
Human-Induced Vibrations in Timber Floor Systems

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Abstract

Using 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 requires significantly more material usage for the floor system. Therefore, the goal of this research is the reduction of ballast in a floor system, while maintaining the desired level of vibration performance. An analytical analysis is performed to research 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-RMS₉₀ 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. This can be explained by their higher self-weight and higher transverse stiffness. The optimisations consist out of two methods: strategically placed mass and tuned mass. The Lignatur floor system was chosen for the optimisation methods, due to its performance and the ability to apply ballast inside the floor elements. The optimization using strategically placed mass shows that the ballast on the floor can be reduced by 36% for a Lignatur floor system. When placing the ballast on top of a spring system, a total reduction in ballast of 25% 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, meaning that the most optimal solution is not always practically feasible.

Keywords: Human-induced vibrations, timber floor systems, OS-RMS₉₀ method, strategically placed mass, tuned mass, Lignatur, optimisations

1. Introduction

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. 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 dwellings 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 and floor systems should be assessed 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 structures.

The goal of this research is to get more knowledge on vibrations in different types of timber floors. 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?”

This research aims to show the opportunities of optimising the additional mass used on timber floor systems to comply with the vibration requirements.

2. Literature

2.1. 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 the 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].

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 [4].

A person walking on a floor will tolerate much larger amplitudes than a person sitting or lying. 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 $0,0005 \cdot g$. Humans are not able to perceive small changes in amplitude; the vibration amplitude often has to be doubled before the change is perceived [4].

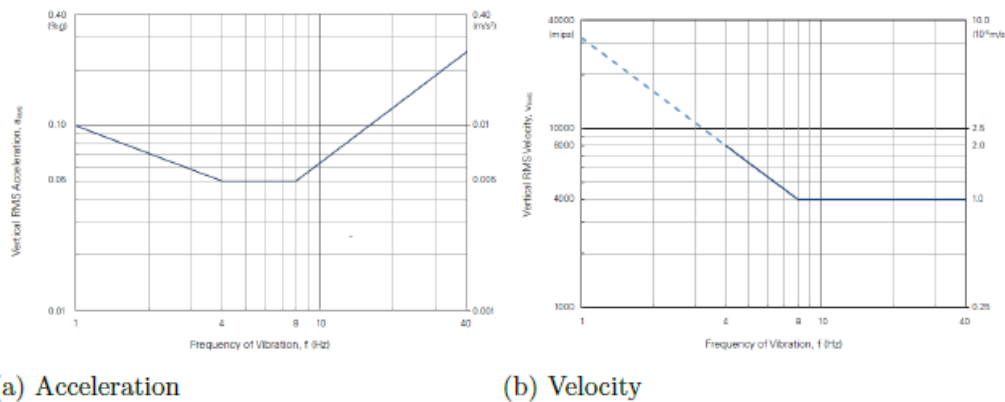


Figure 1: Human limits of perception for acceleration and velocity [4].

From Figure 1, 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 frequency under 8 Hz. Velocity is used for high-frequency floors, with a 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, also 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].

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. 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. 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 [12]. 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 of the floor system [9].

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]. 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.

2.3. OS-RMS₉₀

The OS-RMS₉₀ is a method to determine the floor response values for vertical vibrations. The response value of a floor system depends on the fundamental frequency, the modal mass, and the damping of the floor [1]. The response value obtained from the assessment fits into one of the six response classes, A to F. The response classes have an upper and lower bound concerning the response value of the OS-RMS₉₀. Since the perception of vibrations is dependent on the activities carried out by users, different building functions are assigned different recommended floor response classes, see Figure 2 [12].

Class	OS-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	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
B	0.1	0.2	Yellow	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
C	0.2	0.8	Red	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
D	0.8	3.2	Red	Yellow	Green	Green	Green	Green	Green	Green	Green	Green	Green
E	3.2	12.8	Red	Red	Red	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow
F	12.8	51.2	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Yellow

Figure 2: Response classes compared to different user functions. [12]

The OS-RMS₉₀ 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-RMS₉₀ value. With coloured ranges, the corresponding floor response classes are indicated.

4. Analytical analysis

The analytical analysis is the first part of the vibration analysis. This analysis consists of hand calculations based on the OS-RMS₉₀ method. The goal of this analysis is to find the difference in structural height for a floor designed without and with vibration requirements. For this analysis, four different timber floor systems will be analysed. The analytical part will be used to validate the numerical results and give more insights into the vibrational behaviour of timber floors. The four different floor systems are the following: Joist floor, CLT, Lignatur and Kerto Ripa Rib.

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/m² is taken on top of the floor.

4.1. Methods

4.1.1. Natural Frequency

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

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 Nm²
- m = the mass of the floor systems per unit area in kg/m²

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.

4.1.2. Modal Mass

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

Where:

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

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

The effective width is introduced in the formula of the modal mass instead of using the actual width of the floor. When 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.

4.1.3. Damping

The damping is based on the total damping presented in Table 2. The resulting damping value from that table will determine the OS-RMS₉₀ graph that needs to be used for the particular situation.

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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 2: Damping values OS-RMS₉₀ method.

4.2. 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]. 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-RMS₉₀ value.. 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 Table 3.

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 D of the OS-RMS₉₀ 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 analysis will be performed with several ranging parameters, building function (office or residential) and the damping value of the floor system. For these parameters, different tables are created.

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%

Table 3: OS-RMS₉₀ results for a Lignatur floor system.

4.3. Results

The following not floor system related results are found in the analysis. 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. This results in a better RMS value for this floor. 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.

4.3.1. 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. For spans of four meters or larger, it is not possible to meet the required vibration class with the standardized dimensions of the joist floor.

4.3.2. 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. The CLT floor also has a high self-weight in comparison to the other three floor systems.

4.3.3. Lignatur

The vibration performance of the Lignatur floor system is comparable to the CLT 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. 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.

4.3.4. 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. Furthermore, the Kerto Ripa Rib floor can also be optimised regarding vibrations for spans larger than 4 meters, in contrast to the Joist floor.

5. 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 Modelling (FEM). GSA will be used as FEM software. The analytical analysis shows that the CLT and the Lignatur floor systems perform significantly better than the Joist and Kerto Ripa Rib floors. 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.

5.1. GSA

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.

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. The footfall analysis yields multiple values to analyse the performance of the floor: peak acceleration, RMS acceleration, peak velocity, and RMS velocity. These values will be used for the optimisations of the Lignatur floor system.

6. 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.

6.1. 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. There are several boundaries for the optimisation of this concept. First, there should always be a permanent mass of 50 kg/m² on the whole area of the floor. This permanent mass is the finishing layer on top of the Lignatur floor. A second boundary is that the unity check of the complete floor system should always be under 1.0 even with the additional mass.

6.2. 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.

6.3. Methods

GSA will be used to analyse the floor systems, however, the floors are designed using the OS-RMS₉₀ method. First, a floor system is designed to comply with vibration class D of the 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. 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.

6.3.1. Standard Floor

The floor chosen as the standard floor is a Lignatur 200 floor, with a span of six meters and a width of three 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-RMS₉₀ calculation. Alongside that, on the floor is also 20% of the live load of 250 kg/m^2 . 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, and mass on springs. The goal for all researched floors is to decrease additional mass while maintaining the same level of vibration performance as the standard floor.

6.3.2. Optimisation method

The benchmark value obtained following the design process explained in 6.3 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. A decrease in the percentage of the total mass can be calculated from the values for the old and the new floor, including the permanent mass of 50 kg/m^2 .

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. 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.

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 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.

7. Results

7.1. Standard Floor

The standard floor complies with the requirements for a class D floor following the OS-RMS₉₀ calculation, meaning that the peak acceleration value resulting from the footfall analysis can be taken as the benchmark. The peak acceleration for the Lignatur element of the standard floor is $0,399 \text{ m/s}^2$. This value is taken as the benchmark peak acceleration value.

7.1.1. Longitudinal Variable Mass

For the standard floor, the mass will be increased from the middle of the floor as was explained in 6.3.2. The values resulting from this analysis can be seen in Figure 3. 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.

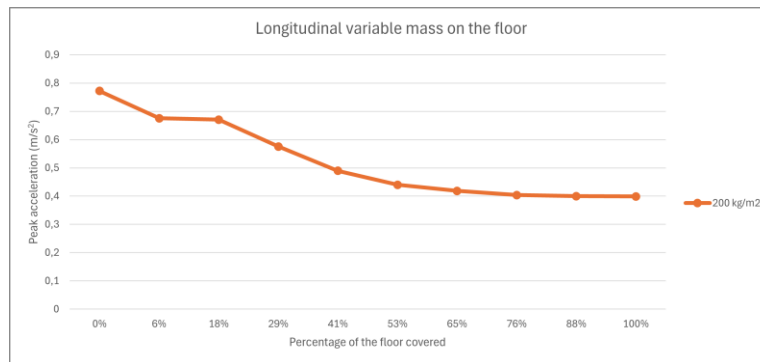


Figure 3: Longitudinal variable mass for the standard floor.

7.1.2. 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 4. When the 580 kg of additional mass is concentrated in the middle of the floor, the peak acceleration is below the benchmark of 0,399 m/s². The mass can be decreased to 460 kg for the standard floor when applied over a maximum length of 0,9 meters. This results in a decrease in mass of 36% in comparison with the standard floor.

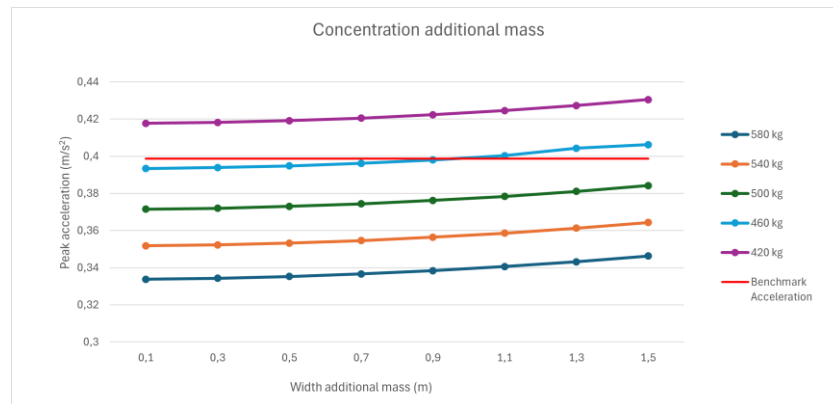


Figure 4: Concentrated additional mass standard floor.

7.2. Different Spans

The optimisation method is assessed for different spans. For every span, the Lignatur section is calculated using the OS-RMS₉₀, as was also performed for the standard floor. The Lignatur floors with a span of 5,5 meters to seven 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. This is because the benchmark for this floor is 0,5 m/s², this is higher than the standard floor, making it easier to stay under the benchmark and thus save more mass.

7.3. 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 7.1.1 only 65%

of the additional mass in the middle of the floor influences the acceleration. Therefore, 65% of additional mass is also taken as starting point for this analysis.

The same principle that was used in 6.3.2 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 5. 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. 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.

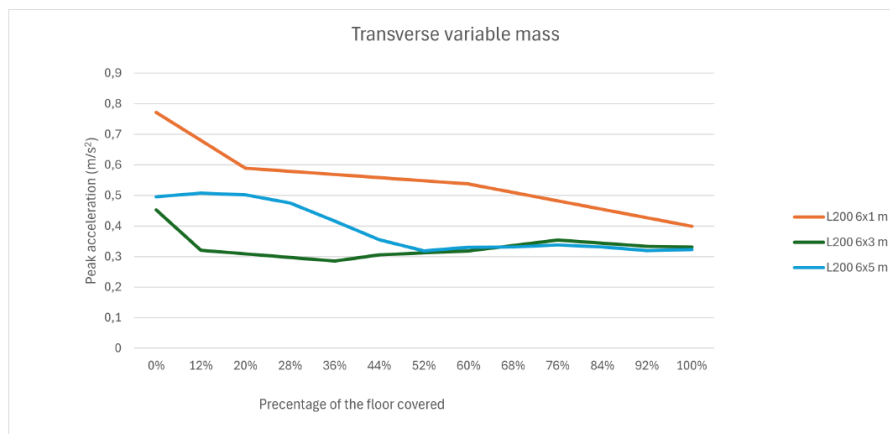


Figure 5: Transverse variable mass for a 1,3- and 5-meters wide floor.

When analysing a one-meter-wide Lignatur element of the standard floor in GSA, it can be observed that only the lowest mode shape contributes to the peak acceleration of the floor. For this mode shape the deformation is constant over the width of the 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. 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.

When moving the person from the middle of the floor towards the edge, the following results can be seen. 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 certain locations, particularly closer to the edge, the mass of the person does not contribute as much to the modal mass of the floor. When both the frequency and modal mass decrease, the acceleration of the floor must increase. Meaning that placing mass close to the edge of the floor is not beneficial for the acceleration value.

7.4. 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. As expected, a higher damping value will lead to a lower peak acceleration value. However, the damping value does not influence the decrease in mass, as floors with different damping values follow the same trend.

7.5. Different Function

The standard floor has an office function. The influence of the function on the mass decrease of the floor will be assessed for the residential function as well. First, the floor should be redesigned using the OS-RMS₉₀ method, while the loading is changed for the residential function. A live load of 175 kg/m² is stated for a residential floor. Applying the reduction for the live load, the live load acting in the vibration analysis is 35 kg/m². This is a decrease of 15 kg/m² 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/m² plus the 50 kg/m² of permanent mass is needed on the floor. This is instead of the 150 kg/m² plus 50 kg/m² 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.

7.5. Mass on Springs

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 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.

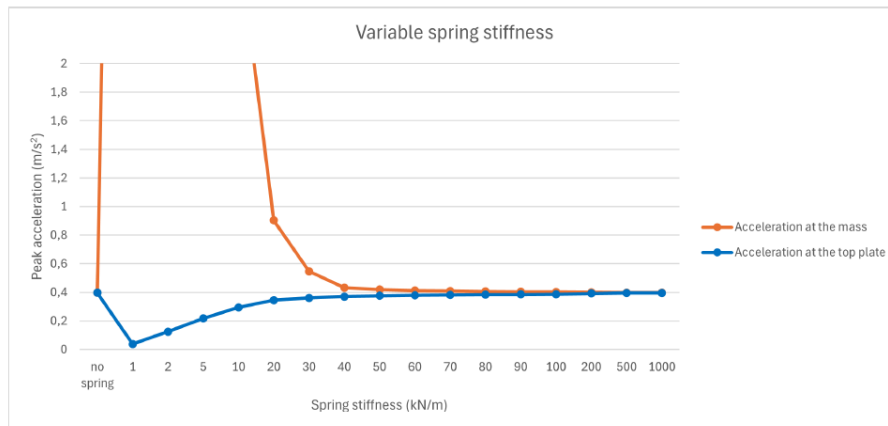


Figure 6: Variable spring stiffness for the standard floor.

The results of the standard floor including springs can be seen in Figure 6. 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.

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/s². The goal is to reduce the mass needed by using springs. The resulting decrease in mass is calculated and presented in Table 4.

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

Table 4: Mass decrease for different spring stiffness.

7.7. 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%. The benchmark of the floor is still stated at the original level of 0,399 m/s².

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 is in line with the earlier found results of the standard floor. However, due to the springs, a total mass of 150 kg/m² is used instead of 200 kg/m², 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.

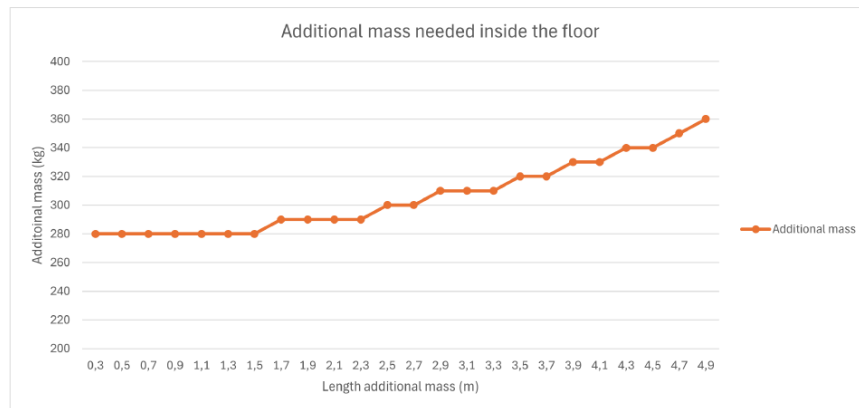


Figure 7: Total mass needed for different concentrations of mass.

The 390 kg of additional mass is used as starting point for the concentrated mass method. 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/m² for the spring stiffness. The results of the concentrated mass method is visible in Figure 7, this figure shows the additional mass that is needed for the different mass concentrations. 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 they range from 52% to 45%.

8. Practical Implementation

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. The standard ballast material used for a Lignatur floor is

concrete [21]. They have a high density and are practical in use. These blocks can be placed at specific locations in the Lignatur floor element.

8.1. 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.

8.2. Strategic Mass

Following the optimisations found for the standard floor, the needed concentration of mass can be found. 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 m² on which the ballast can be placed.

From this it can be calculated that a concentrated ballast of 555 kg/m² is needed. 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 Figure 4 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, a concentrated ballast of 298 kg/m² 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% for the standard floor. This is less than the 36% calculated in the most optimal solution, however, for that situation, the concentrated ballast is too high and cannot be applied inside the floor

8.3. 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.

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. When applying a spring stiffness of 5 kN/m, a ballast of 150 kg/m² is needed. To apply this ballast, a height of 79 mm is needed for the concrete blocks. With the springs stiffness of 5 kN/m the ballast will deform 6 mm, so, the free space needed inside the floor is 85 mm. This means that there is 53 mm of free space left for a spring system that needs to deform 6 mm. This can for example be achieved by a rubber strip, with the appropriate spring stiffness.

8.4. 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.

9. Conclusion

The main goal of this research was to decrease the mass used on timber floor systems to comply with the vibration requirements. 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.

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, next to that, the modal mass is also low due to the small effective width that can be taken into account.

During the second part, optimizations of the mass applied to the floor systems are researched. Two different optimization types can be distinguished: strategically placed mass and mass on springs. For the strategically placed mass, it was found that a decrease in mass of 36% is 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% is possible, due to the volume of the ballast, which will not fit inside the floor.

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 reduction in mass 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% is feasible. However, the decrease is different depending on the floor width.

The mass on springs can theoretically reduce the additional mass by 50%. However, practically this would result in a complex spring system. A reduction of 25% 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 as a theoretical reduction, while this solution would take up too much space inside the floor system. In conclusion, when answering the research question, it can be said that for both of the optimization solutions, a reduction in mass is possible while maintaining the desired acceleration level of the floor.

10. Recommendations

The obtained results allow for further research on the topic. 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 floors, which are more than one Lignatur element wide, the location of the mass in the transverse direction becomes critical. Further research of different widths is recommended so that a common thread can be found for the location of the strategic mass in the transverse direction, like as done for different spans.

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.

The reduction of mass calculated in this research complies with the vibrations caused by humans. 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.

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. 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.

References

- [1] Youssef E L Asri, Engineer-phd Candidate, and Ctictm-insa Ulg. Vibration comfort of floors : State-of-the-art 2 Vibration comfort standards. pages 1–43.
- [2] Redactie Bouwwereld. Houten vloer tussen stalen liggers, 2015.
- [3] G. Braber. Understanding the booming popularity of timber construction, 2019.
- [4] Scott Breneman, Reid Zimmerman, Adam Gerber, Lucas Epp, Carla Dickof, Andrew Taylor, William Loasby, Eric McDonnell, Christian Slotboom, Jack McCutcheon, and Rene Visscher. U.S. Mass Timber Floor Vibration. Wood-Works, 2021.
- [5] Centrum Hout. Naaldhout in de bouw. page 16, 2005.
- [6] Comsol. Eigenfrequency Analysis, 2018.
- [7] Daniel Dlubal. Key Elements of Structural Dynamics: Mode Shape, Natural Period, and Modal Mass, 2024.
- [8] Britannica Online Encyclopedia. Vibration, 2024.
- [9] M Feldmann, Ch Heinemeyer, Chr Butz, Elsa Caetano, Alvaro Cunha, F Galanti, and A Goldack. Design of floor structures for human induced vibrations, volume 3. 2009.
- [10] Markus Feldmann, Christoph Heinemeyer, and B Volling. Design Guide for Floor Vibrations - ArcelorMittal. Built Environment, pages 3–5, 2008.
- [11] Finnforest. Kerto-Ripa. 2009.
- [12] F. Galanti, Ch Heinemeyer, M. Feldmann, and S. Lentzen. Assessment of floor vibration using the OS-RMS90 method. Proceedings of the 8th International Conference on Structural Dynamics, EURO DYN 2011, (July):1072–1076, 2011.
- [13] Ivan Glisovic and Bosko Stevanovic. Vibrational behaviour of timber floors. 11th World Conference on Timber Engineering 2010, WCTE 2010, 4 (January 2010):2785–2793, 2010.
- [14] Anders Gustafsson, Roberto Crocetti, Alar Just, Pierre Landel, Jorgen Olsson, Anna Pousette, and Birgit Silfverhielm, Magnus Ostman. The CLT Handbook. Skogsindustrierna, Stockholm, 2019.
- [15] Jouni Hakkarainen, Lauri Linkosalmi, Anu Houvinen, Seije Vares, and Tarje Hakkinen. LVL Handbook. Federation of the Finnish Woodworking Industries, Helsinki, 2019.
- [16] Oliver Hechler, Markus Feldmann, Christoph Heinemeyer, and Flavio Galanti. Design guide for floor vibrations. Built Environment, (September):3–5, 2008.
- [17] Human induced Vibrations of Steel Structures. Trillingen Van Vloeren Ontwerprichtlijn. Research Fund for Coal & Steel, (33), 2007.
- [18] British Standards Institution. No Title. In Eurocode 5 - Ontwerp en berekening van houtconstructies. 2014.
- [19] Joostdevree. Enkelvoudige balklaag.
- [20] HJ. Larsen and S. Thelandersson. 7. Timber Engineering.pdf. In Timber Engineering, pages 248–265. 2003.
- [21] Lignatur. Workbook.
- [22] H. Ma and D. W. Ruth. A numerical analysis of the interfacial drag force for fluid flow in porous media. Transport in Porous Media, 17(1):87–103, 1994.
- [23] Whokko Schirren and Trixie Swahn. Vibrations in residential timber floors. page 100, 2019.
- [24] SkyCiv. Alles wat u moet weten over kruislings gelamineerd hout, 2021.
- [25] E.C. Slooten. Feasibility study of a wood- concrete hybrid super tall building and optimization of its wind-induced behaviour. 350:273, 2018.
- [26] TU Delft. Houten dooselement, 2016.
- [27] Mechanical Vibration, Prentice Hall, Mechanical Vibration, Structural Dynamics, and Forces Example. ME 4440-5540 Lecture 1.