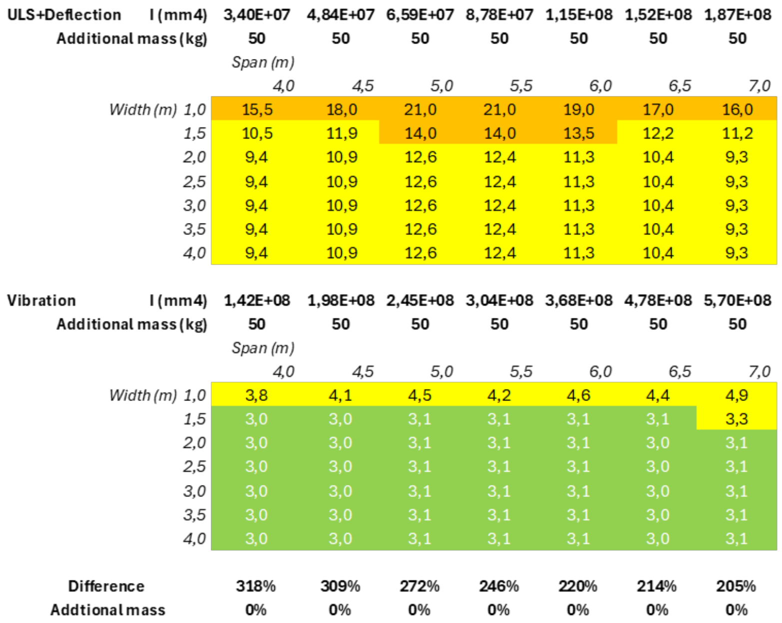
ULS+Deflection	I (mm4)	3,40E+07	4,84E+07	6,59E+07	8,78E+07	1,15E+08	1,52E+08	1,87E+08
	Additional mass (kg)	50	50	50	50	50	50	50
		Span (m)						
		4,0	4,5	5,0	5,5	6,0	6,5	7,0
	Width (m) 1,0	16,0	19,0	25,0	26,0	24,0	21,0	20,0
	1,5	11,3	12,7	17,0	17,5	16,5	16,0	13,5
	2,0	10,0	11,7	14,5	15,5	14,0	12,7	10,0
	2,5	10,0	11,7	14,5	15,5	14,0	12,7	10,0
	3,0	10,0	11,7	14,5	15,5	14,0	12,7	10,0
	3,5	10,0	11,7	14,5	15,5	14,0	12,7	10,0
	4,0	10,0	11,7	14,5	15,5	14,0	12,7	10,0
Vibration	I (mm4)	1,55E+08	2,22E+08	3,04E+08	3,68E+08	4,33E+08	5,24E+08	6,56E+08
	Additional mass (kg)	50	50	50	50	50	50	50
		Span (m)						
		4,0	4,5	5,0	5,5	6,0	6,5	7,0
	Width (m) 1,0	3,8	3,9	4,1	4,2	4,4	4,5	4,6
	1,5	3,1	3,0	3,0	3,1	3,1	3,1	3,1
	2,0	3,1	3,0	3,0	3,1	3,1	3,1	3,0
	2,5	3,1	3,0	3,0	3,1	3,1	3,0	3,0
	3,0	3,1	3,0	3,0	3,1	3,1	3,0	3,0
	3,5	3,1	3,0	3,0	3,1	3,1	3,0	3,0
	4,0	3,1	3,0	3,0	3,1	3,1	3,0	3,0
Difference		356%	359%	361%	319%	277%	245%	251%
Addtional mass		0%	0%	0%	0%	0%	0%	0%

Figure 95: Kerto Ripa Rib Office 6% damping



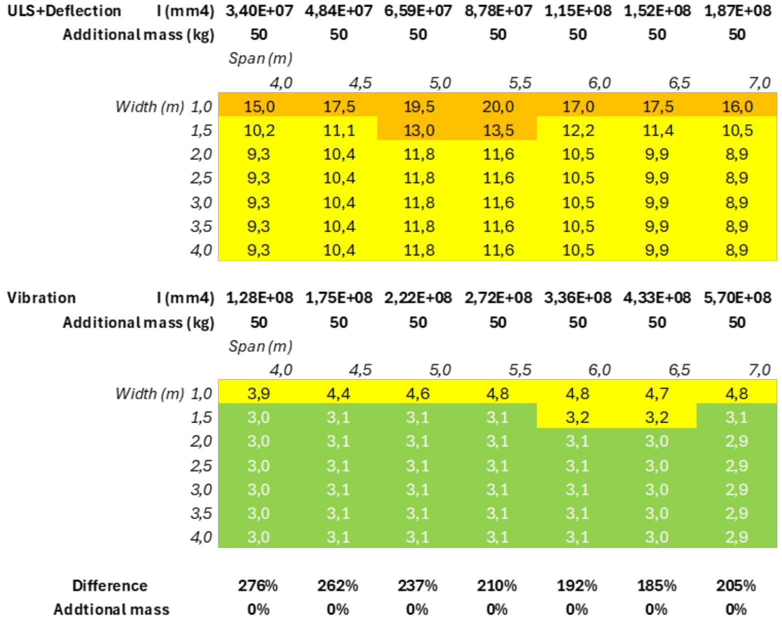
ULS+Deflection	I (mm4)	3,40E+07	4,84E+07	6,59E+07	8,78E+07	1,15E+08	1,52E+08	1,87E+08
	Additional mass (kg)	50	50	50	50	50	50	50
		Span (m)						
		4,0	4,5	5,0	5,5	6,0	6,5	7,0
	Width (m) 1,0	16,0	18,5	23,0	23,0	21,0	20,0	17,5
	1,5	10,0	12,4	15,5	16,0	14,0	13,0	12,0
	2,0	9,6	11,5	13,5	13,5	12,4	11,5	9,9
	2,5	9,6	11,5	13,5	13,5	12,4	11,5	9,9
	3,0	9,6	11,5	13,5	13,5	12,4	11,5	9,9
	3,5	9,6	11,5	13,5	13,5	12,4	11,5	9,9
	4,0	9,6	11,5	13,5	13,5	12,4	11,5	9,9
Vibration	I (mm4)	1,42E+08	1,98E+08	2,72E+08	3,68E+08	4,33E+08	4,78E+08	6,56E+08
	Additional mass (kg)	50	50	50	50	50	50	50
		Span (m)						
		4,0	4,5	5,0	5,5	6,0	6,5	7,0
	Width (m) 1,0	3,9	4,3	4,6	4,0	4,0	4,8	4,3
	1,5	3,1	3,1	3,1	3,0	3,0	3,1	3,0
	2,0	3,1	3,1	3,1	3,0	3,0	3,1	2,9
	2,5	3,1	3,1	3,1	3,0	3,0	3,1	2,9
	3,0	3,1	3,1	3,1	3,0	3,0	3,1	2,9
	3,5	3,1	3,1	3,1	3,0	3,0	3,1	2,9
	4,0	3,1	3,1	3,1	3,0	3,0	3,1	2,9
Difference		318%	309%	313%	319%	277%	214%	251%
Addtional mass		0%	0%	0%	0%	0%	0%	0%

Figure 96: Kerto Ripa Rib Office 7% damping



ULS+Deflection	I (mm4)	3,40E+07	4,84E+07	6,59E+07	8,78E+07	1,15E+08	1,52E+08	1,87E+08
	Additional mass (kg)	50	50	50	50	50	50	50
		Span (m)						
		4,0	*4,5*	*5,0*	*5,5*	*6,0*	*6,5*	*7,0*
	Width (m) 1,0	15,5	18,0	21,0	21,0	19,0	17,0	16,0
	1,5	10,5	11,9	14,0	14,0	13,5	12,2	11,2
	2,0	9,4	10,9	12,6	12,4	11,3	10,4	9,3
	2,5	9,4	10,9	12,6	12,4	11,3	10,4	9,3
	3,0	9,4	10,9	12,6	12,4	11,3	10,4	9,3
	3,5	9,4	10,9	12,6	12,4	11,3	10,4	9,3
	4,0	9,4	10,9	12,6	12,4	11,3	10,4	9,3
Vibration	I (mm4)	1,42E+08	1,98E+08	2,45E+08	3,04E+08	3,68E+08	4,78E+08	5,70E+08
	Additional mass (kg)	50	50	50	50	50	50	50
		Span (m)						
		4,0	*4,5*	*5,0*	*5,5*	*6,0*	*6,5*	*7,0*
	Width (m) 1,0	3,8	4,1	4,5	4,2	4,6	4,4	4,9
	1,5	3,0	3,0	3,1	3,1	3,1	3,1	3,3
	2,0	3,0	3,0	3,1	3,1	3,1	3,0	3,1
	2,5	3,0	3,0	3,1	3,1	3,1	3,0	3,1
	3,0	3,0	3,0	3,1	3,1	3,1	3,0	3,1
	3,5	3,0	3,0	3,1	3,1	3,1	3,0	3,1
	4,0	3,0	3,0	3,1	3,1	3,1	3,0	3,1
Difference		318%	309%	272%	246%	220%	214%	205%
Addtional mass		0%	0%	0%	0%	0%	0%	0%

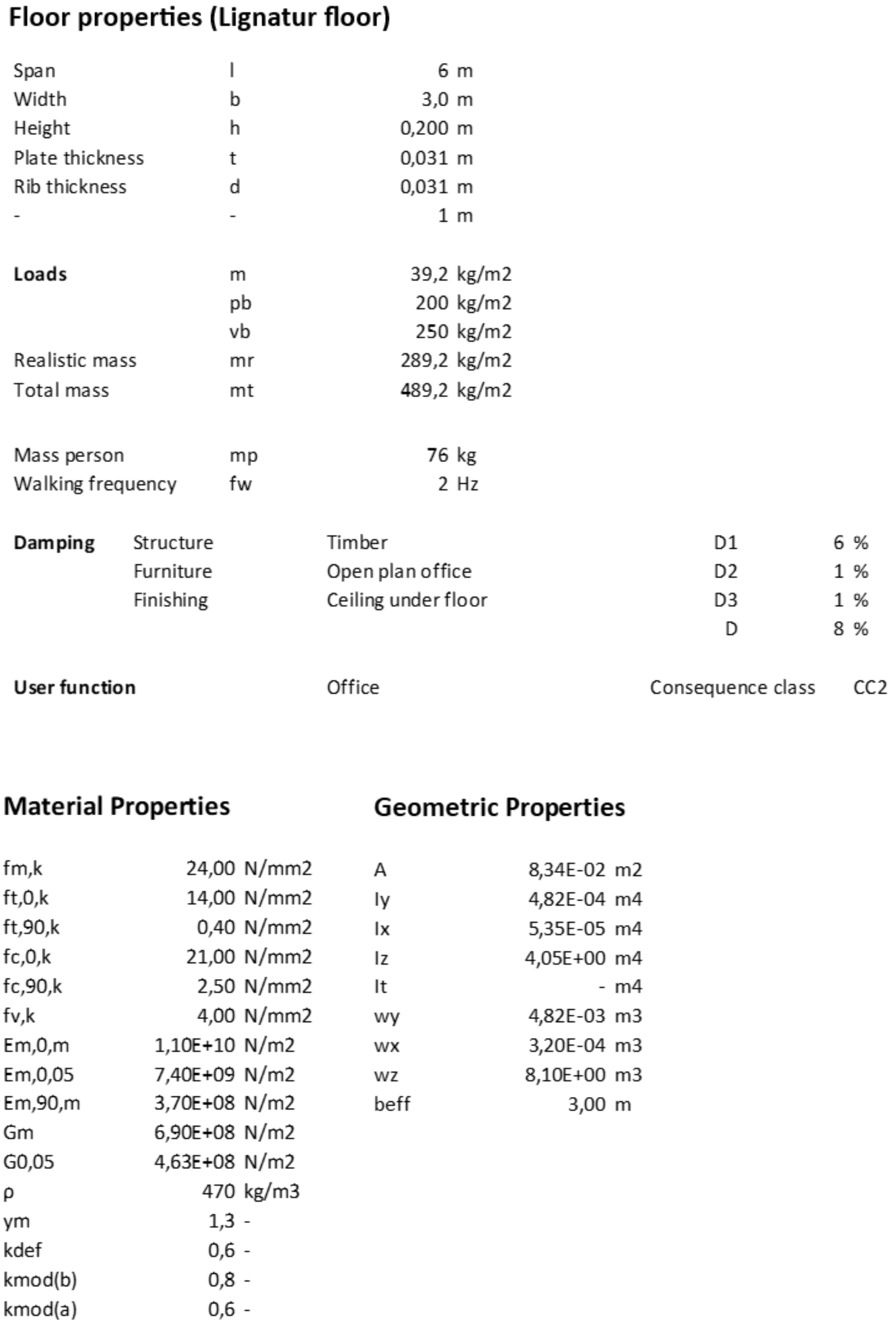
Figure 97: Kerto Ripa Rib Office 8% damping



ULS+Deflection	I (mm4)	3,40E+07	4,84E+07	6,59E+07	8,78E+07	1,15E+08	1,52E+08	1,87E+08
	Additional mass (kg)	50	50	50	50	50	50	50
		Span (m)						
		4,0	*4,5*	*5,0*	*5,5*	*6,0*	*6,5*	*7,0*
	Width (m) 1,0	15,0	17,5	19,5	20,0	17,0	17,5	16,0
	1,5	10,2	11,1	13,0	13,5	12,2	11,4	10,5
	2,0	9,3	10,4	11,8	11,6	10,5	9,9	8,9
	2,5	9,3	10,4	11,8	11,6	10,5	9,9	8,9
	3,0	9,3	10,4	11,8	11,6	10,5	9,9	8,9
	3,5	9,3	10,4	11,8	11,6	10,5	9,9	8,9
	4,0	9,3	10,4	11,8	11,6	10,5	9,9	8,9
Vibration	I (mm4)	1,28E+08	1,75E+08	2,22E+08	2,72E+08	3,36E+08	4,33E+08	5,70E+08
	Additional mass (kg)	50	50	50	50	50	50	50
		Span (m)						
		4,0	*4,5*	*5,0*	*5,5*	*6,0*	*6,5*	*7,0*
	Width (m) 1,0	3,9	4,4	4,6	4,8	4,8	4,7	4,8
	1,5	3,0	3,1	3,1	3,1	3,2	3,2	3,1
	2,0	3,0	3,1	3,1	3,1	3,1	3,0	2,9
	2,5	3,0	3,1	3,1	3,1	3,1	3,0	2,9
	3,0	3,0	3,1	3,1	3,1	3,1	3,0	2,9
	3,5	3,0	3,1	3,1	3,1	3,1	3,0	2,9
	4,0	3,0	3,1	3,1	3,1	3,1	3,0	2,9
Difference		276%	262%	237%	210%	192%	185%	205%
Addtional mass		0%	0%	0%	0%	0%	0%	0%

Figure 98: Kerto Ripa Rib Office 9% damping

D OS-RMS90 calculation standard floor



Floor properties (Lignatur floor)

Span	l	6	m
Width	b	3,0	m
Height	h	0,200	m
Plate thickness	t	0,031	m
Rib thickness	d	0,031	m
-	-	1	m
Loads	m	39,2	kg/m2
	pb	200	kg/m2
	vb	250	kg/m2
Realistic mass	mr	289,2	kg/m2
Total mass	mt	489,2	kg/m2
Mass person	mp	76	kg
Walking frequency	fw	2	Hz

Damping	Structure	Timber	D1	6	%
	Furniture	Open plan office	D2	1	%
	Finishing	Ceiling under floor	D3	1	%
			D	8	%

User function	Office	Consequence class	CC2

Material Properties

fm,k	24,00	N/mm2
ft,0,k	14,00	N/mm2
ft,90,k	0,40	N/mm2
fc,0,k	21,00	N/mm2
fc,90,k	2,50	N/mm2
fv,k	4,00	N/mm2
Em,0,m	1,10E+10	N/m2
Em,0,05	7,40E+09	N/m2
Em,90,m	3,70E+08	N/m2
Gm	6,90E+08	N/m2
G0,05	4,63E+08	N/m2
ρ	470	kg/m3
ym	1,3	-
kdef	0,6	-
kmod(b)	0,8	-
kmod(a)	0,6	-

Geometric Properties

A	8,34E-02	m2
Iy	4,82E-04	m4
Ix	5,35E-05	m4
Iz	4,05E+00	m4
It	-	m4
wy	4,82E-03	m3
wx	3,20E-04	m3
wz	8,10E+00	m3
beff	3,00	m

Vibration properties

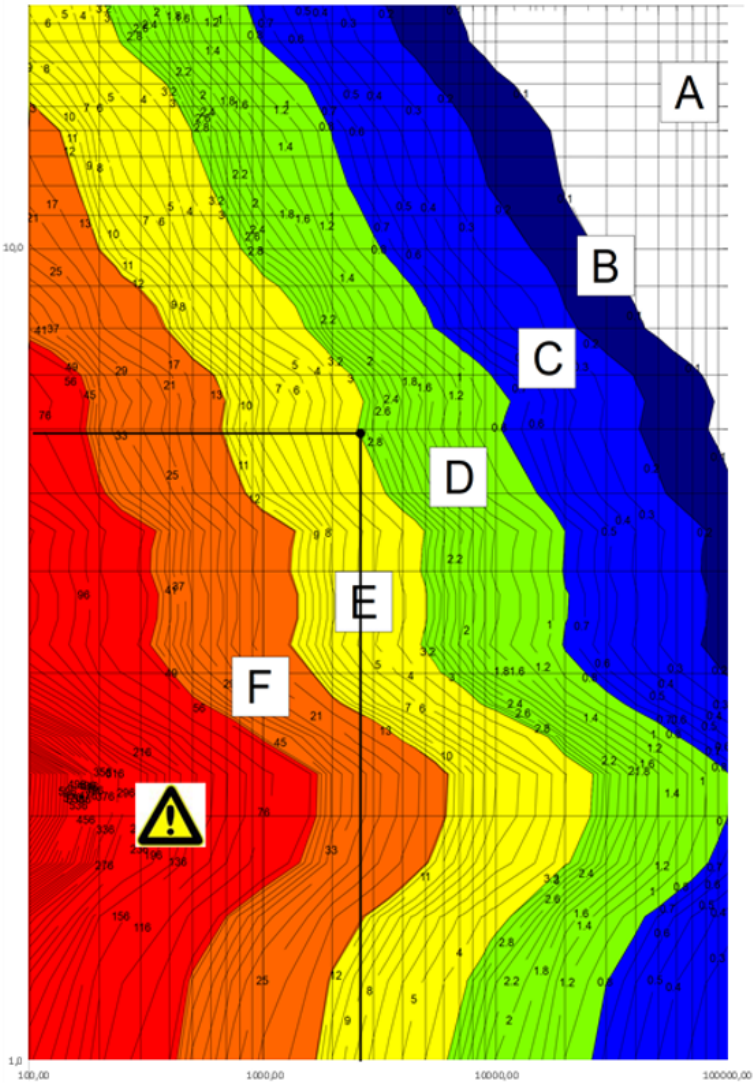
Natural frequency: $\frac{\pi}{2 * l^2} * \sqrt{\frac{EI_y}{m_r}}$ = 5,91 Hz

Modal Mass: $\frac{m_r * l * b_{eff}}{2}$ = 2602,7 kg

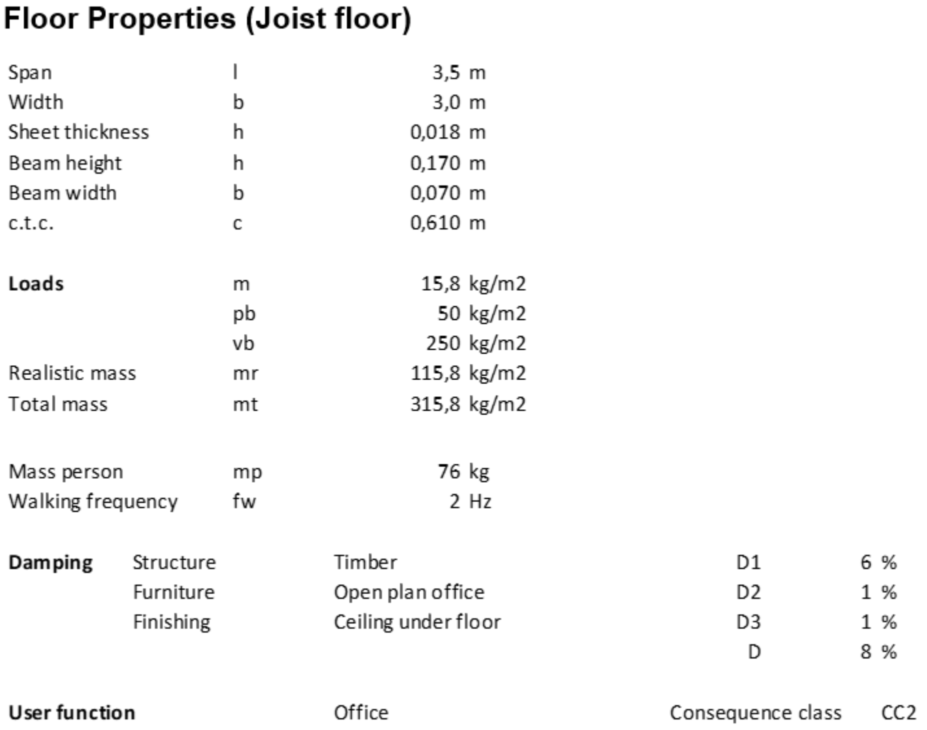
Effective width: $\frac{l}{1{,}1} * \frac{EI_y}{EI_x}^{0{,}25}$ = 3,15 m > 3,00 m

Damping: = 8%

OS-RMS$_{90}$ graph (8% damping)



E Decrease mass different width

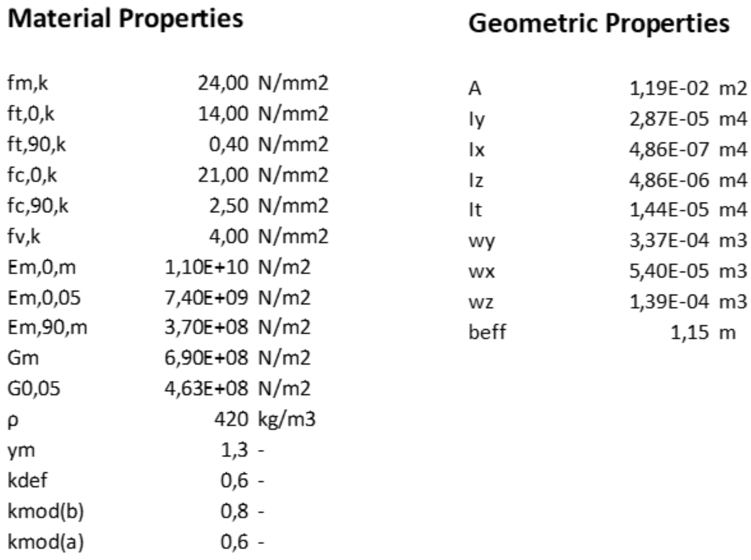


Floor Properties (Joist floor)

Span	l	3,5	m
Width	b	3,0	m
Sheet thickness	h	0,018	m
Beam height	h	0,170	m
Beam width	b	0,070	m
c.t.c.	c	0,610	m
Loads	m	15,8	kg/m2
	pb	50	kg/m2
	vb	250	kg/m2
Realistic mass	mr	115,8	kg/m2
Total mass	mt	315,8	kg/m2
Mass person	mp	76	kg
Walking frequency	fw	2	Hz

Damping	Structure	Timber	D1	6	%
	Furniture	Open plan office	D2	1	%
	Finishing	Ceiling under floor	D3	1	%
			D	8	%

User function	Office	Consequence class	CC2



Material Properties

fm,k	24,00	N/mm2
ft,0,k	14,00	N/mm2
ft,90,k	0,40	N/mm2
fc,0,k	21,00	N/mm2
fc,90,k	2,50	N/mm2
fv,k	4,00	N/mm2
Em,0,m	1,10E+10	N/m2
Em,0,05	7,40E+09	N/m2
Em,90,m	3,70E+08	N/m2
Gm	6,90E+08	N/m2
G0,05	4,63E+08	N/m2
ρ	420	kg/m3
ym	1,3	-
kdef	0,6	-
kmod(b)	0,8	-
kmod(a)	0,6	-

Geometric Properties

A	1,19E-02	m2
Iy	2,87E-05	m4
Ix	4,86E-07	m4
Iz	4,86E-06	m4
It	1,44E-05	m4
wy	3,37E-04	m3
wx	5,40E-05	m3
wz	1,39E-04	m3
beff	1,15	m

Loads

Fgk = 0 kN
Fqk = 0,76 kN
qgk = 0,40 kN/m
qqk = 1,53 kN/m

Loads in ULS

QEd = 0,54 kN/m
= 2,77 kN/m
= 0,54 kN/m
= 0,48 kN/m
FEd = 0 kN
= 1,14 kN

MEd = 0,83 kNm
= 0,83 kNm
= 4,24 kNm
= 1,73 kNm
Ved = 0,95 kN
= 0,95 kN
= 4,85 kN
= 1,98 kN

Deflections

			limiet	**UC**
Uon	=	2,49 mm		
Ubij	=	9,45 mm	10,5 mm	0,90
Ubij	=	2,15 mm	10,5 mm	0,21
Ueind	=	13,43 mm	14 mm	0,96

Moment

σm;crit = 41,23 N/mm^2
λrel;m = 0,762962
kcrit = 0,987779

6.10b

σm,0,d = 12,57 N/mm^2
fm,0,d = 14,77 N/mm^2 0,86

6.10a

σm,0,d = 2,46 N/mm^2
fm,0,d = 11,08 N/mm^2 0,22

Shear Forces

6.10b

tv,d = 0,61 N/mm^2
fv,d = 2,46 N/mm^2 0,25

6.10a

tv,d = 0,12 N/mm^2
fv,d = 1,85 N/mm^2 0,06